DOCTOR OF PHILOSOPHY

Age estimation in the living: a test of 6 radiographic methods

Hackman, S. Lucina M. R.

Award date:
2012

Awarding institution:
University of Dundee

Age estimation in the living: a test of 6 radiographic methods

S. Lucina M. R. Hackman

2012

University of Dundee

UNIVERSITY OF DUNDEE

Age Estimation in the Living: a test of 6 radiographic methods

S. Lucina M.R. Hackman

Ph.D. Thesis

March 2012

Table of Contents

Tables

Figures

Abbreviations

CA – Chronological age

CBA – Carpal bone age

EA – Estimated age

FLE – Female left elbow

FLF – Female left foot/ankle

FLH – Female left hand/wrist

FLK – Female left knee

MLE – Male left elbow

MLF – Male left foot/ankle

MLH – Male left hand/wrist

MLK – Male left knee

RUS - Radius, ulna and short bones

TW1 – Tanner-Whitehouse 1 (the first atlas in the series published in 1962)

TW2 – Tanner-Whitehouse 2 (the second atlas in the series published in 1975)

TW3 – Tanner-Whitehouse 3 (the third atlas in the series published in 2001)

Acknowledgements

Declaration

I, Lucina Hackman, declare that I am the author of this thesis, Age Estimation in the Living: a test of 6 radiographic methods, that, unless otherwise stated, all references cited have been consulted by me and the work of which this thesis is a record has been done by myself, furthermore I confirm that the work contained within has not been previously accepted for a higher degree.

Signed.. Date......................

Lucina Hackman BSc, MSc.

Summary

There is a growing recognition that there is a requirement for methods of age estimation of the living to be rigorously tested to ensure that they are accurate, reliable and valid for use in forensic and humanitarian age estimation. The necessity for accurate and reliable methods of age estimation are driven both by humanitarian, political and judicial need.

Age estimation methods commonly in use today are based on the application of reference standards, known as atlases, which were developed using data collected from children who participated in longitudinal studies in the early to mid-1900s. The standards were originally developed to provide a baseline to which radiographs could be compared in order to assess the child's stage of skeletal development in relation to their chronological age, a purpose for which they are still utilised in the medical community.

These atlases provide a testable link between skeletal age and chronological age which has been recognised by forensic practitioners who have essentially hijacked this medical capability and applied it to their fields. This has resulted in an increased use of these standards as a method of predicting the chronological age from the skeletal age of a child when the former is unknown. This novel use of the atlases on populations who are distinct, ethnically, temporally and geographically, from those whose data was gathered and was used in the design of the standard leaves the forensic outcomes vulnerable to challenge in court. This study aims to examine the reliability and accuracy of these standards in relation to a modern population, providing a sound statistical base for the use of these standards for forensic purposes.

Radiographs were collected from the local hospital from children who had been X-rayed for investigation during attendance at the local A&E department. Four body areas were selected for investigation; the hand-wrist, the elbow, the knee and the foot-ankle and tests were undertaken to assess the radiographs using six commonly uses methods of age estimation. Further images of the wrist and elbow were collected from children in New Delhi, India. These images were subject to age estimation utilising the methods described.

Hypothesis

That the standards which are commonly used in age estimation of the skeleton are appropriate, robust and reliable enough to be utilised in the age estimation of an individual from a modern population for forensic purposes.

Aims

To test six standards used in age estimation in the living on a modern population from the North-East of Scotland.

To examine the robusticity of an analysis of a radiograph of the right side of the body using a standard based entirely on images from the left side of the body

Objectives

1. To collect radiographs (both anterior-posterior and lateral where appropriate) from 4 anatomical areas; the hand-wrist, the elbow, the knee and the foot ankle from female and male children aged between birth and 20 years of age. Data to be collected to include; sex, Date of birth (DOB) and date of image acquisition.

2. To collect radiographs from an equivalent population in New Delhi India for comparison with those collected from the Scottish population.

3. To identify 6 radiographic age estimation methods which are in common use today and test them on the dataset of collected radiographs.

4. To undertake a statistical analysis of the results of the age estimations undertaken using the age estimation methods to assess the reliability of the methods in relation to chronological age.

5. To test the repeatability of the methods by devising an inter-observer test for each method.

6. To compare methods using appropriate statistical methodologies to understand the relationship between them.

7. To test whether the side of the body which is radiographed affects the accuracy of age estimation.

8. To compare radiographs of the right side of the body with radiographs of the left side of the body to understand whether the maturational development of each side differs significantly.

1   Literature Review

Chronological age is defined as the time that has passed since an individual was born and is usually measured in days, weeks and months for young children and in years for older children. Whilst various cultures measure the passing of time in different ways, in many countries chronological age has become a significant part of a person's identity.   As a result the ability to prove chronological age has become a major component of daily life and, most importantly for vulnerable children, is a way of accessing support and education. The inability to prove age to those in authority through the production of documentation, can lead to access to resources being restricted as the individual is treated, perhaps incorrectly, by society and the law as an adult. The treatment of an adult as a child, whilst less potentially harmful for the individual themselves has implications for the safety of others when they are housed with vulnerable children and limits the resources available to those who are in genuine need. Access to accurate and reliable age estimation techniques is undeniably extremely important in these cases where there is no other evidence to support a claim.

In cases where it is not possible to provide evidence of age, there are a number of methods that can be used to estimate chronological age, all of which rely on the maturational changes which an individual undergoes as they progress through childhood. Age estimation assessments relate to the process of establishing the probable chronological age of an individual based on indicators of maturation. These indicators can be grouped into three types, all of which

can be assessed independently; cognitive, psychosocial and biological. Whilst the first two are involved in a large proportion of the age estimation assessments carried out in the UK, age estimations based on biological changes are also undertaken, often for the court. Age estimations involving biological maturation are the leading type of age estimation carried out in most of the remainder of the EU. These biological age estimations assess maturational changes which can be observed in the dentition and skeleton as the child progresses to adulthood.

Age estimation using biological indicators is performed on both the living and the deceased. Each age estimation is ultimately an assessment of biological maturity which is then translated by the practitioner into an estimation of 'probable' chronological age. For the purposes of age estimation of the deceased there are a large number of techniques ranging from the very invasive to the less invasive. For the age estimation of those who are living, invasive age techniques are inappropriate so the utilisation of non-invasive imaging modalities including radiographs, computed tomography (CT) and magnetic resonance imaging (MRI) are applied to enable observation of changes to biological tissues such as bones and teeth.

Age estimation in the living has relevance to a number of areas of serious crime investigation including child pornography, human trafficking, asylum and immigration issues, perpetrators and victims of crime, cross-border adoptions and international competitive sports. Recent decades have seen a significant increase in requests for age estimation as a result of activities in these areas.

In the UK, where the registration of births is mandatory, it is rare to be unable to provide some evidence of chronological age but for a number of reasons many

children who cross borders or who are displaced or otherwise in a vulnerable situation, are not in this position. Frequently they do not have records which are considered adequate or accurate as proof of age. A large number of these children may originate in countries where births are rarely, if ever, registered and where documentary proof of age simply does not exist. Another significant group may have been displaced due to war or natural disaster during which any documentation may have become lost or mislaid. A final group may set out to deliberately conceal their date of birth or have been provided with false papers by their traffickers and therefore when their age is questioned they are unable to provide appropriate and legitimate proof of the age that they claim.

In the UK, as in many other countries, being recognised as a child ensures age-appropriate care and access to education (HMSO, 1989; Kvittingen, 2010). The status of childhood is defined in legislation and lasts up to the age, again defined in legislation, at which an individual is considered to have moved into adulthood. In the UK this change occurs at the designated chronological age of 18 years (section 105(1) Children Act (1989), at which point an individual is considered an adult and legislation which is designed to safeguard children no longer applies. For those who cross borders into the country therefore being older or younger than 18 years of age is highly significant in terms of whether they are entitled to education and full time care (Bolton, 2011). This has implications for the receiving country in terms of provision of support and for the individual themselves in terms of that support (HMSO, 1989). For those who have become victims during their journey, or upon entering the UK, their age will make a difference both in relation to their treatment by the state and to the level of charges which are brought on their abusers.

1.1 The extent of the problem

The exact number of individuals who might find themselves in a position in which their age is disputed is difficult to establish. Numbers can vary from agency to agency depending on their access to data and method of presentation of that data (Bhabha and Finch, 2006). Since 2000, more than 15,000 unaccompanied minors are known to have entered the UK (Bhabha and Finch, 2006). Within Europe, in 2008 alone, there were 11,292 unaccompanied minors applying to enter the 22 member states of the EU (Home Office, 2008a; 2009). Many of these were unable to prove their age and as a result were obliged to undergo age estimation procedures. In the UK, in 2008, there were 4,285 applications from unaccompanied children of which 1,400 (32.7%) were age disputed (Law *et al.*, 2010). The number of age disputes as a percentage of those entering the country has only been recorded since 2004 but this total has remained fairly consistent up until the present day (41-45% of all unaccompanied asylum seeking children, although the figures do vary slightly, again according to the source and the way in which data is defined, collected and calculated (Home Office, 2010; Kvittingen, 2010; Law *et al.*, 2010).

These figures do not take into account the large number of children who are estimated to have been victims of child trafficking each year, or who cross into countries without coming to the attention of the Border Agencies (CEOP, 2009; 2011). Whilst these children do not always come to the notice of authorities immediately, when they do, their age becomes of importance not only in relation to their care but also in relation to the prosecution of those who have preyed

upon them. Child trafficking is becoming an increasingly common problem world-wide, with estimates of victim numbers ranging between 1 and 1.2 million children annually, although this is an estimate since the true numbers affected are not known (I.L.O, 2002).

The countries of origin of those who find themselves undergoing age disputes varies depending upon political and other upheavals which are occurring on a world-wide basis (Bhabha and Finch, 2006). In 2008 the top 10 countries of origin for unaccompanied children were (Home Office, 2008b):

- Afghanistan
- Iraq
- Iran
- Eritrea
- China (including Taiwan)
- Somalia
- Bangladesh
- India
- Sri Lanka
- Albania

Age estimations which involve the assessment of both skeletal and dental maturity rely on the use of standards to estimate the level of maturity that has been achieved. The increased requirement for accurate means of establishing the age of those who are crossing borders has led to a series of reviews of the methods which are available to those who undertake these assessments (Flood *et al.*, 2011; Schmidt *et al.*, 2008b; Schmidt *et al.*, 2008c). Central to this work is a re-examination of the body of work which acts as a standard against which members of modern and very diverse populations are compared (Demirjian *et al.*, 1973; Greulich and Pyle, 1959; Tanner *et al.*, 2001; Tanner *et al.*, 1975; Thiemann *et al.*, 2006)

The increased requirement for age estimation in the living has led to a concomitant increase in research into age estimation practices and their effect on those who are caught up in the whole process (Bhabha and Finch, 2006; Bolton, 2011; Clarke, 2011; Crawley, 2007; Kvittingen, 2010; Smith and Brownlees, 2011). The literature which is available on these studies is substantial and for this literature review only the most relevant have been included. For a list of all of the literature which has been consulted in relation to this body of work please see Appendix 1.

1.2 International Legislation

Two of the most influential documents which have a provided guidance on age estimation practices and legislation in relation to age estimation of suspected minors are the United Nations Convention on the Rights of the Child (CRC) (1989) and the UNHCR Guidelines on Policies and Procedures in Dealing with Unaccompanied Children Seeking Asylum (1997). Legislation in many of the countries of Europe centre on the guiding principles which have been laid out in these documents. These principles enumerate the rights of the child and the responsibility of governments in relation to those rights. These include the right of access to education and living conditions which meet their physical, social and mental needs and importantly that '*the best interests of the child must be a top priority in all actions concerning children.'*(United Nations, 1989).   In addition every member state of the European Union (EU) has a duty placed on them by the Charter of Fundamental Rights and Freedoms (Convention., 2000) to take into account human rights guidelines during the development of new legislation.

In common with the UK, most European countries recognise the age of 18 chronological years as the age at which an individual 'attains maturity', at this point they cease to be considered a child with all the concomitant rights to resources such as education and social care and become legally recognised as an adult, this is reflected in Article 1 in the CRC (United Nations, 1989);

'*For the purposes of the present Convention, a child means every human being below the age of eighteen years unless under the law applicable to the child, majority is attained earlier.*'

In addition to this important chronological age of 18, there are a number of other specified chronological ages which are also legally significant for children (Table 1.1) although these can vary between countries (Table 1.2). A number of these additional ages have also become of increasing interest in relation to age estimation since without paperwork or other 'proof' of age it is not easy to establish if a child has reached these legal thresholds (Baumann *et al.*, 2009).

Activity	Chronological Age
Get married or register a civil partnership with consent Consent to sexual activity with others 16 and over Leave school on the official school leaving date Get a national security number Consent to medical treatment Apply for a passport with parental consent Considered a 'juvenile' offender if convicted of a crime and dealt with in Youth Court except for serious crime	16 years of age
Vote Buy cigarettes, tobacco Marry or register a civil partnership Age at which become a 'young' offender if convicted of a crime Can be sentenced to detention in a young offenders institution Children Act 1989/2004 no longer applies	18 years of age
Age at which considered an 'adult' offender if convicted of a crime If found guilty will be sentenced to detention in adult prison	21 years of age

Table 1.1: An overview of some of the activities which are age specific in the UK.

Age	Age of criminal responsibility	Age of consent
10 years	England and Wales, Switzerland	
12 years	Scotland, Ireland, Netherlands,	
13 years	France	Spain
14 years	Denmark, Austria, Estonia, Germany, Hungary, Italy, Romania, Russia, Slovenia, Spain,	Albania, Austria, Bosnia and Herzgovina, Bulgaria, Croatia, Estonia, Hungary, Germany, Italy, Liechenstein, Macedonia, Montenegro, Portugal, Serbia,
15 years	Czech Republic, Finland, Iceland, Norway, Sweden.	Czech Republic, Denmark, Faroe Islands, France, Greece, Iceland, Poland, Romania, Sweden
16 years	Portugal	Belarus, Belgium, Latvia, Northern Cyprus, Finland, Lithuania, Netherlands. Norway, Russia, Switzerland, England, Wales and Scotland
17 years	Poland	Ireland
18 years	Belgium.	Malta, Turkey

Table 1.2: Examples of country-specific ages of importance.

1.3 National Legislation and Guidance in the UK

In 1991 the UK ratified the CRC with reservations. These reservations were primarily concerned with matters connected to immigration control and child detention and were the subject of much criticism until 2008 when the UK government finally signed up to the CRC in its completeness (Bolton, 2011). This change in policy means that any, and all, decisions made in relation to children who are involved in immigration must comply fully with the guidelines presented in the CRC (United Nations, 1989). This has had a significant effect on policy and on the workings of bodies such as the UK Border Agency who are often, although not always, the first point of contact for any child who enters the country. In the UK the CRC is only justiciable through either case law or through challenges to cases in which rights as specified by the CRC are not upheld. One direct result of the ratification of the entire CRC by the UK without reservation has been the introduction of s55[1] Borders, Citizenship and Immigration Act (HMSO, 2009). This places a duty on all statutory bodies, with a special emphasis on the Secretary of State to '*safeguard and promote the welfare of children who are in the United Kingdom'*. Since 2008 this relates not only to children who are already in the UK, but also to those who are current within the immigration process (Bolton, 2011).

The introduction of s55 Borders, Citizenship and Immigration Act (2009) ensures that any child who is unable to prove his/her age, and whose age is subsequently disputed, has to be treated as a child with all of the accesses to resources outlined in the Children Act (1989) until such times as their claim is substantiated or rejected, unless they are considered to be clearly above the

---

[1] Section 55

age of 18 years. Whilst s55 places a duty on the Secretary of State to ensure that s55 and its guidelines on the welfare of children within the immigration process is carried out (Home Office, 2011), in reality there is little or no guidance from central government on the issue of age assessment and how this should be undertaken, this is summed up by Mr Justice Collins in 2009, where he specified that Parliament has made it clear that this is a decision that should be made by the '*relevant authority*'[2]. In reaction to this lack of input from statutory bodies, the Court of Appeal has also suggested that the Government should review the need for official guidelines[3]. As a result of this lack of guidance from government, age estimation and the handling of age disputes has become based on case law of which a significant body has accrued in relation to age estimation cases, especially in the last decade (Luh *et al.*, 2011).

Due to the lack of political guidance in relation to the specific manner by which age estimation processes should be performed, some local authorities and to a lesser extent the UKBA (UK Border Agency) have created their own guidelines (Hillingdon, 2005; UKBA). Most of the age estimations undertaken in the UK are performed by qualified social workers (Kvittingen, 2010; Luh *et al.*, 2011). Whilst there is no prescribed method by which an age estimation should be performed, any age estimation undertaken by social workers does have to be Merton compliant in accordance with the guidelines laid down by Stanley Burton J. in the High Court in 2003 in *B v London Borough of Merton* [2003] EWHC 1689 (Admin)[4]. The resultant age determinations have been subject on

---

[2] *A v. London Borough of Croydon and Secretary of State for the Home Department; WK v. Secretary of State for the Home Department and Kent County Council*, [2009] EWHC 939 (Admin)

[3] *R (FZ) v London Borough of Croydon* [2011] EWCA Civ 59

[4] *B v London Borough of Merton* [2003] EWHC 1689 (Admin)

occasion to challenge initially due to claims that the assessment itself contravened the Merton guidelines. In 2008 the Supreme Court in *A v London Borough of Croydon and Anor; M v London Borough of Lambeth and Anor* [2009] UKSC 8 ("A v Croydon")[5] ruled that 'whether the issue 'child or not' is a question of 'precedent' or 'jurisdictional fact' to be decided by the court on the balance of probabilities' since the local authority had committed an error of law if its decision was incorrect. The Supreme Court on this occasion also concluded that despite the fact that experts can come to a wide range of decisions on the age of an individual during the process of an age dispute, age is an objective and immutable part of an individual's identity for which there is only one correct but many incorrect answers. The courts as a result are permitted, and should, come to their own conclusion on the age of the individual presenting before them. In conclusion this ruling meant that an age estimation undertaken by the local authority, previously only open to dispute if there was doubt of its Merton compliance was now open to challenge whereby it would be for the Administrative Court to determine the accuracy of the decision of the local authority. This ruling has led to an increase in the number of age dispute challenges, as of 23th January 2011 there were a total of 64 age assessment cases at various stages on the Administration Courts records[6]

In examining the merits of different types of age estimation methods Collins J. concludes that '*While I recognise that age determination impacts on all aspects*

---

[5] *R (on the application of A)* v *Croydon London Borough Council* [2009] 1 WLR 2557

[6] *R (FZ) v London Borough of Croydon* [2011] EWCA Civ 59

of the asylum process…..the reality is that there are no reliable means whereby an exact conclusion can be reached'.[7]

The conclusions reached by the court echo the opinions held by the Royal College of Paediatrics and Child Health (RCPCH) who stated in 1999 that '*age determination is an inexact science and the margin of error can sometimes be as much as 5 years either side*'(Levenson and Sharma, 1999). In their report '*The Health of Refugee Children-Guidelines for Paediatricians',* Levenson and Sharma (1999) do not rule out the possibility of paediatricians undertaking age assessments but argue that any age estimation should be the result of a holistic examination of the child which must take into account social history as well as their skeletal maturation and other anthropometric measurements. The RCPCH has not changed their advice on age assessments since this publication, simply reiterating the opinion outlined above (RCPCH, 2007). The College admits that biological age assessment requires the use of radiographs, but refers readers to the statement by the Royal College of Radiologists (RCR) in 1996 as best practice (Watt, 1996) . The RCR stated both in 1996 and again in 2007, that the use of ionising radiation-based imagery for any procedure except those at a time of clinical need is unjustified, although in cases of clear consent from the individual involved, a radiograph of the left hand/wrist could be taken as this presents the least harm to the person (Hubbard, 2007). Taking images for medico-legal purposes is legal in the UK (DEFRA, 2004; HMSO, 2000) but the practitioner taking the image has a responsibility to ensure that the benefits to the individual are worth the risks that accompany the procedure so can refuse to take the image if they do not feel that it is in the best interest of the individual

---

[7] *A v. London Borough of Croydon and Secretary of State for the Home Department; WK v. Secretary of State for the Home Department and Kent County Council*, [2009] EWHC 939 (Admin)

(Department of Health, 2000). The RCPCH argued that if a child requested that radiographs be taken and analysed as part of their case this would be acceptable but consent had to be clear, informed and without coercion (RCPCH, 2007). Chronological age does have an implication when considering the issue of consent however, which has to be taken into account when dealing with age disputed individuals. The age of consent to a procedure in the UK is defined as 16 years of age, beyond which a person is presumed to be able to consent to a treatment unless it is apparent that there is clear evidence which mitigates against this ability such as unconsciousness or disability (HMSO, 2005). Being younger than 16 years of age however does not prevent a child from giving consent. Under a law known as the 'Gillick competency' a child can be legally competent if they have '*sufficient understanding and maturity to enable them to understand fully what is proposed*'.[8]

Both the RCPCH (2007) and the RCR (Watt, 1996) argue that age estimations undertaken by assessment of skeletal and dental changes are in fact an assessment of biological maturity rather than chronological age and that individual variation, differences in nutrition and disease and the limited skeletal and dental changes that occur during the late teenage period come together to make this insufficiently accurate to differentiate between 16, 18 or 20 years of age. This has proven to be a compelling argument echoed by others (Altinay, 2009; Cameron, 1982). A major problem in any age estimation is that a chronological month or year does not necessarily equate to a corresponding increment of biological change. Differences in the tempo of maturation and ageing occur throughout the growth period of the individual and between individuals, even at comparable chronological ages (Cameron, 1982). The

---

[8] *Gillick v West Norfolk and Wisbech Area Health Authority* [1985] 3 All ER 402

relationship between chronological age and biological age, whilst present, is variable and affected by a multitude of factors, many of which may be unknown to whoever is performing the age estimation. Clear proof of this difficult relationship can be seen in the large number of studies which have tried to identify explicit biological markers which can be used to indicate that a specific 'birthday' has passed (Baumann *et al.*, 2009; Schmidt *et al.*, 2008a). This inherent error presented by individual variation has caused others to argue against the performance of any age estimation at all, since the results have to be given with such a wide age range that they do not in reality assist with the decision making process.

Despite all of this, paediatricians have been and continue to be involved in age estimation. The weight that courts place upon these expert opinions became the focus of a ruling by Mr Justice Collins which is specifically about the role of the expert report in age disputes. Mr Justice Collins states that the report of a paediatrician on the age of a defendant carried no more and no less weight than that presented by an experienced and qualified social worker, although he does state that '*I do not however think that LAs[9] or the Secretary of State can in general disregard reports from Dr Birch or any other paediatrician*'[10]. Justice Collins does go on to clarify that this supposes that the Local Authority assessment was Merton compliant[11]. The reports of a number of paediatricians were considered in the ruling but one was to come under criticism by Judge Parker K in *R v London Borough of Croydon* [2011] EWHC 1473 for employing

---

[9] Local Authorities

[10] *A v. London Borough of Croydon and Secretary of State for the Home Department; WK v. Secretary of State for the Home Department and Kent County Council*, [2009] EWHC 939 (Admin)

[11] *B v London Borough of Merton* [2003] EWHC 1689 (Admin).

statistical analyses which created bias and error in her conclusion. The judge stated that

'*Dr Birch on the basis of evidence that she gave to the court, has in my judgement an erroneous confidence in the accuracy and reliability of the statistical methods that she has employed. That misplaced confidence undermines the other evidence that she has given….Therefore she is very likely to be biased in her assessment of age.*'[12]

It is of note that, in common with the previous ruling by Mr Justice Collins[13], this argument does not mitigate against the use of bone and dental age being presented before the court, since the criticism was aimed at the paediatricians interpretation of results rather than the method of age estimation *per se,* but it does highlight the extent to which an expert opinion must be based on sound principles and decision making for it to be accepted by the court.

In addition to the official stance of the RCPCH and the RCR, there have also been a number of reports which have examined the experience of children who have entered the UK in the last decade or so, a time of increased migration for both adults and children (Bhabha and Finch, 2006; Clarke, 2011; Crawley, 2007; Kvittingen, 2010). The Immigration Law Practitioner's Association (ILPA) regularly produces reports and updates about the treatment of children within the immigration system all of which are available online (ILPA, 2012). A recurrent theme within these relate to age disputes and the way in which they are handled. These reports trace a gradual change in the way in which children who enter the country are treated, especially if their claimed age is challenged.

---

[12] *R v London Borough of Croydon* [2011] EWHC 1473
[13] *A v. London Borough of Croydon and Secretary of State for the Home Department; WK v. Secretary of State for the Home Department and Kent County Council*, [2009] EWHC 939 (Admin)

This change in treatment mirrors the changes in approach to these age disputed children which has been forced by the complete ratification of the United Nations CRC, significantly children are supposedly no longer being detained at any point during this process, although if they are considered to be over 18 this can still occur (Symonds, 2011). Of concern to those undertaking this research is the fact that to be 'age disputed' means that a child can be denied access to the protection and support that they need and to which they are entitled (Luh *et al.*, 2011). This affects them both during the assessment period and if the assigned age was erroneous, after the process was completed. In 2003/4 in Cambridgeshire alone, about 50% of those who were age disputed were eventually judged to be children (Bhabha and Finch, 2006). Ultimately the concern is that for these children the care that they required was not forthcoming at a time when they needed it most.

However it is not only a matter of access to care and resources, access to appropriate justice is also age dependent. Challenges to the age of a victim in cases of sexual offences, for instance, can make a substantial change to the degree of offence with which the alleged perpetrator is charged. Sexual assault on a minor is a different crime from the same offence committed on an older individual. Even for those victims who have entered the country and have been age assessed by recognised experts working for UKBA, it is possible that they will be asked to prove their age if they become victim to a sexual assault. Additionally, for those who are accused and found guilty of a crime, chronological age has an impact on sentencing since in the UK an offender is only sent to adult prison if they are 21 years or older.

1.4 Judicial Acceptance

In the UK, unlike the USA, there is, as yet, no specified set of criteria for the admissibility of expert evidence before the court. It may be that 2011 saw the beginning of a change in this approach to expert evidence with the publication of the Law Commission Report 'Expert Evidence in Criminal Proceedings' (The Law Commission, 2011). This report relates to England and Wales and whilst it does not go so far as suggesting that the courts introduce a test such as the Frye standard[13] or Daubert criteria[14] which underpin the admissibility of expert evidence in American courts (Table 1.3); if its recommendations are implemented it will have a significant impact on the methods deemed acceptable to support expert evidence produced for, and presented in, Court in England and Wales.

The Law Commission Report seeks to set benchmarks for the admissibility of expert evidence. The report was produced as a result of a number of miscarriages of justice for which the key driver in each case was the expert evidence. The expert evidence in each case was shown to be based on unsound statistical data[14], weak empirical research based on insufficient data[15] (The Law Commission, 2011). In each case the report felt that there was insufficient attention paid to whether the evidence was reliable enough to be presented to and therefore considered by, a jury. The expert 'opinion' came under close scrutiny and the report argues that expert opinion should be based on '*sound principles, techniques and assumptions'* rather than 'opinion' without

---

[14] *R v Clark (Sally)* [2003] EWCA Crim 1020, [2003] 2 FCR 447 (second appeal).

[15] *Harris and Others* [2005] EWCA Crim 1980, [2006] 1 Cr App R 5.and *Cannings, R v Court of Appeal* [2004] EWCA Crim 1, [2004] 1 WLR 2607

the appropriate empirical underpinning. When presenting any evidence the

expert would need to refer to the relevant, properly conducted empirical

research which underpins the techniques since these hypotheses and

methodologies '*would be critically examined with reference to guidelines*

relevant to the type of expertise being proffered' (The Law Commission, 2011).

Standard	
Frye Standard (Frye test, general acceptance test)[16]	Scientific evidence must be 'generally accepted; by a meaningful proportion of the scientific community
Daubert[17]	The judge is the gatekeeper for the final decision on admissibility of evidence The expert's testimony must be relevant to the task in hand and rest on a reliable foundation Scientific knowledge must demonstrably be the product of sound scientific methodology The methods used must have been subject to empirical testing, subject to peer review and publication, have a known error rate and have standards and controls in existence.

Table 1.3: Outline of the Frye and Daubert standards.

Whilst the Law Commission Report has not been ratified at the time of writing,

however it has been prepared as a Bill with the intention of being put before the

Government and its potential impact has to be anticipated. To avoid future

---

[16] Frye v. United States 293 F.1013 (D.C.,Cir 1923)
[17] Daubert v Merrell Dow Pharmaceuticals (1993) 509 U.S. 579 (U.S.)

miscarriages of the type examined by the document such as occurred in

Dallagher[18] when earprint evidence was presented as a means of identification

in a murder case. This resulted in a conviction for murder which was later

overturned when DNA evidence demonstrated that the identification had been

erroneous, the recommendations of the report should be taken on board by

every forensic practitioner. Any and all methodologies which are undertaken

and which have the potential for presentation at court must be based upon

sound and relevant research which would stand up to scrutiny. It is for

practitioners therefore to be able to understand the methods that they utilise,

appreciate the relationship of those methods to the evidence being considered

and be able to explain this relationship and justify why it leads to the

conclusions being made. In reality this may have far ranging effects for a

number of professions, including those which undertake osteological analysis.

Methods which are employed have often been developed on different

populations both geographically and temporally and their applicability to a

modern population remains largely untested. These methods have to be

reviewed to enable their meaningful application to modern populations and their

statistical validity to be understood thus allowing them to be presented to the

judicial gaze in ways which do not confuse or conflate.

1.5 Methods of age estimation in the living

In 2000 the increase in cross border migration into and within the European

Union led to the development of the Study Group in Forensic Age Diagnostics

(AGFAD, 2011) in Berlin. This is a multidisciplinary group comprised of

specialists from around Europe who examine age estimation techniques, their

---

[18] *R v Dallagher* [2002] EWCA Crim 1903, [2003] 1 Cr App R 12

validity and their reliability in relation to modern day demands. This group has produced a large volume of research data and their work has resulted in the proposal of a minimum set of requirements which when analysed together, allow the production of a probable age which is sufficiently robust to present to a court. This approach includes the analysis of (Schmeling *et al.*, 2008);

- physical health,

- external physical characteristics,

- skeletal maturity

- dental maturity

In relation to the issue of taking radiographs for age estimation, Schmeling *et al* (2011; 2010) argue that whilst there is some degree of exposure to ionising radiation linked to any radiographic process, when radiographs are taken for age estimation the doses involved are 'within acceptable limits' in relation to naturally occurring environmental radiation exposure. The average dose of radiation from a single radiograph in the UK is 0.01 mSv (millisieverts) (Wall and Hart, 1997), the average annual radiation exposure in the UK per year is 2.7 mSv (Allison, 2009). One hand X-ray is therefore equivalent to approx. 25 minutes of exposure to naturally occurring radiation (Schmeling *et al.*, 2010). However any exposure to radiation is not without risk and the use of X-rays and their potential for harm remains controversial (Allison, 2009; Walker, 2000; Walker, 1997). Unlike the situation in the UK where the majority of age estimations are based on the analysis of psychosocial rather than biological maturity, radiographic imaging for the explicit use of age estimation is routinely performed in many European countries, and less routinely performed in others

(Table 1.4) (European Migration Network, 2010). Skeletal maturity is analysed through the examination of radiographs of the left hand/wrist additional imaging of the medial clavicles is recommended if the hand/wrist exhibits full maturity or if there is a strong suspicion that the individual is older than 18 years, thus reducing the need for unnecessary exposure to X-Rays in younger individuals. Dental maturity is analysed through the examination of an orthopantomogram which allows visualisation of the full dental arch (Liversidge *et al.*, 2003). In order to predict chronological age both the skeletal and dental images are compared to sets of reference data, also known as 'standards' which come from populations of known sex and age allowing the practitioner to extrapolate probable chronological age.

Country	Skeletal maturity	Dental maturity	Medical examination	Interview/documentation	Psychological	Consent required for radiographs
Austria	√	√	√	√		√
Belgium	√	√		√	√	√
Czech Republic	√	√		√		
Estonia	√			√		√
Finland	√	√		√		
France	√	√	√	√	√	√
Germany	√	√		√		
Greece				√		
Hungary			√	V		√
Ireland				√		
Italy	√	√	√	√		√
Latvia			√			
Lithuania	√		√	√	√	
Netherlands	√			√		√
Malta				√	√	
Poland	√	√	√	√		√
Portugal	√	√		√		
Slovak Republic	√			√		
Slovenia	√			√	√	
Spain	√			√		
Sweden	√	√		√		
United Kingdom				√		

Table 1.4: List of methods utilised by EU countries in relation to age estimation of unaccompanied minors (European Migration Network, 2010).

1.6 External physical characteristics

Whilst it is advisory to undertake a medical examination prior to the commission of age estimation, there are two ways to use the information gathered. Firstly a medical examination is recommended which would aim to determine the health of the individual including their height, weight and illness record (Schmeling *et al.*, 2006c). The second part of this examination refers to the assessment of external physical characteristics which can be used to indicate the level of maturity of the individual (Marshall and Tanner, 1970; Marshall and Tanner, 1969). This latter approach is not commonly used in the UK, although paediatricians can and do use it in their age estimations[19]. These external maturational changes are most commonly assessed using the Tanner Stages which were developed from the data collected during the Harpenden study, a longitudinal study of child growth undertaken in the UK between 1948 and 1971 (Tanner, 1962). The maturational stages assessed include the signs of secondary pubertal sexual maturation including; the development of the penis and scrotum, pubic hair growth, breast development and axillary hair growth (Marshall and Tanner, 1970; Marshall and Tanner, 1969).   In relation to the admissibility of age assessments which relies on, or even includes, Tanner staging, a letter to the journal '*Pediatrics'* from Prof Tanner warns against the use of this method for this purpose (Rosenbloom and Tanner, 1998) . This letter relates to the use of Tanner staging for the assessment of age of potential paedophile victims and the subsequent use of these age assessments in a court of law. Rosenbloom and Tanner (1998) state that extrapolating

---

[19] *A v. London Borough of Croydon and Secretary of State for the Home Department; WK v. Secretary of State for the Home Department and Kent County Council*, [2009] EWHC 939 (Admin)

chronological age from the maturity indicators that they have described is an inappropriate use of the Tanner stages.

'..*the staging of sexual maturation (Tanner stage) has been used ..to estimate probable chronological age. This is a wholly illegitimate use of Tanner staging: no equations exist estimating age from stage, and even if they did, the degree of unreliability in the staging would introduce large errors into the estimation of age.*'

Tanner stages were developed to allow a practitioner to judge whether a child of known age is developing within normal parameters and as such the development of their method does not fulfil any of the criteria which would justify its use to estimate chronological age. The issue for many is that the analysis is based on the development of external physical characteristics including the development of external genitalia, pubic hair and breast development in girls. Ethical issues arise in relation to the use of the Tanner scale, not least of which is the maintenance of respect and dignity in relation to asking a child to undress in order to have their external genitalia examined and potentially photographed, especially if their age is found to be below 16 years of age. Because of this, external physical changes are mainly used to assist the clinical practitioner in understanding the extent to which a young person has achieved specific milestones and therefore assists in highlighting maturational discrepancies which might point to a disorder which has affected growth.

1.7 Assessment of dental maturity

The assessment of dental maturity uses the development and eruption pattern of both the deciduous and permanent dentition. Added to the many changes which occur in the first decade and a half of life and the ease with which they can be visualised with the assistance of one radiograph, is the fact that, compared to skeletal development, the tempo of change in the dentition is reported to be relatively unaffected by nutritional and environmental stress (Cardoso, 2007). The timing of the development and eruption of the two sets of teeth have been the matter of a large body of research which has been greatly aided by the use of radiographs. There are a number of methods which are commonly in use today many of which were developed some time ago and have subsequently been subject to testing on modern populations (Demirjian *et al.*, 1973; Moorrees *et al.*, 1963).

Many of the age estimation methods which were originally developed for age estimation from the dentition estimate age up to and including the eruption and completion of the roots of the second molars at or around 15-16 years of age. This means that they do not include the development and eruption of the third molar (Demirjian *et al.*, 1973; Moorrees *et al.*, 1963) . The recent increase in the requirement for age estimations of those who might or might not be over the age of 18 years has led to practitioners re-visiting these techniques in an attempt to make them stretch to include the timing of the development and eruption of the third molars. As a result a large body of work has accumulated in relation to the eruption of the third molar in differing populations (App. 1) (Acharya, 2011; Bassed *et al.*, 2011; Bhat and Kamath, 2007; Blankenship *et al.*, 2007; De Salvia *et al.*, 2004; Dhanjal *et al.*, 2006; Engstrom *et al.*, 1983;

Gunst *et al.*, 2003; Kasper *et al.*, 2009; Lee *et al.*, 2009; Legovi *et al.*, 2010; Martin-de las Heras *et al.*, 2008).

1.8 Assessment of skeletal maturity

The current assessment of skeletal maturity relies on imaging two body areas; firstly the left hand/wrist and secondly the medial end of the clavicle.

A radiograph of the left hand/wrist is recommended for a number of reasons;

- it can be isolated from the rest of the body thereby minimising the exposure to potentially harmful ionising radiation,

- it contains a large number of ossification centres which appear, change morphology and fuse in an established pattern

- the epiphysis of the distal radius, which is the last to fuse, does so relatively late in the adolescent period (14-17 years in females and 16-20 years in males (Scheuer and Black, 2000b)).

This all means that the development of this body area can be of use throughout the childhood period. There is a substantial volume of reference data available when undertaking an analysis of probable age from this body area, most of which originates from data collected during longitudinal studies of child growth from the early 20th century (De Roo and Scröder, 1976; Gilsanz and Ratib, 2005; Gök *et al.*, 1985; Greulich and Pyle, 1959; Pyle *et al.*, 1971; Roche *et al.*, 1988; Tanner *et al.*, 2001; Tanner *et al.*, 1962; Tanner *et al.*, 1975; Thiemann *et al.*, 2006; Todd, 1937).

For age assessment of individuals who are suspected to be in their late teens to early 20s a CT of the medial clavicles is also recommended. The epiphyses at the medial end of these bones appear during the adolescent period (12 years-

14 years) and reportedly are amongst the last of the epiphyses to fuse (16 years-late 20s). Radiographically the medial ends of the clavicles are difficult to image due to the presence of overlaying structures and so a thin slice CT scan is recommended for visualisation (Muhler *et al.*, 2006). There was little reference data available on the fusion times of this epiphysis prior to the demands imposed by the increased need for age estimation in the living and a review of the literature reveals a steady increase in studies which are attempting to rectify this situation (Hillewig *et al.*, 2011; Jit and Kulkarni, 1976; Kellinghaus *et al.*, 2010; Kreitner *et al.*, 1998; Langley-Shirley and Jantz, 2010; Muhler *et al.*, 2006; Quirmbach *et al.*, 2009; Schmeling *et al.*, 2004; Schulz *et al.*, 2005; Schulz *et al.*, 2008; Schulze *et al.*, 2006).

Age estimation from the skeletal tissues has to take into account a number of factors including; ethnicity, sex, lifestyle, medication or illicit drug use, nutritional status both in the present and in the past, the presence of any medical disorders and past medical history (Schmeling *et al.*, 2005; Schmeling *et al.*, 2006c). These factors are discussed later in this chapter since any test of an age estimation methodology should have an understanding of these influences in relation to the population being examined. It should always be remembered that the discussion of these in relation to a population is a matter of generalisation rather than individualisation and any age estimation which is undertaken is executed on the individual as someone who has originated from that population.

1.9 Alternative imaging modalities

The harmful effects of radiation have been understood for a significant period of time (Brenner *et al.*, 2003; Frush, 2009; Hall, 1991; Mazrani *et al.*, 2007; Ramsthaler *et al.*, 2009; Walker, 2000). Despite the argument put forward by Schmeling *et al*, (2011; 2010) in the UK it is not possible to undertake X-ray imaging for age estimation unless informed consent is obtained. Age estimation in the living is also seeing an increased use in sports where there are large financial incentives to enter older children into younger categories thereby increasing their chances, or the team's chances of success (Engebretsen *et al.*, 2010). In competitive sports this issue can result in children being tested on a number of occasions. As a result of health concerns linked to this repeated testing, there has been an increase in the search for an imaging modality which provides sufficient information for age estimation to be undertaken and yet is as safe as possible. Magnetic Resonance Imaging (MRI) and Ultrasound (US) are both being investigated in relation to this call but at the current time of writing both are still in their infancy and therefore of questionable admissibility or probative value (Allen and Wilson, 2007; Dvorak *et al.*, 2007a; Dvorak *et al.*, 2007b; Khan *et al.*, 2009; Kovacs *et al.*, 1999; Laor and Jaramillo, 2009; Mentzel *et al.*, 2005; Quirmbach *et al.*, 2009; Schmidt *et al.*, 2011; Wagner *et al.*, 1995). Whilst the imaging modality might be newer than traditional radiographs, the studies still depend upon the same sets of standards as reference material which are used to undertake age estimation from radiographs such as the Greulich and Pyle atlas (1959). The accuracy and reproducibility issues surrounding the atlases therefore remains the same no

matter which imaging modality is utilised until such time as standards which are bespoke and relevant to these imaging modalities are developed.

1.10 Age estimation from radiographs

Age estimation in the maturing skeleton is dependent upon three processes; the appearance of primary and secondary ossification centres, the growth of these centres and the timing of fusion of primary and secondary centres. These appearances and changes have been well documented both in dry bone and radiographic studies (Flecker, 1932; 1942; Girdany and Golden, 1952; Noback, 1954; Pryor, 1907; 1923; Scheuer and Black, 2000b; Stuart *et al.*, 1962). Comparison of the results of these studies leaves the reader in no doubt that the identification of the timing of the appearance of primary and secondary ossification centres, the beginning of epiphyseal fusion, the identification of the stages of epiphyseal fusion and the point at which epiphyseal fusion can be judged to be complete are dependent on whether the dry bone itself is being observed or it is being visualised through an imaging modality such as radiographs (Coqueugniot and Weaver, 2007; Moss and Noback, 1958; Scheuer and Black, 2000b; Webb and Suchey, 1985).

The estimation of probable chronological age is achieved through a matching process which involves a comparison of a radiograph of the individual to previously defined maturity stages as expressed in a reference sample of known sex and age. Any age estimation is fundamentally a measure of the biological maturity which is translated into a probable chronological age through comparison with a standard (Black *et al.*, 2010; Cameron, 1982).

Reference data for these age estimations come from a number of sources and have most commonly been presented as a series of 'atlases' within which the authors identify, describe and present the morphological and growth changes which they consider to be most important. Most of the data that was utilised to create these atlases was gathered during longitudinal studies which took place in the early 1900s (see Chapter 2 for a detailed examination of the studies). During the studies, sequential standardised radiographs were taken of each child as part of a wider anthropometric data gathering exercise. Since the aim was to chart the growth of 'normal' children all participants had known health histories and were screened for disorders that could affect growth. The aim of this data collection was to provide reference data against which the development of a child of known chronological age could be considered. This was the same as that envisaged by Tanner when developing the Tanner scale who described this as

'*designed for estimating development of physiological age for medical, educational, and sports purposes, in other words, identifying early and late maturers'*.

Essentially these atlases of 'normal' development were designed for two purposes; to identify those children who were not experiencing growth normally either on an individual or population basis and to allow medical practitioners to assess the degree of skeletal maturity of a child to time medical and dental interventions.

 Most of the early literature which examined the atlases in relation to a population used them for this purpose; to judge the health of a population or groups within a population by measuring the growth of its children against an

atlas of children of known well-being. The tempo of the development of children within a society or social group is a measure of the effects of the environment, especially nutritional conditions on their growth (Fernandez *et al.*, 2007; Prentice *et al.*, 2006). Growth in childhood requires calorific intake over and above that of the immediate requirements of daily mental and physical activities. Insufficient nutrition through famine, war or poverty, excess physical activity or a high disease burden can be reflected in reduced skeletal maturation and growth (Cameron, 2002). The atlases were developed on healthy children with sufficient nutritional intake who were thus thought to be appropriate to act as a standard for comparison purposes (Todd, 1930). As with the Tanner staging however, the potential usefulness of a data set which included images of maturational changes as evidenced in these atlases proved a tempting source of data for those who were being asked to undertake age estimations in the living. Rather than assessing the maturational stages of a child of known age, they took the maturational stage of the child of unknown age and found the age of 'best fit' within the atlas thereby extrapolating probable chronological age from the chronological age presented in the atlas. This is a procedure for which none of these atlases in common use today were designed and as such leaves the expert with a number of important methodological issues.

The methodological issues stem from two bases; firstly the methods are being applied in ways for which they were never intended. Should this be considered as Rosenbloom and Tanner (1998) suggest a '*wholly illegitimate use'* of the method which must therefore be avoided, or is it possible to test the methods using sound research techniques and thereby demonstrate that they are sufficiently robust to be considered admissible for court? A survey of available literature demonstrates that a substantial body of work is beginning to accrue of

studies, published in peer reviewed journals which attempt to demonstrate the value and robusticity of this alternate use of these atlases (Appendix 1).

The second major problem with the use of the atlases is that they themselves represent a temporal snapshot of the maturational tempo of one healthy cohort of children of known ethnicity. The question is whether this data is relevant to a modern population or in fact whether secular change, changes in diet, changes in access to medical care and the fact that the atlas is being applied to children of different ethnicities render them unfit to use in the analysis of the maturation of a modern population.

Since the longitudinal studies which provided the data were implemented, the dangers of repeated exposure to X-rays have become not only widely known but a matter for legislation (DEFRA, 2004; HMSO, 2000). Even without legal guidance, ethically it is not possible to repeat longitudinal radiographic data collection studies. The development and potential of imaging modalities which carry no risk of harm are still in their infancy or prohibitively expensive leaving the forensic community in a position in which it is not possible to address data collection on the same scale and in the same detail as was possible in the longitudinal studies of the early-to-mid 1900s. The only choice left is to revisit the atlases in an attempt to ensure that the answers that they give are relevant, admissible and valid.

A large body of literature has resulted from efforts to understand the accuracy of the methods suggested by the atlases, with an emphasis on those atlases based on the development of the left hand/wrist (Appendix 1). These studies can be grouped according to the method they employ to test accuracy. These groupings include;

- testing age estimation methods on specific populations,

- comparison of observer error,

- comparison of the accuracy of different atlases of the same skeletal area with each other on the same population

- comparison of the maturity stages of different body areas with each other, again on the same population.

In common with investigations undertaken to assess the accuracy of different atlases in different populations the results of these studies have varied, with no single atlas coming to the fore as more reliable or more accurate than any other. The studies which have been undertaken to assess inter- and intra-observer accuracy have found that accuracy rates between observers are within acceptable limits, but do show that increased experience and practice increase consistency.

1.11 Potential factors affecting age estimation

There are a large number of interrelated factors which influence growth;

- innate factors such as genetic inheritance, ethnicity and the sex of the individual

- external factors such as the environment, nutrition and health.

Whilst all of these are influential on the speed, duration and timing of maturational events, none act in isolation (Cameron, 2002). This presents a complicated and complex picture when assessing the relationship between biological maturity and chronological age. Many of these factors change over time and as a result their measurable effects on a population and groups within

a population change over time, a process known as secular change. Secular change can be defined as '*the changes over time in the characteristic pattern of growth of the children of a population*' (Johnston, 2002). The issue of secular change is one of the central questions asked in relation to the value of existing standards; to what extent does secular change render these standards irrelevant and as such, inadmissible as a method of age estimation?

The following sections outline the factors which impact on biological growth and maturation. Demographic influences discuss the relationship of sex and ethnicity to the growth process. The impact of nutritional intake, environment and health status are discussed under the generalised heading of socioeconomic factors but at all times it should be borne in mind that these separations are artificial and in reality any organism which is in the process of growing and maturing will experience and react to all of these influences.

1.12 Demographic Influences

Differences in the timing of the appearance of ossification centres, rates of maturational change and fusion between ossification centres between males and females were first noticed in the early 1900s. Generally female maturational changes are advanced in relation to males even prior to birth (Lampl and Jeanty, 2003). The differing growth tempos are controlled by genes located both on the X and Y chromosomes (Tanner, 1962). The differences in timings range from a matter of weeks between the different sexes when young infants, extending to months and years as the juvenile ages and approaches maturity (Thompson *et al.*, 1973). As a result of this different tempo of growth, females complete the juvenile maturational process approximately two years

before males (Scheuer and Black, 2000b). The longer growth period experienced by males allows them time to gain additional height and body mass before their ultimate cessation of growth (Humphrey, 1998; Tanner, 1962).

Calls for sex specific maturational standards quickly followed the discovery of the differences in maturational timings of males and females and is reflected in the separation of the sexes in all of the atlas publications. Authors have found that whilst the timing of maturational change is influenced by the sex of the individual the actual pattern of changes remains relatively constant between sexes (Cheng *et al.*, 1998; Flecker, 1932; 1942; Hoerr *et al.*, 1962; Pyle and Hoerr, 1969). Small differences have been identified in the order of appearance of primary ossification centres, especially those of the wrist and hindfoot (tarsals and metatarsals) but these also vary within sexes and have been found to affect family members in similar ways creating the more realistic argument that they are under a more general genetic influence rather than being based solely on sex differences (Tanner, 1962).

Whilst the assessment of sex in deceased juvenile remains is difficult to perform with any degree of accuracy, this is not an issue when undertaking age estimations on the living. It is not completely without issue however since there are a number of disorders which are linked to the sex of the individual and which can influence the rate of skeletal development including; Klinefelter's syndrome, Turner's syndrome and Fragile-X (Acheson and Zampa, 1961; Even *et al.*, 1998; Midtbø and Halse, 1992). Not all of these are readily diagnosable or indeed are always diagnosed and underline the requirement for a medical examination to be part of any age estimation.

Ethnic differences in maturation rates have been widely examined to establish the degree of influence that they have on the rate of skeletal maturation.

The need to identify whether differences exist between population groups and if differences exist to both qualify and quantify those differences has become ever more important. This is due to the higher demand for age estimations to be undertaken on individuals who originate from populations which are distant from the original population whose data underpins that of the standard (Bhabha and Finch, 2006; Garn, 1981; Home Office, 2008a). Certainly there are large differences between the adults of various ethnic groups such as, for example the Dutch and Chinese, however age estimation assessments are based on the relationship between skeletal maturational events and chronological age. The need to understand this relationship has not only arisen in age estimation of the living. Recent international investigations including those in Rwanda, Sierra Leone and the Balkans, have led to anthropological methodologies being exposed to the scrutiny of the court, resulting in a growing awareness of the need to take into account population differences when applying age estimation methodologies to forensic situations (Kimmerle *et al.*, 2008). Whilst the evidence presented before the International Criminal Tribunal for the Former Yugoslavia was based on age estimation techniques which were being applied to the deceased, this should act as a warning to those who are practising forensic age estimation on both the deceased and the living to ensure that the conclusions that they draw are based on techniques that are applicable, or have known statistical data in relation to the relevant population.

Many past studies appeared to indicate that ethnicity has an effect on the rate of skeletal maturation. Tanner (1962) argued that these studies indicated that

there were differences between groups which could not be explained purely on an environmental basis since differing maturation rates existed between different ethnic groups even when living in similar conditions. It is only recently that this idea has undergone a degree of change which almost reverses this argument. In conjunction with an increase in the requirement for age estimation on different population groups there has been a concomitant increase in the number of studies into the development of the children of these populations. Many of these studies have used the reference material of one or other atlas as a baseline and have compared the differences of the identified population against these standards (Andersen, 1971; Büken *et al.*, 2009; Büken *et al.*, 2007; Chiang *et al.*, 2005; Griffith *et al.*, 2007; Koc *et al.*, 2001). Other studies compare the timing of skeletal maturational events between two or more populations of differing ethnicity who are exposed to similar environmental conditions because they live in the same place (Bogin and Macvean, 1982; Greulich, 1957; Hess and Weinstock, 1925; Loder *et al.*, 1993; Malina and Little, 1981; Nyati *et al.*, 2006; Zhang *et al.*, 2009). In all of these studies, no matter which approach was taken, the results vary. Most studies find some degree of difference in the timings of skeletal maturation between identified ethnic groups, but this differs by population and by atlas used (Loder *et al.*, 1993; Malina and Little, 1981; Zhang *et al.*, 2009). Some find that one atlas has improved accuracy rates in a population when compared to another atlas but again, this is on a case by case basis with no one atlas demonstrating accuracy rates which allow it to be identified as the preferred method of age estimation in every situation (Schmeling *et al.*, 2000).   Schmeling *et al* in 2000 scrutinised more than 80 of these studies which had examined the relationship between ethnicity and age estimation using radiographic data. They found, as expected, that the

sequence of maturational stages remained consistent between ethnic groups but that there was no discernible pattern in differences in maturational timings between ethnic groups such as would be expected if ethnicity were a significant constant in relation to biological maturation of the skeleton. They concluded that this mass of data pointed away from ethnicity being the predominant aspect in maturational timings and firmly towards socioeconomic factors being the more critical influence. In reality there is the danger that this might be interpreted a little too simplistically as studies which compare the maturational rate between monozygotic and dizygotic twins have shown that the similarity in maturational rates between monozygotic twins is extremely high indicating that there is a genetic link to skeletal maturation, although it does not preclude the argument that this link can be over-ridden to a large extent by socioeconomic factors (Kimura, 1983; Skład, 1977). Whilst the argument of Schmeling *et al* (2000) has gained a high degree of acceptance, it does not mitigate against the need to know and understand how a population performs in relation to an age estimation technique, since individuals who are from similar backgrounds are likely to have similar life chances, dietary habits and access to resources which are part of the plethora of socioeconomic factors which do have significant effects on maturation.

1.13 Socioeconomic Factors

Socioeconomic factors relate to a group of environmental influences including; nutrition, disease and social status. These interrelated features have an influence on growth and maturational rates from conception onwards and are closely interrelated (Johnston, 2002). The long growing period which the human organism undergoes between conception and the attainment of maturity

means that they are exposed for a long period of time to the vagaries of outside influences. An increased sensitivity to environmental factors and a concomitant ability to adapt has underpinned the success of the human species however this sensitivity means that environmental influences can act negatively as well as positively and must be taken into account when undertaking age estimation since an increased plasticity can give rise to populational change on a generational basis (Bogin, 1988; Bogin and Rios, 2003; Eveleth *et al.*, 1979; Eveleth and Tanner, 1976; Gustafsson *et al.*, 2007; Stini, 1971).

The environment acts on genetically determined growth potential with the result that in ideal conditions full growth potential can be achieved. This is not always the case however in conditions which are less than ideal, although the timing of detrimental conditions has an influence on the degree of influence on the growth of the individual since there are times in a child's development when they are more susceptible to less than optimal conditions (Dreizen *et al.*, 1967; Facchini *et al.*, 2008; Laska-Mierzejewska and Olszewska, 2004; Mays *et al.*, 2008; Reyes *et al.*, 2003). In optimal living conditions such as those found in many modern societies, with sufficient affordable food, housing and access to medical care, the trend is for successive generations to experience earlier maturation which is most easily recorded through the onset of female menarche which is often used as a marker of the attainment of puberty (Danker-Hopfe, 1986; Dreizen *et al.*, 1967; Jones *et al.*, 2009; Lejarraga *et al.*, 1980; Magnússon, 1978; Malina *et al.*, 1977). Since growth is also controlled by genetics it is no surprise that there are indications of a maximum height at which a population will eventually plateau. These optimal conditions are not the

reality for many who live in other parts of the world including developing countries and much of Sub-Saharan Africa where poverty, conflict, adverse weather conditions and crowded unsanitary living conditions produce a less than ideal growing environment for the majority of the world's children (UNICEF, 2012). These countries are also the most likely to be the source of children who are the subjects of age disputes (European Migration Network, 2010).

Nutrition sits at the very centre of this conglomerate of influences on growth. Poor maternal nutrition can affect the growth of the child *in utero* as observed in studies of babies born to mothers during famines such as those experienced during times of conflict (Clarkin, 2008; Smith, 1947). Of note is the fact that males evidence a greater degree of reduction in birth weight and size in response to these stressors than females in the same conditions (Lampl and Jeanty, 2003; Lampl *et al.*, 1978; Stinson, 1985).

Studies have shown that a low birth weight can have lifelong implications for health but have yet to demonstrate that it also has an effect on skeletal maturation rates *per se* as long as the nutritional intake of the infant is sufficient to maintain growth (Dreizen *et al.*, 1954; Lampl *et al.*, 1978; Scrimshaw and Guzman, 1953). Continuing poor nutrition after birth does however have a detrimental effect on skeletal maturation rates (Dreizen *et al.*, 1964; Fleshman, 2000). This is because, when food becomes limited the body responds by retarding growth in response to calorific inadequacy (Johnston, 2002). This has been recorded in many population studies, one of the first being that of Greulich (1951) on a Guamanian population. His findings have been supported by studies which have shown that it is not just entire populations who might demonstrate the effects of poor nutrition but also groups within populations who

for various reasons might have limited access to resources (Cameron *et al.*, 1991; Facchini *et al.*, 2008; Reyes *et al.*, 2003). The slowed skeletal maturation rates in children who remain in situations of poor nutrition are reflected in the attainment of less than expected heights and later and prolonged puberty (Johnston, 2002). The United Nations Children's Fund (UNICEF) in their 2010 annual report estimation that more than 200 million children worldwide suffered from less than adequate nutrition leading to stunted and slowed growth (UNICEF, 2012). It should be noted that obesity also has an effect on the rate of growth adding weight to the need to assess the BMI (body mass index) of any individual who is undergoing skeletal age estimation (Akridge *et al.*, 2007; Guo *et al.*, 1997; Van Lenthe and Van Mechelen, 1996).

The relationship between environment and growth has been highlighted in studies on children who have moved from situations of high environmental stress, poverty, poor access to nutrition, healthcare and schooling to ones where environmental conditions are vastly improved. Children in these circumstances experience catch-up growth during which they can grow rapidly until they reach a maturational stage equivalent to that experienced by their peers who have not endured poor environmental conditions (Melsen *et al.*, 1986; Proos, 2009). Catch up growth is also observed when nutritional supplements are provided within the environment itself, underlining the importance of the role that nutrition plays in the process of growth (Godoy *et al.*, 2010) .

The calorific intake of a child fuels activities as well as growth and in situations in which children are forced by circumstances to take part in substantial physical activity this reduces the amount of energy available for growth. This

problem was identified in children who worked at heavy physical labour in the mines or in agriculture (Mays *et al.*, 2008), but has more recently been recorded in children who take part in professional sports such as gymnastics (Georgopoulos *et al.*, 1999; Georgopoulos *et al.*, 2001; Malina *et al.*, 2007; Malina *et al.*, 2000).

Nutrition does not sit alone in the multifactorial process which affects growth. Malnutrition is in turn related to a higher risk of infection which lends itself to a higher demand for energy as the body fights that infection. Infections can also cause problems of nutrient absorption, again adding to the calorific deficit which a child is experiencing. Poor access to affordable medical care therefore becomes another significant factor in the energy that a child has available to expend on the growth process (Cameron, 2002; Cameron, 2007; Johnston, 2002). In short it is the limited access to resources; appropriate and sufficient food, medical care, appropriate housing and education which poverty brings which in turn have a detrimental effect on growth. These problems of access are experienced in all cultures on a worldwide basis.

The anthropometric change in a population as it responds to a change in environmental conditions is known as secular change. As noted, this change can be positive as access to resources improves for most of the members of a society (Dittmar, 1998), or it can be negative as events such as war impact on a population. The study of secular change has become popular since it is a method by which the ways in which child growth can be measured in response to environmental conditions and alterations (Cole, 2003). There are a large number of studies which have examined secular change both within and between populations (Laska-Mierzejewska and Olszewska, 2004; Matsuoka *et*

al., 1999; Ozer, 2008; Roberts, 1994; Silva and Padez, 2006; Ulijaszek, 2001) (see Appendix 1). These studies highlight just how extensive the anthropometric differences can be and how quickly change can be detected in response to changing conditions.

Not all members of a population are affected in the same way in every set of circumstances. Poverty exists in all societies bringing with it a specific set of environmental stressors which can and will affect the growth of a child so even in Western societies where access to medical care and affordable food is part of daily life there are minority groups who will experience environmental stress due to poverty and discrimination (Bailey *et al.*, 1984; Facchini *et al.*, 2008; Reyes *et al.*, 2003). Whilst knowledge of the general environmental conditions within which a population exists is helpful this highlights the requirement for anyone undertaking forensic age estimation to take into account the conditions within which each individual child has been living.

There are also a number of chronic conditions such as Crohn's disease or Cerebral Palsy which even with access to affordable high standards of health care create an inability for the body to process its nutritional intake and cause faltering growth curves, many of which should be identified during a medical examination (Belli *et al.*, 1988; Cronk and Stallings, 1989; Gilbert *et al.*, 2004; Henderson *et al.*, 2005; Kelts *et al.*, 1979).

In conclusion every child who is age assessed is the sum of their past influences on their growth; their genetic inheritance, biological sex, ethnicity, diet and health and their access to medical care. An understanding of the population from which the child originates will give some indication of the factors which 'might' have had an influence on the growth of that individual but each

age estimation is an age estimation of an individual, not a population, and this has always to be borne in mind. Most of the anthropometric data which was used to develop the atlases came from healthy children with adequate nutritional intake, who were of western European origin and lived 6 or 7 decades ago. Children far removed from those who come to the attention of authorities in a modern world. Each time an atlas is used, the question has to be; is it appropriate to compare the skeletal development of this individual to this standard?

This study will add to the body of knowledge which has been gathered, and continues to be gathered, in relation to that question.

2 An Overview of Studies and Atlases

2.1 Information Collection

With the discovery of the potential for radiographic imaging in 1895 by Professor Wilhelm Reontgen, practitioners were provided with the ability to 'see' inside the body of living humans creating images of the so called 'hard' tissues, namely bones and teeth (Brogdon and Lichtenstein, 1998). This imaging technology became central to the monitoring and measurement of skeletal changes during subsequent studies into child growth and development (Brenner *et al.*, 2003; Ramsthaler *et al.*, 2009; Walker, 2000). This repeated exposure to ionising radiation would not be acceptable today in the UK for ethical reasons and the radiographic collections which were produced during these studies are likely to remain unique.

Prior to the development of X-Ray imaging, studies of skeletal development were of necessity limited to deceased children. The use of skeletal remains of children to assess maturational milestones and child development is fraught with difficulties which have been fully documented (Scheuer and Black, 2000a). The new found ability to study children of known health, environment, family and developmental history who could be followed as they progressed through to adulthood gave physical anthropologists, auxologists and paediatricians a chance to collect and analyse novel data. This led to the establishment of a significant number of longitudinal growth studies many of which were initiated in the early part of the twentieth century (Garn, 1981). The implementation of these studies marked a point at which the ability to record and measure physical changes coincided with a desire to understand how a child grew and

developed under favourable environmental conditions, thus providing a standard against which to compare the growth and development of other children (Garn, 1981). Many of the studies still continue, although due to changes in an understanding of the dangers of regular exposure to X-rays, it is no longer ethically possible to repeat the sequential imaging of joint areas which was so central to the approach to data gathering on maturational changes of the skeleton. Data collection therefore is limited to the collection of anthropometric data (Roche, 1992). The studies in question targeted healthy children of good nutritional status, since the main aim of the work was to trace the developmental changes of normal children as they progressed towards maturity. Whilst the children who did participate were healthy, differences in income and environments existed between the socioeconomic backgrounds of children whose data was utilised in the different studies therefore the data itself are not comparable on a socioeconomic basis (Garn, 1981).

There are two types of growth study; firstly there are those which rely wholly on the collection of longitudinal data and secondly those that rely on the collection of cross-sectional data. Longitudinal studies are costly and expensive in terms of time and the commitment of those both collecting the data and those who take part and provide the data, however they are the optimum method of the two since the collection of longitudinal data allows details of growth to be recorded on multiple occasions for an individual child over a distinct length of time allowing the periods of greater and lesser growth velocity to be recorded and identified accurately (Eveleth and Tanner, 1976). This longitudinal collection of data allows individual variation which exists between children as they grow to be highlighted. The value of longitudinal studies into growth was recognised as long ago as 1891 by Franz Boas who ran a short study of this

type (Tanner, 1959). These studies are not without issue as a number have been criticised because images were not taken at short enough intervals during the period of participation. Changes which occur during times of peak growth were therefore potentially missed by examinations which were too widely spaced in time (Acheson, 1954; Acheson, 1957). Despite this criticism, these longitudinal studies have provided a significant amount of data and have formed the basis for a number of standards of skeletal and dental maturational atlases.

The use of cross sectional data is more efficient in terms of both cost and time, however there are a number of problems with this form of data collection which are unavoidable; firstly the data collected provides a 'snapshot' of information at a given time, rather than information about what is happening over time to each individual participant. This single view of the skeleton at a given time causes problems when examining juvenile growth because growth is not linear, but instead proceeds through periods of acceleration and stasis, the timings of which vary between individuals (Tanner, 1978). The collection of this single episode of data does not provide the ability to identify whether an individual is experiencing a growth spurt or is in a period of stasis, suggest anything about the increments of growth for an individual over a given time period or provide information about variability around the mean for the population examined (Eveleth and Tanner, 1976). Additionally the effect of the variation in timing of growth and maturational events which exists between children creates a situation where events such as the growth spurt become difficult to identify because the velocity of change becomes statistically smoothed out, creating a situation in which the growth peak becomes lower and the growth spurt appears to last for longer, an effect first noticed and described by Franz Boas (Lampl and Thompson, 2007; Tanner, 1959).

During the last century there were a large number of studies which collected data on human growth and development, those which were most influential on the development of reference standards are discussed below.

2.2 Atlases

The first atlas was created by John Poland in 1898 and was composed of a series of radiographs of the left hand and wrist (Poland, 1898). The infants imaged were almost exclusively male although sex was unspecified in some cases. The spacing of the images is on a yearly basis through most of the atlas and there is a written description of the anatomy of the bones of the hand and wrist for each image. The atlas also includes suggested ages of fusion of epiphyses and appearances of primary ossification centres. After this first atlas the next of note was the hand-wrist atlas developed by Todd (1937), many others have followed since the publication of this atlas, these tend to be grouped into two types. The first group were based on a methodology that has come to be known simply as the 'atlas method'. These comprise a series of radiographs, which are considered to represent the standard for each stage of skeletal maturity (Hauspie et al., 2004). There are a number of such atlases, each concentrating on a different area of the body; the hand-wrist (Greulich and Pyle, 1959; Thiemann et al., 2006; Todd, 1937), the knee (Pyle and Hoerr, 1969), the foot-ankle (Hoerr et al., 1962) and the elbow (Brodeur et al., 1981). Their method of use tends to be a straightforward comparison of images resulting in an apparently "easy to use" approach which can be applied in a timely manner. The straightforward method of use and the speed with which a conclusion can be reached has resulted in the hand/wrist atlas of Greulich and

Pyle (1959) remaining the most frequently utilised method of age estimation in the living.

The second type of atlas employs an ageing method known as the 'single bone method'. This is based on a method originally suggested by Acheson (1954; 1957). He felt that the atlas method was restricted by presenting each body area as a whole which did not take account of the variation in maturational timing which can exist between different bones within that body area. His alternative suggestion was presented as a bone-by-bone method of maturity analysis for the hand-wrist (Acheson, 1954; Acheson, 1957). His ideas and approach to maturity indicators formed the basis of the methodology utilised in the subsequent atlases of Tanner *et al* (1962, 1975, 2001) and of Roche *et al.* (1988)*.* These "single bone atlases" concentrate again on the hand/wrist region and assign numerical maturation scores to specific bones within this area. Each score is related to the stage of development that an ossification centre has attained and is weighted according to its importance in relation to the maturational process. Summing the accumulated scores gives an approximation of the chronological age of the individual (Roche *et al.*, 1988; Tanner *et al.*, 2001; Tanner *et al.*, 1962; Tanner *et al.*, 1975). The Sauvegrain *et al.* (Dimeglio *et al.*, 2005; Sauvegrain *et al.*, 1962) method is a more restricted version of this approach which was specifically designed for use on radiographs of the elbow.

2.3   Maturational Markers

All of the atlases rely on the appearance of, and changes in size and morphology of, ossification centres in the identified skeletal areas. Whilst growth and maturation is a continuous process, authors identify markers and changes which they consider indicative of stages of skeletal maturation within that continuum.   These markers and changes can be related back to a skeletal age. Wingate Todd (1937), following on from the work of Hellman (1928) was the first to introduce the description of maturity indicators when describing skeletal maturity (Cameron, 2002).   There have been many attempts by other researchers to develop and describe their own sets of maturity indicators since the work of Todd but despite a number of small differences between these descriptors and their presentation there are a greater number of similarities than there are differences reinforcing the relationship between the maturational process and the indicators used to measure it.   Cameron (2002) suggests that maturity indicators have to have a number of prerequisites if they are to be of use in age estimation; firstly they must be present in all children of both sexes, appear sequentially and in the same sequence for each child and finally they should reflect continuous maturational development.

2.4   Side of the body

All of the atlases since that of Poland are based on images of the left side of the body.   In their atlas, Greulich and Pyle (1959) justified the use of the left hand-wrist images in their work and in the previous work of Todd, by arguing that they were following guidelines laid down by the "*International Agreement for the Unification of Anthropometric Measurements to be made on the Living Subject*"

(Duckworth, 1919). These guidelines, which came about as a result of an attempt to formalise data collection methods, stated, within a list of general principles on anthropometric measurement that - '*For "paired" measurements, the* left *side is recommended"* (Duckworth, 1919). Greulich and Pyle (1959) also argued that the left hand is less likely to suffer injury or trauma since, within any given population, the number of individuals who are right handed is larger than the numbers who are left handed. This protocol has been followed in relation to all of the atlases which have been created using radiographic images of skeletal areas.

2.5 The Brush Study (1926-current)

This American study, also known as the Cleveland study, was initiated in 1926 by Wingate Todd. The goal of this longitudinal study was to learn about growth and maturational processes from the information gathered from healthy children as Todd questioned the utility of the information that was provided by the study of deceased children relative to child growth and development (Behrents and Broadbent, 1984). He argued that this did not enable a clinical practitioner to understand 'normal' growth and maturation at the skeletal level. His vision was that the teaching of growth and development should be undertaken through the use of information gained from healthy children, rather than that which had been gathered from children whose development could have been affected by their nutritional status and disease burden. Children who were enrolled on the Cleveland study were given physical and psychological tests and concurrent records were made of their nutrition, dental and medical health. Ideally children were examined every three months from birth to 12 months of age, 6 monthly thereafter until the age of five, at which point examinations were scheduled at

12 monthly intervals throughout adolescence. Children were initially recruited from birth however children of various ages could and did enter the study at different times the one stipulation existing for their inclusion was that they were in good health (Todd, 1937).

Central to data collected, were radiographic images which facilitated the examination of skeletal development. Within the study six body areas were imaged; the hand, elbow, shoulder, hip, knee and foot. In total, more than 4,000 children from the Cleveland area were subject to head-to-toe X-rays. The extensive use of X-rays in the study was reduced in the early 1940s and finally stopped in 1942 due to the limit placed on resources by the Second World War. By this time the study had amassed a significant volume of data which is still available to researchers today. The study still exists, albeit in a different form, and has combined with the Bolton Study into the growth and development of the face and teeth to create The Bolton-Brush Growth Study.

The data collected during the Cleveland study formed the basis of a series of atlases which cover three body areas; the hand/wrist, the knee and the foot/ankle.

2.6 The Todd Atlas (1937)

The Todd atlas (1937) was the first of the hand/wrist atlases to be produced with the information collected during the Brush Foundation Study. The children whose images formed the basis of the atlas were examined serially over a 5 year period from 1930 to 1935 and as such, formed the vanguard of the subjects whose data was ultimately to be amassed. The images were collated in periods of 6 months and from these sets of images a list of maturity indicators

typical of that stage of development was identified. Todd defined maturity indicators as changes in the outline of the metaphysis and the contours of epiphyseal ossification centres rather than the appearance of ossification centres since these were considered to be too heavily influenced by external factors to be used consistently. Those images chosen for the atlas were considered to be a best fit for those maturity indicators. Todd (1937) explains this choice as the image which '*most acceptably represents the mode'.*

This atlas examines the skeletal maturation of the left hand and wrist for both males and females. The male series consists of 40 plates spaced at 3 monthly intervals from the age of 3 months until the age of 12 months. Once the age of 12 months is reached the plates are spaced in intervals of 6 months until the final plate which is of a male of 18 years 9 months of age. The images are accompanied by written descriptions of the stages of development reached by each area of the joint which the authors identify as demonstrating maturational changes. A description of the stages and what they mean can be found in the introduction to the atlas. The female series follows the same pattern, consisting of 35 plates ranging from 3 months of age until 16 years and 3 months.

Todd planned to create six of these atlases, however his ambition was never realised due to his death in 1938. The radiographs that he collected formed the basis of a number of subsequent atlases which were produced after his death but of the six atlases that he envisaged-only three were completed. The data collected from the study are still available to researchers on a pay per view basis since the Brush Study amalgamated with the Bolton study to become the Bolton-Brush Growth Study Centre, keeping all of the data collected in accessible archives (Hans and Broadbent, 2008).

2.7 Atlases of the hand-wrist, foot-ankle and knee

These are three of the atlases which had been envisaged by Wingate Todd before he died and which were produced by those who continued to oversee the study after his demise. The atlases were all developed from radiographs taken of children who were enrolled in the Brush Foundation Study, although in a number of cases the radiographs were supplemented with others gathered from complementary projects (Hoerr *et al.*, 1962).

All three atlases were produced using the same methodology and follow similar protocols to those identified by Todd in the first atlas (Todd, 1937), although they were based on a larger body of work since they covered the whole period of the study. The authors began by identifying changes within the identified joint area which they felt reflected the process of maturation, calling these changes 'maturity indicators' (Greulich and Pyle, 1959; Hoerr *et al.*, 1962; Pyle and Hoerr, 1969). Having identified these indicators they then chose 100 radiographs which were most representative of each maturational stage and arranged them according to the maturity indicators which they had identified. The chronological age assigned was the modal age at which these maturity indicators appeared. This was done separately for males and females. Once the 100 radiographs were collated, the radiograph which most represented that phase of maturation was selected for inclusion in the book (Figure 2.1). The first edition of the Greulich and Pyle atlas (1959) has a separate series of images for males and females. This changed later when these plates were combined, so for one plate there were two potential chronological ages, one for female and one for male, this was also done for the knee and foot/ankle atlases. The authors outlined their basic supposition underlying this approach by saying

that '*there are transitional osseous features in each growing bone which are the same for both sexes and all races, and that these features are reproduced as accurately in a radiograph as are the more densely outlined adult features*' (Pyle and Hoerr, 1969). Thus, because they had established that both sexes experienced the same maturational changes and it was simply the timing of these changes which differed, they combined radiographs for the sexes but assigned differing ages to each one according to sex. Each radiographic plate was accompanied by a description of the skeletal elements which could be seen in the image and by a written description of the maturity indicators for that stage of skeletal maturity as identified by the authors.

All of the atlases in this series began with a description of the anatomical and radiographic terms which they used throughout the text when describing each radiograph. Additionally towards the end of the atlas the maturity indicators were also described in a series of line drawings with accompanying descriptions (Greulich and Pyle, 1959; Hoerr *et al*., 1962; Pyle and Hoerr, 1969). Each atlas also includes information on changes to maturity caused by disability or other disorders.

Figure 2.1: 'MALE STANDARD 23'. Skeletal age 13 years (taken from Greulich and Pyle 1959)

Skeletal Age of Individual Bones

The skeletal age assigned to each bone in this standard is 13 years

The radial epiphysis and the epiphyses of the second to fifth metacarpals are now as wide as the adjacent margins of their shafts.

The ossification centre of the sesamoid in the tendon of the adductor pollicis is now visible, just medial to the head of the first metacarpal.

The epiphyses of the proximal phalanges of the second, third, fourth and fifth fingers have increased somewhat in thickness and their radial margins end in distally directed tips. The epiphysis of the middle phalanx of the fifth finger is now as wide as its shaft. The tips of the epiphyses of the distal phalanges of the second to fifth fingers are bent slightly distally and the distal ends of the corresponding middle phalanges are now slightly concave.

The knee and foot/ankle atlas both supplemented their data with radiographs from the Stuart Growth Study based in Boston since there were no series of radiographs which followed any one individual from birth to maturity at 19 years of age in the Brush study (Hoerr *et al.*, 1962; Pyle and Hoerr, 1969). The children in this study were described as originating from similar backgrounds to those enrolled in the Brush Foundation Study by the authors, but Garn has since called this into question in a publication in which he felt that due regard was not paid to the differences in socioeconomic background of the children enrolled in the different studies (Garn, 1981).

The spacing of the plates, which begin at birth and continue through to 17-19 years of age, varies according to sex and joint area, since the atlas identifies important ages not through the passing of chronological time but by the changes of the identified maturity indicators. Instructions for use of the atlases are included within the text, but the authors iterate that these can be replaced by other methods as devised by the individual practitioner (Greulich and Pyle, 1959; Hauspie *et al.*, 2004; Hoerr *et al.*, 1962; Pyle and Hoerr, 1969). The method specified begins by assuming that the practitioner knows the chronological age of the individual being assessed and is not a method for using the atlas to age estimate an individual of unknown age.

2.8 The Harpenden Study (1948-1971)

The Harpenden study was initiated and run by Tanner and Whitehouse on behalf of the Institute of Child Health in the UK. It ran between 1948 and 1971 and was funded by the Ministry of Health. The study was initiated as a means of examining the effects of war time dietary rationing on the growth and

development of children, but became a long running growth study. The majority

of the children involved in the study resided at the Harpenden Children's

Homes. A total of 420 children between the ages of 3 and 18 years of age took

part. The children were studied every 3 months during adolescence throughout

which time additional physical parameters such as height and skinfold thickness

were also measured. All the children were photographed naked at each

examination and a set of radiographs taken. In total between 6 and 8 X-rays

were taken on each occasion, these included; left hand and wrist, orthodontic

images, calf, thigh and upper arm. Unlike the Brush study the only X-rays taken

to specifically check skeletal maturity was the one of the left hand and wrist, all

of the others were used to estimate soft tissue depth.

The resultant hand/wrist radiographs formed both the basis for the Tanner-

Whitehouse atlases and also formed the basis for the creation of growth curves

against which the development of British children were to be checked for many

years (Tanner *et al.*, 1966). These growth curves were designed to assess the

extent to which children achieved 'normal' growth. Ultimately however a

question arose around how circumstances had affected the growth rate of the

children in a care situation. Both the experience of dietary restrictions and the

stress which they may have experienced due to personal circumstances could

be argued to affect growth and development, This, combined with the need to

update the atlas to take secular change into consideration has led to these

growth curves being modernised.

2.9 The Tanner-Whitehouse Atlases (TW1 (1962), TW2 (1975), TW3 (2001))

The single bone method atlases are based on an approach to the assessment of age which was originally suggested by Acheson (1954). Acheson (1954) argued that the methods of Greulich and Pyle and their colleagues, as discussed above had a number of inbuilt assumptions which created methodological errors in their design. These issues included: a presumption that the appearance and development of ossification centres is constant, the interval between imaging times being too great to accurately identify appropriate maturity indicators, the need for two standards, one for each sex and the presumption of a close link between skeletal maturity and chronological time represented by the age of the child (Acheson, 1954). The resulting errors created a situation which did not allow for the individual differences seen between children as they develop and mature.

In an effort to mitigate against these factors, Acheson (1954) suggested the introduction of a scoring system which would allow each ossification centre to be assessed individually, according to their stage of appearance and shape. At the culmination of the examination a final tally of all the scores would be made and this would then be related to a final maturational stage (Acheson, 1954). This idea was adopted by Tanner and his colleagues and an example of the resulting method is shown in Figure 2.2. The resultant atlases were developed using the hand/wrist radiographs collected during the Harpenden Growth Study.

Proximal Phalanges of Third (III) and Fifth (V) Fingers
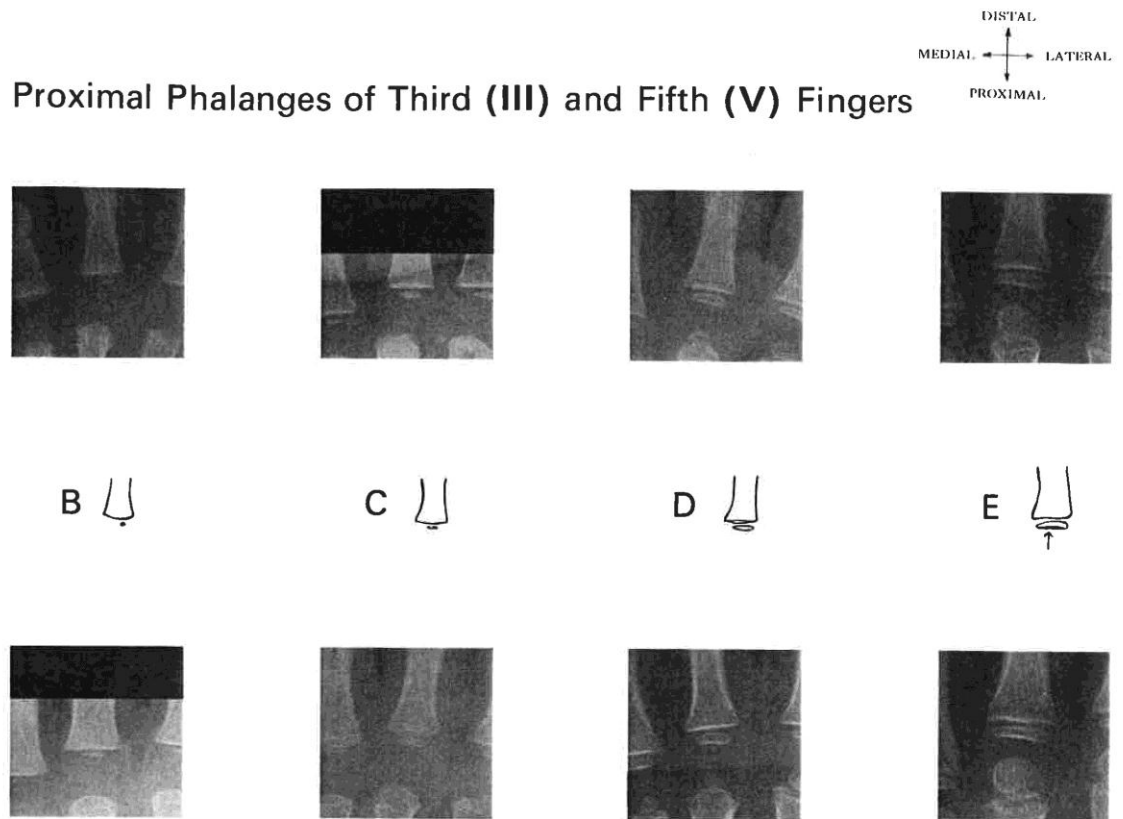
Figure 2.2: Stages of ossification identified in the TW3 atlas for the Proximal Phalanges of the third and fifth fingers (Tanner *et al.*, 2001).

The first and second editions of the atlas were based on the same sample of radiographs which had been taken during the Harpenden study (Tanner *et al.*, 1962; Tanner *et al.*, 1975). The second book was a revision of the first and the authors admitted that they were unable to take supplementary radiographic images, consequently this revision is based upon data which at the time of writing was 20 years old (Tanner *et al.*, 1962; Tanner *et al.*, 1975). The authors discussed the process of maturation which is evidenced within the atlas (Tanner *et al.*, 1975). One of the additional processes included within the atlas was a method for the prediction of adult height from measurements taken in childhood (Tanner *et al.*, 1975). The technique for the assessment of maturation is

described within the text and involves the examination of the ossification

centres of the hand-wrist. The ossification centres which are assessed within

the hand and wrist are divided into two groups; the first group are known as the

RUS (radius, ulna and short bones) and comprises the radius, ulna and

identified metacarpals and phalanges (Table 2.1). The second grouping is

known as the *carpals* and comprises the carpal bones of the wrist, with the

exception of the pisiform. Three scores are possible; the RUS score alone

which is the sum of the scores from the bones identified as belonging in the

RUS group, the carpal score alone which is the sum of the scores from the

bones identified as belonging to the carpals or a combined score, known as the

20-Bone, bone age.

RUS (radius, ulna and finger bones)	Carpals (carpal bones)
Distal Radius	Capitate
Distal Ulna	Hamate
First, third and fifth metacarpals	Triquetral
Proximal phalanx thumb	Lunate
Proximal phalanges of third and fifth fingers	Scaphoid
Distal Phalanx thumb	Trapezium
Distal Phalanges of third and fifth fingers	Trapezoid

Table 2.1: Primary and secondary ossification centres considered for RUS (radius, ulna
and short bones) and Carpal groupings (Tanner *et al.*, 2001; Tanner *et al.*, 1962;
Tanner *et al.*, 1975).

For each bone a series of maturational stages are described both in words, in

line drawings and in radiographic representation demonstrating the upper and

lower limits of each stage (Figure 2.2). The stages are given sequential letters

from A through to either H or I, depending on the bone and a weighted score is

given to each stage. There are different scores depending on whether the

individual is male or female. It is these scores which are added together to

provide a total score. This final score is linked to a table which has

chronological ages assigned to each score. The maximum score is 1000 for

each potential group of observations which relates in turn to a maximum

possible age (Table 2.2 and Table 2.3).

Sex and Area	Maximum Score	Bone 'Age'
Male RUS	1000	18.2
Male Carpal	1000	15.0
Male 20-bone	1000	18.0
Female RUS	1000	16.0
Female Carpal	1000	13.0
Female 20-Bone age	1000	16.0

Table 2.2: The maximum scores and the ages which they relate to in the TW2 system (Tanner *et al.*, 1975).

The second atlas was a revision of the first, involving changes in some of the

descriptional stages of bones although the scoring system remained the same.

The third atlas remains true to the same methodology but draws its information

from a different reference group (Tanner *et al.*, 2001). Acknowledging that

noticeable secular change has occurred in Western countries since the

collection of data during the 1960s the authors' base the TW3 atlas on data

gathered from children who were participating in the First Zurich Longitudinal

Growth Study. Data was also included from Turin, Genoa, Tokyo, Leeds and

America and the authors argue that this collection of data is more relevant to a

modern population. Fundamentally each atlas made only minor changes to the

maturational stages that they had originally identified because the authors

argue that these are unchanging and that all children progress through each of the changes, it is the timing of these changes which alters as populations become more affluent and resources more readily available (Tanner *et al.*, 2001; Tanner *et al.*, 1962; Tanner *et al.*, 1975).

The third edition of the TW method only utilises the RUS and carpal scores in their calculations of maturation since the authors felt that the 20-Bone bone age was unnecessary. It is of interest that whilst the maximum scores remain the same i.e 1000 but that this score relates to a very different maximum age compared to that given in the TW1 and TW2 atlases demonstrating the influence of secular change on maturational rates within these populations (Tanner *et al.*, 2001).

Sex and Area	Maximum Score	Bone 'Age'
Male RUS	1000	16.5
Male Carpal	1000	15.0
Female RUS	1000	15.0
Female Carpal	1000	13.0

Table 2.3: Maximum scores and the bone ages which they relate to in the TW3 atlas (Tanner *et al.*, 2001).

All three atlases contain detailed instructions on their use, although an age estimation undertaken using this method takes significantly longer to perform than that undertaken using a method such as the Greulich and Pyle (1959) atlas. Unfortunately whilst authors argue that the TW3 atlas is more relevant to a modern population, it is now out of print and the text is very difficult to source.

2.10 The First Zurich Longitudinal Study (1954-current)

This study is divided into 3 parts, the first ran from 1954-1978 and involved the study of 351 healthy children, the second involved 111 children and ran from 1971-1998 and the third gave an added dimension when it became possible to record data from the children of the original study participants and ran from 1974 to the current day. This allowed the collection of data across two known generations. Data collection included data on both the physical and mental development of children (Ernst *et al.*, 1992; Jenni *et al.*, 2005; Largo and Prader, 1983a; b; Prader *et al.*, 1989). The study is now being supported by the Swiss National Science Foundation and has generated a significant amount of data which has contributed to a large number of studies including adding to the data utilised in the TW3 atlas of Tanner *et al* (2001).

2.11 The Fels Study (1929-current)

The Fels study began in 1929 as a longitudinal multidisciplinary study into the effects of The Great Depression on child development, one of a number of similar studies which were initiated in the USA at this time. It was originally overseen by Lester Sontag and funded by the Fels Fund of Philadelphia. The study examined children within families who were ideally enrolled whilst the mother was still pregnant thus ensuring that data collection began as soon after birth as possible. Unlike other studies which concentrated only on children data collections were continued throughout adulthood with the result that individuals who took part at the inception of the study are still attending for the collection of information to the present day. A significant amount of work has been published on skeletal and dental growth as a result of work that was done on

the data from this project including many of the publications of Stanley Garn who worked on the project between 1952 and 1968.

2.12 The Fels Atlas

The Fels atlas was developed from 13,823 radiographs of the left hand-wrist collected during the Fels study (Chumlea *et al.*, 1989). This atlas was designed using the same theoretical approach to that suggested by Acheson (1954) and put into practice by Tanner and colleagues. However instead of using the 9 maturity indicators isolated and described by Tanner and his team, which are applied to 20 bones of the hand/wrist, the Fels method relies on a total of 98 maturity indicators, creating a method complex enough that it requires specialist training for use and has an accompanying computer programme to enable maturity estimations to be performed. Whilst the few studies that have been undertaken to test the accuracy of this atlas have shown favourable results, in reality its complexity means that it is a rarely utilised resource (Aicardi *et al.*, 2000; Chumlea *et al.*, 1989; Malina *et al.*, 2007; Van Lenthe *et al.*, 1998; Vignolo *et al.*, 1999).

2.13 Ageing methods using the elbow

The Brodeur *et al* atlas (1981) of the elbow begins by explaining that it was designed to '*complement a standard hand and wrist atlas*' and is based on cross sectional data collected during the years of clinical practice by the author. In addition to creating an atlas which contains the anterior-posterior and lateral images of elbows at set ages, it also seeks to cover abnormalities caused by trauma, congenital abnormalities and haemophilia. As the authors accurately

point out, the maturational sequence of the elbow is complicated. To allow for this, as well as the natural variation which is found between individuals the authors have included images for what they describe as 'high' and 'low' 'normals' for each age group, as well as the image of the elbow which most represents the 'norm'. They separate males from females throughout the atlas (Brodeur *et al.*, 1981) .

The authors begin with an explanation about their atlas. They have developed an ageing process which guides the practitioner through the maturation process of the elbow as seen in the anterior-posterior view. They include descriptions of each secondary centre of ossification, the morphological changes which they undergo and the times at which these can be expected. This atlas is as much about identifying pathology and trauma as the maturation sequence of the elbow and this is reflected in the text where there are descriptions of the normal appearance of the ossification sequence in order to allow the practitioner to identify injury and abnormalities.

In the first half of the atlas each set of age ranges consist of a male and female example of that age and ranges from new-born (5 days old) to 16 years of age. Each of these also has a written description which aids the practitioner in making their assessment. The second section of the atlas contains images and descriptions of elbows which have undergone trauma and disease processes, again underlying the aim of the book which aims to provide the practitioner with knowledge of both normal and abnormal elbow development. The radiographs are spaced at 6 monthly intervals, up to the age of 16 years 6 months of age for both male and females. This upper age limit reduces their use in forensic age estimation for older children but does not prevent its use in younger children.

The scoring method available for the elbow are all variations of an original method described by Sauvegrain *et al.* (1962). This method has been widely used in Europe for the last 40 years (Dimeglio *et al.*, 2005; Hans *et al.*, 2008; Sauvegrain *et al.*, 1962). As with the Brodeur *et al.* atlas (1981) the Sauvegrain method was designed to be used in support of other ageing methods but was aimed specifically at age estimation during the peak velocity height growth which children experience during the pubertal period. The method relies on the assessment of 4 anatomical areas of the elbow joint; the lateral condyle, the trochlea, the olecranon apophysis and the proximal radial epiphysis, each of which was assigned a score. The maximum score is 27 at which stage the elbow is considered to be fully mature. The most commonly used variation of the method is that described by Dimeglio *et al.* (2005) in which they proposed a number of additional increments within the scoring system which increased the accuracy of the method (Figure 2.3).
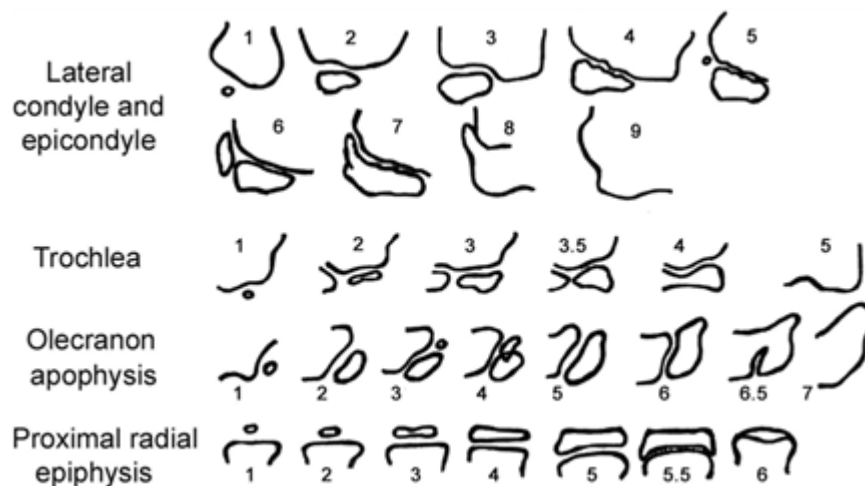
Figure 2.3: Scoring method of Dimeglio *et al.* (2005).

To convert the numeric score to a chronological age, the Sauvegrain method relies on the use of a graph (Figure 2.4), however this is not easy to read or interpret so Dimeglio *et al.* (2005) also redrew the graph to make it easier to interpret and in the process separated females (Figure 2.5) from males (Figure 2.6). These graphs make the relationship between score and chronological age easier to establish. It should be noted that in order to assign a chronological age, it is necessary for the cumulative score to reach 9 for females and 10 for males since these are the lowest points on each of the graphs
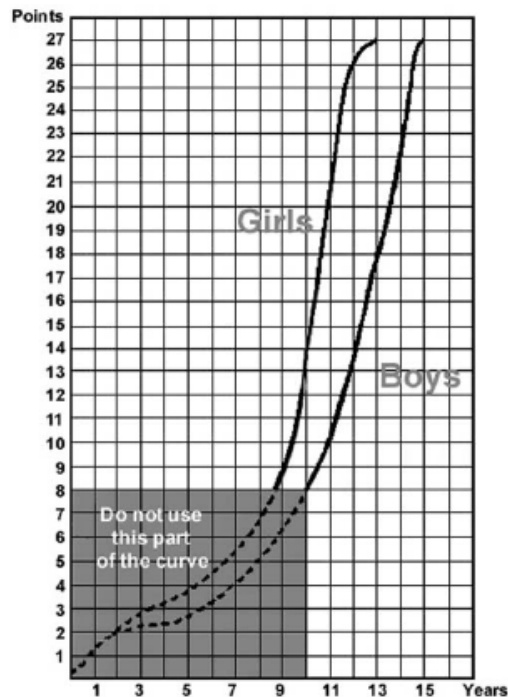
Figure 2.4: Original Sauvegrain *et al.* graph (Sauvegrain *et al.*, 1962).
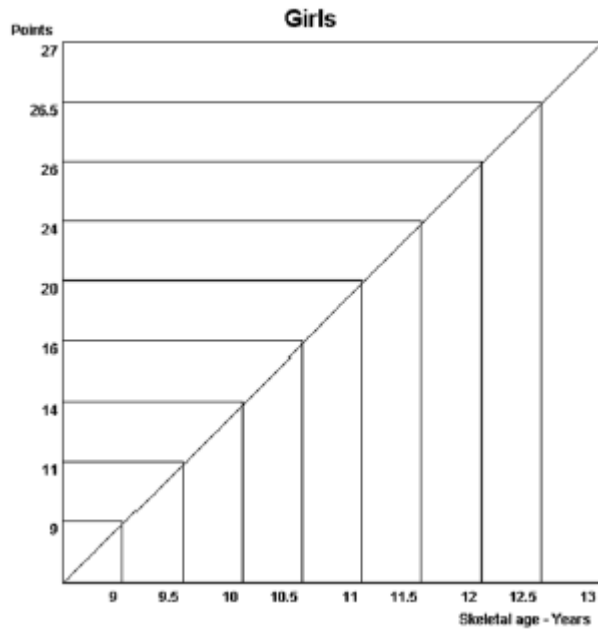
Figure 2.5: Re-drawn Sauvegrain *et al.* (1962) chart for girls (Dimeglio *et al.* 2005).
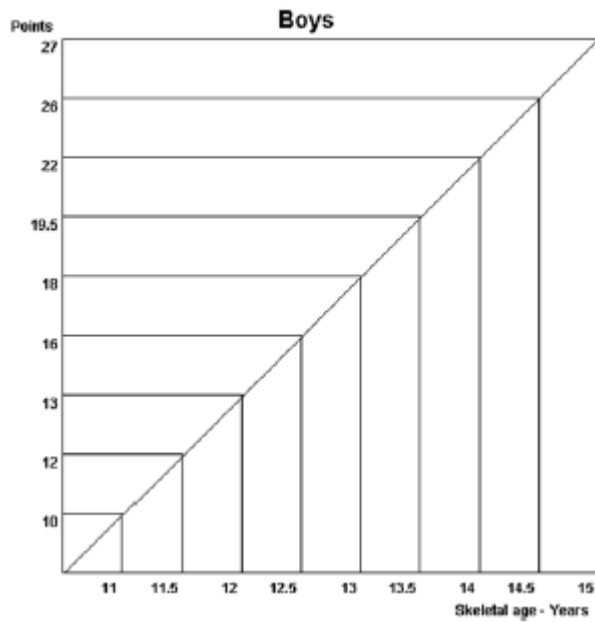
Figure 2.6: Re-drawn Sauvegrain *et al.* (1962) chart for boys (Dimeglio *et al.* 2005).

2.14 Other Atlases

In addition to the atlases listed above, there are a number of other reference atlases which are available to anyone undertaking age assessments (De Roo and Scrӧder, 1976; Fishman, 1982; Gilsanz and Ratib, 2005; Gӧk *et al.*, 1985; Roche *et al.*, 1988; Thiemann *et al.*, 2006). Many of these are limited in their use for a variety of reasons; they are little known (Fishman, 1982), except in their subject area or specific country (Gӧk *et al.*, 1985; Thiemann *et al.*, 2006), are very recent (Cameriere *et al.*, 2006; Gilsanz and Ratib, 2005) or very complicated to use (Roche *et al.*, 1988).

Many of the atlases named above have been tested for accuracy and reliability, especially with the recent increased interest in age estimation methods.

The Gӧk and Thiemann-Nitz atlases have been tested in their countries of origin (Bűken *et al.*, 2008; Büken *et al.*, 2009; Gӧk *et al.*, 1985; Schmeling *et al.*, 2006a; Schmidt *et al.*, 2007) . Both have shown that their accuracy and reproducibility is acceptable for forensic purposes on these populations but neither have been translated into English or are freely available thereby reducing their usefulness (Gӧk *et al.*, 1985; Thiemann *et al.*, 2006).

2.15 The Test of the Atlases

This study aims to re-examine 6 of the skeletal standards in relation to a modern population to review their accuracy and reliability. Tests of the reliability of each standard will allow practitioners to judge whether the standard is appropriate for use as an age estimation method for an individual from a modern population. The section above shows that the standards were

developed using data from populations which were different geographically and socioeconomically from modern populations and it is legitimate to ask whether they are still relevant to the demands of forensic age estimation processes in the UK as demands are increasingly placed upon forensic experts to ensure that their conclusions are based on sound practice.

The skeletal age in the standards will be compared to radiographs of children of known age to gain an understanding of the relationship between the maturational tempo which is demonstrated in the standard and the rate of maturation found in a modern population. Secondly the performance of each standard in relation to the modern Scottish population will be compared to each other to establish the accuracy rates of each standard in relation to its specified body area and in relation to the other standards available. The third stage of the study will include the examination of data collected from children who are living in India.

There are a large number of standards which are available for age estimation and for the purposes of this study six of these have been selected for testing. The reasons for choosing these relate to the popularity of the method (Greulich and Pyle, 1959), the use of recent data to develop the standard (Tanner *et al.*, 2001) or the limited choice of methods for specific body areas (Brodeur *et al.*, 1981; Hoerr *et al.*, 1962; Pyle *et al.*, 1971; Sauvegrain *et al.*, 1962).

3 Materials and Methods

Due to the dangers inherent in repeated exposure to X-Rays this study could not involve taking X-Ray images specifically for the purposes of research (Brenner *et al.*, 2003; Hall, 1991). The longitudinal studies which have produced the reference material we now depend upon can never be repeated. For this reason this study had to be cross-sectional in nature utilising images which had been taken from children and adolescents as part of their medical treatment or investigation.

3.1 Scottish Population

Permission was gained from Ninewells Hospital, Dundee, to access their radiographic database. Ninewells Hospital is a large teaching hospital which serves a community of around 400,000 people across Tayside and has a large Accident and Emergency Department. The images selected for this study had been taken as part of the medical investigation of female and male children and adolescents when they had attended the A&E department at Ninewells Hospital after a fall or similar incident. Initially, images viewed were on radiographic film. This image was photographed against a light box, using an 8 mega-pixel digital camera and a record made of; sex, date of birth, date of image and side of the body. Due to the method of data collection it was not possible to identify the ethnicity of the individual. The chronological age of the individual was calculated as the difference between the date of birth and the date that the

image was taken. Because the exact dates were given it was possible to calculate the difference between the two dates to the exact number of years, months and days, however for the purposes of the calculations in this study this was rounded to the month.   Images which contained recent untreated fractures were used unless the fracture displaced the epiphyses to such an extent that they became unidentifiable e.g. some elbow fractures. If treatment had commenced or there had been a previous fracture then the image was not collected to avoid the possibility that the fracture or subsequent treatment had affected growth of the area (Reynolds, 1981). Brief medical notes accompanied the images and the presence of an existing pathology, such as Perthes' disease or a disorder, such as osteogenesis imperfecta or precocious puberty also meant that the image was not collected. After Ninewells Hospital changed their system to include digital imaging in 2009 the X-Ray images were downloaded directly from the database.

The population served by Ninewells Hospital includes a population of which around 17% live in poverty as defined by the Scottish Indices of Multiple Deprivation, 20% are students who attend the local universities and approximately 1.9% are considered to be non-white. It should be noted that a large dependence on agriculture means that there is an increase in migrant workers on a seasonal basis. Life expectancy is 78.8 years (female 80.6 years, males 76.9 years) slightly higher than the national average (Directgov., 2009).

Both female and male radiographs were collected. The age of this sample ranged from birth to 20 years of age and was separated into one year cohorts ie 1-2 year, 2-3 years etc. Images were collected for each age cohort up to a maximum of 20 images however this was not always achieved due to the availability of appropriate images. The joint areas collected were the

hand/wrist, elbow, knee and foot/ankle, since these are the areas of the body which have existing atlases. For all of these, except the hand/wrist, only images from the left side of the body were collected, and both anterior-posterior views as well as lateral views were collected when both of these were included in the relevant standard, such as the elbows, feet and knees. Whilst radiographs were collected for all of the body areas subsequent analysis revealed that there were a small number that could not be used due to the angle of the image or due to the degree of fracturing which obscured an epiphyseal area. Final cohort sizes are shown in Table 3.1.

Traditionally, age estimations are performed using joint areas from the left side of the body since it is argued that the skeleton undergoes age related changes with enough symmetry that one side reflects the state of maturity of the whole (Todd, 1937). The collection of hand/wrist images from both the right and left sides of the body allowed this to be tested statistically.

All of the images were made anonymous and given a sequential number to which was linked the information collected, the chronological age was then hidden from the researcher. Each image was viewed and age estimation undertaken using the relevant atlas. The differences between chronological age and estimated age were examined statistically once the ages had been transformed to months to facilitate statistical analysis. Due to well documented differences in the rate of development between females and males the two sexes were treated separately.

Sex, area and side	Number of Images	Sex, area and side	Number of Images	Total Number of Images
Female left hand	157	Male left hand	249	406
Female right hand	117	Male right hand	298	415
Female left elbow	260	Male left elbow	332	592
Female left knee	228	Male left knee	296	524
Female left foot	265	Male left foot	281	546
Total	1027	Total	1456	2483

Table 3.1: Number of images collected by skeletal region and sex

3.2 The standards

A total of 6 standards were tested against the four body areas (Table 3.2). All standards were designed to allow an assessment of the skeletal maturity of living children to be undertaken using radiographs.

Joint	Atlas
Hand/Wrist	GREULICH, W. W. & PYLE, S. I. 1959. *Radiographic Atlas of Skeletal Development of the Hand and Wrist,* Stanford, Stanford University Press.
Hand/Wrist	TANNER, J. M., HEALY, M. J. R., GOLDSTEIN, H. & CAMERON, N. 2001. *Assessment of skeletal maturity and prediction of adult height (TW3 method).* London, Saunders.
Elbow	BRODEUR, A. E., SILBERSTEIN, M. J. & GRAVIS, E. R. 1981. *Radiology of the Pediatric Elbow,* Boston, G.K. Hall Medical Publishers.
Elbow	DIMEGLIO, A., CHARLES, Y.P., DAURES, J-P., DE ROSA, V. & KABORE, B. (2005) Accuracy of the Sauvegrain method in determining skeletal age during puberty. *The Journal of Bone and Joint Surgery.* 87-A(8):1689-1696.
Knee	PYLE, S. I. & HOERR, N. L. 1969. *A Radiographic Standard of Reference for the Growing Knee,* Springfield, Charles C. Thomas.
Foot/Ankle	HOERR, N. L., PYLE, S. I. & FRANCIS, C. C. 1962. Radiographic Atlas of Skeletal Development of the Foot and Ankle., Springfield, Illinois., Charles C. Thomas.

Table 3.2: Skeletal area examined and the relevant atlases used in this study.

3.3 Indian Population

Permission was gained to access radiographic images in New Delhi, India. The

hospital is the Maulana Azad Medical College which is located near to the

centre of the city. Medical treatment at this hospital has no charge so it serves

a large local population from all socioeconomic backgrounds, although the

majority who access the facilities are of lower socioeconomic groups. No

children were subject to radiographic imaging for this project, all images were

taken as part of medical treatment or investigation when they accessed the emergency department and there was no information recorded which could be used to identify the child at a future date. The same background data was collected from each child as from the Scottish population. Whilst legally children should be registered at birth in India, in reality in a country with high population densities and large rural areas, this is not always the case, especially amongst the less well educated. This limited the collection of data of children who had a stated (although not proven) chronological age.

During the data collection process it quickly became clear that recording birth date was problematic and therefore an issue for the study. Dates of birth were not recorded as dates but had been recorded as a year, such as '11 years' on the medical records. This information was recorded in this manner because the parents of the children did not know the date of birth of the child and when asked they made a 'best guess' or if they did not know then the radiographer entered a 'best guess' into the records. As a result of the lack of a confirmed date of birth for the children whose images were collected, it was not possible to use the radiographs in this study. The presence of such as large population who have no recorded date of birth, despite living in the capital city of a country in which it is the law to record the birth of a child highlighted the issues which lead to the need for age estimation processes. This discrepancy had not been raised prior to travel to collect data for the study but sharply defines the importance of the research in question. The final number of radiographs which were collected from children of 'known' chronological age was very small (Table 3.3). A test of the sample was undertaken using the Greulich and Pyle atlas (1959) for the hand-wrist radiographs and the Brodeur *et al* (1981) to assess whether the stage of skeletal maturation reflected that seen in the atlas.

Sex and Side	Number of Images
Female left hand-wrist	25
Female left elbow	25
Male left hand-wrist	30
Male left elbow	31

Table 3.3: Number of images from New Delhi, India by sex and side.

3.4   Inter and Intra-observer Error

Age estimations were performed on all of the images for each joint area using the relevant atlas. Intra-observer error was tested by returning to each joint one month after the initial estimations were concluded and re-assessing a random sample of 30 images from each joint area.

Inter-observer error was tested by gathering 30 random images of each joint area and giving them to a practicing forensic anthropologist to age assess. No instructions were given on the use of each atlas other than that available within the atlas. The only information which was given was the sex of the individual whose joint appeared in the image.

3.5 Terminology

Any discussion of age estimation techniques can result in confusing terminology. For the purposes of this study, all calculations were designed so that a negative result indicates an underage and a positive result indicated an overage. The following definitions of underage and overage were followed consistently throughout.

Underage; this refers to the situation in which an individual is assigned an age which is younger than their actual chronological age.

Overage; this refers to the situation in which an individual is assigned an age which is older than their actual chronological age.

3.6   Statistical Analysis

Statistical analysis was undertaken using *SigmaStat*® and where this was not appropriate *Graphpad*®. Regression analysis was undertaken to establish the reliability of each age estimation with estimated age treated as the independent variable in all of the calculations. All ages were converted into months to facilitate statistical analysis.

4 The Hand-Wrist

Of all the potential body regions, radiographic images of the left-hand wrist are most commonly used for assessment of maturation and chronological age. As a result a large volume of literature has accumulated. Whilst the most representative of these will be included in this section, to facilitate readability the majority of references relating to this work and which have been consulted will be included in the bibliography in Appendix 1.

The hand-wrist area of the skeleton has received a lot of interest in relation to the estimation of skeletal maturity and skeletal age. Maturity in the hand-wrist can be estimated using one of a selection of atlases (De Roo and Scröder, 1976; Gilsanz and Ratib, 2005; Gök *et al.*, 1985; Greulich and Pyle, 1959; Poland, 1898; Pyle *et al.*, 1971; Tanner *et al.*, 2001; Tanner *et al.*, 1962; Tanner *et al.*, 1975; Thiemann *et al.*, 2006; Todd, 1937).   Studies which examined maturation in the left hand-wrist fall into two groups. The first group use the atlases in the manner for which they were originally designed by studying radiographs as a means of measuring the skeletal age of children of known chronological age. The studies investigate the skeletal maturity of children; to assess the effects of disorder and ill-health (Christoforidis *et al.*, 2007), to compare skeletal maturity with other indicators of maturity such as dental development (Krailassiri *et al.*, 2002; Lewis, 1991) and to understand the influence of ethnicity, socioeconomic factors secular change or environment on the development of children (Greulich, 1957; Hawley *et al.*, 2009; Lampl *et al.*, 1978; Pickett *et al.*, 1995) .

The second group of studies are concerned with examining the efficacy of the atlases themselves in relation to the assessment of age in the living for forensic purposes. These studies examine the accuracy of atlases; in relation to other atlases (Bull *et al.*, 1999), in relation to specific populations (Büken *et al.*, 2009) or specific chronological ages (Schmeling *et al.*, 2006b) or in relation to other age estimation methods (Haiter-Neto *et al.*, 2006; Kanbur *et al.*, 2006) . The emphasis of these studies is on the ability of an age estimation methodology to predict whether an individual has passed an identified birthday. In addition to a concentration on ages of legal importance, this literature also aims to explore the accuracy and reliability of existing methods of age estimation (Büken *et al.*, 2007; Schmidt *et al.*, 2008c).

The German Study Group on Forensic Age Diagnostics of the German Association of Forensic Medicine (AGFAD) is a multidisciplinary group which was formed with the express aim of developing and researching age estimation in the living (AGFAD, 2011). Much of the work of AGFAD has informed the development of this field of age estimation and in 2001 this culminated in a recommendation for the optimum method of undertaking age estimation (Schmeling *et al.*, 2008; Schmeling *et al.*, 2001; Schmidt *et al.*, 2008c). This work recommended the use of a triumvirate of images in any estimation of age in the living individual, one of which is a radiograph of the left hand-wrist. This recommendation has concentrated research on maturity indicators of the three identified areas and the relationship of each to chronological age. Despite the work of AGFAD and others, no single atlas has proven to be of greater utility in relation to age estimation than any other and the ultimate choice of atlas is left to the practitioner.

4.1 The Greulich and Pyle atlas (1959)

This section aims to examine the applicability of the Greulich and Pyle atlas (1959) to a modern Scottish sample to assess whether it is appropriate for forensic use as a method of age estimation when applied to a contemporary population. The section will include a pilot study into the applicability of the Tanner *et al.*, (2001) atlas to a subset of the same population. The atlases rely on the examination of left hand-wrist radiographs and this section culminates in an examination into whether the orientation of the radiograph has an impact on the accuracy of the estimation of probable age.

4.1.1 Materials and method

To test the applicability of the Greulich and Pyle atlas left hand-wrist radiographs were age estimated following the method laid down in the atlas. A total of 406 left hand-wrist radiographs were collected; 157 females and 249 males (Figure 4.1). Table 4.1 and Figure 4.2 show the distribution of individuals for each sex by age. It can be seen that there are a smaller number of individuals in the lower age ranges (under 6 years of age).

Figure 4.1: Left hand-wrist image identified as MLH41. Chronological age 11 yr 1 month, estimated age 11 years (132 months) using the Greulich and Pyle atlas method (1959).

Years	Female Left	Male Left	Total
1	3	3	6
2	3	3	6
3	3	3	6
4	6	6	12
5	0	7	7
6	8	2	10
7	7	8	15
8	3	8	11
9	11	12	23
10	19	15	34
11	6	17	23
12	11	15	26
13	17	16	33
14	10	18	28
15	5	21	26
16	10	19	29
17	7	21	28
18	12	19	31
19	6	19	25
20	10	17	27
	157	**249**	**406**

Table 4.1: Number of radiographic images of the left hand/wrist separated by sex and age.
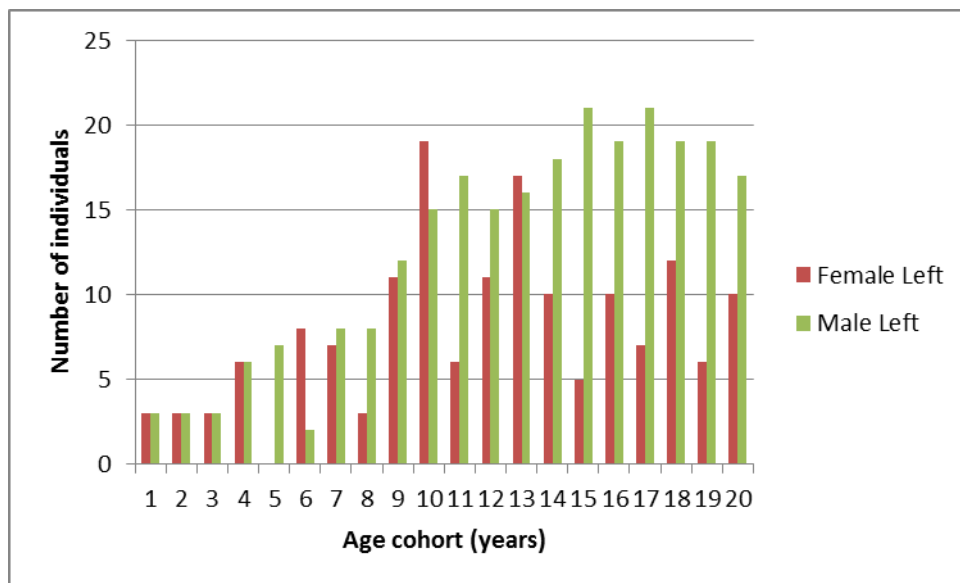
Figure 4.2: Number of images of the left hand/wrist by age cohort and sex.

An estimation of age was undertaken for each of the radiographs using the Greulich and Pyle Atlas (1959). The age estimation was undertaken without prior knowledge of the chronological age of each child examined. Due to well-recorded differences in the development of females and males, age estimation was undertaken separately for each sex (Loesch *et al.*, 1995; MacKay, 1952; Pryor, 1923; 1925). The 1959 edition of the Greulich and Pyle atlas has separate standards for males and females: in males, the image at which full skeletal maturity has been achieved is '*Male standard 31*' which is assigned a chronological age of 19 years. For females the corresponding image is that of '*Female Standard 27*' which is assigned a chronological age of 18 years. In this study, all of the radiographs were age estimated up to, and including 20 years of age to confirm when age related maturation could no longer be identified in the current sample. Within the 18-21 years age groups for females there were 14 individuals who had not reached the stage of maturity seen in '*Female Standard 27*' and in the 19-21 year age groups for males there were 11 individuals who had not reached '*Male Standard 31*', despite the individual having passed the identified chronological age for these standards (Table 4.2). Finding individuals who were still undergoing fusion was not unexpected since in any population there will be individuals who, for a variety of reasons, achieve maturational milestones at a different chronological age to others (Hagg and Taranger, 1992; Lopez-Blanco *et al.*, 1995). The radiographs in the Greulich and Pyle atlas represent the average or median skeletal development for that chronological age, and do not illustrate outliers. Since these outliers were shown to exist in this cohort, all images were included in the statistical assessments as this is a true representation of the sample.

Sex and Side	Number of Individuals in age groupings 18-21 years for females and 19-21 years for males	Number in which fusion still active	% in which fusion still active
Female Left Hand/Wrist	28	14	50%
Male Left Hand/Wrist	46	11	23.9%

Table 4.2: Number of radiographs of the left hand/wrist in which fusion was still active.

Intra-observer accuracy was tested using a subset of 30 randomly selected radiographs from the female left hand radiographs and 30 randomly selected radiographs from the male set of radiographs. These were observed 3 months after the first group were estimated. An inter-observer test was devised using 30 randomly selected female left hand-wrist radiographs. The second assessor is a practising forensic anthropologist with knowledge of, but not experience with, the Greulich and Pyle atlas (1959). For the purposes of this test the observer was given no additional instructions in the use of the atlas, was blind to the chronological age and was only informed of the sex of the individual.

4.1.2 Intra and inter-observer test of the Greulich and Pyle atlas (1959)

The intra-observer test involved retesting 30 randomly selected images from the male left hand images and 30 randomly selected images from the female left hand images. Regression analysis was undertaken on the results of this second set of age estimations. The regression coefficients and R^2 values are presented in Table 4.3. For the intra-observer test in females the R^2 value =0.973 and for the intra-observer test for males the R^2 value =0.963. A Mann-Whitney U test of the intra-observer results indicated that there was no

significant difference between the two sets of observations for either the female

left hand (P=0.925) or the male left hand images (P=0.859).

	Regression Coefficient	R value	R²-value	p-value
Intra-observer Results for female left hand	0.930	0.986	0.973	<0.001
Intra-observer results for male left hand	0.955	0.981	0.963	<0.001

Table 4.3: Results of the linear regression undertaken on the intra-observer
relationship between chronological age and estimated age by sex.

The inter-observer test involved the age estimation of 30 randomly selected

radiographs of female left hand-wrists (Table 4.4). Linear regression was

undertaken to examine the correlation between estimated age and

chronological age for the age estimations undertaken by the second examiner,

the R²-value for this analysis was 0.940 (p <0.001). The inter-observer results

were compared to the analysis performed by the first observer using a t-test

which indicated that there was no significant difference between the two sets of

results (P=0.982).

	Regression Coefficient	R value	R²-value	p-value
Female Left Hand/Wrist	0.905	0.969	0.940	<0.001

Table 4.4: Results of the linear regression undertaken on the inter-observer
relationship between chronological age and estimated age.

4.1.3 Results for the test of the Greulich and Pyle atlas (1959) method

Both the chronological ages and estimated ages were translated from years into months for the purposes of statistical analysis.

Linear regression analysis was undertaken on the data with estimated age treated as the independent variable in all of the calculations. The results are presented in Table 4.5 and Figures 4.3 and 4.4. The R^2 value for the correlation between chronological age and estimated age in females is 0.939 and for males is 0.940, both of these values are highly significant ($p<0.001$).

	Regression Coefficient	R value	R²-value	p-value
Female Left Hand/Wrist (n=157)	0.894	0.969	0.939	<0.001
Male Left Hand/Wrist (n=249)	0.979	0.970	0.940	<0.001

Table 4.5: R values, R²-values and regression coefficients by sex for the relationship between estimated and chronological age undertaken by the first observer.

The relationship between chronological age and estimated age was tested for significance using a Mann-Whitney U test. For both females and males the difference between chronological age and estimated age using the Greulich and Pyle atlas (1959) was not statistically significant (females P=0.771, males P=0.899).
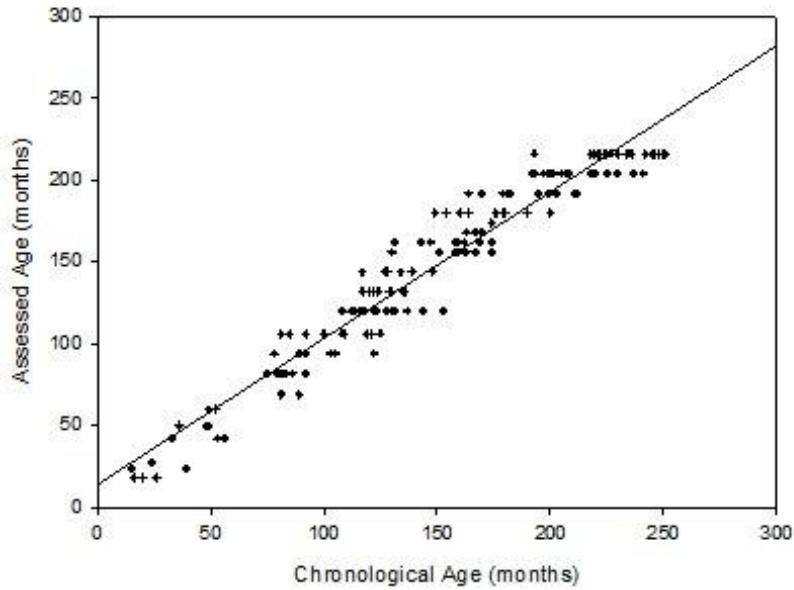
Figure 4.3: Linear Regression between Chronological Age (CA) and Estimated Age (EA) using the Greulich and Pyle Atlas for Female Left Hand *(EA = 14.043 + (0.894 x CA)).*
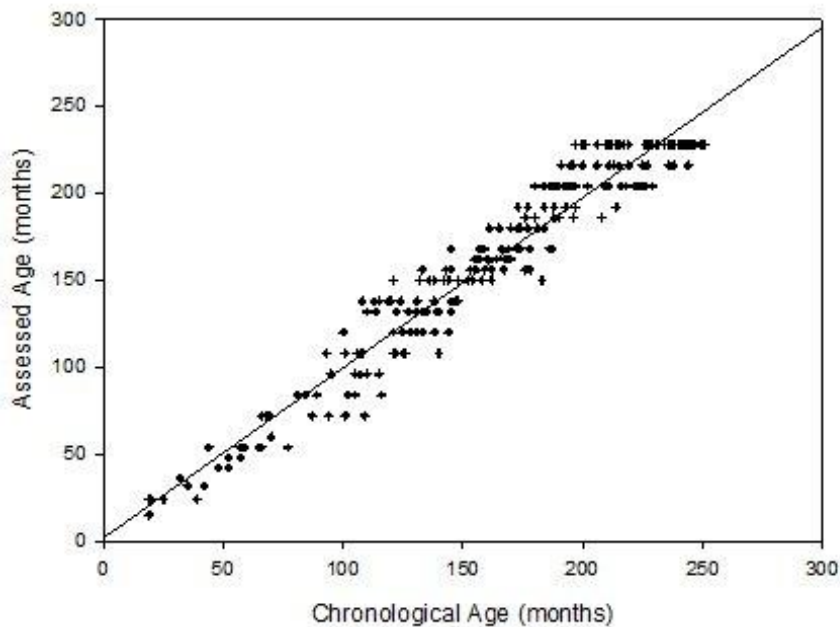
Figure 4.4: Linear Regression between Chronological Age and Estimated Age using the Greulich and Pyle Atlas for Male Left Hand *(EA = 1.859 + (0.979 x CA)).*

A Mann-Whitney U test was undertaken to further examine the relationship

between chronological age and estimated age for females and males (Table

4.6). This demonstrated that the difference between chronological age and estimated age was not significant for both female and male groups.

Sex	P-value	Result
Female left hand-wrist	P=0.771	Not statistically different
Male left hand-wrist	P=0.889	Not statistically different

Table 4.6: The results of the Mann-Whitney U test for each sex.

The differences between chronological age and estimated age were calculated by subtracting the chronological age from the estimated age. A negative value indicated that using the Greulich and Pyle atlas (1959) method assigned a skeletal age which was less than the chronological age i.e. underaged and a positive value indicates an individual who had been assigned a skeletal age which was greater than the chronological age i.e. overaged.
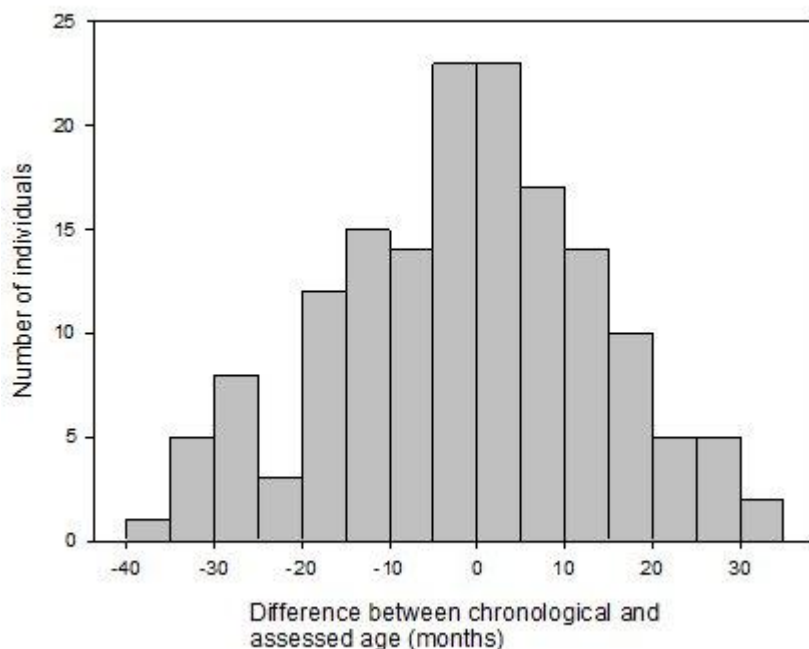
Figure 4.5: Distribution of mean differences between Chronological age and Estimated Age (months) for Female Left Hand Images.
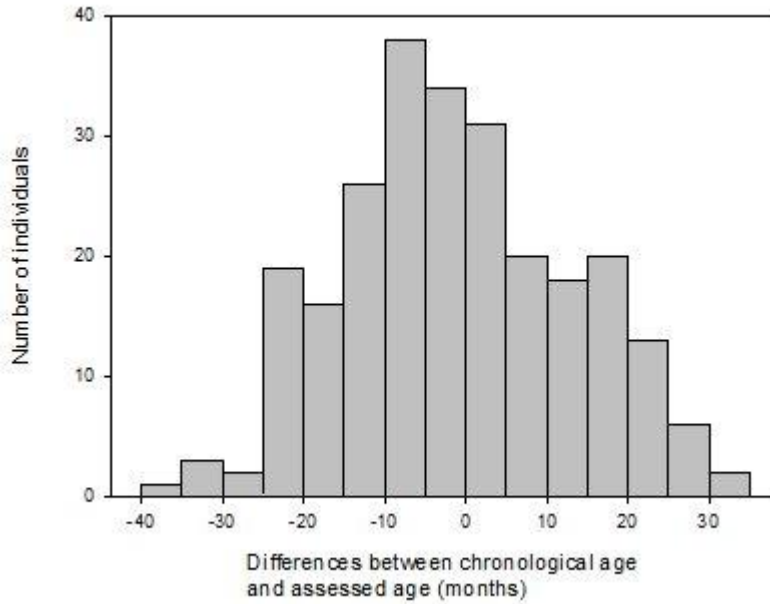
Figure 4.6: Distribution of mean differences between Chronological age and Estimated Age (months) for Male Left Hand Images.

The differences between chronological age and age estimated by the Greulich and Pyle atlas (1959) ranged from between an underage of 37 months (3 years 1 month) and an overage of 31 months (2 years 7 months) for females and between an underage of 37 months (3 years 1 month) and an overage of 31 months (2 years 7 months) for males. Both sets of differences show a Gaussian distribution, although for males there is a slightly negative skew indicating that deviations from the mean are more likely to be negative (Figure 4.5 and Figure 4.6). The mean difference between chronological age and estimated age for each sex is negative in value (Table 4.7) indicating that within this sample, the average chronological age is in advance of the estimated age by 1.95 months for females and 1.63 months for males i.e. there is a slight tendency to underage.

	Mean Difference between chronological age and estimated age (months)	Maximum overage and maximum underage (months)	Standard deviation (months)	Standard error (months)	Confidence interval (months)
Female Left Hand/Wrist	-1.95	Max overage 31.00 Max underage 37.00	14.97	1.19	2.36
Male Left Hand/Wrist	-1.63	Max overage 31.00 Max underage37.00	14.16	0.89	1.77

Table 4.7: Mean differences between chronological age and estimated age for the complete dataset by sex. Standard deviation, standard error, confidence interval of the mean and the maximum over and under-estimation of age observed within the groups.

To obtain a more detailed picture of the differences and relationship between chronological age and estimated age, the data were broken down into age cohorts of 5 years. It can be seen in Table 4.8 that for females age is consistently over-estimated in comparison to the chronological age by between 2.04 and 3.06 months from 0 to15 years of age. For males age is underestimated in comparison to chronological age, by between 2.44 and 3.54 months from birth to 10 years of age and over-estimated by 1.74 months for 11-15 year olds. The trend for both sexes in the 16-21 age groups is a lag between estimated age and chronological age resulting in individuals being assigned a younger age using the atlas in comparison to their actual chronological age. The under-estimation of age is to be expected in this age group since for both the male and female groups the atlas cannot assess age past the point at which maturity is achieved. Although radiographs were

collected and estimated up until the 20th year, there were only a small number

of individuals who were still experiencing fusion at this time.

Age Cohort	Female Left Hand/Wrist Mean difference by cohort (months)	Female Left Hand/Wrist maximum over and underage (months)	Female Left Hand/Wrist Standard Deviation (months)	Female Left Hand/Wrist Standard Error (months)	Female Left Hand/Wrist Confidence Interval (months)
0-5 years	2.25 (n=15)	Overage 14.00 Underage 15.00	9.85	2.46	5.25
6-10 years	2.04 (n=48)	Overage 31.00 Underage 28.00	13.36	1.93	3.88
11-15 years	3.06 (n=49)	Overage 31.00 Underage 33.00	13.46	1.90	3.83
16-20 years	-13.38 (n=45)	Overage 23.00 Underage -37.00 months	14.05	2.09	4.22
Age Cohort	Male Left Hand/Wrist mean differences by cohort (months)	Male Left Hand/Wrist maximum over and underage (months)	Male Left Hand/Wrist Standard Deviation (months)	Male Left Hand/Wrist Standard Error (months)	Male Left Hand/Wrist Confidence Interval (months)
0-5 years	-3.54 (n=22)	Overage 10.00 Underage 15.00	7.06	1.50	3.13
6-10 years	-2.44 (n=45)	Overage 30.00 Underage 37.00	17.25	2.57	5.18
11-15 years	1.74 (n=87)	Overage 25.00 Underage 36.00	12.95	1.39	2.76
16-20 years	-3.87 (n=95)	Overage 31.00 Underage 28.00	14.42	1.48	2.94

Table 4.8: Mean differences between chronological age and estimated age for the complete dataset by sex. Standard deviation, standard error, confidence interval of the mean and the maximum over and under-estimation of age observed within the groups divided into 5 year cohorts.

The difference between chronological age and estimated age was broken down

further into year cohorts for each sex (Table 4.9). The number of images in the

younger groups was small with larger numbers of individuals in older age

groups. For the females, prior to the age of 9 years there was a mixed pattern of under and over aging, although for the majority of groups for which there was data the trend was to overage by between 1.14 and 5.12 months. From the age of 9 to 16 years of age, the atlas method consistently overaged females by between 0.20 and 5.73 months, that is the individual was estimated to be older than they were. The trend then reversed due to the completion of the atlas series for females so that from the age of 17 years in females the atlas method consistently underaged, that is under-estimated the age of the individual. For males there is a tendency to overage individuals between the ages of birth and 2 years of age, after this the Greulich and Pyle atlas approach (1959) underages the majority of age groups by between 0.2 and 10 months, except for boys between the age of 9 years and 10 years who are on average overaged by 2.92 months. The atlas method consistently overages boys from the age of 13 years to 17 years by between 1.62 months and 11.05 months, at 18 years of age this trend reverses again due to the completion of the atlas series so that after this age males tend to be consistently underaged.

When the differences between the maximum overage and underage are scrutinised for each sex it can be seen that for females the maximum overage of 31 months occurs in both the 10 year and 12 year age groups. The maximum underage of 37 months occurs in females in the 20 year age group. If this last group is taken out due to the potential bias introduced by the distance that this age is from the culmination of the female age range presented by the atlas there is a maximum underage of 33 months (2 years 9 months) in both the 12 and the 19 year old age groups. The timings for the equivalent maximum differences for males is slightly different, the maximum over age of 31 months

occurs in the 16 year age group and the maximum underage of 37 months occurs in the 9 year age group.

These individuals represent children whose development is at the far extremes of advanced and delayed skeletal development. It is interesting to note that for both sexes they are children for who fall into post-pubertal age range where individual differences are most pronounced due to the variation of onset of the pubertal growth spurt.

Age Cohort (years)	Female Left Hand/Wrist	Male Left Hand/Wrist
1	3 (n=3)	1.67 (n=3)
2	1.33 (n=3)	0.0 (n=3)
3	4.33 (n=3)	-5.00 (n=3)
4	-0.5 (n=6)	-6.17 (n=6)
5	------	-4.43 (n=7)
6	5.12 (n=8)	-10.0 (n=2)
7	1.14 (n=8)	-7.88 (n=8)
8	-4.67 (n=3)	-7.38 (n=8)
9	5.73 (n=11)	2.92 (n=12)
10	0.00 (n=19)	-0.2 (n=15)
11	1.67 (n=7)	-0.53 (n=17)
12	5.09 (n=11)	-0.94 (n=15)
13	5.06 (n=17)	1.62 (n=16)
14	0.20 (n=10)	0.00 (n=18)
15	4.2 (n=5)	7.09 (n=21)
16	2.00 (n=10)	11.05 (n=19)
17	-7.86 (n=7)	2.52 (n=21)
18	-10.83 (n=12)	-7.21 (n=19)
19	-21.67 (n=6)	-9.53 (n=19)
20	-30.70 (n=10)	-18.41 (n=17)

Table 4.9: Differences between chronological and estimated age in months by age cohort for each group.

4.1.4 Discussion

This was a test of the Greulich and Pyle atlas method of age estimation on a modern population. In light of the recent Law Commission Report (The Law Commission, 2011) in England and Wales, the re-examination of anthropological methodologies is appropriate, especially those which are applied in ways for which they were never originally designed and which are highly likely to be presented to a court of law fundamentally as a novel science. The Greulich and Pyle atlas (1959) is one of these techniques. In addition to the use of the atlas for forensic application, it is also based on the development of children who were maturing in 1930s America, creating a situation in which not only secular change but differences in ethnicity and access to medical and nutritional resources could be widely altered in those who are undergoing age estimation to those whose images assisted in the creation of the atlas (Schmeling *et al.*, 2000; Schmeling *et al.*, 2006d). An understanding of the reliability and validity of a method in relation to the population to which it is being applied, is vital in these circumstances especially when the approach has such far reaching consequences in terms of social and legal responsibility.

Due to the ethical considerations of undertaking longitudinal radiographic studies on maturing children, it is not possible to develop modern equivalents of the radiographic atlases and so it has become necessary to regularly test existing methods to understand the inherent errors that might exist if the technique is applied to a targeted population.

This study on a Scottish population resulted in strong correlations between estimated age and chronological age by both observers, a finding which was consistent for both males and females. Other studies have also found that the

correlation between assessed age and chronological age is strong (Berst *et al.*, 2001; Büken *et al.*, 2007; Bull *et al.*, 1999; Calfee *et al.*, 2010; Chan *et al.*, 1961; Cole *et al.*, 1988; Garamendi *et al.*, 2005; Griffith *et al.*, 2007; Groell *et al.*, 1999; Mora *et al.*, 2001; Van Rijn *et al.*, 2001; Zhang *et al.*, 2009). However despite this, many authors argue that the Greulich and Pyle atlas should be applied either with population specific modifications (Büken *et al.*, 2007; Calfee *et al.*, 2010; Griffith *et al.*, 2007; Koc *et al.*, 2001; Koski *et al.*, 1961; Loder *et al.*, 1993; Mora *et al.*, 2001; Ontell *et al.*, 1996; Rikhasor *et al.*, 1999; Tisè *et al.*, 2011; Zhang *et al.*, 2009) or should be combined with other age estimation techniques for increased accuracy (Garamendi *et al.*, 2005) . There are also a number of studies which find that the Greulich and Pyle atlas (1959) is inappropriate for use on the population that they studied because there is a large difference between the chronological age of the children tested and the age as estimated using the atlas (Lewis *et al.*, 2002; Nahid *et al.*, 2010; Zafar *et al.*, 2010). In each study the atlas method gave a large underage for the majority of the children examined. These latter studies were arguably of populations in which access to nutrition and healthcare was reduced in comparison to a Western population such as is found in Scotland. Whilst there are a number of children who live in poverty in the area served by Ninewells Hospital, access to resources such as affordable healthcare ensure that these children are less physically stressed by their environment than those growing to adulthood in other countries. These studies support the findings of Schmeling *et al.* (2005) who argued that both socioeconomic factors as well as ethnicity should be taken into consideration when undertaking a forensic age estimation.

The level of agreement between inter and intra observer assessments in this study is high, agreeing with the findings in other studies where the reproducibility of the Greulich and Pyle method has been shown to be high (Garamendi *et al.*, 2005; Lynnerup *et al.*, 2008; Ontell *et al.*, 1996; Tisè *et al.*, 2011; Van Rijn *et al.*, 2001; Zafar *et al.*, 2010). This inter and intra-observer agreement remains high even when the accuracy of the method as applied to the target population is reduced (Ontell *et al.*, 1996; Tisè *et al.*, 2011; Zafar *et al.*, 2010). It is worth noting that whilst there is no significant difference between the first set of age estimations and the second set as undertaken by the first observer, there is a slight increase in the R^2 value from the first to the second groups, for females this improved from $R^2=0.939$ to $R^2=0.973$ and for males the improvement was from $R^2=0.940$ to $R^2=0.963$. This may suggest that with experience the accuracy of age estimations increased for this practitioner. This agrees with the findings of Roche *et al.* (1970) that intra observer reliability increased slightly with practice and experience, a finding supported by other authors who found slight differences in accuracy between experienced and non-experienced assessors (Groell *et al.*, 1999). It is argued that the Greulich and Pyle atlas (1959) method is the one of choice for age estimation due to its ease of use. It is a relatively straightforward method to understand and apply, however the improvement in correlations which are seen in the repeated test by the first observer would indicate that experience with the method does improve accuracy. Given the potential implications for an individual when age estimation is undertaken, this improvement in accuracy with experience suggests that this is not a method that should be used in a forensic situation by someone who is not familiar with this method unless they are supervised by an experienced practitioner.

The Scottish sample showed a general pattern of under-estimating the age of males prior to puberty (13 years) and over-aging after puberty. This pattern for males has been reported in other studies (Büken *et al.*, 2009; Koc *et al.*, 2001; Nahid *et al.*, 2010; Ontell *et al.*, 1996; Rikhasor *et al.*, 1999; Zafar *et al.*, 2010). The pattern for females was different since, with the exception of two groups, the atlas approach tended to overestimate age throughout the maturation process. Post puberty, the atlas method consistently overaged females in the group, which is in agreement with the findings of other studies (Büken *et al.*, 2007; Calfee *et al.*, 2010; Griffith *et al.*, 2007; Nahid *et al.*, 2010; Rikhasor *et al.*, 1999). It appears from these results that the process of maturation which Greulich and Pyle (1959) aimed to illustrate has remained similar whilst the pattern of progression remains largely unchanged and is echoed in different groups of varying ethnicity and nutritional status. Therefore there is an implication that the methodology shows considerable robusticity and stability despite the origin of the sample under investigation.

The mean of the difference between estimated age and chronological age ranged from 0 months (2 year old males and 10 year old females) to 11.05 months (16 year old males). The maximum differences between chronological age and estimated age however showed a maximum underage of 37 months (3 years 1 month) for both males and females, and a maximum overage by 31 months for both sexes (2 years 7 months). For this method therefore the maximum age range for both sexes was 68 months (5 years 8 months). The maximum differences between estimated age and chronological age, both as an overage and as an underage occur at different ages for each sex. The

maximum overage for females was found at 10 years of age and for males was at 16 years of age. The maximum underage for females was found at 20 years of age and for males was found at 9 years of age. The over and underage for both sexes is the same for this atlas indicating that there is no sex bias in this for this atlas method. The maximum range for females and male for this test of the Greulich and Pyle (1959) age estimation method is 5 years 8 months.

For individuals in the 0 to 5 year age range, the maximum underage was 15 months for both females and males and the maximum overage was 14 months for females and 10 months for males. This smaller range of over-aging and under-aging in the younger individual is in agreement with other studies which also found that the difference between age as estimated by the Greulich and Pyle atlas (1959) and chronological age is smaller in younger individuals (Loder *et al.*, 1993; Mora *et al.*, 2001; Ontell *et al.*, 1996; Rikhasor *et al.*, 1999). It is highly likely that the greater degree of accuracy seen in these younger cohorts is due to the shorter timespan that elapsed between successive radiographs in these groups. Radiographs were taken every 3 months for the first year moving to every 6 months until the age of 5 years and annually thereafter. Care should be taken with the conclusions within this study however since the numbers in the younger age groups were small this is an area for further investigation.

Greulich and Pyle (1959) suggest that an age range which includes two standard deviations should allow for the natural variation in skeletal age seen in the majority of children. In this study the standard deviation across the male and female groups as a whole was 14.97 months for females and 14.16 months for males. When groups are broken down into 5-year cohorts the standard deviation is noticeably smaller in the 0-5 year age groups for both sexes-9.85 months for females and 7.06 months for males. This would suggest that if an

individual is suspected to be in this younger age group the appropriate standard

deviation should be utilised when giving the age range.

4.1.5 *The use of the Greulich and Pyle atlas (1959)*

The hand-wrist atlas of Greulich and Pyle (1959) is based on a series of

anterior-posterior radiographic images (Fig 4.7). Each image is accompanied

by a written description (Fig 4.8) and at the back of the atlas are line drawings

of each bone at each maturational stage.

Figure 4.7: Female Plate 18, Skeletal age 10 years (Greulich and Pyle, 1959)

Skeletal Age of Individual Bones

Distal End of Radius	10 yr. 0 mo.	Proximal Phalanx I	10 yr. 0 mo.
Distal End of Ulna	10 yr. 0 mo.	Proximal Phalanx II	10 yr. 0 mo.
		Proximal Phalanx III	10 yr. 0 mo.
Capitate	10 yr. 0 mo.	Proximal Phalanx IV	10 yr. 0 mo.
Hamate	10 yr. 0 mo.	Proximal Phalanx V	10 yr. 0 mo.
Triquetral	10 yr. 0 mo.		
Lunate	10 yr. 0 mo.	Middle Phalanx II	10 yr. 0 mo.
Scaphoid	9 yr. 9 mo.	Middle Phalanx III	10 yr. 0 mo.
Trapezium	10 yr. 0 mo.	Middle Phalanx IV	10 yr. 0 mo.
Trapezoid	10 yr. 0 mo.	Middle Phalanx V	10 yr. 0 mo.
Metacarpal I	10 yr. 0 mo.	Distal Phalanx I	10 yr. 0 mo.
Metacarpal II	10 yr. 0 mo.	Distal Phalanx II	10 yr. 0 mo.
Metacarpal III	10 yr. 0 mo.	Distal Phalanx III	10 yr. 0 mo.
Metacarpal IV	10 yr. 0 mo.	Distal Phalanx IV	10 yr. 0 mo.
Metacarpal V	10 yr. 0 mo.	Distal Phalanx V	10 yr. 0 mo.

Pisiform	10 yr. 0 mo.
Adductor Sesamoid of Thumb	*
Flexor Sesamoid of Thumb	*

* These centers are still cartilaginous at this stage of development.

The outline of the tip of the hamulus of the hamate is now discernible. The distal half of the triquetral has enlarged and its hamate surface has begun to adjust to the shape of that bone. A part of the volar margin of its hamate surface can now be seen. The scaphoid and radial articular surfaces of the lunate are beginning to be defined.

An indentation has developed in the articular surface of the epiphysis of the first metacarpal. Parts of the volar margin of the epiphysis of the fifth metacarpal are now discernible as white linear markings along its radial and ulnar borders.

The developing trochlear surfaces on the distal ends of the proximal phalanges of the second, third, and fourth fingers now have shallow central indentations. The epiphyses of the proximal and middle phalanges of the fifth finger are now as wide as their shafts. The radial tip of the epiphysis of the distal phalanx of the third finger has begun to cap its shaft.

Figure 4.8: Written description for Plate 18 (Greulich and Pyle, 1959)

Figure 4.9: Image of female left hand-wrist identified as FLH30. Chronological age 10 years 2 months. Estimated age using the Greulich and Pyle atlas (1959) 10 years.

The morphology of the left hand-wrist shown in the radiograph identified as

FLH30 (Fig 4.9) was judged to be consistent with Plate 18. The areas of

similarity include; the size and shape of the distal radial and ulnar epiphyses. It

is now possible to discern the tip of the hamulus of the hamate, the pisiform is

also visible. The epiphyses of the proximal and middle phalanges of the 5th

finger are as wide as their shaft and the surfaces of the distal ends of the

proximal phalanges of the 2nd 3rd and 4th finger have indentations.

For anyone utilising the atlas for age estimation purposes, it is necessary to

familiar with the atlas and the different maturity indicators which are highlighted

in the written description. Whilst it is tempting to use the appearance of the

ossification centres of the carpals to age younger individuals, this results in a

consistent underage and so greater weight should be given to the stages of

development of the metacarpals and phalanges.

4.2 Test of the Tanner-Whitehouse 3 (TW3) atlas (2001) on a Scottish population

The third edition of the Tanner-Whitehouse atlas (TW3) was published in 2001.

Unlike the previous two editions which had both been based on data gathered

during the Harpenden Growth Study, this atlas was based on data collected in

Europe and America which included a mixture of longitudinal and cross

sectional data from different population groups (Tanner *et al.*, 2001). The

authors argued that this allowed for the influences of secular change, ensuring

that the data contained within the atlas was appropriate for use on modern

populations. Whilst the second edition of the Tanner-Whitehouse atlas (TW2)

has proven to be popular, use of the third edition has never proved to be as

widespread as the TW2 version despite calls for its use (Ahmed and Warner,

2007), although it is unclear how much of this is due to the fact that the book is

out of print and difficult to obtain. This third edition has been tested, both on

different populations and in relation to other atlases (Büken *et al.*, 2009; Haiter-

Neto *et al.*, 2006; Kim *et al.*, 2008; Malina *et al.*, 2007; Ortega *et al.*, 2006;

Proos, 2009; Schmidt *et al.*, 2008c; Silva *et al.*, 2010; Tristan-Vega and Arribas, 2008; Zhang *et al.*, 2008)

A small subsample of 222 radiographs of male and female left hand-wrist were age estimated using the TW3 atlas to gain an understanding of its accuracy in relation to this modern Scottish population and the Greulich and Pyle atlas (1959). The original subsample of radiographs consisted of 90 radiographs of female left hand-wrists and 132 radiographs of male hand-wrists. The age spread of the radiographs is given in Table 4.10 and Figure 4.10.

Age (year)	Female left hand-wrist	Male left hand-wrist	Total
1	2	1	3
2	0	1	1
3	1	1	2
4	2	1	3
5	1	1	2
6	8	2	10
7	4	5	9
8	2	5	7
9	7	6	13
10	10	6	16
11	3	9	11
12	9	11	20
13	9	7	16
14	7	9	16
15	3	7	10
16	4	10	14
17	2	14	16
18	7	12	19
19	3	14	17
20	6	10	16
Total	90	132	222

Table 4.10: Spread of images by age and sex which were included in the analysis of the TW3 atlas.
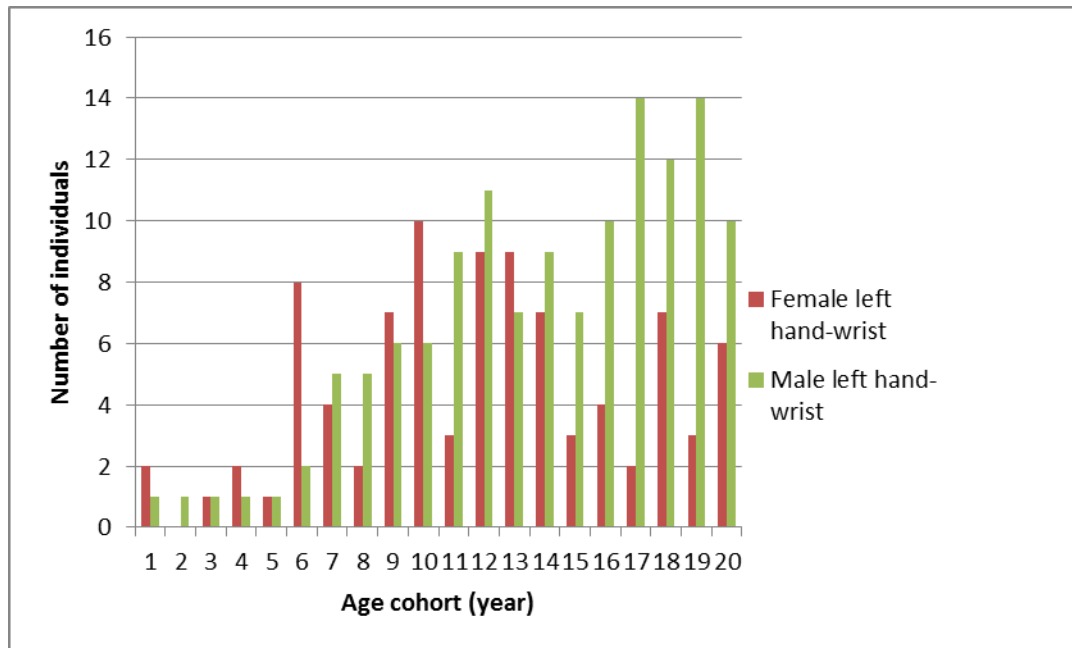
Figure 4.10: Spread of images by age and sex which were included in the analysis of the TW3 atlas.

As with all of their previous editions of the atlas the TW3 atlas (2001) assembles the areas of interest from within the hand-wrist osteology into two; these are known as the RUS (radius, ulna and short bones) and the CBA (carpal bone age) groups. Unlike the previous two editions of this method, the authors do not present a combined scoring method but keep the RUS and CBA scores separate, presenting tables which allow the scores to be converted into skeletal age. This method therefore results in two estimated ages for each radiograph studied. To test the validity of the TW3 atlas method the radiographs were age estimated using the TW3 atlas and the results were compared against chronological age for each individual. The results of these analyses are presented below.

The TW3 atlas has a limited age range of applicability (Table 4.11). The scoring method means that once the maximum score of 1000 is achieved for either the RUS or CBA scoring method the skeletal age assigned is '*Adult'.* It is

also not possible to assign a skeletal age to those individuals for whom the minimum majority score was not achieved, for example the minimum RUS maturity score for the male chart is 42 corresponding to a bone age of 2 years. This imposes a lower and an upper limit on age estimations.

Scoring method	Minimum age possible	Maximum age possible
RUS female	2.0 years	15.0 years
CBA female	1.6 years	13.0 years
RUS male	2.0 years	16.5 years
CBA male	2.4 years	15.0 years

Table 4.11: The minimum and maximum skeletal ages presented in the TW3 atlas

For the female group there were a number of individuals who were continuing to undergo maturational changes up to the age of 20 years. There were no individuals in the male group for whom this was the case. In each case the bones which were still maturing were the distal radius and ulna. These age estimations were included in the final statistical analysis. Where the maximum score of 1000 was assigned, since the designation by the atlas was '*Adult'* it was not possible to give a skeletal age and therefore these were omitted from the analysis and those radiographs which were older than the maximum age possible for each sex were also omitted unless they were still undergoing fusion. With the exception of three of the female radiographs this resulted in the loss of the 16-20 year old cohorts from the final RUS analysis for both the female and male groups and the 15-20 year old cohorts from the CBA analysis (Table 4.12).

Scoring method	Final number of radiographs analysed after removal of specified age groups and errors due to positioning
RUS female	52
CBA female	51
RUS male	75
CBA male	61

Table 4.12: Final numbers of radiographs successfully analysed for each scoring method for the TW3 atlas.

4.2.1 Inter and Intra-observer error

Due to the small sample size, 15 radiographs of female hand-wrist and 15 radiographs of male hand-wrists were examined to test the inter- and intra-observer errors. The radiographs were randomly selected and were age estimated using the TW3 atlas.

For both the inter- and intra-observer tests the results were subjected to a Mann-Whitney U test. For both the RUS based age estimations and the CBA estimations the differences between each assessment were not significant (Table 4.13).

	Female RUS	Female CBA	Male RUS	Male CBA
Inter-observer test	P=0.922	P=0.066	P=0.757	P=0.882
Intra-observer test	P=0.659	P=0.582	P=1.00	P=0.429

Table 4.13: Showing the P values for the inter and intra observer Mann-Whitney U test.

4.2.2 Results

The radiographs examined were taken for medical investigation purposes and therefore they may not comply with the positioning criteria outlined by Tanner *et al.* (2001). A direct result of this, it was not always possible to visualise and assign a score to all of the areas of the hand-wrist. A consequence of this was that for a small number of radiographs it was only possible to assign RUS or CBA scores rather than both. If it was not possible to assign a score, this method was left out, although the successful method was included in the final analysis.   The final sample size is shown in Table 4.12. In order to facilitate statistical analysis, all ages were converted to months.

Linear regression was undertaken for each set of scores, comparing estimated age with chronological age (Table 4.14 and Figs 4.11-4.14). This showed that the R^2 values for the RUS scores were higher (females $R^2=0.780$, males $R^2=0.845$) than the CBA scores for both sexes (females $R^2=0.628$, males $R^2=0.759$). All correlations were statistically significant ($p<0.001$). The R^2 value for the RUS score for males (0.845) was higher than for females (0.780) a similar pattern was also seen in relation to the carpal bone scores (female $R^2=0.628$, male $R^2=0.759$).

Group by sex	Score	Regression Coefficient	R value	R² value	p value
Female left hand-wrist	RUS	0.775	0.883	0.780	<0.001
Female left hand-wrist	CBA	0.586	0.792	0.628	<0.001
Male left hand-wrist	RUS	1.073	0.921	0.845	<0.001
Male left hand-wrist	CBA	1.025	0.871	0.759	<0.001

Table 4.14: Regression coefficients, R value and R² values by sex and scoring method.
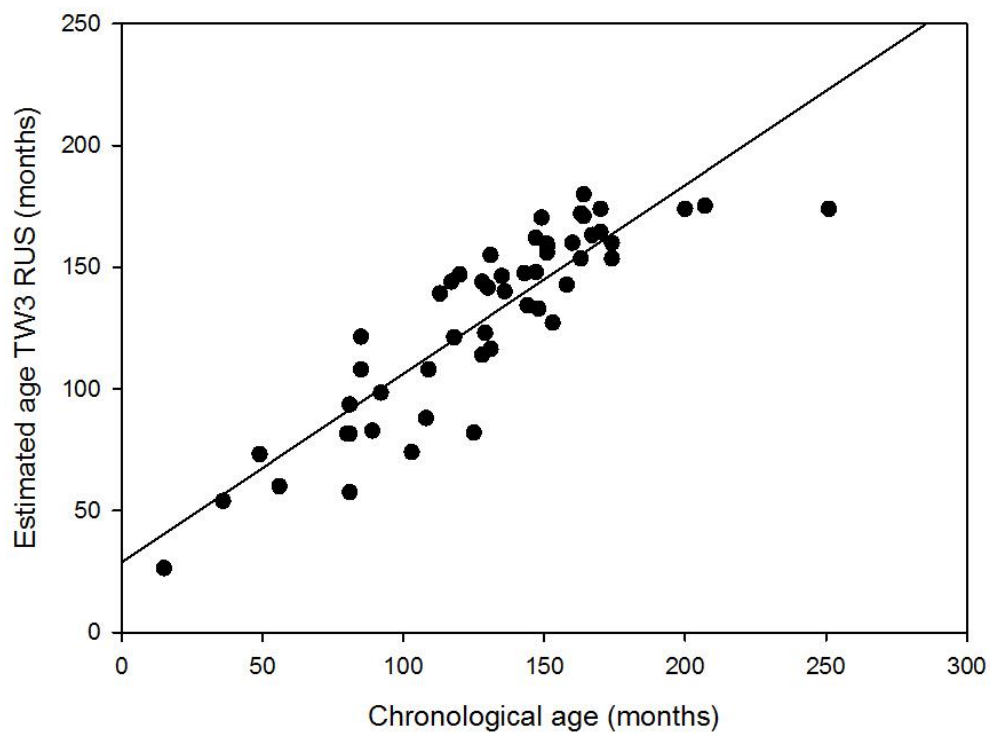
Figure 4.11: Linear regression between chronological age (CA) and RUS (radius, ulna and short bones) bone age (RUS EA) for TW3 analysis of radiographs of female hand-wrist (*RUS EA=28.832 + (0.775 x CA)*).
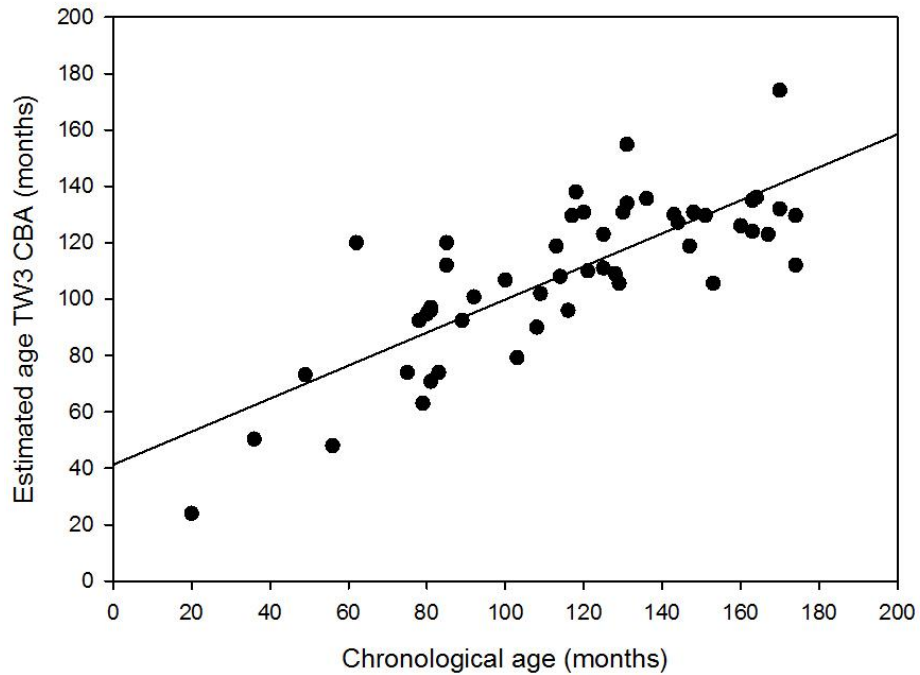
Figure 4.12: Linear regression between chronological age (CA) and CBA (carpal bone age) age (CBA EA) for TW3 analysis of radiographs of female hand-wrist (*CBA EA = 41.315 + (0.586 x CA)*).
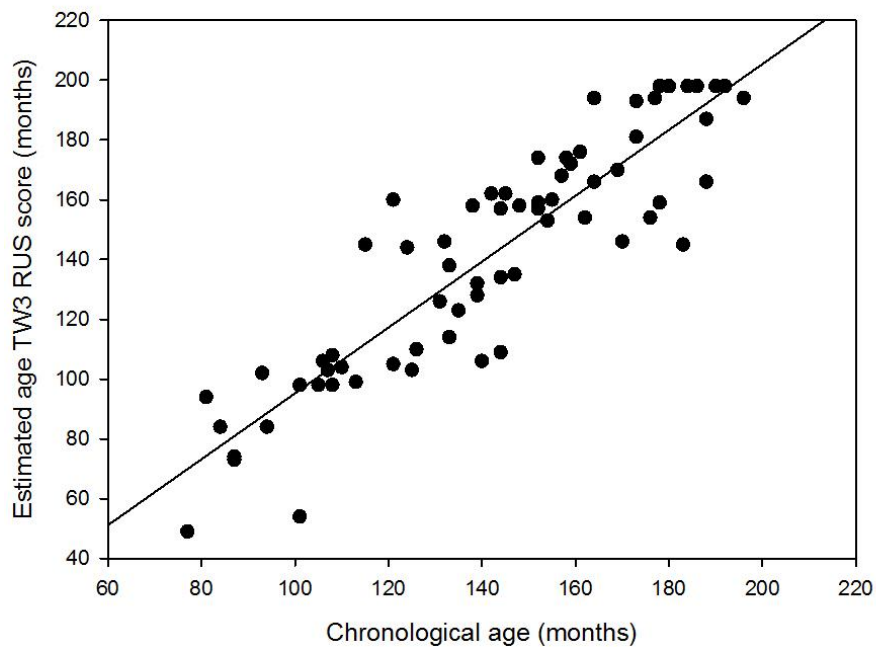
Figure 4.13: Linear regression between chronological age (CA) and RUS (radius, ulna and short bone) bone age (RUS EA) for TW3 analysis of radiographs of male hand-wrist (*RUS EA = -10.305 + (1.068 x CA)*).
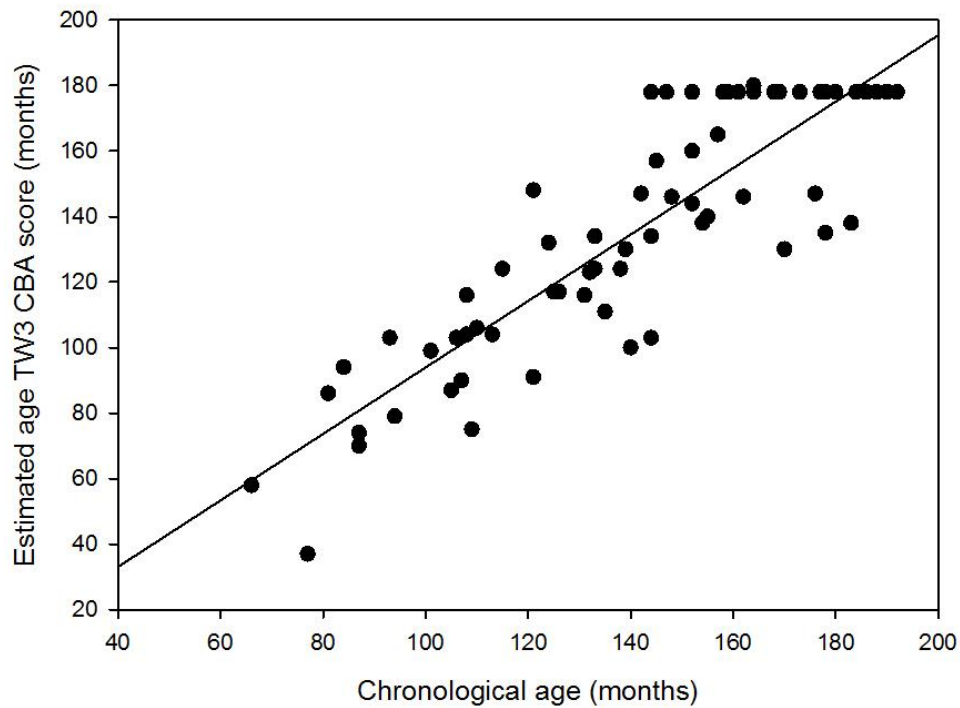
Figure 4.14: Linear regression between chronological age (CA) and CBA (carpal bone age) (CBA EA) for TW3 analysis of radiographs of male hand-wrist (*CBA EA = -15.621 + (1.084 x CA)*).

The relationship between chronological age and estimated age was further explored using a Mann-Whitney U test (Table 4.15). Each of the two methods within the TW3 atlas (2001) (RUS and CBA) were compared to chronological age. For the RUS scoring method there was no statistical difference for either female or males but for the CBA scoring method there was a significant difference between chronological age and estimated age for both sexes.

Sex and method	P-value	Result
Female RUS score	P=0.241	Not statistically different
Female CBA score	P=0.032	Statistically different
Male RUS score	P=0.651	Not statistically different
Male CBA score	P=0.021	Statistically different

Table 4.15: Results of the Mann-Whitney U test between chronological age and estimated age for each TW3 scoring method.

Because of the poor results for the CBA score, a Mann-Whitney U test was undertaken to examine the relationship between the RUS estimated age and the CBA estimated age for each sex (Table 4.16). The differences between the two were significantly different for both sexes.

Sex	P-value	Result
Female RUS and CBA score	P<0.001	Statistically different
Male RUS and CBA score	P=0.024	Statistically different

Table 4.16: Results of the Mann-Whitney t-test between RUS (radius, ulna and short bone) scoring method and CBA (carpal bone age) scoring method.

The difference between the chronological age and the age estimated using each of the TW3 atlas (2001) methods was calculated. This involved subtracting the chronological from the RUS age or the CBA age, therefore a negative value indicated an underage using the atlas method and a positive value indicated an overage. The differences were calculated for each group and each score for each group and the mean, maximum overage and maximum underage were calculated and are presented in Table 4.17. For both females and males the mean was noticeably smaller and closer to zero for the RUS estimated age than for the CBA estimated age by a noticeably larger margin.

The standard deviations were smaller for the RUS and CBA groups for males (16.65 and 18.70 months) than for females (20.43 and 23.31 months). It should be noted that for the female group, if the 20 year old individual is removed from this calculation then the standard deviation is 17.59 months which is very close to that seen in the male group.

Group and Score	Mean difference (months)	Maximum overage and maximum underage (months)	Standard deviation (months)	Standard error (months)	Confidence interval (months)
Female RUS score	-0.811	Max overage 36.50 Max underage 77.00	20.43	2.81	5.63
Female CBA score	-6.42	Max overage 58.00 Max underage 62.00	23.31	3.26	6.56
Male RUS score	-0.37	Max overage 39.00 Max underage 47.00	16.65	1.97	3.94
Male CBA score	-5.26	Max overage 34.00 Max underage 45.00	18.70	2.30	4.60

Table 4.17: Mean differences between chronological age and estimated age for the complete dataset by sex. Standard deviation, standard error, confidence interval of the mean and the maximum over and under-estimation of age observed within the groups.

Each group was divided into year cohorts to investigate the relationship between estimated age and chronological age for each age examined, shown in Table 4.18.

Age (years)	Mean difference female RUS age and chronological age (months)	Mean difference female CBA and chronological age(months)
1	-4.3 (n=2)	4.0 (n=1)
3	18 (n=1)	14.40 (n=1)
4	14.1 (n=2)	8.1 (n=2)
5	-	58.0 (n=1)
6	-2.15 (n=4)	3.0 (n=8)
7	14.95 (n=7)	18.55 (n=4)
8	-29.0 (n=1)	-8.5 (n=2)
9	7.08 (n=5)	-1.8 (n=7)
10	0.112 (n=8)	-3.44 (n=9)
11	6.7 (n=3)	-6.7 (n=2)
12	-0.72 (n=10)	-26.2 (n=5)
13	3.13 (n=6)	-34.6 (n=5)
14	-9.0 (n=4)	35.1 (n=4)
16	-26.0 (n=1)	-
17	-31.8 (n=1)	-
20	-77.0 (n=1)	-

Table 4.18: Mean RUS (radius, ulna and short bones) estimated age and CBA (carpal bone age) estimated age by year cohort for females.

For the TW3 RUS method the mean of the difference between the chronological age and estimated age was positive for 7 of the cohorts indicating that the TW3 RUS atlas (2001) method is inclined to over-estimate age for these groups. Whilst individuals were assigned an age in the 16, 17 and 20 year old groups these were older than the maximum possible skeletal age of 15 years of age and therefore had a large negative mean difference between estimated age and chronological age. When the CBA ages are calculated, it can be seen that the

younger groups are consistently overaged until the age of 8 years of age. After

the age of 8 years the atlas consistently underages individuals, the size of the

underage increases after the age of 12 years of age until the age of 14 years.

Age cohort (year)	Mean difference male RUS estimated age and chronological age (months)	Mean difference male CBA estimated and chronological age (months)
4	5.0 (n=1)	6.00 (n=1)
5	-	-8.00 (n=1)
6	-7.5 (n=2)	-14.33 (n=2)
7	-5.6 (n=5)	-5.0 (n=5)
8	-3.5 (n=4)	-10.0 (n=4)
9	0.00 (n=5)	-5.67 (n=6)
10	0.00 (n=6)	-4.5 (n=6)
11	-2.67 (n=9)	-12.00 (n=9)
12	1.91 (n=11)	1.73 (n=11)
13	11.29 (n=7)	11.14 (n=7)
14	0.12 (n=8)	-9.11 (n=9)
15	-1.29 (n=7)	-N/A
16	1.00 (n=10)	N/A

Table 4.19: Mean RUS (radius, ulna and short bones) estimated age and CBA (carpal bone age) estimated age by year cohort for males.

The male mean ages give a mixed pattern of over-aging and under-aging from

the age of 2 until the age of 16 years of age for age calculated from the RUS

bone scores and 14 for skeletal age calculated from the CBA scores (Table

4.19).

4.2.3 Discussion of results from TW3 analysis

The scoring system of age estimation offers an alternative, albeit slightly more time-consuming method which should be considered when an age estimation is being undertaken. The assessment of the TW3 atlas (2001) against this modern population is highly relevant. Authors have suggested that the TW3 atlas (2001) method should replace the TW2 atlas (1975) method when undertaking forensic age estimations on modern populations (Ortega *et al.*, 2006; Schmidt *et al.*, 2008c; Vignolo *et al.*, 1999). Indeed, Tanner writes '*The British TW2 reference values given in the first and second editions of this book are derived from samples of children from the 1950-1960 period and we no longer recommend their use' (Tanner et al., 2001).* Despite this statement which potentially has a large impact on the use of the TW2 and TW1 age estimation methods for forensic purposes and the urging of other authors (Ahmed and Warner, 2007), the TW3 remains the least tested and least frequently used of all of the Tanner-Whitehouse atlases. This study represents an opportunity to test the premise that this atlas should be the preferred method when undertaking age estimation of an individual from a modern population.

The authors of the TW3 atlas felt that the accuracy of the RUS score in relation to the prediction of age was accurate enough to render the combined 20-bone score redundant (Tanner *et al.*, 2001). As a result they offer the user a dual scoring system which separates the distal radius, ulna, the metacarpals and phalanges from the carpal bones. This separation is deliberate and based on the assertion that the development of the carpal bones is of greater variability when applied to the relationship between chronological age and skeletal age. This assertion is supported by the results of this analysis in which the prediction

of age using the RUS scores give a greater degree of accuracy and repeatability for both female and male age estimations for this population than does the CBA score. Further, when the relationship between estimated age and chronological age was tested using a Mann-Whitney t-test, there was a significant difference between chronological age and estimated age calculated using the TW3 CBA method for both females and males.

Within the text, the authors supply reference charts which give the centiles for each sex and scoring method, however they also state that the standard deviation for both sexes from 5 years of age to the point at which maturity is reached according to the atlas as '*approximately 1 year*' for both scoring systems. The standard deviation for female and male RUS scoring systems in this analysis is a little higher than this at 20.43 months (1 year 8.5 months) for females and 16.65 months for males (1 year 4.6 months). As noted, for females the standard deviation reduces to 17.59 months if the 20 year old female outlier is removed from the calculation making it similar to that found for the male group. The standard deviation is higher again for the carpal bone analysis which reflects the weaker relationship between carpal bone development and chronological age supporting the separation of the RUS and CBA scores.

The accuracy and reliability of the predication of bone age using the TW3 RUS score is high enough for it to be considered an alternative to the Greulich and Pyle atlas (1959) for individuals who are suspected to be 15 years of age or younger. However given the results in relation to the CBA score, the additional use of the CBA score would be in doubt. With the difference in accuracy between the RUS score and the CBA score there is a strong suggestion that the CBA score should be omitted and the RUS score left to stand alone for both sexes. In the TW3 atlas the authors state that '*It has been suggested that the*

difference between RUS and Carpal bone ages may be of differential diagnostic

significance' (Tanner *et al.*, 2001) but they go on to explain that this issue

required further research. However Johnston and Jahina (1965) used the

Greulich and Pyle atlas (1959) to examine the value of carpals for the

determination of skeletal age in children and concluded that bone age was more

accurate if carpal bone age was removed for both males and females. They

found that the poorest relationship between the stage of development of the

carpal bones and age was found in the female group rather than the male group

although they do not put forward any explanation for this. They go on to say in

reference to the carpals that '*..they contribute little, if anything, of a positive*

nature. Our data indicate that they are a significant source of observer error in

girls'. Acheson *et al* (1963) also conclude that when carpal estimates caused

skewed age estimates they should be disregarded. The research which has

been undertaken points simply to the poor relationship between the

development of the carpal bones and chronological age and it remains to be

seen whether further work on this would reveal whether carpal bone

development might be more useful in age estimation in the future.

These studies support the observation that the carpal bones do not necessarily

mature in harmony with the other bones of the hand and wrist and that this poor

relationship between chronological age and estimated age is a contraindication

for the use of the CBA method in forensic age estimation.

This study confirms that whilst the two scoring systems have been developed in

parallel, the RUS scoring method should be the method of choice due to its

increased accuracy for both the female and male group in this study. Even with

the RUS bone age method, a caveat must be placed in the use of this for

forensic purposes. The spread of the mean difference between chronological

age and estimated age does show that whilst there is an upper age limit on the potential for assigning age using the RUS system, in individuals whose skeletal development is slower than their peers, the method can assign an age which is significantly lower (26-77 months) than the chronological age. An error of this type would not be acceptable for a forensic case and for this reason this method should not be used if the individual is suspected to be about the age of, or older than the maximum possible age predicted by this method (15 years for females and 16.5 years for males). With many forensic age estimations concentrating on the possibility of an individual passing the age of 18 years, this age estimation method may be largely redundant.

There is one additional difficulty with the TW3 atlas which could conceivably cause it not to be utilised on a regular basis in the forensic arena. For all of the bones which are assessed, the position of the hand-wrist on the radiograph is vital to enable a comparison with the image presented. Whilst this is especially true for the RUS scoring system which requires adequate visualisation of the distal phalanges, it also applies to visualisation of the irregularly shaped carpal bones.

4.2.4 The TW3 method

The TW3 atlas (2001) method is a scoring method. The TW3 atlas (2001) groups the areas to be scored into 2 methods; the RUS method (Fig 4.15) and the CBA method (Fig 4.16).

The degree of ossification and changes to the morphology of the ossification centres and degree of fusion are all taken into account. Whilst the RUS and CBA methods each involve the analysis of multiple bones
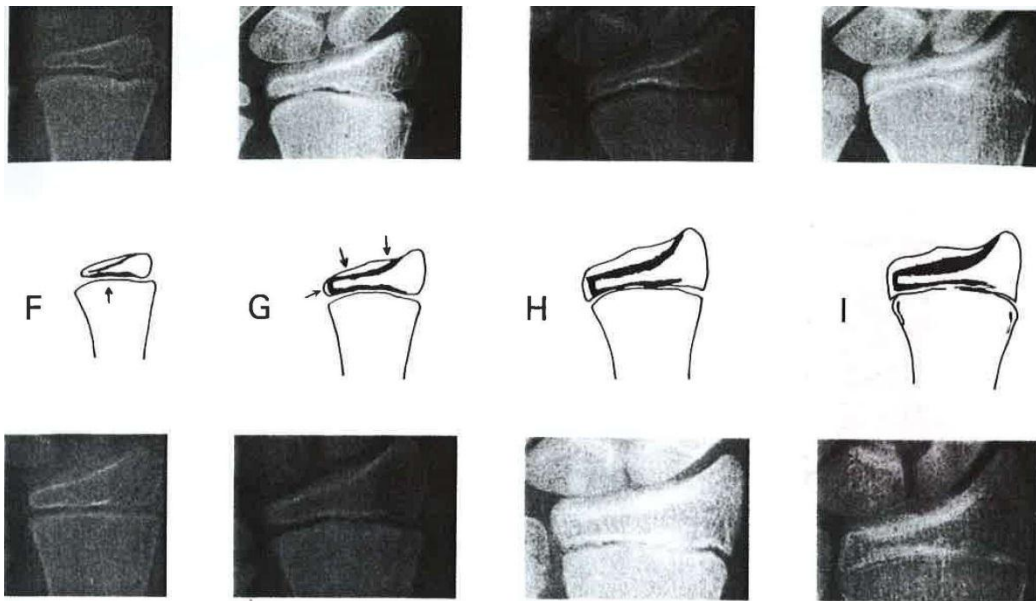
BOYS' SCORES		GIRLS' SCORES
	Stage F	
RUS 59	(i) The proximal border of the epiphysis is now differentiated into palmar and dorsal surfaces; the palmar surface is visible as a broad, irregularly thickened white line at the proximal edge of the epiphysis.	RUS 78
	(ii) Both ends of the epiphysis, but particularly the medial one, have grown outwards and proximally since the last stage so that the proximal border now conforms to the shape of the metaphysis along most of its extent.	
	Stage G	
RUS 87	(i) The dorsal surface now has distinct lunate and scaphoid articular edges joined at a small hump.	RUS 114
	(ii) The medial border of the epiphysis has developed palmar and dorsal surfaces for articulation with the ulnar epiphysis; either the palmar or the dorsal surface may be the one that projects medially, depending on the position of the wrist.	
	(iii) The proximal border of the epiphysis is now slightly concave.	
	Stage H	
RUS 138	(i) The epiphysis now caps the metaphysis on one (usually the medial) or both sides.	RUS 160
	Stage I	
RUS 213	(i) Fusion of the epiphysis and metaphysis has begun. A line may still be visible, composed partly of black areas where the epiphyseal cartilage remains and partly of dense white areas where fusion is proceeding; or the line may have disappeared.	RUS 218

Figure 4.15: Distal radius images, written description and scoring system (Tanner *et al* 2001).

F

G

H
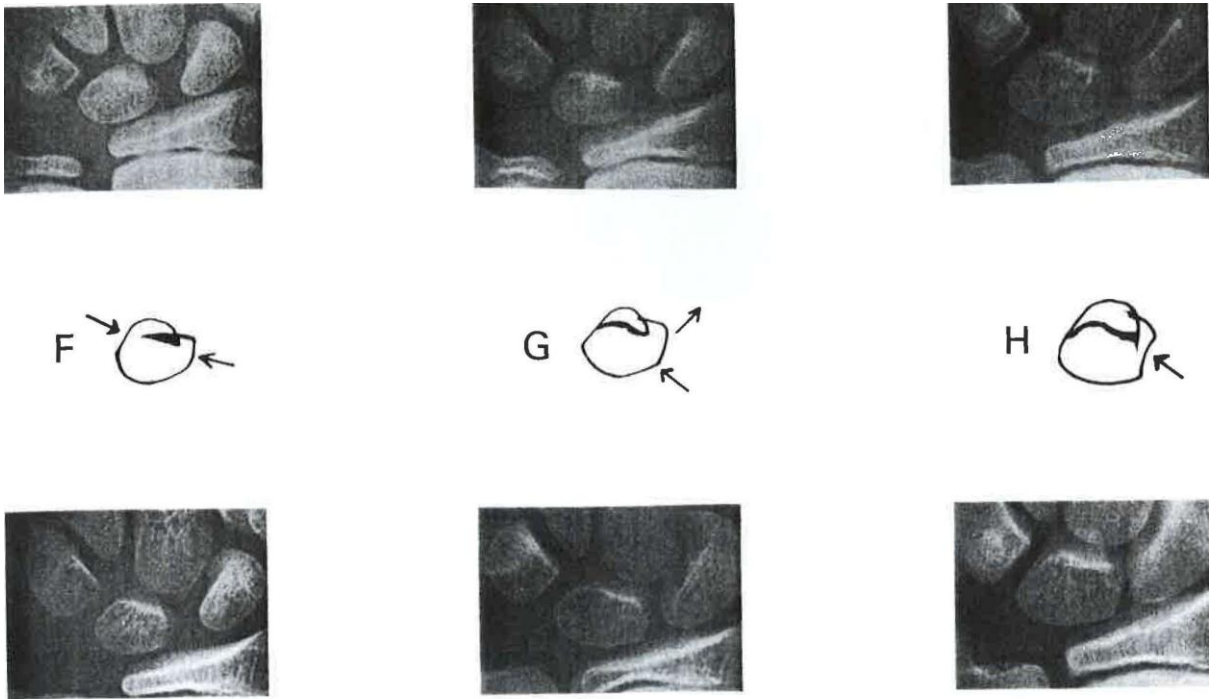
BOYS' SCORES		GIRLS' SCORES
	Stage F	
Carp 84	(i) The distal surface now forms a definite saddle for articulation with the capitate, due chiefly to an outgrowth of its dorsal part towards the scaphoid. This dorsal part extends out beyond the lateral edge of the palmar (thickened) part of the saddle, but less than halfway from the palmar edge to the edge of the scaphoid.	Carp 84
	(ii) The scaphoid and triquetral borders are now flat and slightly thickened.	
	Stage G	
Carp 101	(i) The dorsal surface of the capitate saddle has further enlarged since the last stage and now covers more than half the distance from the palmar edge of the saddle to the scaphoid.	Carp 106
	(ii) There is a definite angle between the scaphoid border (which is still straight) and the radial border.	
	Stage H	
Carp 120	(i) The dorsal surface of the capitate saddle now extends laterally to touch or overlap the edge of the scaphoid. (Either the palmar or dorsal surface, or both, depending on individual shape and positioning, touch or overlap the capitate.)	Carp 122
	(ii) The scaphoid border is now concave.	

Figure 4.16: Images, written description and scoring system for lunate (Tanner *et al.*, 2001)

Figure 4.17: Image of female left hand identified as 'FLH9'. Chronological age 10 years 9 months. Estimated RUS (radius, ulna and short bone)10.3 years, Estimated CBA (carpal bone age) 8.8 years (TW3 2001)

The scores assigned to the distal radius and lunate for the image of the female

left hand (Fig 4.17) identified as 'FLH9' were;

- Radius Stage G score RUS 114

- Lunate Stage H score carp 122

For the distal radius, there is a distinct 'hump' where the lunate and scaphoid

articular edges join. There are surfaces for articulation with the ulna epiphysis

and the proximal border of the epiphysis is slightly concave. For the lunate the

dorsal surface of the capitate overlaps the edge of the scaphoid. The scaphoid border of the lunate is now concave.

By taking a bone at a time the TW3 atlas (2001) ensures that the scoring method is based on the close study of just the bones presented. Each bone is studied in turn and a decision made on a bone by bone basis by comparison of the radiograph to both the image in the atlas and the written description, this allows the practitioner to concentrate on the development of one bone at a time rather than trying to find the 'best fit' match to the whole area.

4.3 A comparison between the Greulich and Pyle (1959) age estimation methods and the TW3 (2001) age estimation methods on a Scottish population

One of the most commonly asked questions is 'which age estimation method gives more accurate results?'. A number of studies have been undertaken which attempt to compare age estimation methods of the same anatomical area. Both the Greulich and Pyle atlas and the Tanner-Whitehouse method have become popular techniques of age estimation from the left hand-wrist. There are legitimate reasons to ask which should be the method of choice since these two disparate methods were developed from information gathered from two contrasting populations; the Greulich and Pyle atlas was developed on American children from the 1930s and 1940s. The children whose data was collected were chosen for their high health and nutritional status, whereas the TW3 atlas was developed from information gathered from European and American children from the 1980s and 1990s. The methods also assign age through two different methodologies. The Tanner-Whitehouse atlas was specifically designed in response to perceived weaknesses in the Greulich and

Pyle atlas (Tanner *et al.*, 2001; Tanner *et al.*, 1962; Tanner *et al.*, 1975) and authors have argued that it provides greater accuracy because of its emphasis on the development of individual bones (Malina, 1971).   For practitioners who are undertaking forensic age estimation the first decision has to be which age estimation method to use and this decision has to be justifiable.

Tests have been done which compare the accuracy of the Greulich and Pyle atlas with the TW3 atlas method. In this study the tests of the Greulich and Pyle atlas method and the TW3 scoring method were undertaken on the same group of radiographs. It is therefore possible to compare the results of both atlases with each other to examine the relationship between the two methods

The standard deviations were compared for each method to give an idea of the accuracy of each method by sex. The RUS and CBA methods of the TW3 atlas (2001) were presented separately (Table 4.20). The standard deviations are lower for the Greulich and Pyle atlas (1959) method for both sexes compared to the standard deviations from either the RUS or the CBA method of the TW3 atlas (2001).

Method	Female	Male
Greulich and Pyle (1959)	14.97 months	14.16 months
TW3 RUS Method	20.43. months	16.65 months
TW3 CBA Method	23.31 months	18.70 months

Table 4.20: Showing the standard deviations for each method by sex

The statistical relationship between the chronological ages and age estimated by the Greulich and Pyle atlas and the TW3 atlas was investigated using ANOVA. The TW3 age estimation method is separated into two scoring techniques, the RUS score and the CBA score. These have been examined

separately in relation to the chronological age and Greulich and Pyle estimated age (Table 4.21).   The results show that the relationship between chronological age, the age as estimated by the Greulich and Pyle method and the age estimated by the TW3 RUS method is not significantly different for either the female or the male group. This is not the case for the relationship between chronological age, age estimated by the Greulich and Pyle method and age estimated using the TW3 CBA score. For both the female group (P=0.029) and the male group (P=0.028), this relationship is significantly different.

Chronological age compared to:	Female	Result	Male	Result
Greulich and Pyle (1959) and TW3 RUS (2001)	P=0.507	Not significantly different	P=0.935	Not significantly different
Greulich and Pyle (1959) and TW3 CBA (2001)	P=0.029	Significantly different	P=0.028	Significantly different

Table 4.21: The results of ANOVA by sex, a comparison of the results of the test of the Greulich and Pyle (1959) atlas, the results of the test of the TW3 (2001) atlas with chronological age.

Figures 4.18 and 4.19 show the relationship between chronological age and estimated age for females and males respectively. Chronological age is represented by a blue line in each case (FLH CA/MLH CA), the Greulich and Pyle estimated age is represented by a red line (FLH GP/MLH GP), the TW3 RUS estimated age is represented by a green line (FLH TW3 RUS/MLH TW3 RUS) and the TW3 Carpal estimated age is represented by a purple line (FLH TW3 Carpal/MLH TW3 Carpal). The difference between estimated age using the TW3 carpal bone method and chronological age and the other ageing methods can be seen, especially in the older groups. Whilst these are 'busy figures they give an indication of how the methods interact with each other and with chronological age.
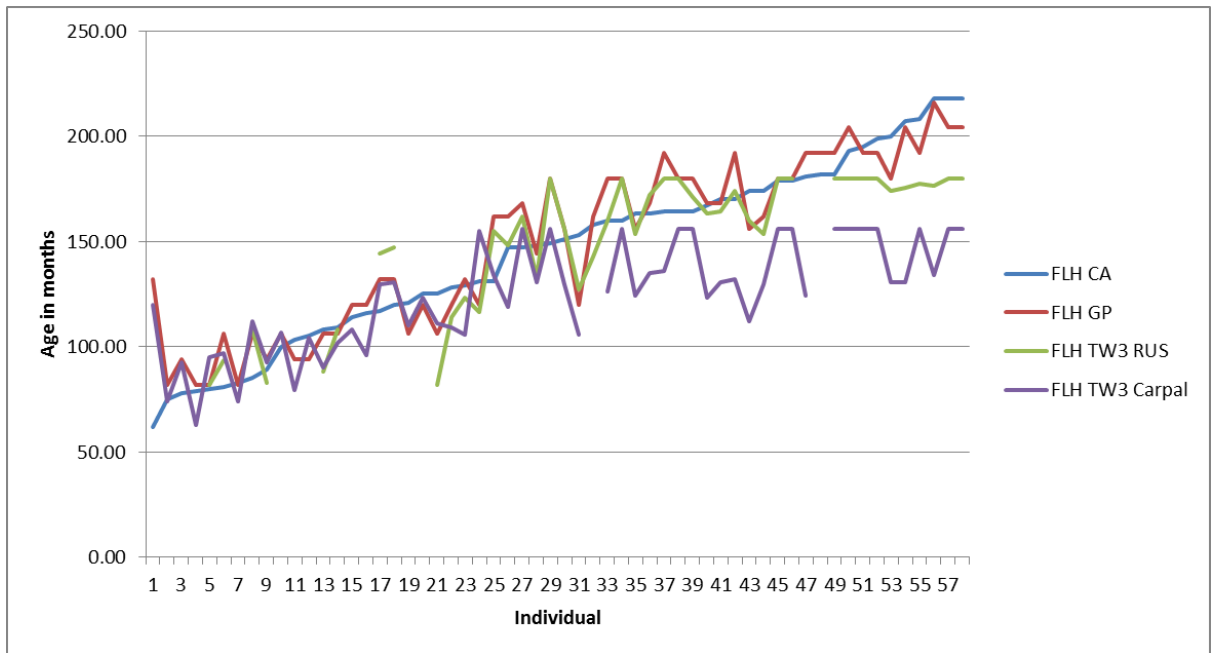
Figure 4.18: Demonstrating the relationship between chronological age and age as estimated by the Greulich and Pyle atlas (1959) (GP) and the TW3 atlas (2001) for radiographs of the female left hand-wrist (FLH).
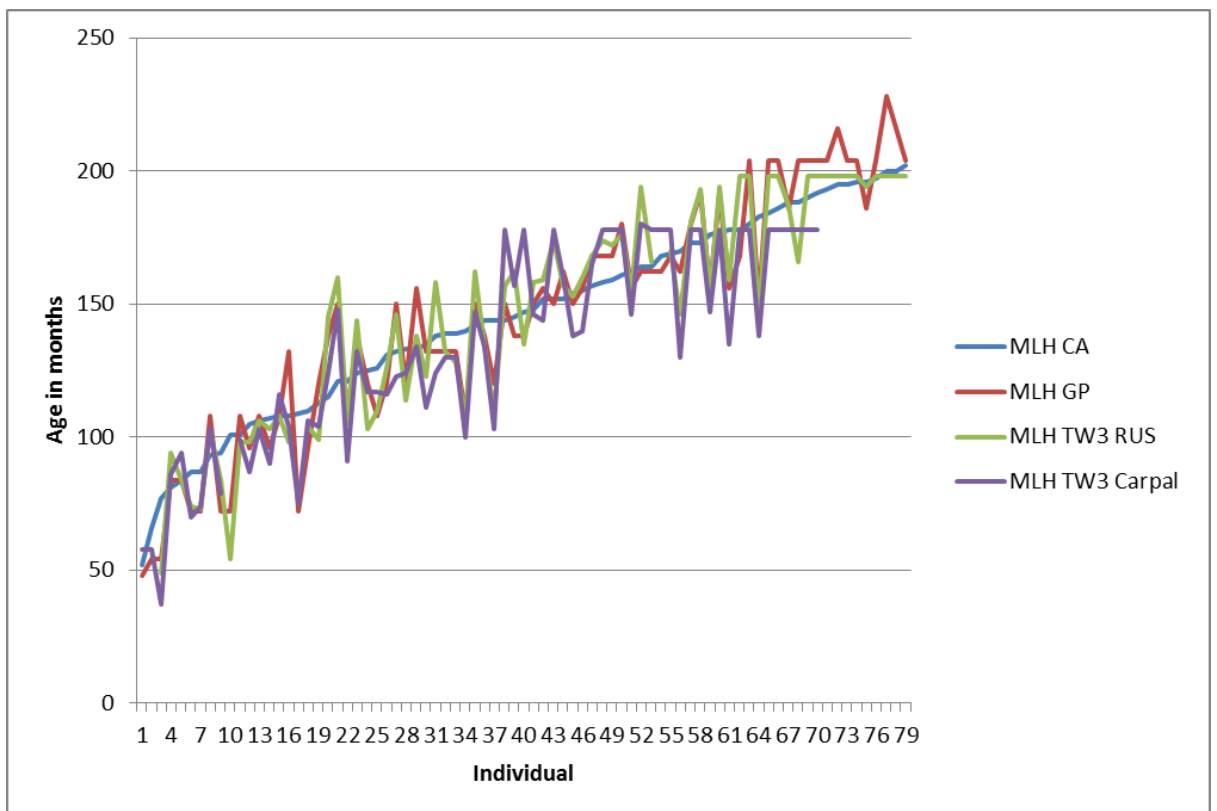
Figure 4.19: Demonstrating the relationship between chronological age and age as estimated by the Greulich and Pyle atlas (1959) (GP) and the TW3 atlas (2001) for radiographs of the male left hand wrist (MLH).

4.3.1 Discussion of the comparison of the Greulich and Pyle (1959) and the TW3 (2001) age estimation methods

The comparison of the Greulich and Pyle atlas method and the TW3 atlas method indicates that the TW3 RUS (2001) scoring method and the Greulich and Pyle atlas (1959) method can be compared for individuals who are suspected to be under the age of 15 years. The comparison of the Greulich and Pyle method and different editions of the Tanner-Whitehouse method have been investigated by a number of authors and results have varied (Andersen, 1971; Büken *et al.*, 2009; Bull *et al.*, 1999; Haiter-Neto *et al.*, 2006; Milner *et al.*, 1986; Vignolo *et al.*, 1990). Many argue that the speed with which the Greulich and Pyle atlas can be used is the deciding factor when choosing a method, however in a forensic situation this is not a valid argument for choosing a less accurate method because of ease of application. The results of a comparison between the Greulich and Pyle atlas (1959) method and any edition of the Tanner-Whitehouse method should not be extrapolated to suppose that the results would be the same if the comparison was done with the first, second, or indeed the third edition of the Tanner-Whitehouse atlas. This is because each Tanner atlas, whilst applying the same methodology in each case has been revised so that scores are weighted differently or has been based on the maturational tempo of a different population.

The comparison of the results of the Greulich and Pyle age estimation method and the TW3 atlas method in this study agrees with other studies which have compared the two age estimation methods on other populations (Büken *et al.*, 2009; Christoforidis *et al.*, 2007; Haiter-Neto *et al.*, 2006). In all of these studies the authors relied upon the TW3 RUS scoring method rather than the CBA

method. This comparison of methods and scoring systems supports the use of the TW3 RUS method rather than the TW3 CBA scoring method at all times. The results of the ANOVA test show that the TW3 RUS (2001) and the Greulich and Pyle atlas (1959) methods do not give significantly different results from each other, which is not the case in relation to the TW3 CBA scoring method (2001). Any age estimation which is undertaken should use the Greulich and Pyle atlas (1959) method as the primary method of age estimation and use the TW3 RUS scoring method (2001) to give support to the conclusions which are reached. The TW3 CBA scoring method would not be recommended as a method of choice in age estimation of either female or male individuals. The main difference between the two age estimation methods is that the Greulich and Pyle atlas (1959) has a higher upper age limit for both females and males and a lower standard deviation which lends itself to a smaller predicted age range, this indicates that it should be the primary method of choice but it would be good practice to support the conclusions with the second age estimation method of TW3 (2001).

4.4 Image orientation and the accuracy of age estimation

The first radiographic atlas was created by Poland (Poland, 1898), three years after the discovery of X-Rays by William Roentgen in 1895. This atlas consists of a mixed series of radiographs including images from both males and females and from both the left and right sides of the body. It was not until the work of Todd (1937) that the exclusive use of the left side of the body was advocated. This has been adopted by all other atlases since that time, irrespective of which area of the body is being considered (Gilsanz and Ratib, 2005; Greulich and

Pyle, 1959; Hoerr *et al.*, 1962; Pyle and Hoerr, 1969; Pyle *et al.*, 1971; Tanner *et al.*, 2001; Tanner *et al.*, 1962; Tanner *et al.*, 1975; Thiemann *et al.*, 2006).

The question originally raised by the exclusive use of the left side of the body in the atlases was whether this is reflective of the maturational status of the right side within the same individual. Greulich and Pyle (1959) addressed this question by referencing the work of Dreizen *et al.* (1957) who examined the relationship between maturational levels of the right and left hands of over 400 children. They found that whilst differences did exist between the two sides of the body, these were relatively minor and were insignificant in relation to the estimation of maturational stages of the skeleton as a whole. This result was subsequently supported by other studies including (Baer and Durkatz, 1957). The Todd (1937) and Greulich and Pyle (1959) atlases were the forerunners of a large series of reference texts, some of which originated from the same growth study population (Hoerr *et al.*, 1962; Pyle and Hoerr, 1969; Pyle *et al.*, 1971) and others which utilised information from other studies and therefore different sample sources (Brodeur *et al.*, 1981; Gilsanz and Ratib, 2005; Tanner *et al.*, 2001; Tanner *et al.*, 1962; Tanner *et al.*, 1975; Thiemann *et al.*, 2006). Without exception, all examined the left side of the body.

In addition to issues of methodological robustness, there are a number of reasons why the accuracy of right side hand-wrist radiographs in age estimations should be examined further. In the UK, radiographs are not taken for the purpose of age estimation without the informed consent of the individual (Levenson and Sharma, 1999). For those individuals who have been in the country for a period of time, it may be possible to trace and access radiographic images taken during treatment at an Emergency Department should permission for radiography not be granted. These may not be of the 'ideal' left side of the

body, especially since it is more likely that the right hand is imaged as the result of potential injury (Hill *et al.*, 1998; Rosberg and Dahlin, 2004). Radiographs may have been ordered by the Court prior to consultation for advice, and the right side of the body may have been imaged. A return to the individual for a left hand radiograph may not be considered good ethical practise. Further, it is possible that trauma or untreated developmental disorders might render the use of the left side of the body unsuitable for analysis.

Today many age estimations can, and do, become the focus of court proceedings and so there is a strong argument for the need to demonstrate that age assessments using the right side of the body carry similar discriminatory value to those undertaken utilising the left side as per the traditional recommendations. As the suggested methodology for age estimation in the living recommends the use of the left hand-wrist, it is vital that any practitioner understands the implications for alterations to this ideal requirement and how that might impact upon their reliability and accuracy. Finally, proving that the right and left sides of the body are interchangeable for the purposes of age estimation would permit data to be combined for the purposes of research, increasing the data pool available for analysis as it is, quite rightly, no longer possible or permissible to obtain longitudinal radiographic data. Many of the resource data available, dates from more than half a century ago and with alterations to nutritional status, environmental influences and other factors which will impact on secular trend (Cole, 2003; Garn, 1987; Loesch *et al.*, 2000) it is essential that methods are continually updated by testing on modern samples of different origin.

The following section sets out to answer two questions; firstly whether the Greulich and Pyle atlas (1959) is an appropriate age estimation method for radiographs of the right hand and secondly, would rotating the image of the right hand, so that it is in the same anatomical orientation as the images in the atlas (i.e. left), cause a significant change in reliability when undertaking an age estimation?

4.4.1 Methods and Materials

Radiographic images were examined for 818 individuals (545 males and 273 females) between the ages of one and 21 years of age (Table 4.22).

It should be noted that the images examined were taken for diagnostic or therapeutic purposes only and therefore the radiographer imaged the area of the hand-wrist that was relevant for their purposes and in an orientation that met the needs of the task. This resulted in a number of images which could not be utilised due to poor contrast or unsuitable anatomical orientation for the purposes of comparison with the atlas. It should also be realised that for each individual it was normal for only a right or a left hand to be radiographed and few individuals were represented by both hands, therefore bilateral symmetry could not be examined in this study.

Sex	Side	Number of Images
Female	Left Hand/Wrist	156
Female	Right Hand/Wrist	117
Male	Left Hand/Wrist	247
Male	Right Hand/wrist	298
	Total	**818**

Table 4.22: Number of radiographic images separated by sex and side

Table 4.23 indicates the number of radiographic images available for each age cohort grouped into year cohorts (Table 4.23 and Figure 4.20). The lower number of individuals in the very young age groups is to be expected as they are less prone to requiring emergency orthopaedic attention. Older age groups contain larger numbers of individuals reflecting greater exposure to higher risk occupations including physical activities, sports etc. which may result in attendance at an Accident and Emergency Department following an accident.

Years	Female Left	Female Right	Male Left	Male Right	Total
1	3	0	3	1	7
2	3	1	3	1	8
3	3	3	3	2	11
4	6	2	6	2	16
5	1	1	7	2	11
6	7	0	2	7	16
7	8	6	8	6	28
8	3	3	8	7	21
9	10	5	12	9	36
10	18	8	15	8	49
11	6	6	17	13	42
12	10	8	15	33	66
13	17	10	16	25	68
14	10	11	18	27	66
15	5	11	19	23	58
16	10	11	19	15	55
17	8	7	21	23	59
18	12	8	19	33	72
19	6	5	19	29	59
20	10	11	17	32	70
Total	156	117	247	298	818

Table 4.23: Number of radiographic images separated by sex, side and chronological age.
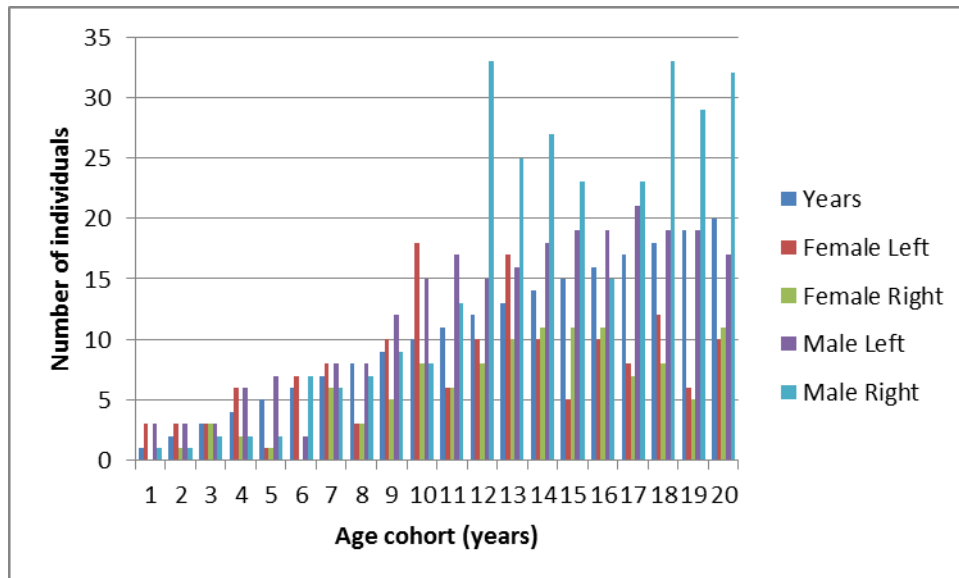
Figure 4.20: Spread of radiographic images by year cohort.

Skeletal age estimation was undertaken for each of the radiographs using the Greulich and Pyle Atlas (1959) without prior knowledge of the chronological age of each of the children examined. Due to well-recorded differences in the development of females and males, age estimation was undertaken separately for each sex (Pryor, 1923; 1925). As with the previous test of the Greulich and Pyle atlas the full range of radiographs were included since fusion was still on-going in a number of cases (Table 4.24).

Sex and Side	Number of Images in age groupings 18-21 years for females and 19-21 years for males	Number in which fusion still active	% in which fusion still active
Female Left Hand/Wrist	24	7	29%
Female Right Hand/Wrist	28	7	25%
Male Left Hand/Wrist	61	2	3%
Male Right Hand/Wrist	36	9	25%

Table 4.24: Number of radiographic images where fusion still active in individuals older than the maximum skeletal age indicated in the Greulich and Pyle atlas (1959).

Upon completion of the age assessment for each group, all images (both right and left hands) were rotated about the vertical axis, thus the left hand images were reversed so that they were in the same orientation as a radiograph of a right hand-wrist and the right images were reversed to mimic a left hand image (Figure 4.21). Once the image was reversed they were again age assessed using the Greulich and Pyle atlas (1959), with a delay of two weeks between assessments.
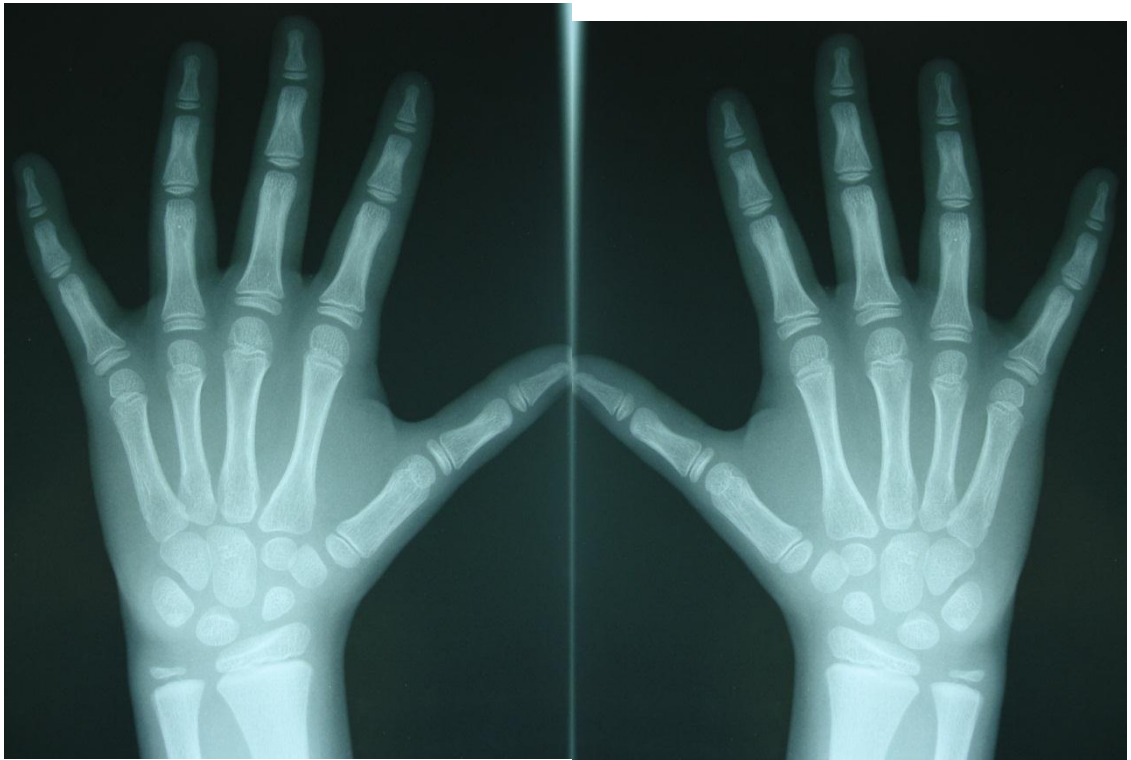
Figure 4.21: Showing the left hand-wrist image prior to (left) and after (right) rotation about the vertical axis.

An inter-observer test was devised in which 57 randomly selected images from the female left hand group were age assessed by a second forensic anthropologist with experience of viewing radiographs and a knowledge of, but little experience with, the Greulich and Pyle (1959) age estimation system. Any indicator of side on the radiograph such as the large 'L' marker used by radiographers was obscured and the observer was provided with a copy of the Greulich and Pyle atlas (1959) but was given no instructions in its use. Additionally the images were given in a digital format rather than on an X-ray film, again reducing the likelihood of them being rotated by accident. Two weeks after completion of this test the original images were reversed around the vertical axis so that they appeared to be right images of the right hand. These images were given to the same observer in digital format, who was again asked

to age assess them using the same atlas. The observer was informed that the images were from female subjects but given no further information.   At no point was the observer informed that they were the same images as had previously been assessed. Post-test questioning confirmed that the observer had not made any effort to rotate them during the age estimation process.

Once skeletal age had been assessed, linear regression analyses and correlations were performed for each group and for both observers. All of the radiographs were from different patients since this is a cross sectional data source and so it was not possible to compare bilateral reliability of age estimation. A comparison of the regression slopes for each sex and side were compared using G*raphpad®*.

4.4.2   Results
Linear regression analysis was undertaken on the data with chronological age treated as the independent variable in all of the equations. Table 4.25 and Table 4.26 show the results of the analysis of the groups both before and after vertical axis mirroring for each of the observers. Table 4.25 shows that the regression coefficients remained high for all of the groups indicating that there is a strong relationship between chronological age and assessed age using the Greulich and Pyle atlas (1959) for both sexes and for both sides of the body. The p-values for all of the analyses were highly significant (p=<0.0001). For three out of the four comparisons, males had a marginally higher correlation value than females for the same hand but this was not statistically significant. In their correct anatomical orientation, there was a slightly higher R^2 value for the left hands than for the right hands.

	Regression Coefficient	R value	R²-value	p-value		Regression Coefficient	R value	R²-value	p-value
Female Left Hand/Wrist	0.894	0.969	0.939	<0.0001	**Reversed Female Left Hand/Wrist**	0.879	0.962	0.929	<0.0001
Female Right Hand/Wrist	0.859	0.939	0.887	<0.0001	**Reversed Female Right Hand/Wrist**	0.893	0.948	0.935	<0.0001
Male Left Hand/Wrist	0.979	0.970	0.940	<0.0001	**Reversed Male Left Hand/Wrist**	0.963	0.968	0.931	<0.0001
Male Right Hand/wrist	0.940	0.952	0.907	<0.0001	**Reversed Male Right Hand/wrist**	0.957	0.958	0.942	<0.0001

Table 4.25:   R² values and regression coefficients by sex and side for the assessments undertaken by the first observer.

The correlations remained consistently high after vertical reversal of the images for both observers although interestingly there was a slightly higher R^2 value for the right hands that were reversed to look like left hands. This was true for both males and females. The inter-observer test showed an equal strength of relationship between the correct sided hands and those that were reversed when correlated with chronological age (Table 4.26).

	Regression Coefficient	R value	R²-value	p-value		Regression Coefficient	R value	R²-value	p-value
Female Left Hand/Wrist	0.921	0.962	0.927	<0.0001	**Reversed Female Left Hand/Wrist**	0.927	0.961	0.927	<0.0001

Table 4.26: R² values and regression coefficients for second observer.

The regression coefficients were compared for each group, before and after rotation, to determine whether the repeatability of age estimation differed significantly as a result of changing the image orientation.

Table 4.27 presents the results of these comparisons. The results show that regardless of the orientation of the images, the repeatability of the age estimation performed with the Greulich and Pyle atlas (1959) did not differ significantly. There were no significant differences between either the slopes or intercepts for any of the groups when 'before' and 'after' rotation analyses were compared. As a result, pooled regression coefficients can be presented (Tables 4.27 and 4.28). The comparison of regression coefficients for the second observer gave a comparable result indicating that their age estimations for the images in both orientations did not differ significantly (Table 4.28).

Sex and Side	Pooled regression coefficient	Significance
Female Left Hand/Wrist compared to Female Right Hand/Wrist	0.880	NSD
Male Left Hand/Wrist compared to Male Right Hand/Wrist	0.954	NSD
Female Left Hand/Wrist compared to Female Left Hand/Wrist Reversed	0.880	NSD
Female Right Hand/Wrist compared to Female Right Hand/Wrist Reversed	0.872	NSD
Male Left Hand/Wrist compared to Male Left Hand/Wrist Reversed	0.967	NSD
Male Right Hand/Wrist compared to Male Right Hand/Wrist Reversed	0.944	NSD

Table 4.27: Pooled regression coefficients for each group for the first observer (NSD = no significant difference).

Sex and Side	Pooled regression coefficient	Significance
Female Left Hand/Wrist compared to Female Left Hand/Wrist Reversed	0.925	NSD

Table 4.28: Pooled regression coefficient for female left hand/wrist and rotated images of female left hand/wrist for second observer (NSD = no significant difference).

In the case of age estimation from the hand/wrist, this test has supported previous research where the Greulich and Pyle atlas has been shown to still be applicable for use in modern material (Groell *et al.*, 1999; Schmidt *et al.*, 2008b; Van Rijn *et al.*, 2001; Zafar *et al.*, 2010). In addition the results have shown that there is no significant difference in whether a right or a left hand is used for comparison with the reference atlas or indeed whether a radiograph is mirrored about the vertical axis. However, the results did indicate that the relationship is marginally stronger when mirror image matching is not employed (i.e. comparing a mirrored right hand to a left hand standard) and this is perhaps to be expected given the spatial cognitive skills required in such processes (Wolff, 1971) . Therefore although there is no significant difference in the strength of the relationship between chronological age and the selected Greulich and Pyle standard, it is advised that, given the slightly stronger relationship seen for the images which were viewed in the same orientation as those presented in the atlas, where possible, left hands should be selected for comparison. Where this is not possible, then images of the right hand radiograph should be mirrored across the vertical axis to maintain a conformity of approach as a standard operating procedure.

5 The Elbow

Anatomically the elbow joint is formed by the junction between the distal humerus, proximal radius and proximal ulna. Authors have drawn parallels between the development of the forelimb and that of the hindlimb in the fetus and argue that their development follows a similar series of changes during the maturation process with the elbow equating to the knee joint (Lewis, 1901; O'Rahilly and Gardner, 1975). In quadrupeds the forelimbs weight-bear in a manner similar to that of the hind limbs, however in humans the upper limbs are no longer involved in locomotion and have an increased capacity for manipulative type movements, this is echoed in the arrangement of the elbow joint (Brabston *et al.*, 2009; Scheuer and Black, 2000b).

Ossification at the elbow joint has been studied through the examination of radiographic images. The order of radiographic appearance of the ossification centres have been recorded by a number of authors (Davies and Parsons, 1927; Flecker, 1932; 1942). In common with other skeletal areas, reported timings of appearance of ossification centres and their fusion are influenced by the method of study (Meijerman *et al.*, 2007). The pattern of ossification and fusion at the distal end of the humerus has been described as 'complex' (Scheuer and Black, 2000b), however, as with other body areas, the process of ossification and fusion follows a sequential pattern which remains relatively consistent for both females and males (Cheng *et al.*, 1998; Patel *et al.*, 2009), although it is no surprise that small variations in this sequence are reported (Cheng *et al.*, 1998; Resnick and Hartenberg, 1986). The large number of elbow fractures which are seen in young people has ensured that the six

secondary ossification centres of this region have been studied closely in relation to their ossification sequence and changes in morphology and alignment since on occasion, changes in these can indicate the presence of injury (McCarthy and Ogden, 1982; Silberstein *et al.*, 1979; 1981; 1982). Many of these studies involve the examination of radiographs since the use of this imaging modality is vital to diagnosis of elbow injury.

The radiographic atlas of Brodeur *et al.* (1981) describes the development of the elbow from birth to maturity and provides a separate series of radiographs for females and males. The radiographs are spaced at six-monthly intervals for which the authors offer two sets of images, presenting the earliest and latest levels of development seen at that chronological age. An anterior-posterior radiograph and a lateral radiograph are used to visualise each stage. In the introduction to the atlas the authors argue that it is designed to complement a hand-wrist atlas (Brodeur *et al.*, 1981). In a similar manner to the Greulich and Pyle atlas method (1959) the Brodeur *et al* (1981) atlas acts as a comparison method of developmental estimation in which the radiograph of the child being assessed is compared to those which are included in the atlas to find those which the area most resembles morphologically.

The second method of age estimation from the elbow was developed by Sauvegrain *et al.* (1962) and is known as the Sauvegrain method (Canavese *et al.*, 2008; Chaumoitre *et al.*, 2006; Dimeglio *et al.*, 2005). This is a scoring method in which scores are assigned to each of four anatomical areas; the lateral condyle, the trochlea, the olecranon apophysis and the proximal radial epiphysis (Charles *et al.*, 2007). The Sauvegrain method was designed for use in children who are just entering puberty and so the age group that this method can be used with is restricted (Chaumoitre *et al.*, 2006; Dimeglio *et al.*, 2005).

This section tests both of these age estimation systems on radiographic images of left elbows of both sexes.

5.1 Materials and Method for testing the Brodeur *et al.* atlas (1981) method

Ethical permission was gained from Ninewells Hospital to collect radiographic images of left elbows from patients aged between birth and 20 years of age. The radiographic images had been taken during examination for suspected injury when the individual had attended the Accident and Emergency department. The sex, date of birth and date of injury were the only additional data collected. Since the atlas included both lateral and anterior-posterior images both of these were collected in each case (Figure 5.1). In total, images from 592 individuals were collected, consisting of 260 females and 332 male individuals.   The images were screened for the presence of pathology or previous trauma which might have affected growth and if any of these were present the radiograph was not included.

Figure 5.1: Anterior-posterior (left) and lateral radiograph of a male left elbow. Identified as 'MLH 66'. Chronological age 5 years of age (60 months). Estimated age 36 months-84 months of age using Brodeur *et al.* atlas (1981) method.

The spread of the data across the age groups is presented in Table 5.1 and Figure 5.2. It is of interest to note that there are relatively large numbers in the younger age groups for both sexes, especially from 2 years of age onwards which decline again in the older age groups.

The chronological age of each individual was calculated by subtracting the date of birth from the date on which the radiograph was taken. The analysis was undertaken separately for each sex, taking into account the differences in timing of maturational change for females and males (Pryor, 1923; 1925).

Age in years	Female left elbow	Male left elbow	Total
1	9	10	19
2	19	15	34
3	10	11	21
4	11	19	30
5	15	20	35
6	12	20	32
7	12	12	24
8	15	20	35
9	23	16	39
10	20	19	39
11	19	19	38
12	18	22	40
13	16	24	40
14	7	20	27
15	13	13	26
16	9	17	26
17	6	11	17
18	8	17	25
19	6	11	17
20	12	16	28
Total	260	332	592

Table 5.1: Spread of images by chronological age and sex.

Figure 5.2: Spread of images by chronological age and sex.

Each radiograph was assessed for age using the Brodeur *et al.* atlas (1981) method. The chronological age was obscured during the assessments and only the sex of the individual was known. The resultant estimated ages were converted into months for ease of statistical analysis. Inter and intra-observer accuracy were tested using a randomly chosen subset of 30 female images and 30 male images which were retested by the first author after a period of 3 months from the first analysis and by a second observer who had some experience with radiographic analysis but had not used the Brodeur *et al.* atlas (1981) method previously.

In the atlas, the oldest radiograph in the female set is 16 years of age and in the male set is 16 years and 6 months of age at which chronological ages the authors of the atlas present completed fusion for both females and males. All of the images between birth and 20 years of age were examined in order to establish the maximum age at which active fusion could still be observed for either sex within the data set tested. Fusion was complete for all female individuals who had achieved the age of 16 years and for all males by the age of 16 years. For this reason the images of female individuals from 16-20 years of age were discarded from further analysis and in the male group the images of individuals from 16-20 years of age were discarded from further analysis. As a result the final analysis consisted of 506 images (images of 229 female elbows and 277 male elbows).

5.2 Inter and intra-observer error

To test inter- observer and intra-observer errors the radiographs of 30 randomly selected female individuals and 30 male individuals were re-tested under the

same circumstances with the chronological age obscured and only the sex of the individual known.

In order to compare the two sets of assessed ages a Mann-Whitney U test was undertaken by comparing the lowest ages of each age range and the upper ages of each age range between observers (Table 5.2). This shows that there were no significant differences for either sex between the estimated age ranges.

Mann-Whitney U test	Female	Male
Lower age inter observer age ranges	P=0.970	P=0.602
Upper age inter observer age ranges	P=0.656	P=0.944
Lower age intra observer age ranges	P=0.868	P=0.833
Upper age intra observer age ranges	P=0.905	P=0.963

Table 5.2: Showing the results of the Mann-Whitney U tests for the inter and intra observer tests

The number of correct and incorrect age assessments were calculated for each observer. These were compared to the first test that was undertaken by the first observer (Table 5.3). For female individuals the second observer was the most successful at age estimation using the Brodeur *et al.* (1981) atlas method, compared to either test undertaken by the first observer. For male individuals

the first observer was more successful than the second observer on both

occasions. The first observer was also more successful at age estimating

males on both occasions compared to females. The second observer had a

consistent success rate across both sexes compared to the first observer.

First Test				
	Female Correct	**Female Incorrect**	**Male Correct**	**Male Incorrect**
	21	9	25	5
Intra-observer Test				
	Female Correct	**Female Incorrect**	**Male Correct**	**Male Incorrect**
	20	10	26	4
Inter-observer Test				
	Female Correct	**Female Incorrect**	**Male Correct**	**Male Incorrect**
	24	6	23	7

Table 5.3: Number of individuals whose age was included in the assessed age range for each test and each observer and those whose chronological age fell outside the estimated age range.

5.3 Results for the test of the Brodeur et *al.* atlas (1981) method

There is no overt guide for the use of the Brodeur *et al.* atlas (1981). The atlas

is organised into 6 monthly increments with two images presented at each of

these increments, one representing an individual with advanced skeletal

maturation for that chronological age and one representing an individual whose

stage of skeletal maturation would be considered to be slower, although still

within the normal expected range. This organisation results in a predicted age

estimation which presents as an age range rather than as a single predicted

age.

The analysis of the results of these age estimations was examined to gain an

understanding of the accuracy of the atlas method. If the chronological age of

the individual assessed fell within the estimated age range, the age estimation

was considered to be 'correct'. If the chronological age was less than the

lowest age of the estimated age range this was considered to be an example of

an overage and if the chronological age was greater than the upper limit of the

age range than this was considered to be an example of an underage. The

results of the test of the method on the female group are presented in Table 5.4.

For this group the chronological age fell into the estimated age range for 146

(63.7%) of the individuals. A greater number of females were overaged

(45/19.65%) than were underaged (38/16.59%) using this method. The majority

of underaged individuals were spread across the younger age groups prior to 9

years of age and the greatest numbers of these were found within the 6,7 and 8

year old age groups. After the age of 8 only one underaged individual was to

be found in each of the 9 and 10 year old age groups. In the older groups,

except for 2 individuals in the 12 year age group and 1 in the 15 year old group

there were no other individuals who were underaged.

Female Left Elbows			
Chronological age (years)	Correct	Underage	Overage
1 (n=9)	7	2	0
2 (n=19)	15	3	1
3 (n=10)	8	1	1
4 (n=11)	11	0	0
5 (n=15)	13	2	0
6 (n=12)	5	7	0
7 (n=12)	6	5	1
8 (n=16)	12	4	0
9 (n=23)	17	1	5
10 (n=20)	18	1	1
11 (n=19)	14	0	5
12 (n=18)	11	2	5
13 (n=16)	7	0	9
14 (n=7)	2	0	5
15 (n=13)	0	1	12
16 (n=9)	0	9	0
Total (n=229)	146 (63.76%)	38 (16.59%)	45 (19.65%)

Table 5.4: The number of images of females whose age fell into the assigned age ranges, those that were underaged and those that were overaged

For the male individuals (Table 5.5) the chronological ages of 241 (87%) individuals fell within the assessed age ranges and could therefore be considered to be correct, 21 (7.58%) were underaged and 15 (5.42%) were overaged. The underaged individuals are distributed throughout the groups with an equal number found in the 1 year to11 year old age groups (7) and the 11 year to 16 year age groups (7). The greatest number of individuals who were overaged (11) were found in the 11-16 year old age groups.

Male Left Elbows			
Chronological age (years	Correct	Underage	Overage
1 (n=10)	10	0	0
2 (n=15)	14	1	0
3 (n=11)	11	0	0
4 (n=19)	17	1	1
5 (n=20)	18	2	0
6 (n=20)	19	1	0
7 (n-12)	12	0	0
8 (n=20)	19	0	1
9 (n=16)	15	0	1
10 (n=19)	16	2	1
11 (n=19)	18	1	0
12 (n=22)	21	0	1
13 (n=24)	19	0	5
14 (n=20)	20	0	0
15 (n=13)	10	0	3
16 (n=17)	2	13	2
Total (n=277)	241 (87%)	21 (7.58%)	15 (5.42%)

Table 5.5: The number of images of males whose age fell into the assigned age ranges, those that were underaged and those that were overaged.

The degree to which the chronological age fell outside the estimated age range was calculated (Table 5.6). The maximum ranges were found in the female groups. The maximum difference between the upper limit of an estimated age range and the chronological age for females was 34 months which was found in the 8 year old age group and the maximum difference between the lower limit of an estimated age range and the chronological age was 43 months, found in the 12 year old age group. For males the maximum difference between the upper limit of an estimated age range and the chronological age is 13 months which was found in the 10 year old age group, this is separated from the similar peak

in the female group by a difference of 2 years. The maximum difference between the lower limit of an estimated age range and the chronological age was 24 months which was found in 12 year age group which is the same age that this peak is seen in the female group.

Sex	Minimum (months)	Maximum (months)
Female Underage	1 months	34 months
Female Overage	2 months	43 months
Male Underage	1 months	13 months
Male Overage	1 months	24 months

Table 5.6: The number of months by which chronological age fell outside the estimated age ranges for those individuals for whom the estimated age did not include the chronological age.

The position of the chronological age within the age range was examined for females and males. The results are demonstrated in Figure 5.3 and Figure 5.4. For each of the figures the point on the line is the chronological age and the vertical line indicates the age range estimated using the Brodeur *et al.* (1981) atlas method.

An overview of the age ranges which were produced are shown in Table 5.7. The mean of the ranges, that is the number of months which lie between the minimum and maximum ages suggested by the atlas in relation to each radiograph assessed, is similar for both the female and the male groups.

Sex	Minimum age range	Maximum age range	Mean age range
Female (n=229)	3 months	78 months	35.87 months
Male (n=277)	6 months	66 months	38.75 months

Table 5.7: Showing the minimum age ranges assigned, the maximum age range assigned and the average age range for each sex

Age in

months
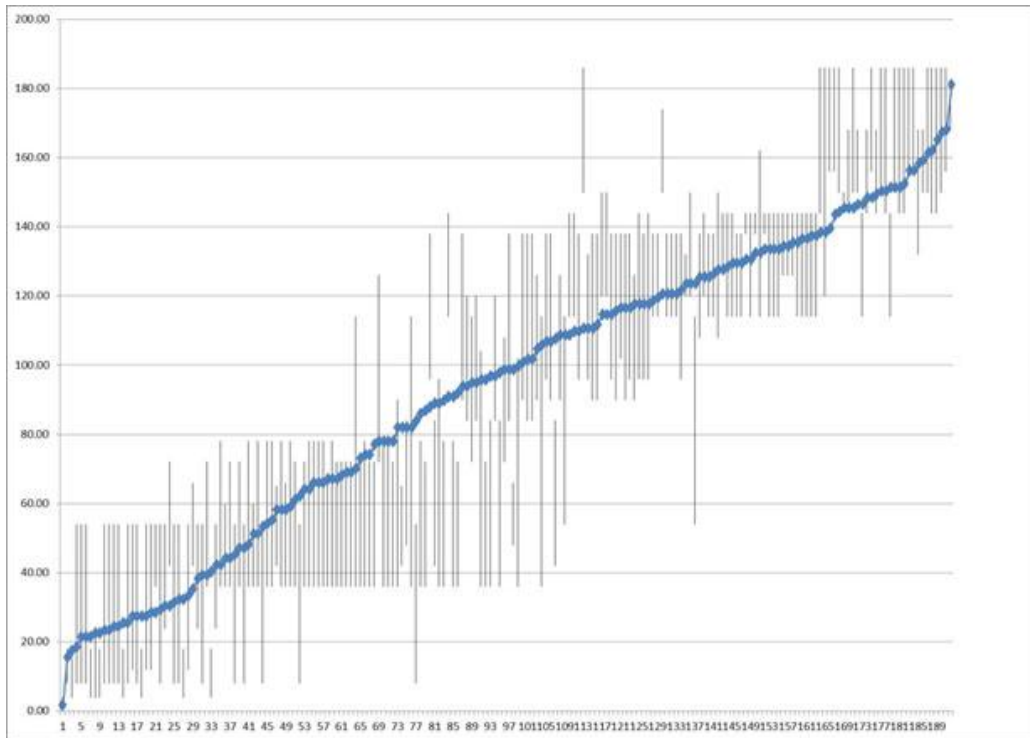
Individual

Figure 5.3: Age ranges assigned by the Brodeur *et al* atlas (1981) method for females in relation to the chronological age (blue line)
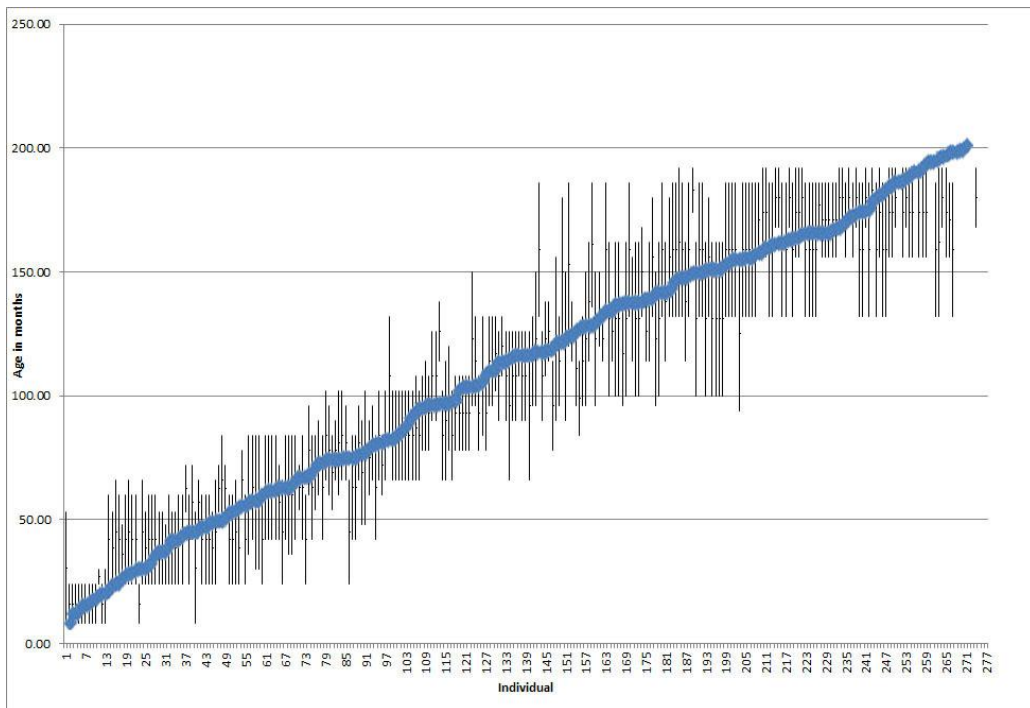
Figure 5.4: Age ranges assigned by the Brodeur *et al* atlas (1981) method for males in relation to the chronological age (blue line).

5.4 Discussion of the results of the Brodeur *et al* (1981) atlas

There are many countries in Europe including the UK in which radiographs can only be utilised in age estimation after the individual has given informed consent for the procedure (Table 1.4). The use of existing radiographs which have already been taken during visits to Accident and Emergency may be one way in which a lack of consent can legally be overcome since in the UK it is possible to get access to these with either the consent of the individual or during a criminal investigation the Police and Criminal Act 1984 allows access to medical records on the order of a judge (HMSO, 1984). The investigation of the accuracy of age estimation methods from the elbow is therefore highly relevant to forensic practitioners.

In the Brodeur *et al* atlas (1981) the authors describe the organisation of their atlas with the inclusion of early and late maturers and they suggest that '*it is left for the reader to interpolate between the extremes that are shown'*. Because of this organisation the comparison between radiographic images and the atlas result in an age range. The atlas does come under some criticism from Garn (1982) since it does not give any background information on the children whose radiographs were used in the compilation of the atlas. He also felt that it would be more useful to add an 'average' image to the upper and lower examples of ossification for each chosen chronological age.

The age ranges assigned by the Brodeur *et al.* atlas (1981) method precluded the analysis of the results using linear regression however it was possible to assess how often the chronological age fell within the assigned age range for each sex.   The age assessment method was more accurate for male

individuals than for female individuals in this dataset. This was influenced by the inclusion of the complete cohort for the 15 and 16 year old individuals in the female group. With the exception of one, all of the 15 year old individuals evidenced complete fusion and as a result were assigned an estimated age of 16 years resulting in an overage for most of the group. For the 16 year old age group all of the group showed full fusion and were assigned an age of 16 years (192 months) which meant that they were all underaged and therefore incorrectly aged. If these groups were removed from the analysis the accuracy of the method for radiographs of female individuals increases to 70.5%. The maturational timings of the female group in this dataset were in agreement with Brodeur *et al* (1981) who found that '*most females are fully mature by the age of 15*'.

The greatest difference between chronological age and estimated age range for underaged individuals for the female and the male groups could be found at 8 years of age in females and 10 years of age in males which might conceivably coincide with the beginning of the adolescent growth spurt for each sex, a time when individuals have entered the phase of high growth velocity. This is a time of maximum differences between individuals due to the difference in timings of the growth spurt. The greatest difference between chronological age and estimated age range for the overaged individuals was seen at 12 years of age for both females and males, again a time when some individuals will be ahead of others, and some behind due to individual differences (Tanner, 1962).

In the female group the majority of individuals who were underaged were found in the 0-8 year old age groups. The incidence of under-aging was highest in both the 6 year old cohort where 58.33% are underaged and the 7 year old

cohort in which 50% are underaged. After this the pattern changed and the majority of individuals whose age did not fit into the estimated age range are overaged. Figure 5.3 shows this pattern clearly, it can be seen that between 70 months and 90 months of age there is a gap in which most individuals are underaged. The pattern of errors changes around 110 months of age to one in which the error is more likely to be an overage. A closer study of the plates in the atlas and the radiographs give some indication of why this error occurs in these age groups. The underage which is seen in the 6 and 7 year old cohorts is linked to the appearance of maturity indicators such as the beginning of ossification of the olecranon apophysis which is seen at 7 ½ years of age (Figure 5.5).

The ossification center for the trochlea has not yet appeared. The shape of the capitellum and the early saucerization of the radial head are indicative of some degree of maturity. Note the molding of the radial epiphysis to the metaphysis.

Figure 5.5: 'Low Normal Female' showing the beginning of ossification of the olecranon apophysis (taken from Brodeur et al. 1981).

For the 6 year (Fig 5.6), 6 ½ year (Fig 5.7) and 7 year old (Fig 5.8) radiographs there is an increase in the size of the proximal radial epiphysis in relation to the metaphysis, the olecranon fossa appears deeper and the distal humerus is more developed and the trochlea is a different shape to that seen previously. The radiographs which are underaged did not show these changes and were therefore not assigned this, often more appropriate, level of skeletal maturity.
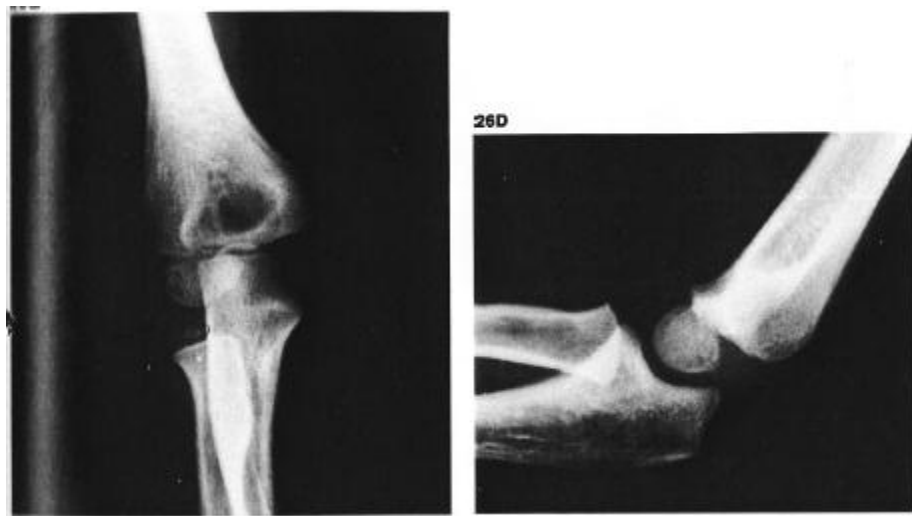
Figure 5.6: Low Normal Female 6 years (Brodeur *et al.* 1981).
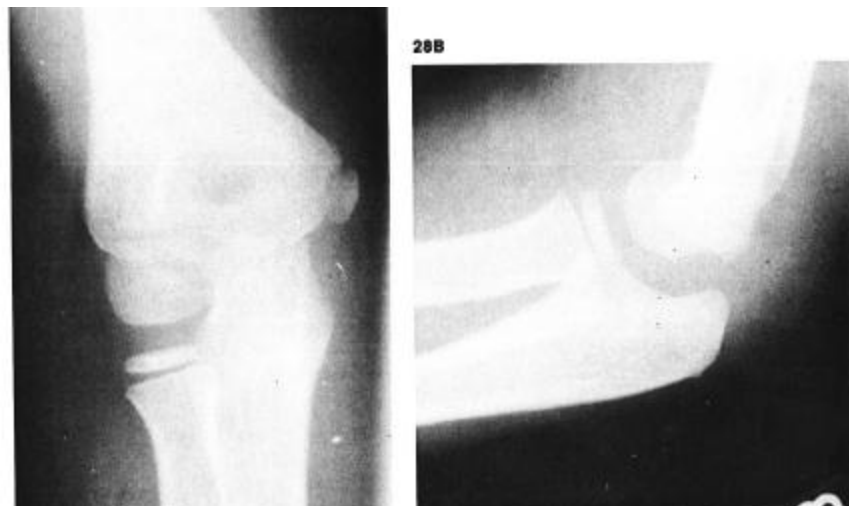
Figure 5.7: High Normal Female 6 1/2 years (Brodeur *et al.* 1981).
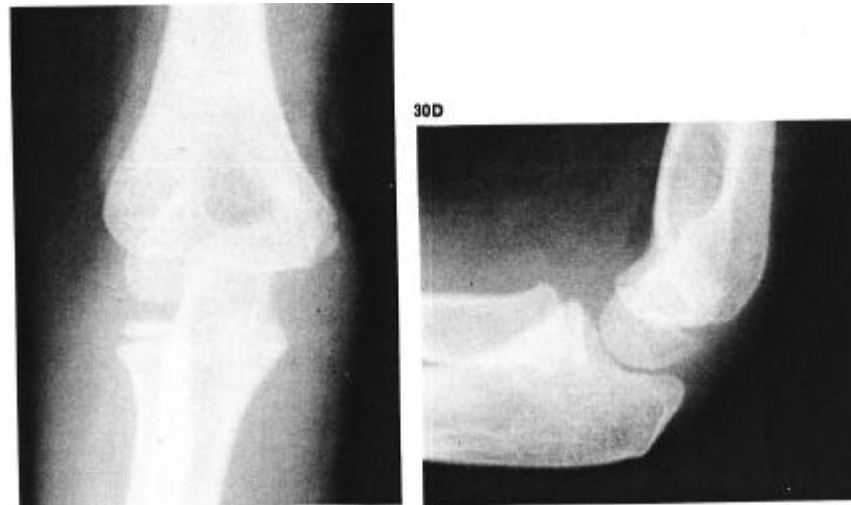
Figure 5.8: Low Normal Female 7 years (Brodeur *et al.* 1981).

The tendency to overage individuals in the older female age groups can be explained by a number of maturity indicators which are seen in the atlas, firstly the appearance of the lateral epicondylar epiphysis which occurs at 10 years of age, this is closely followed by the fusion of the capitulum with the trochlea and fusion of the capitulum, trochlea, lateral and medial epicondylar epiphyses. The olecranon apophysis is shown to change shape and fuse from the age of 12 years onwards. Any radiograph which is showing these indicators will be placed in these older age ranges.

For the male series whilst age ranges are linked to the appearance of maturity indicators there are no points at which these result in a tendency to over or under age. This may be due either to the organisation of the atlas or to the fact that the changes in the maturity indicators in this male group are more closely linked to the timing of the changes seen in the atlas than those for the female group.

For males the majority of overaged individuals are found in the older age groups rather than the younger groups. Unlike the female group the tendency to underageing is widely spread through the age groups. The greater number of individuals whose chronological age fell outside the estimated age ranges in the older groups can be explained by the greater variation in the timing of skeletal changes that are seen between individuals as they progress through the pubertal growth spurt.

This test of the atlas found that full fusion in the female group was first seen in an individual whose chronological age was 12 years 11 months, for older groups; complete fusion was observed in 56.25% of the 13 year old group, 71.43% of the 14 year old group and 92.30% of the 15 year old group. This pattern was not reflected in the male group where the first individual who showed complete fusion was 15 years 3 months of age, in total 23.07% of this cohort demonstrated complete fusion, 64.70% of the 16 year old group demonstrated complete fusion and by the age of 17 years 100% of the male individuals had achieved full maturity. In the Scottish dataset the male individuals were therefore delayed by approximately 2 years compared to the female cohort in the completion of skeletal maturation at this joint area. Other authors who have studied the fusion times of the elbow epiphyses have found similar times of fusion for both females and males to those seen in this Scottish dataset, despite differences in country of origin and socioeconomic background (Barrett, 1936; Jnanesh *et al.*, 2011; Patel *et al.*, 2009; Sahni *et al.*, 1995).

The Brodeur *et al.* atlas (1981) has been designed in a different manner from that of the other atlases discussed in other sections (Greulich and Pyle, 1959; Hoerr *et al.*, 1962; Pyle and Hoerr, 1969). Those atlases worked by locating

maturity criteria which they then related to a chronological age. For this reason the series of radiographs are not spaced according to chronological age but according to the maturational changes which the authors felt were important. In the Brodeur *et al* (1981) atlas the radiographs are spaced at 6 monthly intervals and it is for the user of the atlas to work out which maturity indicators to utilise when undertaking age estimation. Additionally the atlas does not present the image which demonstrates the individual whose skeletal development represents the 'mode' of development.

Maturity indicators are still important however, the ranges which are demonstrated in Figures 5.3 and 5.4 show that there are identifiable maturity indicators which are used to assign an age range to each radiograph. This creates a step-like pattern when viewed sequentially as different maturity indicators move into and out of prominence at different ages. When examined the average age range assigned was 35.87 months (3 years) for females and 38. 75 months (3 years 3 months) for males. The accuracy of these age ranges are shown by the number of individuals who were correctly age estimated (Tables 5.1 and 5.2). Accuracy is greater for males than females and the figures indicate that anyone undertaking an age estimation using radiographs of this skeletal area should be aware of the decrease in accuracy seen in children between 9 and 16 years of age. Given the earlier fusion seen in the female group serious thought should be given to whether this is an appropriate method to use for any female who is suspected to be 13 years of age or older, early fusion at this site would give an estimated age which would be widely inaccurate.

5.5 The use of the Brodeur *et al* (1981) atlas

The atlas makes full use of all areas of ossification at the elbow. The use of anterior-posterior in addition to the lateral radiographs allows for all epiphyses to be observed and therefore both views are required (Table 5.8).

View	Skeletal Area
Anterior Posterior	Distal humerus
	Proximal ulna
	Proximal radius
Present but unable to see due to overlying	Olecranon apophysis
Lateral	Olecranon apophysis
	Proximal ulna
Present but unable to see due to overlying	Distal humerus
	Proximal radius

Table 5.8: Skeletal areas which were visible for each radiographic view.

The inclusion of the 'High normal' and 'low normal' images makes the Brodeur *et al* .atlas (1981) method difficult to use. Skeletal maturation stages are not differentiated and appear to be extremely similar, for example 'Low normal-Male 8 ½ years' (Figure 5.9) and 'Low normal-Male 10½ years' (Figure 5.10). There are no instructions on the use of the atlas so a 'best' method of use had to be devised which in this case led to the assignment of age ranges (Figures 5.11-5.13).

There were some issues with the standard of images which were presented in the atlas. Poor images prevented a clear view of many skeletal changes including fusion between the smaller epiphyses (Figure 5.10). The written descriptions were limited and of little assistance.

Low Normal-Male   **8½ years**

The capitellum and the olecranon fossa are suffi-
ciently well developed to fit into the 8½-year group.
The trochlea has not yet begun to ossify, and the
medial epicondylar and radial head epiphyses are
still in the early stages of maturation.

The metaphysis of the trochlea is sclerosing, indicat-
ing that the epiphysis will soon ossify.

Figure 5.9: 'Low normal' male 8.5 years (Brodeur *et al.*, 1981).

Low Normal-Male   **10½ years**

The double curve on the lateral side of the lower
humerus formed by the lateral epicondyle and the
capitellum in Figure 43C gives a characteristic No. 3
appearance. Once the lateral epicondyle has fused,
the lateral side has a gentle, sloping edge. The epi-
physes for the olecranon and trochlea have not yet
ossified, but their metaphyses are well developed,
showing that ossification is not far off.

Figure 5.10 'Low normal' male 10.5 years (Brodeur *et al.*, 1981).

3½ years   **Male-High Normal**

15A

15B

The capitellum is almost beyond the hemispheric stage. There is very early ossification of the epiphysis of the radial head. This usually occurs at age 5 years, and its presence indicates a high normal for 3½ years.

Figure 5.11: 'High Normal' Male 3.5 years including the written description for the image (Brodeur *et al.*, 1981).

The image labelled as MLE60 (Fig 5.13) was identified as falling between the two images of 'High Normal 3.5 years' (Fig 5.11) and 'Low Normal 7 years' (Fig 5.12) due to the depth of the olecranon fossa which whilst not reproduced well in this image, is described as shallow. The development of the capitulum is similar for both images but there is no ossification of the medial epicondyle evident, although the metaphyseal edge is straight indicating that it will occur soon.

Low Normal-Male   **7 years**

29C

29D
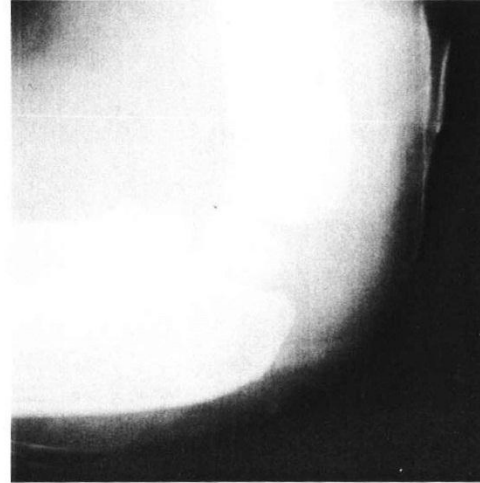
The capitellum is well developed. The sharp meta-
physeal edges for the medial epicondylar epiphysis
and the radius are indications that ossification will
begin soon in their respective epiphyseal centers.

Figure 5.12: 'High Normal' Male 7.5 years including the written description (Brodeur *et al.* 1981).

Figure 5.13: Image of left elbow of male identified as MLE50. Chronological age 5 years 10 months (70 months). Estimated age range using the Brodeur *et al.* (1981) atlas method 3.5-7 years (42-84 months).

5.6 Test of the Sauvegrain method of age estimation

The second age estimation method to be tested was the Sauvegrain method of age estimation. This method was developed for use on children who are undergoing pubertal growth spurt (Dimeglio *et al.*, 2005; Sauvegrain *et al.*, 1962). Dimeglio *et al.* (2005) suggest that the method is limited to children aged between 11 and 13 years of skeletal age in females and between 12 and 15 years of skeletal age in males.

5.7 Methods and materials for the test of the Sauvegrain method

For the purposes of this test the age ranges were extended to allow for individual variation in the initiation of the pubertal growth spurt. The ages of those tested ranged from 8 to 15 chronological years for females and between 9 and 16 chronological years of age for males. The Sauvegrain method uses both an anterior-posterior radiograph and the lateral radiograph so only those individuals for whom both views had been collected were included in the assessment. Unlike the age estimation methods based solely upon a comparison of morphological change it was necessary to view both radiographs so if one was not available this limited the ability to assign a score and ultimately a skeletal age. In total the radiographs for 279 individuals were tested, 130 females and 149 males.

The radiographs were assessed using a revised version of the Sauvegrain method published by Dimeglio *et al.* (2005). The Sauvegrain method is a

scoring system which relies on the analysis of four anatomical areas of the elbow. The maximum total score that can be achieved is 27 relating to complete maturity which in turn is allocated to 13 chronological years of age in females and 15 years of age in males. The revised scoring method of Dimeglio *et al.* (2005) increases the number of increments within the scoring system which the authors argue increases the sensitivity of the method. Once the four areas of the elbow have been assigned scores, these are added together to give a total which is referred to a graph to establish the chronological age. It is not possible to assign an age to an individual whose cumulative score is less than 9 which is related to a skeletal age of 9 years of age for females and 10 years of age for males.

Inter and intra observer error was tested by reassessing the radiographs of 40 randomly selected individuals (20 female and 20 male). These were re-tested under the same circumstances as the first test with all information obscured apart from the sex of the individual.

5.8 The Sauvegrain method

The Sauvegrain method is a scoring method. The scoring method requires the use of both radiographic views. The images used are the same as those used in the test of the Broduer *et al.,* (1981) method.

5.9 Inter and intra-observer test

Inter- and intra-observer results for the Sauvegrain method were tested on a random selection of images of 40 individuals; 20 female and 20 male. Mann-

Whitney U tests were used to assess the repeatability of the method (Table 5.9).

Sex and Observer Test	P-value	Result
Female inter-observer	P=0.771	Not statistically significant
Male inter-observer	P=0.512	Not statistically significant
Female intra-observer	P=0.668	Not statistically significant
Male intra-observer	P=0.715	Not statistically significant

Table 5.9: Results of Mann-Whitney U tests for inter- and intra-observer tests.

The inter- and intra-observer results show that this method has a high degree of repeatability.

5.10 Results for the test of the Sauvegrain method

The analyses were completed and all of the ages were changed to months to facilitate statistical analysis. There were a number of individuals for whom the cumulative score was not sufficient to assign an age (that is the score was less than 9). In the female set this consisted of 7 (6.4%) individuals; 6 from the 8 year old age group and one from the 9 year old age group. In the male set there were 22 (16.2%) individuals whose score was not sufficient to assign an age (the score was less than 9); 10 individuals from the 9 year old age group, 11 individuals from the 10 year old age group and one individual from the 11 year old age group. These were left out of further analysis. In the female group, the maximum possible chronological age was 13 years. For the upper age ranges, there were two individuals in the 14 year age group whose skeletal age was assessed as below 13 years of age, so the 14 year old age group were included in the final analysis. There were no individuals whose estimated age

fell below the maximum possible assigned age of 13 years of age within the 15

year age group (n=13) and therefore these were omitted from the final statistical

analysis. For the males, there were 4 individuals in the 16 year old age group

whose age was assessed as below 15 years of age and therefore the 16 year

old age group were included in the final statistical analysis (Table 5.10).

Sex	Total	Number with insufficient scores (less than 9)	Total with scores which were sufficient to assign an age
Female	108	7	101
Male	137	22	115

Table 5.10: Total number of images available for analysis by sex.

The chronological age and estimated age using the Dimeglio *et al.* (2005)

version of the Sauvegrain *et al.* method (1962) was subject to linear regression

analysis for both of the sexes (Table 5.11). This indicated that the R^2 value for

both sexes was high, for females $R^2=0.716$ and for males $R^2=0.718$, both of

these were statistically significant (p<0.001).

Sex	Regression Coefficient	R value	R^2-value	p-value
Female left elbow	0.551	0.846	0.716	<0.001
Male left elbow	0.533	0.848	0.718	<0.001

Table 5.11: The regression coefficients, R values, R^2 values and p-values for each sex for the Sauvegrain method.

The relationship between chronological age and estimated age was further

tested using a Mann-Whitney U test. For both females and males the results

show that the difference between the chronological age and estimated age were
not statistically significant (Table 5.12).

Sex	Results of Mann-Whitney U test	Meaning
Female	P=0.870	Not statistically significant
Male	P=0.191	Not statistically significant

Table 5.12: Results of Mann-Whitney U test for females and males for the Sauvegrain method.

The differences between the estimated age and chronological age were
calculated by subtracting the chronological age from the estimated age. A
negative result indicated that the estimated age was less than the chronological
age indicating that the individual was underaged and a positive result indicated
that the estimated age was more than the chronological age indicating that the
individual was overaged. The maximum, minimum and mean of the differences
between the chronological age and estimated age for each group are seen in
Table 5.13. The maximum overage for females is 27 months (2 years 3
months) and the maximum underage is 26 months (2 years 2 months). For
males the maximum overage is 35 months (2 years 11 months), the maximum
underage is similar to that seen in the female group at 23 months (1 year 11
months).

Sex	Maximum overage and maximum underage (months)	Mean difference (months)	Standard deviation (months)	Standard error (months)	Confidence interval (months)
Female left elbow	Max overage 27 Max underage 26	-0.31	11.45	1.15	2.27
Male left elbow	Max overage 35 Max underage 23	-3.11	13.48	1.26	2.49

Table 5.13: Mean differences between chronological age and estimated age for the complete dataset by sex. Standard deviation, standard error, confidence interval of the mean and the maximum over and under-estimation of age observed within the groups.

Each group was broken down into age groups to assess how the differences between chronological age and estimated age change during the maturation process. The results of this can be seen in Table 5.14. For females the mean difference reduces as the age groups get older from 8 years of age to 11 years of age, after 12 years of age all of the differences are negative indicating a mean underage in these groups. For males the mean differences also reduce as the age groups get older until the 14 year old age group. The means differences in both the 15 year group and the16 year group are negative indicating that the tendency is to underage in these groups.

Age group	Mean difference between chronological age and estimated age for females (months)	Mean difference between chronological age and estimated age for males (months)
8 years	17 (n=5)	N/A
9 years	11 (n=20)	20.67 (n=6)
10 years	-0.1 (n=19)	13.86 (n=7)
11 years	0.56 (n=18)	11.62 (n=16)
12 years	-3.82 (n=17)	12.77 (n=17)
13 years	-10.47 (n=15)	4.41 (n=22)
14 years	-8.71 (n=7)	1.68 (n=19)
15 years	N/A	-8.85 (n=13)
16 years	N/A	-18.67 (n=15)

Table 5.14: Mean differences between chronological age and estimated age for females and males by year group.

5.11 Discussion

The Sauvegrain method was developed for use in children who were undergoing the pubertal growth spurt. The decision to test this refined method was primarily based on the fact that this variation was tested and developed on a relatively recent population, which should make it more accurate and appropriate when applied to another modern population, avoiding problems associated with secular change (Cole, 2000; Roberts, 1994; Zhang and Wang, 2009). Previous studies have found that the method has a high degree of accuracy within a defined age range (Canavese *et al.*, 2008; Chaumoitre *et al.*, 2006; Dimeglio *et al.*, 2005; Hans *et al.*, 2008).

In this study the method shows a similar degree of accuracy for both females and males indicating that for this Scottish population the method is a potentially viable alternative to the use of the Brodeur *et al.* atlas (1981). The differences between the chronological age and estimated age for each age group show a pattern of decreasing difference with increasing age. The mean difference is significantly larger in the younger age groups and again in the oldest of the groups, especially in the male group. The smallest mean differences for females are found in the 10, 11 and 12 year old groups and for males the smallest mean differences are found in the 13 and 14 year age groups. This pattern is consistent with the difference in maturational timings which are found between females and males in this case the males are experiencing the same maturational milestones about 2 years later than the females, creating a situation where the age estimation method is more accurate for year cohorts at later chronological ages. The greater accuracy in the central groups compared to the older and younger groups tested could be explained by the design of the age estimation method which was intended to be used on children who were actively going through the pubertal growth spurt.

The standard deviations from the test of the Sauvegrain method are 11.45 months for the female group and 13.48 months for the male group. Thus the estimated age of 68.27% of all the children tested using this method were found within a spread of 11.45 months from their chronological age for females and 13.48 months for males. It is suggested that any age estimation should be given as an age range which includes 2 standard deviations. This would account for 95% of children who exhibit normal variation seen in the skeletal maturation process. The large size of the mean differences between estimated age and chronological age that are seen in the younger groups, the 8-9 year old

female cohorts and the 9, 10, 11 and 12 year old male cohorts would argue against this being used for anyone in these age groups, it is conceivable that there were a large number of individuals who had not begun to experience the pubertal growth spurt and this affected the results. It was not possible to know if someone had begun their growth spurt due to the cross-sectional method of data collection. It might therefore be appropriate to use this age estimation method on individuals in these age groups if it is known that the individual has begun their growth spurt. This method was designed to be appropriate for use on children during a very short space of time developmentally and this is demonstrated clearly in the results of the test. The use of this method for forensic age estimation should be limited to individuals who are strongly suspected of being between 10 and 14 years of age if female and between 13 and 14 years of age if male. For both sexes this method should not be used if the individual is suspected of being 15 years or over and if suspected of being younger the method should be combined with the Brodeur *et al* atlas (1981) method or an alternative method used.

Both of these age estimation methods show a high degree of accuracy and repeatability. Ossification and fusion is complete by 16 years of age in females and 17 years of age in males which limits the usefulness of this skeletal area in individuals whose age is expected to be 18 years of age or over, and the utility of the Sauvegrain method is further reduced by being restricted to the pubertal age groups for both sexes. For children whose age does fall into these age ranges both the Brodeur *et al.* atlas (1981) method and the Sauvegrain method (1962) are a viable alternative to the use of more traditional skeletal areas.

5.12 The use of the Sauvegrain method (Demiglio *et al* 2005)

The Sauvegrain method relies on the comparison of a radiograph to the line drawings seen in Fig 5.14. The stages of development for each area are assigned a score (Figure 5.15 and Table 5.15). Once all the areas are assessed the scores are added up and the final score is compared to the graph seen in Figure 5.16 where scores are related to chronological age.
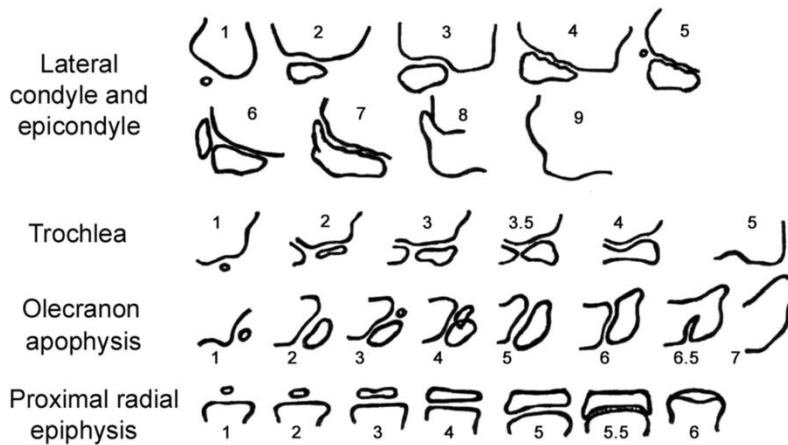
Figure 5.14: Standard and relevant scores (Demiglio *et al.* 2005).

Figure 5.15: Left male elbow identified as MLE113. Age estimation 13.5 years (158 months) using the Sauvegrain method, Chronological age 11 years 7 months (139 months).

The image of MLE113 (Figure 5.15) was assigned scores (Table 5.15). These scores were inserted into the approriate graph (Figure 5.16) and converted to a skeletal age.

Area	Score	
Lateral condyle and epicondyle	7	
Trochlea	3.5	
Olecranon apophysis	4	
Proximal radial epiphysis	4	
Total	18.5	158 months

Table 5.15: Area and score for image MLE113.
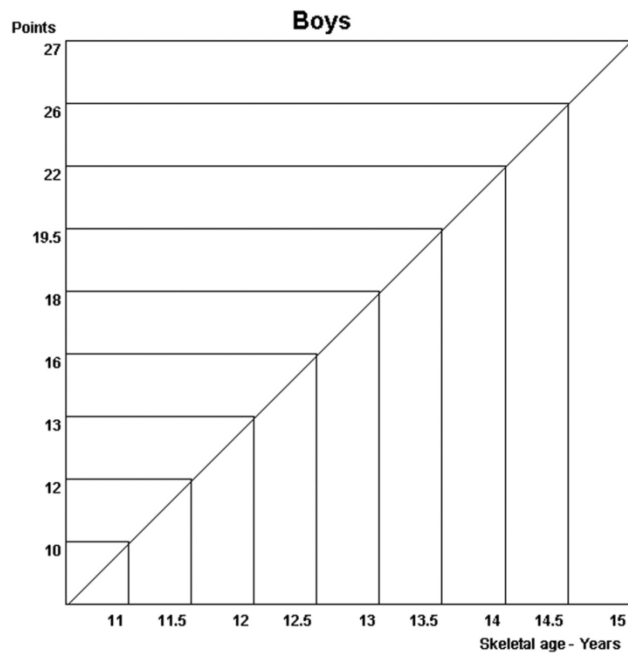
Figure 5.16: Graph for boys (Demiglio *et al.,* 2005)

The Sauvegrain method (1962) is a straightforward scoring method which was easy to use as long as both radiographic views were available. There are two problems with this method, the greatest problem is the limited age group for which it has been designed. The method was developed as a way of assessing skeletal development in children who were experiencing puberty, but due to variation that exists between individuals this can cause problems in age estimation of late developers who may fall into the appropriate chronological age range but are not undergoing the skeletal changes associated with puberty. Secondly, however the method is hampered by the small age range which creates a graph in which small divisions of age are not easily estimated.

6 The Knee

There is an increasing need for anthropological methods to be validated on modern populations (Ritz-Timme *et al.*, 2000). This requirement has been given added impetus in the UK by the recent Law Commission Report (2011) which in turn was driven by a number of miscarriages of justice, largely brought about by failures in expert testimony. Age estimation techniques have already been subject to scrutiny in the International Criminal Court after the genocides in Bosnia and Kosova where judiciary questioned their relevance and accuracy when applied to a population other than the one on which they were developed (Kimmerle *et al.*, 2008). This should be treated as a warning to those who prepare forensic reports for the court.

Methodologies which have been developed for age estimation from radiographs of the knee such as the knee atlas of Pyle and Hoerr (1969) require testing on a modern population.   Currently age estimation utilising radiographs of the left hand-wrist and medial clavicles are recommended for use in forensic age estimation of the living (Schmeling *et al.*, 2008; Schmeling *et al.*, 2001) as a result, age estimation utilising these two areas has come under increasing scrutiny. There are on-going objections to the use of radiographs for age estimation in the UK and as a result there is an understandable reluctance to undertake radiographic imaging for the sole purpose of estimating age (RCPCH, 2007). As a result of this, it is entirely possible that existing radiographs of body areas other than those commonly used such as the left hand wrist may be employed in a forensic situation. If this does become the

case, an understanding of the accuracy of these methods is of paramount importance if the estimation of age is to be sufficiently robust to withstand close judicial scrutiny.

Radiographic data on the development of the knee had been collected during a number of longitudinal studies. This has resulted in a number of reference standards which can be used in age estimation (Acheson, 1957; Pyle and Hoerr, 1969; Roche *et al.*, 1976) and all are based on the assessment of radiographs. Both the Acheson (1957) and Roche *et al.* (1976) methods utilise scoring systems in which numerical scores are applied to maturity indicators according to their appearance and morphology. Of these, the Acheson method (1957) is simpler in design than the Roche *et al.* (1976) method which scores between 17 and 24 maturity indicators and requires a computer programme to calculate probable age. The third of these methods is the Pyle and Hoerr atlas (1969). The atlas method differs from that presented in the previous two approaches since it is not based upon a scoring system but is based on finding the best match between the radiographic image of the individual and the series of radiographs displayed in the atlas.

This section examines the accuracy of estimating chronological age when undertaken on a modern Scottish population using the Pyle and Hoerr (1969) knee atlas. This atlas was developed from data collected during the Cleveland Study which ran in North America from its initiation in 1926. The longitudinal study into child growth involved the collection of anthropometric data and radiographs from birth through to 21 years of age. In total the data of 4483 children formed the dataset which was also enhanced by radiographs of children collected in Boston by Dr Harold C. Stuart (Pyle and Hoerr, 1969). Radiographs of identified body areas were taken at regular intervals from 3

months of age throughout adolescence.   Supplementary radiographs from Boston addressed the period from birth to 3 months of age when the radiographic imaging began in the Cleveland study (Pyle and Hoerr, 1969).

The atlas was designed by placing the knee radiographs in chronological age order. This enabled the authors to identify maturity indicators allowing the process of skeletal maturation to be tracked and skeletal age to be assigned. The authors chose the radiographs which were most representative of each identified skeletal age and arranged them into the age progressive atlas. The authors recognised the differences between developmental timing in males and females but, unlike other atlases presented only one common series of radiographs. Each radiograph was assigned two skeletal ages, one for males and one for females. The authors reasoned that the process of maturational change and the order of appearance of maturational indicators were the same for males and females. The differences which existed between the two sexes were thus based solely on the timing of these changes rather than the order in which they occurred.

As with other atlases, the use of the Pyle and Hoerr (1969) approach to assessing chronological age raises a number of methodological issues. The data which formed the basis of the atlas was collected from children who were growing to adulthood in the first decades of the 20th century and were described by the authors as being white children of high socioeconomic class. Additionally the children were deliberately chosen for their good health and nutritional status (Behrents and Broadbent, 1984). This background, both socioeconomically and ethnically is very different from that of children being age estimated for forensic purposes today. Maturational rate is known to depend on a large number of factors not least of which are the nutritional intake and the

health status of the individual (Tanner, 1962). The Cleveland population formed

the basis of the widely utilised Greulich and Pyle atlas of the hand-wrist

(Greulich and Pyle, 1959). Subsequent studies of the hand-wrist atlas have

shown the importance of understanding the relationship between the standard

presented in the atlas and the population from which the individual to be age

estimated originates (Büken *et al.*, 2007; Calfee *et al.*, 2010; Schmidt *et al.*,

2008b; Zafar *et al.*, 2010). Whilst the knee atlas has not been tested so

extensively, the data was derived from the same children and therefore the

potential remains for the atlas to demonstrate the same inbuilt difference in

developmental timing which is demonstrated by the hand-wrist atlas. The

applicability of an age estimation method which was developed on a population

potentially so far removed from a modern population must be tested robustly if it

is to be used and accepted for forensic purposes.

6.1 Methods and Materials

Ethical approval was granted by Ninewells Hospital, Dundee for collection of

radiographic images of left knees. Images were collected from children aged

between birth and 21 years of age. The images had been taken during the

process of examination for potential injury when the individual had attended at

the Accident and Emergency department. The only information collected was

the sex of the individual, the date of birth and the date that the image was

taken. The atlas consists of both lateral and anterior-posterior images of left

knees and the collection of images reflected this (Figure 6.1). In total the

radiographs of 523 individuals were collected, this total consisted of the knee

radiographs of 228 females and 295 males. Each individual was screened for

the presence of pathology or previous trauma which might affect growth and if these were present the images were excluded.

Figure 6.1: Anterior-posterior image (on left) and lateral image (on right) of male left knee identified as 'MLH11'. Chronological age 5 years 5 months, Estimated age using the Pyle and Hoerr (1969) atlas, 5 years.

The spread of the data across the age groups is presented in Table 6.1 and Figure 6.2. It can be seen that there are relatively few individuals in the younger age groups which is an inevitable consequence of the data collection methodology since these age groups are less likely to injure their lower limbs and therefore require radiographic imaging of this region.

The chronological age of the individual was calculated by calculating the difference between date of the image and the date of birth. The analysis for

each sex was undertaken separately taking into consideration the differences in the timing in development between males and females (Pryor, 1923).

Chronological age was removed from the image and age estimation of each set of images was undertaken for each sex separately using the Pyle and Hoerr atlas (1969). The resulting estimated ages were converted to months for ease of statistical analysis. Inter observer and intra observer accuracy were tested using a randomly chosen subset of 30 female images and 30 male images which were retested by the first author after a period of 3 months from the first analysis and by a second observer who had some experience with radiographic analysis but had not used the Pyle and Hoerr atlas (1969) previously.

Age in years	Female left knee	Male left knee	Total
1	5	0	5
2	1	2	3
3	5	1	6
4	1	6	7
5	4	5	9
6	2	8	10
7	9	6	15
8	5	12	17
9	3	17	20
10	13	19	32
11	22	22	44
12	16	21	37
13	22	21	43
14	19	31	50
15	21	27	48
16	20	22	42
17	20	19	39
18	18	15	33
19	10	20	30
20	12	21	33
Total	228	295	523

Table 6.1: Distribution of images by sex for female and male left knee radiographs.
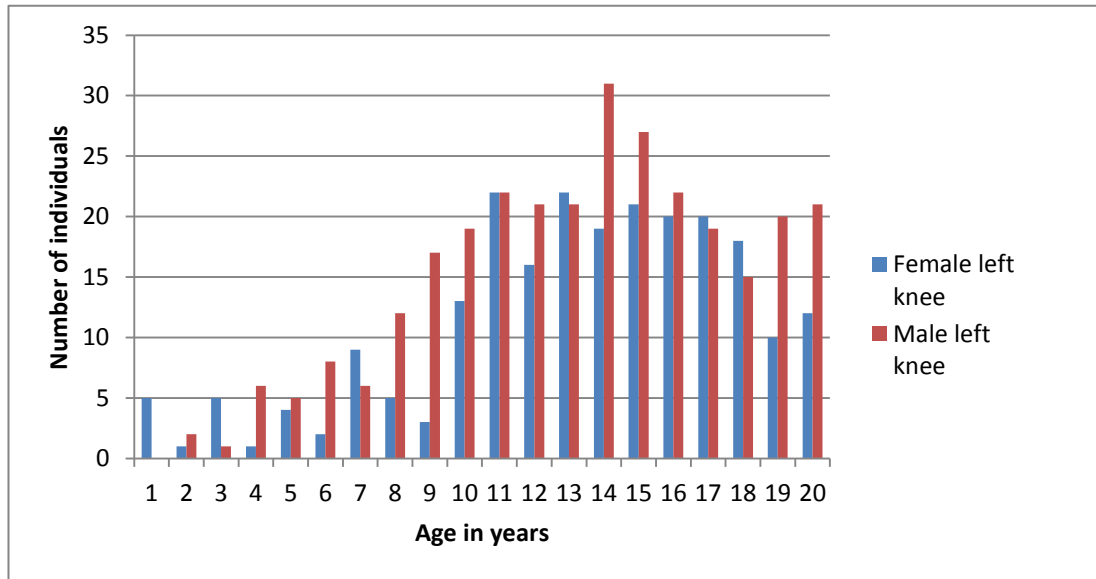
Figure 6.2: Distribution of images by sex and age for left knee radiographs.

6.2 Inter and intra-observer tests

Inter and intra observer tests were undertaken separately for the radiographs of female and male knees. The second round of age estimation was undertaken 3 months after the first round and on both occasions the chronological age was obscured. For both sexes the differences between the two sets of age estimation were not significant (Table 6.2).

Sex	P value	Significance
Female inter-observer test	P=0.756	Not statistically significant
Male inter-observer test	P=0.937	Not statistically significant
Female intra-observer test	P=0.876	Not statistically significant
Male intra-observer test	P=0.993	Not statistically significant

Table 6.2: Results of t-test for inter and intra observer tests for the left knee analysis.

Results

The final plate in the Pyle and Hoerr atlas (1969) is assigned the female skeletal age of '*at least 16 years*' and for males the skeletal age of '*at least 19 years'*. The dataset which was collected from Ninewells Hospital consisted of the images of females from birth to 21 years of age. Initially the full age range of images was examined. This confirmed that there were no female individuals still undergoing maturational changes after the age of 16 years. Therefore the 60 females in the age ranges 17-21 years were removed from further analysis. For males there were no individuals who were undergoing maturational changes after the age of 19 years and therefore the 21 male images over the age of 20 were removed from further analysis. The final numbers for analysis were therefore 168 images of female knees and 274 images of male knees.

The chronological age and estimated age using the Pyle and Hoerr atlas method (1969) was subject to linear regression analysis for each of the sexes (Table 6.3, Figures 6.3 and 6.4). These showed high values for both the R and the R^2 value for both sexes, for females R=0.977 and R^2= 0.954 and for males R= 0.976 and R^2=0.952, both of these were statistically significant ($p<0.001$).

Sex	Regression coefficient	R value	R^2 value	P-value
Female Left Knee	0.968	0.977	0.954	<0.001
Male Left Knee	0.983	0.976	0.952	<0.001

Table 6.3: Regression Coefficients, R values and R^2 values by sex for the left knee analysis.
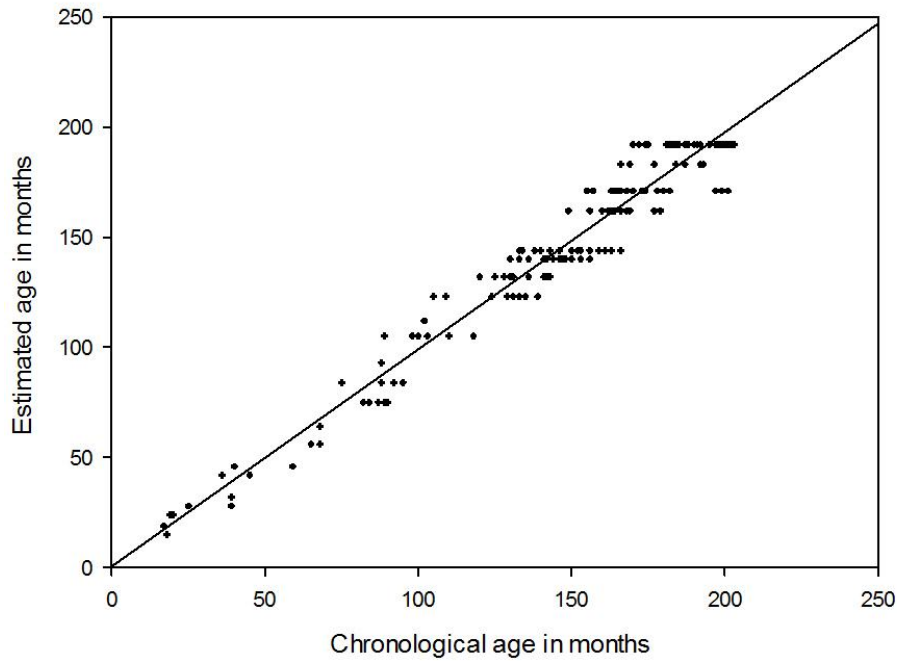
Figure 6.3: Linear regression between chronological age (CA) and estimated age (EA) for female individuals using the knee atlas method (*EA = 6.11 + (09.68 x CA)*).
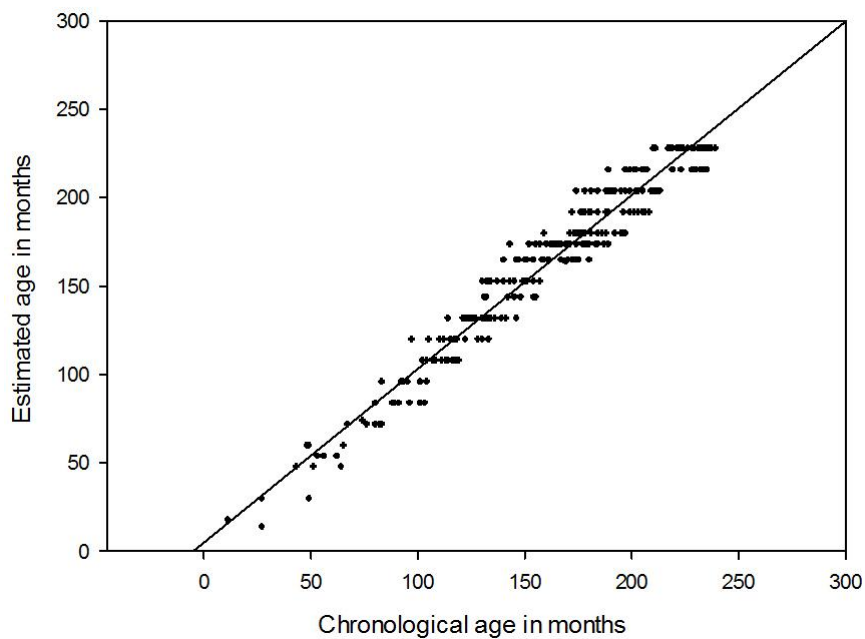
Figure 6.4: Linear regression between chronological age (CA) and estimated age (EA) for male individuals using the knee atlas method (*EA = 4.911 + (0.983 x CA)*).

The relationship between the chronological age and estimated age was further tested by subjecting it to a Mann-Whitney U test. For both females and males the difference between chronological age and estimated age was not significant (Table 6.4).

Sex	Mann-Whitney
Female left knee	P=0.725
Male left knee	P=0.521

Table 6.4: Results of the Mann-Whitney U test for each sex for chronological age and estimated age for the left knee analysis.

The differences between chronological age and estimated age were calculated by subtracting chronological age from estimated age. A positive result therefore indicated an overage utilising the atlas method and a negative result indicated an underage by the atlas method.

The mean difference between the chronological ages and estimated ages were calculated by sex (Table 6.5). The overall mean difference for females was -1.6 months and for males was 2.16 months. The actual range is demonstrated by the largest overage and the largest underage for each group. The largest overage for females was 22 months (1 year 10 months) and for males was 31 months (2 years 7 months). The greatest underage for female was 30 months (2 years 6 months) and for males was 19 months (1 year 11 months).

	Mean difference (months)	Maximum overage and maximum underage (months)	Standard deviation (months)	Standard error (months)	Confidence interval (months)
Female left knee	-1.6	22.00 -30.00	9.86	0.76	1.50
Male left knee	2.16	31.00 -19.00	10.75	0.65	1.28

Table 6.5: Mean differences between chronological age and estimated age for the complete dataset by sex. Standard deviation, standard error, confidence interval of the mean and the maximum over and under-estimation of age observed within the groups.

Each group was broken down into year cohorts and the mean of the differences between chronological age and estimated age was calculated to establish the presence of a pattern which might exist between the estimated age as calculated by the Pyle and Hoerr atlas method (1969) and the chronological age in this population. The results are presented in Table 6.6. For females the maximum underage was 13 months in the 4 year old category, although there was only one individual in this group. Of the other age categories the means ranged from -9.75 months at 16 years of age to 8.4 months at 8 years of age. The cohorts between 9 years of age and 15 years of age showed a smaller range, extending between -2.81 months at 12 years of age and 2.38 months at 10 years of age. For males the means ranged between -9.6 months at 19 years of age and 8.81 months at 13 years of age. In addition all of the means for the male groups between the ages of 9 years and 16 years were positive, ranging between 0.14 months at 16 years of age to 8.81months at 13 years of age.

The female mean difference at 8 years of age is 8.4 months and the male mean difference at 11 years of age is 7.54 months, these represent a similar peak in over-aging by the atlas method for both sexes, although separated by 3 years. A similar spike in under-aging is seen between females at 16 years of age (-

9.75 months) and males at 19 years of age (-9.6 months). The spread of the differences between estimated age and chronological age are presented as a box plot by sex (Figure 6.5 and Figure 6.6). These plots demonstrate the spread of the data for each year cohort and the spread between the 25th and 75th percentiles and 10th and 90th percentiles. The dots on the graph indicate the position of the outliers for each year which show the full potential range of individuals. The size of the group influences whether or not the percentiles can be calculated and therefore for the smaller groups (female 1-6 years and males 1-6 years) this data is missing due to the limited numbers in these groups.

Year group	Female- mean difference in months	Male- mean difference in months
1	1.00 (n=5)	N/A
2	3.00 (n=1)	-5.00 (n=2)
3	-1.80 (n=5)	5.00 (n=1)
4	-13.00 (n=1)	0.00 (n=6)
5	-9.25 (n=4)	-3.80 (n=5)
6	1.00 (n=2)	-2.5 (n=8)
7	-5.78 (n=9)	-1.33 (n=6)
8	8.40 (n=5)	-0.42 (n=12)
9	-1.33 (n=3)	0.53 (n=17)
10	2.38 (n=13)	5.58 (n=19)
11	-1.04 (n=22)	7.54 (n=22)
12	-2.81 (n=16)	5.05 (n=21)
13	-2.27 (n=22)	8.81 (n=21)
14	2.26 (n=19)	4.23 (n=31)
15	1.57 (n=21)	3.44 (n=27)
16	-9.75 (n=20)	0.14 (n=22)
17	N/A	-1.89 (n=19)
18	N/A	4.80 (n=15)
19	N/A	-9.6 (n=20)

Table 6.6: Mean of differences between chronological age and estimated age by year cohorts for females and males.
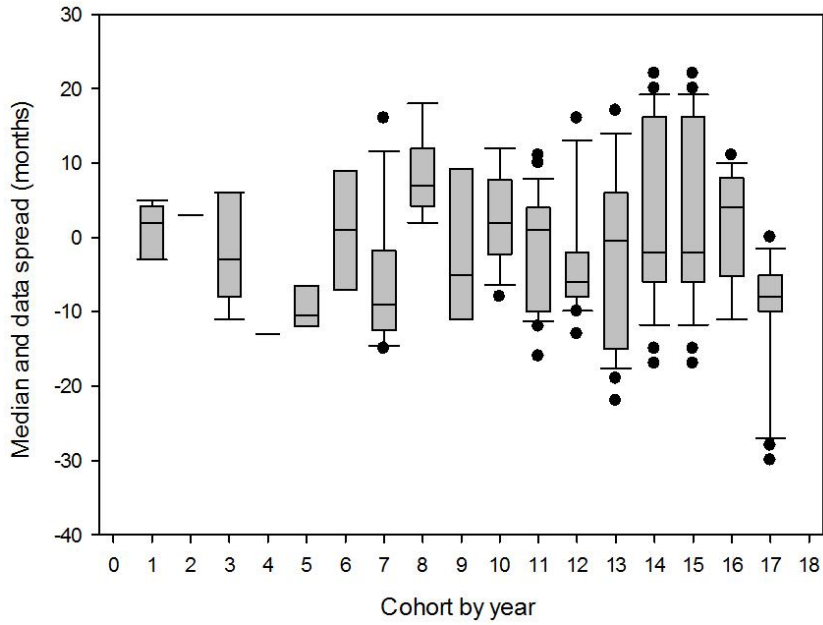
Figure 6.5: Showing the median (line within the box) 25th and 75th percentiles (lower and upper limits of box), 10th and 90th percentiles (lower and upper bars) for female data.
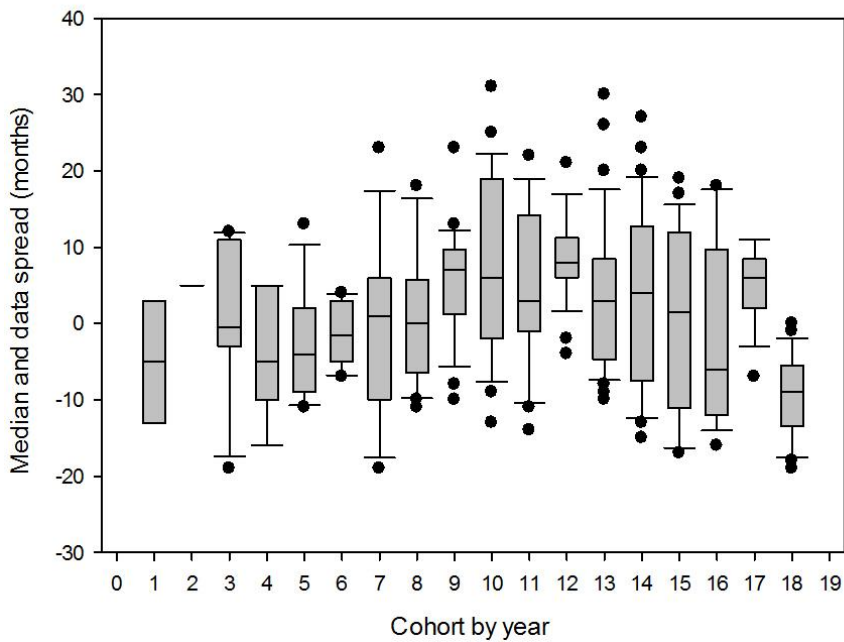
Figure 6.6: Showing the median (line within the box) 25th and 75th percentiles (lower and upper limits of box), 10th and 90th percentiles (lower and upper bars) for male data.

6.3 Discussion

The relationship between maturational stages of the knee and chronological age has been examined by a number of authors (Acheson, 1957; Gentili *et al.*, 1984; O'Connor *et al.*, 2008; Pyle and Hoerr, 1969; Roche *et al.*, 1976). All of the methods rely on the use of imaging technologies to visualise the osteological changes which occur as the individual develops. Some of these methods have undergone testing on alternate populations (Vignolo *et al.*, 1990; Xi and Roche, 1990) whilst others are still to be tested or are population specific (O'Connor *et al.*, 2008). With the potential demands on the standards for forensic evidence which the Law Commission Report (2011) heralds, and the increasing concern about the use of radiographic imaging purely for age estimation purposes, the use of radiographs of the knee in forensic situations could well be held up to scrutiny in a court of law. Ethically it is no longer possible to repeat the collection of longitudinal data which have allowed the creation of maturational atlases in the past. It is necessary therefore to re-examine the methods which are already available to understand whether they continue to be of sufficient accuracy when utilised for the purposes of age estimation of members of a modern population.

The relationship between chronological age and estimated age which was undertaken using the Pyle and Hoerr atlas (1969) presented similarly high R^2 values for both sexes indicating that the relationship between chronological age and estimated age was strong for both sexes. The overall mean difference between chronological age and estimated age for the groups was small, with an average underage for females (-1.6 months) and an average overage for males (2.16 months).

The examination of year cohorts revealed a different relationship between chronological age and estimated age for females and males. For females there was a mixture of over and under aging throughout the series, but the age groups from birth to 8 years show a wide range of means of between 8.4 months and -9.25 months, excluding the 4 year cohort which contained only one individual or between 13.0 months and -9.25 months if this cohort was included. This pattern changed between the ages of 9 and 15 years where the range was more limited, ranging between -2.81 months and 2.38 months. Figure 6.5 demonstrates that in the age cohorts from 9 years onwards there is an increasing number of individuals who lie at the extremes of the expected ranges, this would be expected in these age ranges due to individual differences in the timing of the pubertal growth spurt. The male group demonstrated a different pattern. Prior to the age of 9 years the mean difference between chronological age and estimated age ranged from -5 months to 5 months if the 3 year cohort is taken into account, although this group contains only one individual, so care should be taken when including this in the analysis. Without the 3 year individual, the range is between 0 months and -5 months with a tendency to underage demonstrated throughout the cohorts from 2 years to 8 years of age. After the age of 9 years the range spreads from 0.14 months to 8.81 months, showing a tendency for the atlas to overage throughout this adolescent period.   Figure 6.6 shows that from the age of 3 onwards, individuals whose development lies at the edge of expected age ranges can be found. There is however and increase in the numbers of these individuals in the over 9 year old age cohorts, tying in with the different growth velocities experienced by individuals during puberty.

The underage which is seen in females at 16 years and males at 19 years of age coincides with the completion of maturity indicated by the atlas for each sex. This 3 year separation between the timing of maturational changes amongst the sexes can also be seen between the age of 8 years for females and 11 years for males where an overage is experienced which is similar in size for both sexes. It is unclear what might be responsible for this overage, but it may coincide with the beginning of the pubertal growth spurt for each sex. It may be that this peak represents a real difference between developmental timings in the Cleveland population compared to the Scottish sample examined or simply this may be product of the organisational system for the atlas as discussed below (Table 6.7).

Plate	Female Skeletal Age	Male Skeletal Age
20	93 months	120 months
21	105 months	132 months
22	112 months	144 months

Table 6.7: Plates 20-22 and the 'skeletal ages' assigned to them within the Pyle and Hoerr atlas.

Plate 20 (Fig 6.7) relates to a female 'skeletal age' of 93 months (7 years 9 months) however none of the 8 year old cohort in the Scottish sample was assessed as resembling this plate. The remaining individuals in this age group were assessed as older, either plate 21 (Fig 6.7) or plate 22 (Fig 6.8). For males the majority (12) of 11 year olds were assessed as resembling plate 22 or older, 9 were assessed as resembling plate 21 and one was assessed as resembling plate 20. Plate 21 corresponds to a female of skeletal age 132 months (11years) and a male of 'skeletal age' 105 months (8 years 9 months). Plate 22 relates to a female 'skeletal age' 112 months (9 years 4 months) and a

male 'skeletal age' of 144 months (12 years). One of the maturity indicators which is manifest on this plate shows evidence of ossification of the '*distal extent of the tibial tuberosity'* (Pyle and Hoerr, 1969). Of the radiographs which were given a probable age of 112 months or older for females or 144 months or older for males the majority (71%) showed evidence of ossification of the tibial tuberosity which indicated that there was a high probability that this maturity indicator played an important role in over-aging these groups for both females and males. Additionally for females, 105 months relates to 8 years 9 months of age which is skewed to the upper end of the age range.

Figure 6.7: Plate 20 (left) and Plate 21 (right) reproduced from the Pyle and Hoerr atlas (1969).

Figure 6.8: Plate 21 reproduced from the Pyle and Hoerr atlas (1969).

Whilst the figures given in Table 6.6 represent the mean of the differences it is necessary to be aware of the full potential range of differences between the estimated age and chronological age. From Figure 6.5 and Figure 6.6 the ranges for the different centiles around the median can be seen. The widest ranges for females are seen to fall between 10 and 16 years of age which coincides with the adolescent growth spurt, a time in which the maximum difference in the timing of growth and maturational changes can be seen between individuals. The spread is not as great for the other cohorts indicating that for females the atlas is more reliable when used on younger pre-pubertal individuals. For the male cohorts the larger ranges extend beyond the expected timings for the adolescent growth spurt, they fall in the 7 to 17 year cohorts. This indicates that the variation between individuals and age estimated by this atlas method is greater for a longer period of time in males compared to females. This is reflected in the greater standard deviation seen in the male cohort.

The full range between the maximum over age and maximum underage for females in this study was 52 months (4 years 4 months) and for males was 50 months (4 years 2 months). This range is very similar for both groups. The female maximum overage of 22 months was found in the 14 year age group where it may be explained by the differences in timing and speed of the adolescent growth spurt between individuals (Tanner, 1962). The maximum female underage of -22 months was found in the 16 year age group, this coincided with a large number of individuals completing the growth and maturation process. For males the maximum overage of 31 months was found in the 11 year old cohort, this coincides with the beginning of the male adolescent growth spurt and is indicative of the differences in timing of this growth spurt between individuals (Tanner, 1962). The maximum male underage of 19 months was found in a number of groups, one in the 4 year old group, one in the 8 year old group and one in the 19 year old group. This maximum underage is the only one which falls within 2 standard deviations of the mean as indicated by this test of the Pyle and Hoerr method (Table 6.7) and therefore these individuals would be included in any age range given to two standard deviations.

The authors of the Pyle and Hoerr atlas (1969) did not present any indications of standard deviations for their method. When presenting age estimation for forensic purposes it is necessary to be able to present the range and the standard deviations which are inherent in the analysis. The standard deviations for females and males are similar in this analysis, 9.86 months for females and 10.75 months for males.   Any estimation of age given to two standard

deviations would allow for the majority of individual variation since it would include 95% of children from this population who were aged using this method. Greulich and Pyle (1959) argue that any age range which included two standard deviations would therefore cover the majority of children who were developing normally.

The development of the knee and its relationship to age has a long history. The femur and tibia have been utilised in age estimation both in relation to their length (Maresh and Deming, 1939) and in relation to the appearance, change in morphology and fusion of their ossification centres (Gentili *et al.,* 1984; O'Connor *et al.*, 2008; Roche *et al.*, 1976; Vignolo *et al.*, 1990). The maturity indicators of the knee have been utilised as an adjunct to other body areas in studies that measure the maturational development of children or young adults within specified populations (Das Gupta *et al.*, 1974; McKern and Stewart, 1957; Saksena and Vyas, 1969; Schaefer and Black, 2005). Other studies have also compared the maturity of the knee with maturational development in other body areas (Aicardi *et al.*, 2000; Xi and Roche, 1990) or have examined the knee itself in relation to chronological age (O'Connor *et al.*, 2008; Pyle and Hoerr, 1969; Roche *et al.*, 1976). O'Connor *et al.* (2008) found that their results differed significantly from the results of studies which examined dry bone (McKern and Stewart, 1957; Schaefer and Black, 2005). It is not clear if this difference is due to the method of data gathering or the very different populations from which the data was gathered (Cardoso, 2008; O'Connor *et al.*, 2008).

The atlas is organised using recognised maturity indicators which the authors have identified and have related to different maturational stages. The process of growth is saltatory and varies from individual to individual (Lampl, 2002). Maturity indicators allow the observer to identify the stage of skeletal development which the child has reached (Cameron, 2002). There are a number of factors in addition to individual variation which can cause a child to lag behind other children in their skeletal development, or conversely to experience advanced skeletal maturation (Tanner, 1962). These include both genetic and environmental influences, which vary from child to child and are a reminder of why age estimation can never be truly accurate.

The Pyle and Hoerr atlas (1969) was developed on the same Cleveland population that the widely utilised Greulich and Pyle atlas (1959) was based upon. Studies have shown that this latter atlas continues to be accurate and reliable enough to be applied in age estimation cases of children from disparate populations, albeit in some cases with small modifications which ensure that the results are population specific (Calfee *et al.*, 2010; Chiang *et al.*, 2005; Griffith *et al.*, 2007; Groell *et al.*, 1999). It is reasonable to hypothesise that the Pyle and Hoerr atlas would give similar results to those shown in studies of the Greulich and Pyle atlas and this study and the next section will directly compare the two standards. This study has shown that the Pyle and Hoerr atlas gives acceptably repeatable and accurate results when used to age estimate children from a modern Scottish population and can be considered as a useful alternative to the use of the traditional left hand wrist radiographs if necessary. The main limitation to this atlas however, is the fact that the upper limit of the atlas is restricted, especially in relation to the age estimation of females. The

upper limit for females is 16 years of age which mitigates against the use of this method in relation to whether a female individual has passed 18 years of age. The situation is a little different for males since the atlas has an upper limit of 19 years of age and it could therefore conceivably be utilised for older male individuals.

6.4 Overview of the Knee Atlas

The knee atlas of Pyle and Hoerr (1969) includes two radiographic views of the knee for each age, an anterior-posterior image and a lateral image (Table 6.8 and Figure 6.9). The atlas presents two skeletal ages for each radiograph, a female age and a male age (Figure 6.10).

View	Skeletal Area
Anterior Posterior	Distal femur
	Proximal tibia
	Proximal fibula
Present but unable to see due to overlying	Patella
Lateral	Distal femur
	Proximal tibia
	Patella
Present but unable to see due to overlying	Proximal fibula

Table 6.8: Skeletal areas of the knee which are used for age estimation in the Pyle and Hoerr (1969) atlas.

Todd suggests that '*if one were training a pupil in the technique of assessment, one would always start with the knee'*. He argues that this is because the distal femur and proximal tibia give the same maturity rating, and the fibula and patella are both erratic in the timing of their maturational changes and have few maturity indicators which can be identified (Todd, 1937). The atlas itself appears straightforward to use and has clear images, assisted by the limited overlaying that occurs in this joint area. Any bony area which is overlaid in one view can be clearly seen in the alternate view.

Figure 6.9: The anterior-posterior (left) image (Plate 22A) and lateral (right) image (Plate 22B) (Pyle and Hoerr 1969)

1. The menisci are tough but slightly adaptable in shape. The most peripheral part of each meniscus is largely fibrous; there it is vascular and has a rich nerve supply. The more central part is largely cartilaginous; there it is avascular and has no nerve supply. The fluid-producing synovial membrane is maintained over the periphery of the meniscus. The more central part is devoid of synovial membrane. The key attribute of synovial fluid is its viscosity.

2. Flexion and extension take place above the menisci; rotation takes place below the menisci. The medial meniscus, without direct muscle control, must tilt and turn passively with the medial condyle (femur) within the limits of the slightly elastic attachments at its horns. The lateral meniscus is less widely fixed. Moving with the lateral condyle (femur), it tilts with muscle control and turns with muscle and ligament controls. The popliteus muscle assists to rotate the femur and directly retracts the posterior arch of the lateral meniscus. When motion at the four parts in the articular space begins—two condyles, one meniscus, and one synovial fluid layer—the synovial fluid does not travel independently.

3. To explain what occurs in the synovial fluid layer, MacConnaill took the moving femoral condyle as a reference surface. The synovial fluid follows the moving condyle like a viscous layer rather than a lubricating film of grease. Starting from flexion, for example, the meniscus acts as a thrust block between the pair of condyles. It "sets itself" according to the shape of its own tibial condyle. The tilting-rotation motion between flexion and extension produces whorls in the synovial fluid which converge toward the loadline through the articular epicenter of the pair of condyles, i.e. the loadline through the synovial fluid layer, as well. In profile, the whorls resemble a series of molecular strings. Commencing at the popliteal space, they are tallest and concave, are gradually shorter and straighter toward the loadline, and progressively convex beyond the loadline. The loadline is always through the thinnest portion of a synovial fluid layer during its flow and ebb between complete flexion and full extension.

MATURITY INDICATORS AND OSSEOUS MODELING

A, C, D. Center of the knee joint. P A view. The transverse trabecular pattern beside the shadow of the patella now radiates distinctly toward the medial condyle (femur) where the trabeculae are clearly vertical. *P A view.* The intercondylar tubercles (tibia), although unusually large, have become typically more pointed.

L, 3, 6. Lateral half of the knee joint and tibiofibular joint. P A view. Three changes in the vertically aligned lateral surface markings were 1) a white marking appearing beside the tip of the styloid process (fibula); this is the first osseous marking in the tibial half of the tibiofibular joint, 2) reciprocal squaring of the two osseous corners beside L and 3, and (3) the beak of the lateral epicondyle capping the lateral end of the metaphysis (femur).

M, 3. Medial half of the knee joint. P A view. The medial end of the terminal plate (femur) now curves close to the sharp triangular tip of the metaphysis; this is the adductor tubercle. *P A view.* This is the last standard plate in which the side of the medial condyle (femur) forms a smooth continuous curve with its articular surface without any indication of an osseous corner beside M.

A, E, 7. Femorotibiopatellar joint. Lateral view. The nodule beside E is the first osseous indicator of the distal extent of the tibial tuberosity.

Figure 6.10: Written description for Plates 22A and 22B (Pyle and Hoerr 1969).

Figure 6.11: Radiograph of female left knee, identified as 'FLK 18'. Chronological age 8y 6m (102m). Estimated age 112m.

The images identified as FLK 18 (Figure 6.11) and MLK 292 (Figure 6.12) were both considered to most closely resemble Plate 22. In both cases ossification can be seen in the distal tibial tuberosity, an indicator which separates this plate from the previous one. The tibial epiphysis can be seen to follow the metaphysis but is not yet 'capping' it and the intercondylar tubercles are 'pointy'. The femoral epiphysis caps the metaphysis but still shows a degree of separation at either corner.
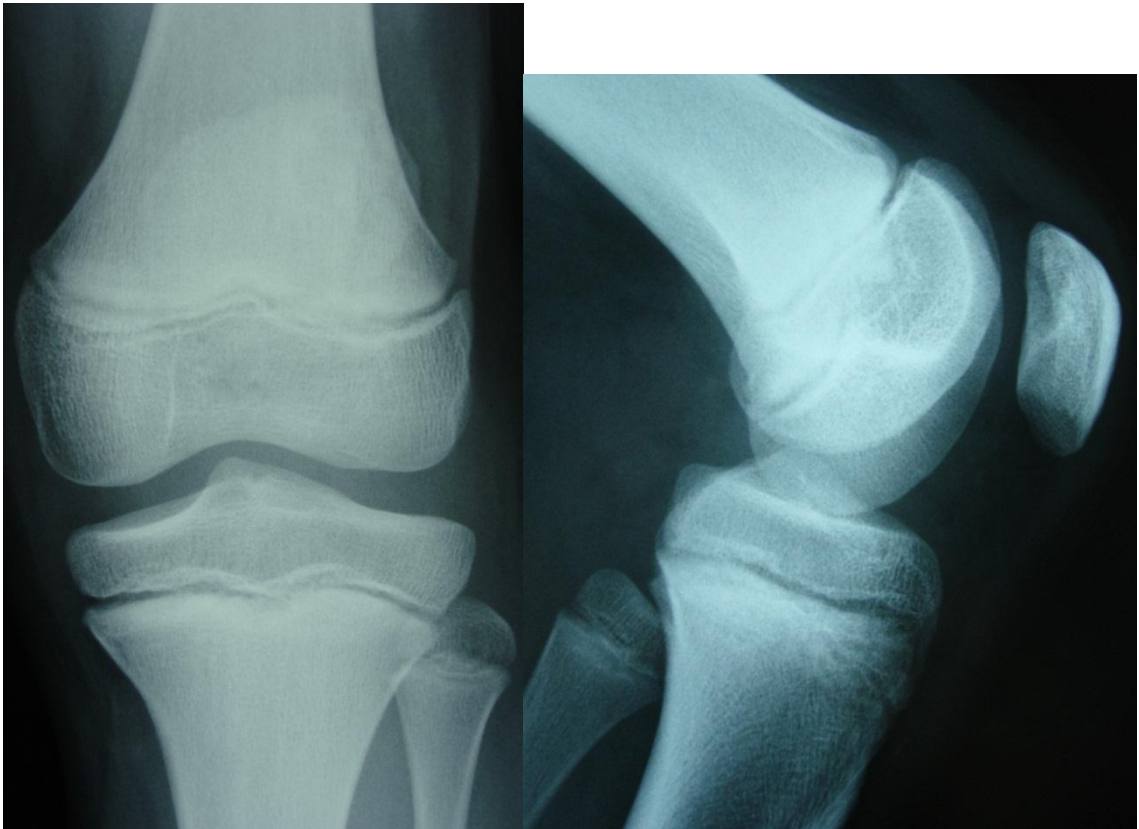
Figure 6.12: Image of male left knee identified as 'MLK292'. Chronological age 12 y 1m (145 months). Estimated age 144 months using the Pyle and Hoerr atlas (1969).

This atlas, in common with the Greulich and Pyle atlas (1959) had clear and easily discernible images. The main issue with using the knee atlas is that in comparison to other atlases there can appear to be a limited number of maturational indicators available to differentiate between plates. Care does have to be taken since in some cases the distal femur and proximal tibia do not give the same maturity rating and can be separated by, usually, one stage. For this reason and because changes between plates can be subtle, this atlas should not be used without prior study and experience. Due to issues of overlaying, any age estimation must involve both radiographic views.

7 The Foot-Ankle

The development of the foot-ankle in humans is broadly analogous to the development of the hand-wrist (Matthews, 1998; O'Rahilly, 1973). The limb bud develops in a proximodistal sequence from the proximal part of the limb through to the distal phalanges, so the tibia and fibula, which create the upper part of the ankle joint, form slightly earlier than the tarsals (Matthews, 1998). During the fetal period, all of the future skeletal elements of the foot are formed in cartilage, followed rapidly by the beginning of ossification (O'Rahilly *et al.*, 1960). By birth ossification of all of the bones of the foot, with the exception of the cuboid, three cuneiforms and the navicular has commenced (Gardner *et al.*, 1959; Hubbard *et al.*, 1993). This early ossification pattern is slightly at odds with the ossification pattern seen in the hand-wrist where the carpal bones have rarely begun ossification at birth (Scheuer and Black, 2000b).

Because of the relatively early development and maturation of the foot, both foot length and the appearance of ossification centres have been utilised to estimate the gestational age of the fetus (De Vasconcellos and Ferreira, 1998; Donne *et al.*, 2005; Gentili *et al.*, 1984; Goldstein *et al.*, 1988; Huxley, 1998; Kjar, 1974; Mercer *et al.*, 1987; Merz *et al.*, 2000; Mhaskar *et al.*, 1989; Platt *et al.*, 1988). The correlation between foot length and chronological age has also been investigated in older children (Attallah and Marshall, 1989), but is more commonly linked to attempts to estimate stature and body weight of an individual (Agnihotri *et al.*, 2007; Anderson *et al.*, 1956). Age estimation in the living using the maturational changes within the skeleton of the foot do not appear to be commonly used, although Garn and Rohmann (1966) examined

the relationship between maturation and the individual bones of the foot, identifying those which showed the greatest commonality with age and Whitaker *et al.* (2002) attempted to devise a scoring system which allowed the estimation of chronological age from the developing bones of the foot.

Skeletal age estimation, in a forensic context, relies on the examination of multiple areas of the body however there are times when fragmentation or disarticulation results in a limited availability of skeletal elements for analysis. The foot becomes important in forensic anthropology due to the frequency with which it is preserved. If encased in a shoe or boot the foot can survive intact after other body parts have been lost due to taphonomic influences, explosions or plane crashes (British Broadcasting Corporation, 2008a; b; c; Gunn, 2008). Often in these situations soft tissue is still *in situ* and the use of radiographs for analysis of the contents of the clothing is strongly advised as the least intrusive method of information gathering.

The foot-ankle atlas of Hoerr *et al.* (1962) is the third of a trio of atlases based on the data collected during the Brush study (Greulich and Pyle, 1959; Pyle and Hoerr, 1969). The atlas was based on data collected from 4483 children from Cleveland (Brush Study) and is supplemented by data collected during a longitudinal study which was also running in Boston, USA. The latter radiographs formed the basis of the maturity indicators which were identified at the distal tibia and fibula since these areas were more successfully viewed on these films. The foot-ankle atlas presents one film which relates to a single developmental stage for both females and males (Hoerr *et al.*, 1962). The authors applied the same argument which had been suggested during the design of the atlas of the hand-wrist and which was based on their observations and the study of the literature at the time (Greulich and Pyle, 1959; Hoerr *et al.*,

1962). They argued that the maturity indicators and the sequence in which they formed, which in turn fashioned the basis for the identification of maturation and subsequent skeletal age were unaffected by sex or ancestry. As a result, the same series of radiographs could be treated as a discrete method of assessing age and two sets of skeletal age are assigned to each radiograph accordingly.

Since this atlas presents a series of radiographic plates of the foot and ankle of children of known age and sex, it provides a resource whereby the radiograph of the child can be compared directly to the series of radiographs which it contains. The atlas was originally designed to create a record of the normal maturational process in the foot and ankle of healthy children. The potential for the use of these images in the estimation of chronological age from a radiograph of an unidentified individual was quickly recognised and the atlas has been utilised in this manner by forensic practitioners for the last 50 years. The children whose data were collected were growing to maturity between 1931 and 1942 and therefore represent a population 70-80 years in the past. This time lapse has prompted the argument that secular change, ethnic and population differences between the white children of high socioeconomic class who were growing to adulthood in the early 1900s and 21st century children from any population around the world, could affect the accuracy of the link between skeletal age and chronological age as defined by Hoerr *et al.* (1962).

Hoerr *et al* (1962) divided the foot into three areas; the hindfoot, midfoot and forefoot. The hindfoot includes the distal tibia and fibula, calcaneus and talus; the midfoot includes the cuboid, navicular, medial, intermediate and lateral cuneiforms. The forefoot includes the metatarsals and phalanges. The changes which they identified within these defined areas are in turn limited, since they do not utilise all of the bones and epiphyses available. They

identified maturity indicators on the distal tibia, distal fibula, tarsals, metatarsals, proximal phalanges and the distal phalanx of the first toe when assigning ages. They also selectively include the distal phalanges of the 2nd, 3rd and 4th toes when they have both epiphyses and diaphyses present although this is not always the case. There is normal variation in the number of phalanges present within the foot, a fact which has been recognised and commented on by other authors (Billmann and Minor, 2007; Garn *et al.*, 1965; Venning, 1956). By being selective in their use of skeletal areas, the authors of the atlas ensured that this normal variation did not affect the skeletal age assessment process. The authors of the atlas suggested that those using the atlas might wish to identify their own maturity indicators as they work through, and with, the atlas.

The recent Law Commission report has reaffirmed the requirement for methods to be both appropriate and applicable to the population on which they are being practiced (The Law Commission, 2011). This is especially relevant to the case of the age estimation method utilising the Hoerr *et al.* atlas (1962), where an atlas that was designed to measure skeletal development of children is used for age estimation and therefore is being applied in ways for which it was not designed and on a very different geographical and temporal population. Both of these factors underline the requirement for ensuring the current validity of the method.

This study aimed to evaluate the accuracy of the Hoerr *et al* atlas (1962) when utilised to age estimate children from a modern Scottish population.

7.1 Materials and Methods

Radiographs of the left foot-ankle region were collected from Ninewells

Hospital, Dundee. These images had been taken from children between the

ages of birth and 20 years who had accessed the Accident and Emergency

department of the hospital for suspected injury of the foot or ankle. Information

on sex, date of birth and date of image were also collected. Images were

screened for indicators of pathology or injury which might have affected growth,

these included; previous injury of the hip, knee, foot or ankle, the presence of

pathological conditions such as hip dysplasia or illnesses such as cancer. If

these were present the images were rejected. The Hoerr *et al.* (1962) atlas

contains both the anterior-posterior view and the dorsoplantar view of each foot

so each of these were included in the data collection for each individual, the

atlas is based entirely on images of the left foot and as a result only left side

images were collected (Figure 7.1). In total the images from 546 individuals

were collected, of these 265 were female and 281 were male Table 7.1 and

Figure 7.2.

Figure 7.1: Image identified as 'MLF157' collected from Ninewells Hospital. Chronological age 13y 9m, estimated age using the Hoerr *et al* atlas (1962) method 13 years.

Age estimation was undertaken for each group of images. Females and males were age estimated separately due to the well documented differences that exist in maturational timings between the two sexes (Pryor, 1923; 1925). Only the sex of the individual whose foot was represented in the image was known to the assessor. Estimated age and chronological age were both converted to

months to facilitate statistical evaluation. The chronological age was calculated

by subtracting the date of the birth from the date of image acquisition.

Age (years)	Female Left Foot	Male Left Foot	Total
1	5	3	8
2	4	8	12
3	5	13	18
4	3	8	11
5	6	2	8
6	18	18	36
7	5	7	12
8	10	15	25
9	16	13	29
10	19	15	34
11	14	23	37
12	20	39	59
13	18	18	36
14	16	15	31
15	16	11	27
16	15	10	25
17	22	10	32
18	19	16	35
19	17	19	36
20	17	18	35
Total	265	281	546

Table 7.1: Distribution of individuals by sex and age for left foot/ankle radiographs.
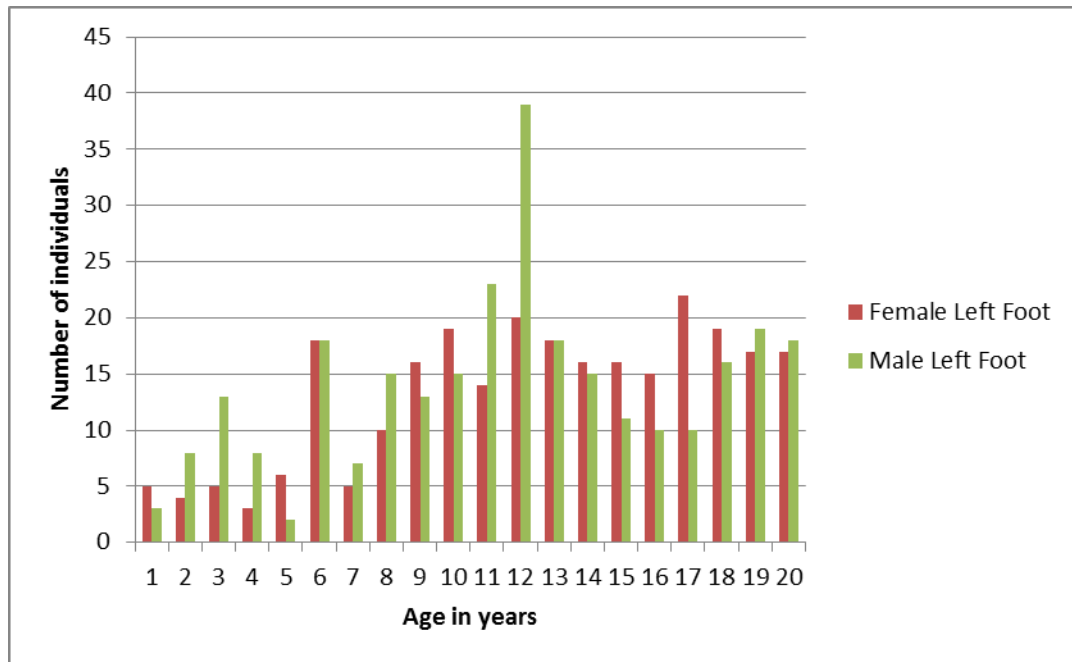
Figure 7.2: Distribution of individuals by sex and age for left foot/ankle radiographs.

The plates in the atlas display full maturity for the female foot at 15.2 years of age, at which point the foot and ankle have allegedly reached adult morphology and all epiphyses are fused (Hoerr *et al.*, 1962). In order to confirm the age at which maturity is reportedly complete, all of the female images which were collected for the ages 16-20 years of age were assessed to ensure that no visible epiphyses were present and that all of the skeletal elements had achieved adult morphology. This was the case for all of the radiographs which fell into these age groups and therefore the images for these 90 individuals were omitted from the female final analysis leaving a total of 175 individuals. Due to the delayed development in males compared to females, complete maturity of the male foot in the Hoerr *et al.* atlas (1962) is not reached until 17.5 years of age. As with the female assessment, all images were observed up to, and including, the age of 20 years. Full maturity was observed in all of the individuals from the 18-20 age groups therefore these 53 individuals were omitted from the male final analysis leaving a final total of 228 individuals. The

results from the analysis of the images from the final 403 individuals therefore formed the basis of the data set.

Inter- and intra-observer analysis was undertaken on the same 30 randomly selected images from the female group and 30 randomly selected images from the male group giving 60 images in total. The intra-observer analysis was carried out 3 months after the first round of age estimations and under the same conditions as the first round of analyses. The inter-observer analysis was undertaken by a post-graduate student who was experienced in estimating age from radiographs.

7.2 Results of the inter and intra-observer tests

The results of the inter-observer test were subject to a Mann Whitney test which showed that the differences between observers were not significant for either females (P=864) or males (P=853). To check intra-observer error the results of the intra-observer test were subject to a Mann Whitney test which showed that the differences between the two sets of results were not significant for either females (P=0.934) or males (P=0.994)

7.3 Results for the age estimation of foot radiographs utilising the Hoerr *et al.* (1962) atlas method

Linear regression was undertaken to examine the relationship between estimated age and chronological age with chronological age treated as the dependent variable in each calculation. The results are presented in Table 7.2, Figures 7.3 and 7.4. The R^2 values for the correlation between chronological

age and estimated age were high for both females (0.952) and males (0.965), both of these results were statistically significant (p<0.001).

Sex	Regression coefficient	R value	R²-value	P value
Female left ankle-foot	0.966	0.975	0.952	<0.001
Male left ankle-foot	1.050		0.965	<0.001

Table 7.2: Regression coefficients and R² values for the comparison between estimated age and chronological age for the left foot-ankle.
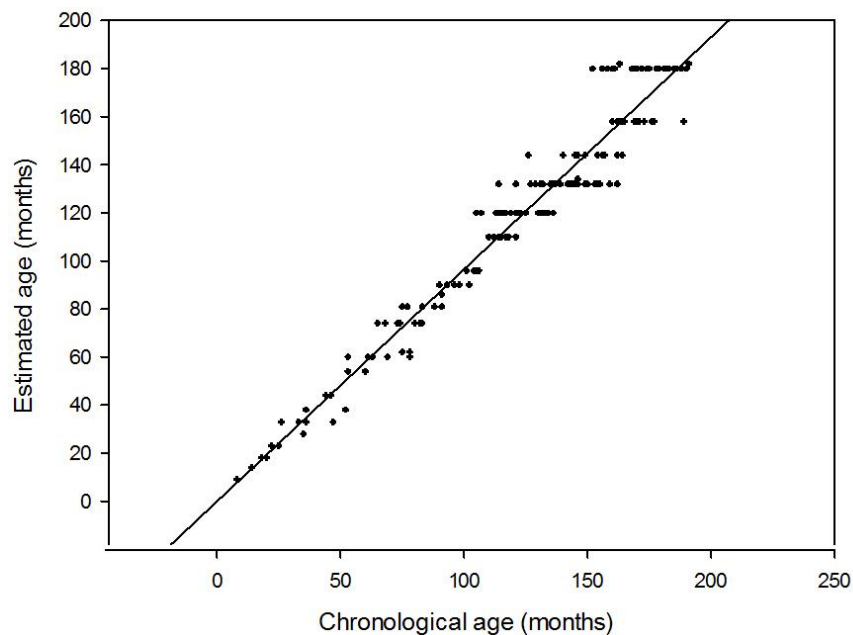
Figure 7.3: Linear regression for estimated age (EA) (months) and chronological age (CA)(months) for radiographs of female left feet (*EA = -0.0694 + (0.966 x CA)*).
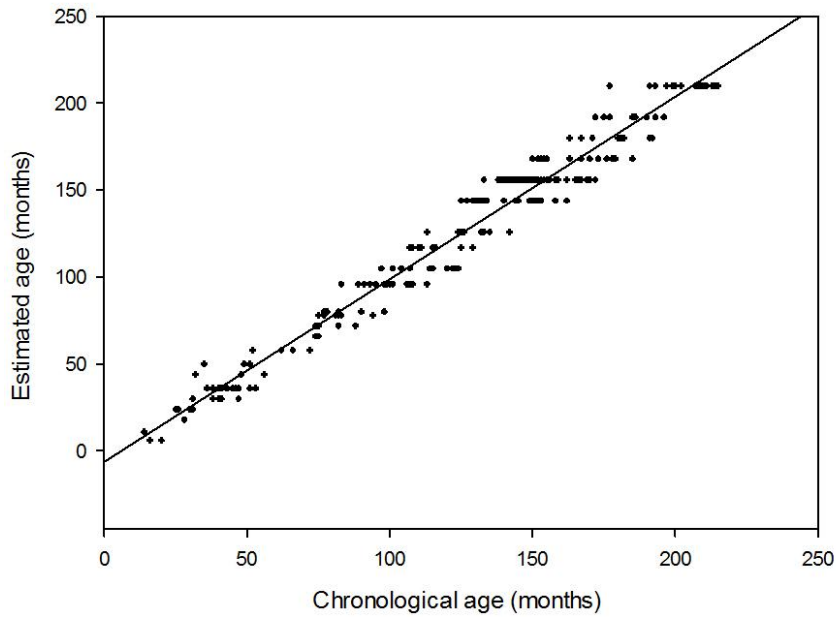
Figure 7.4: Linear regression for the relationship between estimated age (EA) (months) and chronological age (CA) (months) for radiographs of male left feet (*EA = -6.288 +(1.050 x CA)*).

The relationship between chronological age and estimated age was compared using a Mann-Whitney U test. The results of the test showed that the differences between chronological age and estimated age were not significant for either females (P= 0.291) or males (P=0.663).

The mean difference between the estimated age and chronological age was calculated for each group. Chronological age was subtracted from estimated age therefore a positive value indicated an estimated age in advance of chronological age and a negative value indicated an estimated age which lags behind the chronological age.

Table 7.3 shows the mean differences for each sex. The minimum and maximum differences are also given. Females have the largest range between the maximum over age and the minimum under age of 59 months (4 years 11

months) with males having a smaller difference between the two of 52 months

(4 years 4 months). The standard deviation for females is 9.95 months and for

males is 10.19 months.

Sex and Side	Mean Difference (months)	Maximum overage and Maximum underage (months)	Standard Deviation (months)	Standard Error of the Mean (months)	Confidence Interval of the Mean (months)
Female left foot	-4.331	Max overage 28 Max underage -31	9.95	0.752	1.521
Male left foot	0.008	Max overage 33 Max underage -19	10.19	0.675	1.331

Table 7.3: Mean, standard deviation, standard error and confidence interval of the
mean for the left foot analysis.

Each group was divided into year cohorts and the mean difference between

estimated age and chronological age was calculated for each of the groups

(Table 7.4).

Age	Female left foot	Male left foot
1 year	0.00 (n=5)	-9.00 (n=3)
2 years	-0.50 (n=4)	0.00 (n=8)
3 years	-3.40 (n=5)	-7.85 (n=13)
4 years	-2.00 (n=3)	-6.75 (n=8)
5 years	-0.67 (n=6)	-6.00 (n=2)
6 years	-4.94 (n=18)	-3.11 (n=18)
7 years	-5.00 (n=5)	-3.71 (n=7)
8 years	-4.00 (n=10)	-2.60 (n=15)
9 years	0.87 (n=16)	-3.15 (n=13)
10 years	-1.95 (n=19)	-0.53 (n=15)
11 years	-7.57 (n=14)	9.26 (n=23)
12 years	-12.10 (n=20)	5.08 (n=39)
13 years	-2.78 (n=18)	-3.78 (n=18)
14 years	-2.00 (n=16)	0.13 (n=15)
15 years	-7.62 (n=16)	-0.54 (n=11)
16 years	n/a	4.10 (n=10)
17 years	n/a	-1.30 (n=10)

Table 7.4: Mean differences between chronological age and estimated age by year cohort.

For the female age groups the majority of the mean differences are negative indicating that the estimated ages lag behind the chronological ages. The mean difference between estimated age and chronological age for females range between 0.00 months in the 1 year old age group and -12.10 months at 12 years of age, the only group for which age was overestimated were 9 year old

females who were overestimated by an average of 0.87 months. For the male groups again the trend was to underestimate chronological age with these underestimations ranging from between 0.00 months at 2 years of age to -9.0 months in the 1 year old age group, which extended from 1 year of age to the day before the individual had their 2nd birthday. The overestimations of age are in the 11, 12, 14 and 16 year age groups and range from between 0.13 months at 14 years of age to 9.26 months at 11 years of age.

With the breakdown into year cohorts the location of the maximum overage and maximum underage can be understood. The female maximum underage of 31 months was found in the 15 year old age group with the next highest underage of 30 months found in the 13 year old age group. The maximum overage for females of 28 months was found in the 12 year old age group. For males the maximum underage of 19 months was found in the 10 year age group with the maximum overage of 33 months found in the 14 year age group.

The range of differences between chronological age and estimated age are presented in Figure 7.5 and Figure 7.6. The box plots show the median for each group, the lower and upper limits of the box show the 25th and 75th percentile and the lower and upper bars show the 10th and 90th percentiles respectively. The points outside these are those individuals who fall outside these parameters.
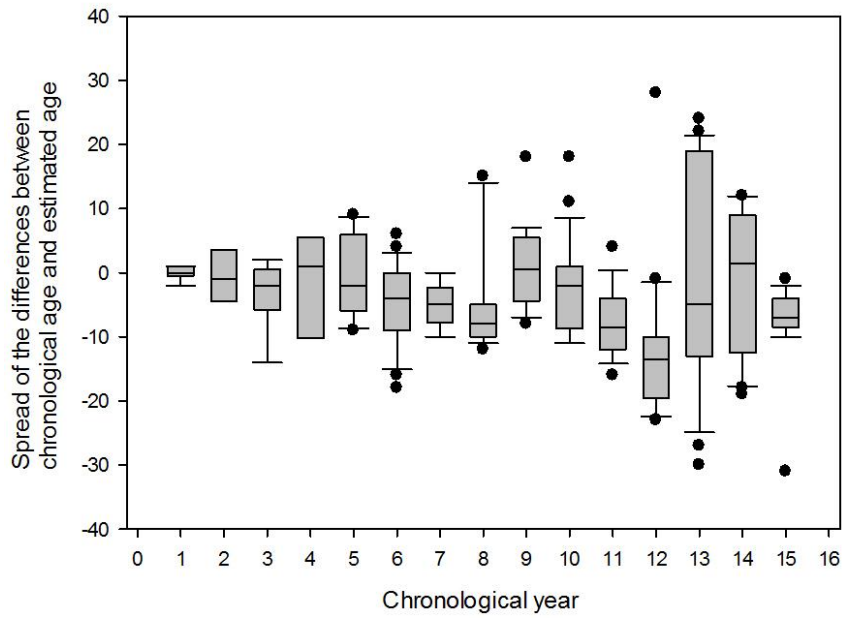
Figure 7.5: Showing the median (line within the box) 25th and 75th percentiles (lower and upper limits of box), 10th and 90th percentiles (lower and upper bars) for female data.
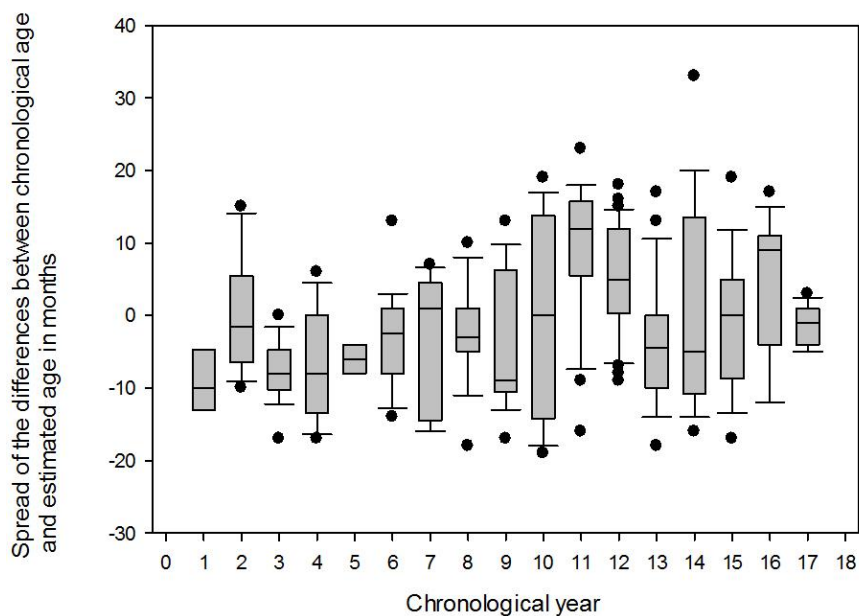
Figure 7.6: Showing the median (line within the box) 25th and 75th percentiles (lower and upper limits of box), 10th and 90th percentiles (lower and upper bars) for male data.

7.4 Discussion

There is a responsibility inherent in any identification situation involving body fragments to ensure that the conclusions which are reached are as accurate, reliable and realistic as possible. Many of the methods which are available for the forensic practitioner to estimate age using the foot of the juvenile are based on dry bone data (Cardoso and Severino, 2010; McKern and Stewart, 1957). Work has shown that age estimations which are derived from dry bone data vary from those which are derived from radiographic imaging underlining the need to have reference data which is relevant to the data collection technique (Cardoso, 2008; Krogman and Iscan, 1986; Schulz *et al.*, 2008). Therefore any forensic examination of radiographic images must utilise appropriate reference data which is why testing of the Hoerr *et al* atlas is essential (Hoerr *et al.*, 1962).

This study found that for both females and males there is a strong relationship between chronological age and estimated age from assessment of radiographs of the foot/ankle using the Hoerr *et al* atlas (1962). When undertaking age estimation in a forensic scenario however it is not just the strength of the relationship which is important. The differences between estimated age and chronological age must also be considered. For the radiographs of female feet the overall average difference between chronological age and estimated age was negative indicating that overall the age estimated by the atlas lags behind chronological age. This trend in underaging was demonstrated when the cohorts were broken down into groups by year. All of the estimated ages were younger than the chronological ages except for the 9 year-old female group where the difference was 0.87 months.

With the exception of three groups the size of the difference between chronological age and estimated age ranged from 0 months at 1 year of age to -5 months at 7 years of age. There were noticeably larger differences at 11 years (-7.57 months), 12 years (-12.10 months) and 15 years of age (-7.62 months). The lag between chronological age and estimated age in the 15 year age group can be explained by the way in which the atlas is designed. This penultimate plate is assigned a skeletal age of 15.2 years by the authors, this skews the assigned age to the bottom of the year group creating an underage for those individuals whose chronological age is older. The large underage seen in the 11 and 12 year age groups coincide with the commencement of the adolescent growth spurt at which point there would be a significant amount of variation seen between individuals. This was also seen in Figure 7.5 where there were an increased number of individuals whose skeletal development was at the outer edges of the expected age.

For males the average difference for the entire group is 0.01 months, indicating that overall there is little difference between estimated and chronological age. When this is broken down into year cohorts it can be seen that all but five of the groups also display a tendency to underestimate age using the atlas. It is of interest however, that of the five groups which showed a tendency to overage, four of these were amongst the age groups in which the adolescent growth spurt would be expected to have commenced; the 11 year, 12 year, 14 and 16 year olds. There was a significant lag between estimated age and chronological age in the 1-5 year old boys, the differences seen in these groups range from -6 months in the 5 year cohort to -9 years in the 1 year old cohort indicating that the Hoerr *et al.* atlas method is less accurate at ageing these younger male individuals. It is not clear why there is this lack of fit between the

atlas and the younger male individuals since the radiographs for these early developmental stages are spaced at intervals of 3-6 months in the atlas. There were also an increasing number of outliers seen throughout the age groups indicating that this age estimation method gives the possibility of individuals whose skeletal development appears to lie at the limits of expected age ranges.

Forensic age estimation undertaken on an individual of unknown background must be able to take into account all of the factors which might affect the growth of the individual, both in a positive and in a negative way, as well as attempt to provide an age range which is both reliable and valid (Ritz-Timme *et al.*, 2000), thus the greatest differences between chronological age and estimated age are of interest. Age estimation of this population utilising the Hoerr *et al* atlas (1962) gave an age range between maximum overage and maximum underage of 4 years 11 months for females and 4 years 4 months for males.

The standard deviations are similar for females and males and fall within the range of standard deviations given in the original Hoerr *et al.* (1962) atlas. The ranges of difference as presented in Figure 7.5 showed that for females by year the range remained small in the younger age groups until the age of 6 years. After this age there is an increase in the variation seen between chronological age and estimated age with individuals falling outside the 10th and 90th percentiles especially in the 9, 10, 12 and year old groups. These outliers within these older groups most likely correspond with the differing rates with which children experience the growth spurt and adolescent growth (Tanner, 1962). For the male groups (Figure 7.6) there is less variation in the younger age groups. Although some spread in variation can be seen in the 3 year and 6 year age groups it is after the age of 8 years that the wider variation is seen. This pattern mirrors that seen in the females but occurs two years later in the

male cohort, as anticipated by the lag in maturational timings which exist between females and males (Pryor, 1925).

The atlas of Hoerr *et al.* (1962) combines male and female ages on single plates. Garn and Rohmann (1966) argue that this represents an organisational weakness because they found that there was a stronger correlation between age changes in female foot bones and chronological age compared with their male counterparts. It is unclear if the stronger relationship between the maturational changes indicated by Hoerr *et al* (1962) and the chronological age in males seen in this study might be a reflection of the organisation of the atlas. Combining female and male ages in the single plate has created some large gaps in the visualisation of the changes of the female foot, for example there are no plates between the chronological age of 13.2 years and 15 years for females which is highly likely to have been the cause of the large range of differences between chronological age and estimated age seen in this age group. The greater accuracy and lower ranges seen in the younger age groups may also therefore be a reflection of the smaller spacing seen between plates and also a reflection of the smaller spacing of radiographs that were taken in the early years. For this reason and because of the increased potential for outliers in this population, care must be taken when using the atlas for age estimation in the older age groups.

Both the inter-observer and intra observer tests demonstrated that this method of age estimation gives consistent results, although it should be noted that the inter observer results were slightly more accurate for females that they were for males.

Many of the reproductions of radiographs within the atlas are very poor quality. Whilst skeletal age assessments do not rely solely on the images, it is useful to be able to relate the written descriptions to an image, something which is impossible to do in some of the plates. It is also difficult, even in the better images, to visualise some of the bones due to their location in relation to other bones e.g. the distal tibia and distal fibula overlie each other in the dorsoplantar view, causing the distal fibula to become obscured. It is frustrating that the distal tibia and fibula can only be seen in the dorsoplantar view, rather than the anterior-posterior view since these bones are of use in age estimation (Crowder and Austin, 2005). This overlying also applies to other bones and has been commented upon by other authors (Whitaker *et al.*, 2002). The problems with imaging can potentially cause issues with the use of this atlas even though the written descriptions are helpful. Issues also arise with these since they are inclined to use terminology which can become confusing (Hoerr *et al.*, 1962).

7.5 The use of the foot-ankle atlas

The foot-ankle atlas consists of a series of radiographs of the foot-ankle area. Each skeletal age is represented by two radiographs; an anterior-posterior radiograph and a dorsoplantar radiograph (Figure 7.7). Each radiograph includes all of the bones of the foot as well as the distal tibia and fibula whose change in morphology, appearance of ossification centres and fusion of these centres are all included in the final comparison. Each pair of plates is accompanied by a written description of the changes and maturity indicators which the authors feel are important in identifying this stage of skeletal maturity (Figure 7.8). This atlas presents one series of radiographs for both sexes each

set of radiographs is therefore assigned two skeletal ages, a female age and a

male age.

Figure 7.7: Plate 24 from the Hoerr *et al.,* (1962) atlas of the foot-ankle.

PLATE 24

INDIVIDUAL BONE AGES

The skeletal age assigned to each bone in this plate is 12 years 0 months for boys and 9 years 2 months for girls.

SELECTED MATURITY INDICATORS

Hindfoot

Upper portion of the ankle joint, lateral view: The inner bone margin and the articular facet of the tibial epiphysis each form a distinct angle of demarcation with the anterior "side" (surface) of the epiphysis. Posteriorly the epiphyseal outlines remain thin and indistinct.

Lower portion of the ankle joint, lateral view: The medial and lateral margins of the trochlea can be traced backward from the crest to the posterior tubercle.

Since Plate 4, dense trabecular patterns have filled each of the trochleas. The dense portion of the bone now extends to the center of the talus, and into the triangular lateral wall of the sinus tarsi. In the anterior portion of the talus, a horizontal trabecular pattern has become visible. No doubt this latter pattern is continuous from the dense subtrochlear portion of the bone.

A tiny bone nodule is visible close to the posterior tubercle of the talus; we have observed one ossification center here routinely. Sometimes, as in this child's film series, another ossicle forms at the posterior tubercle after a first ossicle has become fused with the talus. It is usually the second ossicle which remains separated in the adult foot. In either case, a separated (adult) nodule is called the os trigonum. The ossicle marks the position of the posterior end of the groove for the tendon of the flexor hallucis longus muscle.

Calcaneus, lateral view: The squarish outline of the sustentaculum tali is visible within the silhouette and across the groove of the calcaneus. The margin of the middle talocalcaneal facet appears as the middle etched outline.

The calcaneal portion of the posterior talocalcaneal joint is begining to appear concave.

Midfoot and Forefoot

The mid-tarsal joint, both views: The full span of each of the four articular facets can be identified by means of osseous corners. Trabecular patterns of differential density within the calcaneus, talus, navicular and cuboid now extend to the structural center of each articular facet.

Navicular, dorsoplantar view: Within the bone shadow, the concave articular arc of its talar surface "caps" the anterior surface of the talus. Bone now projects beyond the medial end of the arc; the tuberosity of the navicular is calcifying. Sometimes the tuberosity develops from a separate ossification center to become one of the most frequently-occurring accessory bones of the adult foot.

Forefoot

Metatarsals, dorsoplantar view: Each of the five growth cartilage plates within the metatarsals has been reduced to uniform thickness across the entire shaft.

Distal epiphysis of the great toe, dorsoplantar view: A tiny osseous nodule is visible at the medial end of the inner bone margin of the distal phalanx. This nodule later fused with the margin before epiphyseal-diaphyseal fusion began in the phalanx. Compare the "capping" outline, including the nodule, with the analogous outline (an inner bone margin without an accessory nodule) in Plate 25.

Figure 7.8: Written description of Plate 24 of the Hoerr *et al.,* (1962) atlas of the foot-ankle.

Figure 7.9 and Figure 7.10 give examples of a female and male radiograph which were both assessed as most closely resembling Plate 24 through direct comparison and reference to the written description. Indicators which were

used include: the epiphyses of the proximal metatarsals are not yet 'capping' the shafts. The five growth cartilage plates within the metatarsals present with uniform thickness across the entire shaft. The pattern of trabeculae within the talus is horizontal and the medial and lateral borders can be traced from the crest to the posterior tubercle. Finally the calcaneal epiphysis 'caps' but is still separate from the calcaneus.

Figure 7.9: Image identified as 'FLF158' (female left foot-ankle). Age estimated at 9.2 years (Plate 24).

Figure 7.10: Image identified as 'MLF160' (male left foot-ankle). Age estimated as 12.9 years (Plate 24).

Of all the atlases which were examined in this study, this was the most difficult to use due to the quality of the radiographs. Many of the reproductions in the atlas were overexposed and appeared to be out of focus which meant that it was not possible to see any detail. There are also problems with overlying structures, especially in the older age groups, which caused problems in both views this is especially noticeable in relation to the proximal metatarsals and the tarsals.

The radiographs which were used in the design of the atlas were all taken using designated positioning of the subject. This is not the case for the images taken in Ninewells which were taken for investigation purposes so analysis of the images had to take this into account. It quickly became clear that any age estimation which involved foot-ankle radiographs did require both views in order for the maximum amount of information to be analysed.

8   Analysis of the images from India

The images from India were analysed using the region appropriate atlases. Data was collected for each individual including the sex of the individual however unlike the UK data the date of birth was not provided. Age was provided as an actual age in increments of 0.5 years for each child. Having undertaken an analysis of the use of the atlases on a modern western population it was decided to estimate age for the children in this group and treat the given ages as chronological age with the understanding that this might not be the case. The age would have been given by the child or their family when they were asked by medical staff.

The full range of the data is presented in Tables 8.1 and 8.2 and Figure 8.3. There were a number of individuals who had both a left hand-wrist image and an image of their elbow. This applied to all of the female left hand-wrist and elbow images. For the male images this applied to 25 of the images. Most of the images were less than optimal. A large number were not in focus and many of the hand-wrist images do not include a view of the phalanges additionally some do not include a view of the metacarpals. This meant that it was not possible to use the TW3 atlas (2001) which required a view of the metacarpals and phalanges so the analysis of the hand-wrist radiographs was undertaken using only the Greulich and Pyle atlas method (Greulich and Pyle, 1959).

The elbow images consisted of one view which was usually the anterior-posterior view. This restricted the ability to view the olecranon apophysis and

greatly reduced the potential accuracy of the age estimation using the Brodeur *et al* atlas (Brodeur *et al.*, 1981). The Sauvegrain method (Dimeglio *et al.*, 2005) was not appropriate since this method is limited to children who are experiencing puberty and the children in this set spanned a longer time period than this, so only the Brodeur *et al* atlas (1981) was used.

Figure 8.1: Image identified as 'DMLH16' (male left hand) with a limited view of the phalanges.

Figure 8.2: Image identified as 'DMLE18' (male left elbow).

The aim of the analyses was twofold. Firstly to assess whether the child had been placed in the correct age group since it became clear that families gave an approximate age for children and if this appeared to be too vague the radiologist would assign what they considered to be a most apposite age.

Secondly the Greulich and Pyle atlas (1959) method could be compared to the Brodeur *et al* atlas (1981) method for a limited number of individuals to assess whether they gave a similar age/age range for these individuals.

Age (year)	Female left hand-wrist	Female left elbow	Total
0	1	1	2
1	4	4	8
2	2	2	4
3	1	1	2
4	3	3	6
5	1	1	2
6	1	1	2
7	2	2	4
8	1	1	2
9	0	0	0
10	0	0	0
11	1	1	2
12	5	5	10
13	1	1	2
14	1	1	2
15	1	1	2
16	0	0	0
17	0	0	0
18	0	0	0
	25	25	50

Table 8.1: Number of left hand/wrist and left elbow images for females collected from New Delhi, India by 'age'.

Age (year)	Male left hand-wrist	Male left elbow	Total
0	0	0	0
1	1	1	2
2	1	4	5
3	2	2	4
4	0	0	0
5	2	2	4
6	0	0	0
7	0	0	0
8	3	3	6
9	6	6	12
10	4	4	8
11	3	2	5
12	1	1	2
13	1	1	2
14	1	1	2
15	0	0	0
16	2	2	4
17	2	1	3
18	1	1	2
	30	**31**	**61**

Table 8.2: Number of left hand/wrist and left elbow images for males collected from New Delhi, India by 'age'.
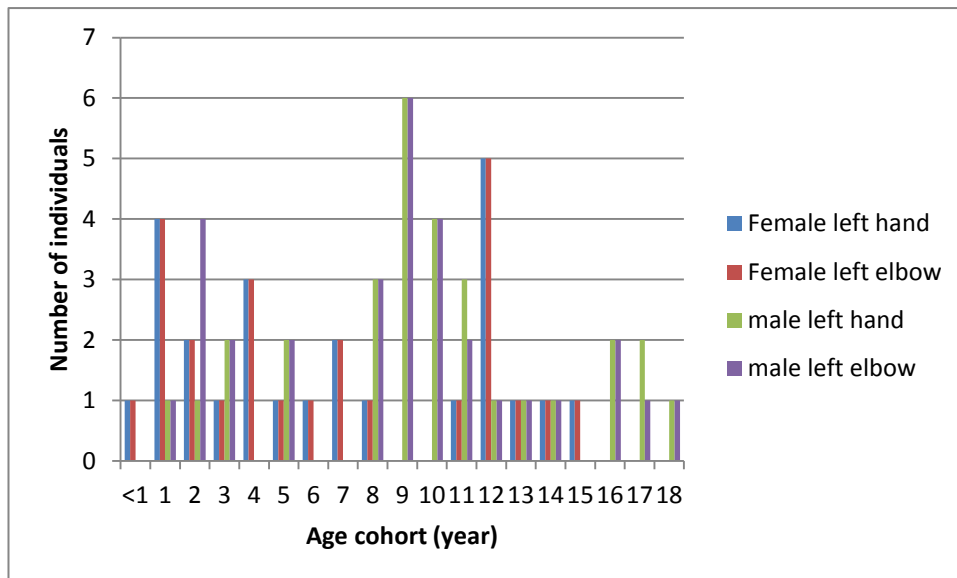
Figure 8.3: Number of individuals from India by age and sex.

8.1 Results of Greulich and Pyle atlas (1959) method

The results of the age estimation by the atlas are presented in Tables 8.3 and 8.4. The difference between the chronological age as shown on the radiograph and the estimated age using the Greulich and Pyle atlas (1959) was calculated by subtracting the chronological age from the estimated age. A negative value indicated an underage and a positive value indicated an overage. It can be seen that for the female group the majority of individuals (76%) are underaged. This tendency to underage was also found in the male group where 70% are underaged. The degree of under and overaging was examined more closely using the standard deviations which were calculated from the previous test of the Greulich and Pyle atlas (1959) on the Scottish population. The standard deviations were 14.97 months for females and 14.16 months for males. Since the age range in any age estimation is given to 2 standard deviations above and below the predicted age (29.94 months for females and 28.32 months for

males). In the analysis of the radiographs from India, 3 female and 7 male

individuals fell outside the age range defined by +/- 2 standard deviations

(indicated in bold).

Female left hand		
Chronological age (months)	Estimated age (months)	Difference between chronological age and estimated age (months)
3	3	0
12	15	3
12	3	-9
18	6	-12
18	0	-18
24	12	-12
30	15	-15
36	30	-6
48	36	-12
48	36	-12
48	30	-18
60	36	-24
72	**42**	**-30**
84	94	10
84	69	-15
102	82	-20
132	156	24
144	120	-24
144	**94**	**-50**
144	132	-12
144	120	-24
144	132	-12
156	**106**	**-50**
168	168	0
180	192	12
	Total	25

Table 8.3: Results of the Greulich and Pyle atlas (1959) method test of female individuals, 3 individuals who fell outside the age range predicted by 2 standard deviations.

Male left hand		
Chronological age (months)	Estimated age (months)	Difference between chronological age and estimated age (months)
18	36	18
30	24	-6
36	24	-12
36	18	-18
60	36	-24
60	32	-28
96	84	-12
96	72	-24
96	108	12
108	108	0
108	84	-24
108	**72**	**-36**
108	84	-24
108	108	0
108	**72**	**-36**
120	108	-12
120	**84**	**-36**
120	120	0
120	96	-24
132	120	-12
132	**96**	**-36**
132	138	6
144	**96**	**-48**
156	132	-24
168	**138**	**-30**
192	192	0
192	186	-6
204	204	0
204	**162**	**-42**
216	228	12
	Total	30

Table 8.4: Results of the Greulich and Pyle atlas (1959) method for male individuals, individuals whose age fell outside the range predicted by 2 standard deviations are indicated in bold.

8.2 The results of the analysis using the Brodeur *et al* (1981) atlas

The examination of the elbow was undertaken using the Brodeur *et al* (1981) atlas method. There were two radiographs which were out-of-focus and could not be used in this assessment. The results of the age estimations are presented in Table 8.5 and Table 8.6. The Brodeur *et al.,* (1981) results are presented as predicted age range with a lower and upper age limit. The chronological ages were compared to these predicted age ranges to determine how many of the chronological ages fell within the predicted age range. For the female group 64% of individuals were assigned an age range which included the chronological age which was on their radiograph and 36% did not. If the chronological age was lower than the predicted age range this was described as an overage and if the chronological age was higher than the predicted age range this was described as an underage. In the female group, all 9 individuals for whom the chronological age fell outside the predicted age range were underaged.

In the male group 58.6% had an age range which included the chronological age indicated on their radiograph (Table 8.6)) and could be classed as 'correct'. For the 12 individuals whose age did not fall into the predicted age range, nine were underaged and 3 were overaged.

For both the female and male groups the individuals whose age was misidentified were evenly spread throughout the age groups with no indication of clustering which would indicate that there was an error with the age estimation method.

Female left elbow			
Chronological age (months)	Lower age range-estimated (months)	Upper age range-estimated (months)	Does age range include chronological age
3	0	4	Y
12	4	24	Y
12	4	24	Y
18	4	24	Y
18	4	24	Y
24	4	24	Y
30	4	24	N
36	4	24	N
48	24	60	Y
48	4	60	Y
48	4	24	N
60	36	72	Y
72	12	54	N
84	90	120	N
84	42	78	N
102	84	120	Y
132	120	138	Y
144	144	180	Y
144	84	120	N
144	126	150	Y
144	90	120	N
144	120	144	Y
156	60	108	N
168	162	Adult	Y
180	162	Adult	Y
		Total	25

Table 8.5: Results of the age estimation of the left elbow radiographs from female children from India.

Male left elbow			
Chronological age (months)	Lower age range-estimated (months)	Upper age range-estimated (months)	Does age range include chronological age
18	0	8	N
24	12	36	Y
24	36	60	N
24	12	36	Y
30	0	18	N
36	12	36	Y
36	12	36	Y
60	102	138	N
60	36	60	Y
96	66	102	Y
96	66	102	Y
96	66	120	Y
108	102	138	Y
108	66	102	N
108	48	78	N
108	66	96	N
108	66	126	Y
108	66	102	N
120	108	144	Y
120	66	102	N
120	102	132	Y
120	66	120	Y
132	102	138	Y
132	138	150	N
156	102	138	N
168	102	138	N
192	192	Adult	Y
192	192	Adult	Y
216	192	Adult	Y
		Total	29

Table 8.6: Results of the age estimation of the left elbow radiographs from male children from India.

8.3 Comparison of the results of the Geulich and Pyle atlas (1959) method analysis with the Brodeur *et al* (1981) atlas method

A number of images had been acquired from the same individual therefore it was possible to compare the results of the Greulich and Pyle (1959) age estimation with the results of the age estimation undertaken using the Brodeur *et al.,* (1981) atlas.

When the results are compared for the female group (Table 8.7) it can be seen that for all of the individuals whose chronological age did not fall into the age range predicted by the Brodeur *et al.,* atlas (1981) method, the error was in the same 'direction' as the errors which were given by the Greulich and Pyle atlas (1959) method. This meant that both atlases agreed in relation to whether an individual was over or underaged. For the three of the individuals who fell outside the expected range of 2 standard deviations predicted by the Greulich and Pyle atlas (1959) method the chronological age fell outside the age range predicted by the Brodeur *et al.,* (1981) atlas method, again for each individual this consisted of an underage.

The results of the male comparison (Table 8.8) show that two of the individuals who were overaged using the Brodeur *et al.* (1981) method were underaged using the Greulich and Pyle (1959) atlas method and one of the individuals who was underaged using the Brodeur *et al.,* (1981) atlas method was overaged using the Greulich and Pyle atlas (1959) method. For these individuals there are a couple of possibilities which might explain this, firstly it may be that the radiographs are not from the same individual, secondly that there is an issue with the two age estimation methods or finally it might be that this error might be

a practitioner error. The remainder of the individuals who were underaged using the Brodeur *et al.,* (1981) atlas method were also underaged using the Greulich and Pyle atlas (1959) method. For all five of the individuals who fell outside the expected range of 2 standard deviations predicted by the Greulich and Pyle atlas (1959) method the chronological age fell outside the age range predicted by the Brodeur *et al.,* (1981) atlas method.

Female left hand-wrist and elbow					
Chronological age (months)	Estimated age using the Greulich and Pyle atlas (months)	Difference between chronological age and estimated age for the Greulich and Pyle atlas (months)	Lower age range-estimated using Brodeur *et al* (months)	Upper age range-estimated using Brodeur *et al* (months)	Does age range include chronological age for the Brodeur age range?
3	3	0	0 (neonate)	4	Y
12	15	3	4	24	Y
12	3	-9	4	24	Y
18	6	-12	4	24	Y
18	0	-18	4	24	Y
24	12	-12	4	24	Y
30	15	-15	4	24	N
36	30	-6	4	24	N
48	36	-12	24	60	Y
48	36	-12	4	60	Y
48	30	-18	4	24	N
60	36	-24	36	72	Y
72	42	-30	12	54	N
84	94	10	90	120	N
84	69	-15	42	78	N
102	82	-20	84	120	Y
132	156	24	120	138	Y
144	120	-24	144	180	Y
144	94	-50	84	120	N
144	132	-12	126	150	Y
144	120	-24	90	120	N
144	132	-12	120	144	Y
156	106	-50	60	108	N
168	168	0	162	Adult	Y
180	192	12	162	Adult	Y
Total number of individuals					25

Table 8.7: Comparison of the results of the age estimations using the Greulich and Pyle (1959) atlas method and the Brodeur *et al.* (1981) atlas method for females.

Male left hand-wrist and elbow					
Chronological age (months)	Estimated age using the Greulich and Pyle atlas (months)	Difference between chronological age and estimated age for the Greulich and Pyle atlas (months)	Lower age range-estimated using Brodeur *et al* (months)	Upper age range-estimated using Brodeur *et al* (months)	Does age range include chronological age for the Brodeur age range?
18	36	18	0 (neonate)	8	N
30	24	-6	0 (neonate)	18	N
36	24	-12	12	36	Y
36	18	-18	12	36	Y
60	36	-24	102	138	N
60	32	-28	36	60	Y
96	84	-12	66	102	Y
96	72	-24	66	102	Y
96	108	12	66	120	Y
108	108	0	102	138	Y
108	84	-24	66	102	N
108	72	-36	48	78	N
108	84	-24	66	96	N
108	108	0	66	126	Y
108	72	-36	66	102	N
120	108	-12	108	144	Y
120	84	-36	66	102	N
120	120	0	102	132	Y
120	96	-24	66	120	Y
132	120	-12	102	138	Y
132	96	-36	138	150	N
168	138	-30	102	138	N
192	192	0	192	Adult	Y
192	186	-6	192	Adult	Y
216	228	12	192	adult	Y
Total number of individuals					25

Table 8.8: Comparison of results of the age estimations using the Greulich and Pyle (1959) atlas method and the Brodeur *et al.* (1981) atlas method for males.

8.4 Discussion

There are a number of potential problems with the analysis of the images from India. Firstly the images were not of good quality. Most of the hand-wrist images were limited to a view of the wrist meaning that any analysis was not able to take into account changes to the metacarpals and phalanges. The atlas of Brodeur *et al.,* (1981) includes both an anterior-posterior image and a lateral image for the elbow allowing all of the epiphyses to be viewed and analysed. This was not possible to do using only one view due to overlying structures. In this data set there was only one view available for each elbow which meant that not all of the skeletal areas which would normally be used in this age estimation method could be visualised, potentially affecting the conclusion which could be drawn from the image. Many of the images for both the hand-wrist and elbow were not in focus which led to difficulties reading the radiographs and 2 of the elbow radiographs having to be omitted since they were not readable.

The second potential difficulty which the analysis of these images posed was that the chronological age which was originally given for each child was most likely to be an estimate. It is possible that this estimate might be erroneous and therefore it is not possible to depend upon this as a 'true' age. Whilst this limits the conclusions which can be drawn from a 'test' of the age estimation methods of Greulich and Pyle (1959) and Brodeur *et al.,* (1981) it can be argued that this is exactly the type of scenario which faces a forensic practitioner who is asked to undertake an age estimation from a radiograph of an individual who 'claims to be' a given age. This is less therefore a 'test' of the accuracy of the age estimation standards which have just been tested on a modern population of known chronological age, than a way of assessing their relationship to

individuals from a country whose population experiences a different socioeconomic reality from that found in the West.

The Greulich and Pyle atlas (1959) method showed a tendency for both the female and the male standard to underage individuals. Despite this tendency estimated ages were within 2 standard deviations of the chronological age in 88% of cases (22/25) for the female group and 76.7% of cases (23/30) for the male group.

In relation to females the Brodeur *et al* (1981) atlas method showed a similar accuracy rate for the Indian population (64% correctly aged) and the Scottish population (63.7%). All of the female individuals whose chronological age did not fall into the predicted age range were underaged. The male group had a reduced accuracy rate (58.62%) compared to both the female group and their Scottish counterparts (87%). The remainder of the group were made up of a mixture of under and over-aging, although the majority were underaged.

Of note, all of the individuals whose age fell outside the 2 standard deviation range suggested by the Greulich and Pyle atlas (1959) were also assigned an age range which did not include the chronological age using the Brodeur *et al* (1981) atlas method.

Due to the lack of records it is not possible to be sure that the chronological age which was assigned to the individuals included in this group from India was correct and for this reason it is not possible to say whether those children whose age fell outside the 2 standard deviations were assigned an incorrect chronological age or if their skeletal development was severely delayed due to developmental or environmental factors. There is no doubt that this population experiences poor nutrition and a high disease burden, many of the children

were diagnosed with tuberculosis and a degree of skeletal delay is to be

expected. In light of this it is of interest that both of the atlas methods tested

performed well, although of all of the groups and methods the poorest

performance was seen in relation to the performance of the Brodeur *et al* (1981)

atlas and the radiographs of male elbows.

9 Comparison of all methods and skeletal areas

This study examined six age estimation methods in relation to four body areas; 2 for the hand-wrist area, one each for the knee and foot and 2 for the elbow. Each of these methods is readily available to practitioners and all are, and have been, used in practice. Each of the previous chapters have looked at the body areas in isolation, this section will consider these collectively.

The four body areas which were examined were; the hand-wrist, the elbow, the knee and the foot-ankle. With the exception of the hand-wrist, the radiographs studied were of the left side of the body only in keeping with those presented in the majority of the ageing techniques studied. The age estimation methods consisted of 2 scoring methods (Dimeglio *et al.*, 2005; Tanner *et al.*, 2001) and 4 direct comparison methods (Brodeur *et al.*, 1981; Greulich and Pyle, 1959; Hoerr *et al.*, 1962; Pyle *et al.*, 1971).

The images which formed the basis of the assessment were collected from Ninewells Hospital which serves the population of the Tayside area which is based in the North-East of Scotland. The radiographs had been taken as part of medical investigations during visits to the Accident and Emergency department of the hospital. Due to the collection method the dataset was cross-sectional in nature and it was not possible to collect either sequential radiographs of body areas or to collect images of more than one body area from the each individual. The images were screened for the presence of pathology and/or trauma which might have affected their growth or development, and images were not collected where there was any indication that either of these might have been in existence.

Each age estimation method was tested on radiographs from the appropriate skeletal area. The chronological age was obscured and the only information which the assessor was aware of was the sex of the individual. The majority of the body areas were represented by the left side of the body. This allowed a like-for-like comparison between the radiographs and images depicted in the reference atlases. Right side radiographs were collected for the hand-wrist to enable both a comparison between sides of the body and to gain an understanding the importance of the orientation of the images in relation to the standards.

One of the aims of the project was to examine the efficacy of different age estimation methodologies in relation to a modern population. Whilst it was not possible to collect images from all body areas for each individual it was possible to look at the efficacy of each technique. Using Graphpad® it is possible to compare the regression coefficients for each of the body areas to establish if these differ significantly. Due to the arrangement of the Brodeur *et al* atlas (1981), age estimation resulted in an age range rather than a single value. It was not possible to undertake statistical analysis with the results and therefore it is not possible to compare the results of this age estimation to the others using this approach.

In the literature there are two types of comparison that are made; firstly comparisons between different age estimation methods on the same body areas from the same population (Andersen, 1971; Bull *et al.*, 1999; Christoforidis *et al.*, 2007) or secondly comparison of age estimation undertaken on different body areas in the same individuals (Das Gupta *et al.*, 1974; Sangma *et al.*, 2007). Initially the question which was asked was whether the hand-wrist was representative of maturational changes which were happening

across the body. The maturational timings of each area were compared to each other in an attempt to answer this question.

In this study all of the assessments were brought together to compare how they performed in relation to each other. In-depth analysis of the results for the analysis of each body area utilising each of the 6 age estimation methods are presented in the individual sections but the question arises of whether more accurate age estimation is possible by combining analysis of more than one body area.

9.1 Results

The results of all of the assessments were examined in relation to each other. It was not possible to directly compare body areas since none of the radiographs studied came from the same individual so it is necessary to examine the results of each set of analyses. A comparison of the regression coefficients and R^2 values for each of the tests are shown in Table 9.1. This shows that after linear regression was undertaken all of the methods tested had high regression coefficients and high R^2 values, it was not possible to undertake statistical analysis on the results of the Brodeur *et al.*, (1981) atlas so it is not possible to directly compare this with the other techniques. The highest R^2 values were seen as a result of the analysis of the foot-ankle and knee radiographs. The R^2 values were high for both females and males in both of these groups although the R^2 value for the male foot-ankle analysis was the highest (R^2=0.965). Despite the popularity of the Greulich and Pyle atlas (1959) method, this method had a lower R^2 value compared to those of the foot-ankle or knee analyses. The lowest R^2 values were seen as a result of the test of the

Dimeglio *et al.* (2005) version of the Sauvegrain *et al* (1962) method for the elbow. The R² value for both the female and male groups was very similar for this analysis. The other low R² value was found in both the female and male groups when age estimation of the left hand wrist was undertaken with the CBA method given in the TW3 atlas (2001).

When a comparison is made between the sexes, it can be seen that for 6 out of 8 analyses the statistical analysis indicates that the method is slightly more accurate for the male groups than for the female groups, this includes the analyses of the elbow radiographs with the Brodeur *et al.* atlas (1981) method in which 87% of the male group had their ages estimated correctly compared to 63.7% of the female group. This is not the case for the TW3 RUS (2001) analysis and the age estimation of the knee using the Pyle and Hoerr atlas (1959) where the female group had a higher R² value.

Method	Body area and side	Female Regression coefficient	Female R²	Male Regression coefficient	Male R²
Greulich and Pyle (1959)	Left hand-wrist	0.894	0.939	0.979	0.940
Greulich and Pyle (1959)	Right hand-wrist	0.859	0.887	0.893	0.907
Tanner-Whitehouse (RUS)(2001)	Left hand-wrist RUS method	0.775	0.780	1.073	0.845
Tanner-Whitehouse (CBA)(2001)	Left hand-wrist CBA method	0.586	0.628	1.025	0.759
Hoerr *et al* (1962)	Left foot	0.966	0.952	1.050	0.965
Pyle and Hoerr (1969)	Left knee	0.968	0.954	0.983	0.952
Brodeur *et al.* (1981)	Left elbow	N/A	63.76% correct	N/A	87% correct
Dimelgio *et al.* (2005)	Left elbow	0.551	0.716	0.533	0.718

Table 9.1: The regression coefficients and R² values for each area by sex and side.

The regression coefficients were compared for each group, to determine whether the repeatability of age estimation differed significantly as a result of differing body areas and/or methods presents the results of these comparisons. This comparison was not undertaken for the Greulich and Pyle atlas (1959) method and the TW3 atlas (2001) method since these were compared previously using a Mann-Whitney U test (Chapter 4) (Table 9.2 and Table 9.4).

For females (Table 9.3) there were no significant differences between either the slopes or intercepts for the left elbow analysis undertaken with the revised Sauvegrain et al (1962) method and the CBA scoring method of the TW3 atlas (2001). The comparison of the regression analysis gave a pooled regression coefficient. Similarly there was no significant difference between the slopes or the intercepts from the regression analysis of the age estimation of the left knee undertaken using the Hoerr et al. atlas (1962) method and the age estimation of the left foot using the Pyle and Hoerr atlas (1969) method. There was no significant difference between either the slopes or intercepts. Additionally a Mann-Whitney t-test shows that there were no significant differences between the Greulich and Pyle (1959) and the RUS scoring method of the TW3 method (Table 9.2).

When the regression coefficients were compared for the male groups, all of the analyses except four were significantly different (Table 9.5). The age estimation of the left hand-wrist using the Greulich and Pyle atlas (1959) method and the age estimation of the left knee using the Pyle and Hoerr atlas (1969) method showed no significant differences between either the slopes or intercepts. Both the male left knee using the Pyle and Hoerr atlas (1969) and the male left foot using the Hoerr et al atlas (1962) showed no significant difference to the CBA method of the TW3 atlas (2001). There was also no

significant difference between the left foot analysis using the Hoerr *et al* atlas (1962) and the RUS method of the TW3 atlas (2001). The Greulich and Pyle atlas (1959) method and the TW3 (2001) method were compared previously using a Mann-Whitney t-test since they were both tested on the same set of radiographs (Table 9.4). There was no significant difference between either the Greulich and Pyle (1959) age estimation and the TW3 RUS (2001) scoring method or the Greulich and Pyle (1959) age estimation method and the TW3 CBA (2001) scoring method.

Female Mann-Whitney Comparison	Left hand-wrist (Greulich and Pyle, 1959)	Left hand-wrist RUS (TW3, 2001)	Left hand-wrist CBA (TW3, 2001)
Left hand-wrist (Greulich and Pyle, 1959)		No significant difference (P=0.570)	Significantly different (P=0.013)
Left hand-wrist RUS (TW3, 2001)	No significant difference (P=0.570)		Significantly different (P=<0.001)
Left hand-wrist CBA (TW3, 2001)	Significantly different (P=0.013)	Significantly different (P=<0.001)	

Table 9.2: Mann-Whitney U test comparison for Greulich and Pyle atlas (1959) and TW3 atlas (2001) for the female individuals.

Female	Left hand-wrist (Greulich and Pyle,1959)	Left hand-wrist RUS (TW3, 2001)	Left hand-wrist CBA (TW3, 2001)	Left elbow (Dimeglio et al, 2005)	Left knee (Pyle and Hoerr, 1969)	Left foot (Hoerr et al, 1962)
Left hand-wrist (Greulich and Pyle)				Significantly different P<0.0001	Significantly different P=0.0004	Significantly different P=0.0314
Left hand-wrist RUS (TW3)				Significantly different P<0.0001	Significantly different P<0.0001	Significantly different P<0.0001
Left hand-wrist CBA (TW3)				**NSD Pooled regression coefficient**	Significantly different P<0.0001	Significantly different P<0.0001
Left elbow (Brodeur et al)	Significantly different P<0.0001	Significantly different P<0.0001	**NSD Pooled regression coefficient**		Significantly different P<0.0001	Significantly different P<0.0001
Left knee (Pyle and Hoerr)	Significantly different P=0.0004	Significantly different P<0.0001	Significantly different P<0.0001	Significantly different P<0.0001		**NSD Pooled regression coefficient**
Left foot (Hoerr et al)	Significantly different P=0.0314	Significantly different P<0.0001	Significantly different P<0.0001	Significantly different P<0.0001	**NSD Pooled regression coefficient**	

Table 9.3: Showing the results of the comparisons between the regression coefficients for the different methods and body areas for the female groups (NSD=no significant difference).

Male Mann-Whitney comparison	Left hand-wrist (Greulich and Pyle, 1959)	Left hand-wrist RUS (TW3, 2001)	Left hand-wrist CBA(TW3, 2001)
Left hand-wrist (Greulich and Pyle, 1959)		No significant difference (P=0.857)	Significantly different (P=0.028)
Left hand-wrist RUS (TW3, 2001)	No significant difference (P=0.857)		Significantly different (P=0.024)
Left hand-wrist CBA (TW3, 2001)	Significantly different (P=0.028)	Significantly different (P=0.024)	

Table 9.4: Mann-Whitney U test comparison for Greulich and Pyle atlas (1959) and TW3 atlas (2001) for the male individuals.

Male						
	Left hand-wrist (Greulich and Pyle, 1959)	Left hand-wrist RUS (TW3, 2001)	Left hand-wrist CBA (TW3, 2001)	Left elbow (Dimeglio *et al* 2005)	Left knee (Pyle and Hoerr, 1969)	Left foot (Hoerr *et al,* 1962)
Left hand-wrist (Greulich and Pyle, 1959)				Significantly different P<0.0001	**NSD Pooled regression coefficient**	Significantly different P=0.0024
Left hand-wrist RUS (TW3, 2001)				Significantly different P<0.0001	Significantly different P=0.0339	**NSD Pooled regression coefficient**
Left hand-wrist CBA (TW3, 2001)				Significantly different P<0.0001	**NSD Pooled regression coefficient**	**NSD Pooled regression coefficient**
Left elbow (Dimeglio *et al,* 2005)	Significantly different P<0.0001	Significantly different P<0.0001	Significantly different P<0.0001		Significantly different P<0.0001	Significantly different P<0.0001
Left knee (Pyle and Hoerr, 1969)	**NSD Pooled regression coefficient**	Significantly different P=0.0339	**NSD Pooled regression coefficient**	Significantly different P<0.0001		Significantly different P=0.0004
Left foot (Hoerr *et al,* 1962)	Significantly different P=0.0024	**NSD Pooled regression coefficient**	**NSD Pooled regression coefficient**	Significantly different P<0.0001	Significantly different P=0.0004	

Table 9.5: Results of the comparisons between the regression coefficients for the methods and body areas for the male groups (NSD=no significant difference).

Arguably one of the best measures of accuracy for any age estimation method is the standard deviation of the method (Table 9.6) since it measures the spread of the variation around the mean, or expected value. When all of the methods are compared it can be seen that the atlas of Hoerr *et al.*(1962) for age estimation of the foot-ankle and the atlas of Pyle and Hoerr (1969) for age estimation of the knee had the smallest standard deviations of between 9.86 months and 10.75 months. Of the two sexes the female groups had the smallest standard deviation for both methods (9.95 months and 9.86 months) compared to the standard deviation of the male groups (10.19 months and 10.75 months). These were the only 2 standards in which the standard deviations were less than a year. The highest standard deviation was seen for the CBA (carpal bone) scoring method of the TW3 atlas (2001), 21.95 months for females and 18.70 months for males. The other standards ranged between 11.45 months and 16.54 months.

The mean differences between chronological age and estimated age were negative in five out of six methods for the female groups and for four out of the 6 methods for the male groups. Due to the method by which the calculations were undertaken the negative ages indicated an underage by the atlas method. The differences ranged between 2.16 months for the male Pyle and Hoerr atlas (1969) and -7.89 months for the Carpal scoring method of the TW3 atlas (2001).

Method	Side and body area	Female Mean difference (months)	Female standard deviation (months)	Male Mean difference (months)	Male standard deviation (months)
Greulich and Pyle (1959)	Left hand-wrist	-1.95	14.97	-1.63	14.16
TW3 RUS (2001)	Left hand-wrist	-0.81	20.43	-0.37	16.65
TW3 Carpal (2001)	Left hand-wrist	-6.42	23.31	-5.26	18.70
Hoerr *et al* (1962)	Left foot-ankle	-4.33	9.95	0.008	10.19
Pyle and Hoerr (1969)	Left knee	-1.6	9.86	2.16	10.75
Brodeur *et al* (1981)	Left elbow	-	-	-	-
Dimeglio *et al* (2005)	Left elbow	-0.13	11.45	-3.11	13.48

Table 9.6: The mean differences between chronological age and estimated age and standard deviations by sex, side and method of age estimation.

9.2 Breakdown of area by age cohort

The breakdown of the mean difference between the chronological age and estimated age for each sex and for each method is presented below. These tables show that for females (Table 9.7) the mean of the difference between the chronological age and estimated age is fairly evenly spread between over-aging (45.21%) and under-aging (54.79%). For males the pattern is different (Table 9.8). In the younger age groups, up until the age of 8 years, the majority of groups are underaged (77.42%) rather than overaged (22.58%). After the age of 8 years the groups are evenly spread between overaging (56.66%) and under-aging (43.33%).

Age Cohort (years)	Female Left Hand/Wrist Greulich and Pyle (1959)	Female Left Hand/Wrist TW3 RUS (2001)	Female Left Hand/Wrist TW3 CBA (2001)	Female Left Elbow Dimeglio et al (2005)	Female Left Elbow Broduer et al (1981)	Female Left knee Pyle and Hoerr (1969)	Female Left Foot Hoerr et al. (1962)
1	3 (n=3)	-4.3 (n=2)	4.0 (n=1)	-	77.78% (n=)	1.00 (n=5)	0.00 (n=5)
2	1.33 (n=3)	-	-	-	78.95% (n=19)	3.00 (n=1)	-0.50 (n=4)
3	4.33 (n=3)	18 (n=1)	14.40 (n=1)	-	80% (n=10)	-1.8 (n=5)	-3.40 (n=5)
4	-0.5 (n=6)	14.1 (n=2)	8.1 (n=2)	-	100% (n=11)	-13 (n=1)	-2.00 (n=3)
5	-	-	58.0 (n=1)	-	86.67% (n=15)	-9.25 (n=4)	-0.67 (n=6)
6	5.12 (n=8)	-2.15 (n=4)	3.0 (n=8)	-	41.67% (n=12)	1.00 (n=2)	-4.94 (n=18)
7	1.14 (n=8)	14.95 (n=7)	18.55 (n=4)	-	50% (n=12)	-5.78 (n=9)	-5.00 (n=5)
8	-4.67 (n=3)	-29.0 (n=1)	-8.5 (n=2)	17 (n=5)	75% (n=16)	8.4 (n=5)	-4.00 (n=10)
9	5.73 (n=11)	7.08 (n=5)	-1.8 (n=7)	11 (n=20)	73.19% (n=23)	-1.33 (n=3)	0.87 (n=16)
10	0.00 (n=19)	0.11 (n=8)	-3.44 (n=9)	-0.1 (n=19)	90% (n=20)	2.38 (n=13)	-1.95 (n=19)
11	1.67 (n=7)	6.7 (n=3)	-6.7 (n=2)	0.56 (n=18)	73.68% (n=19)	-1.04 (n=22)	-7.57 (n=14)
12	5.09 (n=11)	-0.72 (n=10)	-26.2 (n=5)	-3.82 (n=17)	61.11% (n=18)	-2.81 (n=16)	-12.10 (n=20)
13	5.06 (n=17)	3.13 (n=6)	-34.6 (n=5)	-10.47 (n=15)	43.75% (n=16)	-2.27 (n=22)	-2.78 (n=18)
14	0.20 (n=10)	-9.0 (n=4)	-35.1 (n=4)	-8.71 (n=7)	28.57% (n=7)	2.26 (n=19)	-2.00 (n=16)
15	4.2 (n=5)	-	-	-	0% (n=13)	1.57 (n=21)	-7.62 (n=16)
16	2.00 (n=10)	-26.0 (n=1)	-	-	0% (n=9)	-9.75 (n=20)	-
17	-7.86 (n=7)	-31.8 (n=1)	-	-	-	-	-
18	-10.83 (n=12)	-	-	-	-	-	-
19	-21.67 (n=6)	-	-	-	-	-	-
20	-30.70 (n=10)	-77.0 (n=1)	-	-	-	-	-

Table 9.7: Mean differences between estimated age and chronological age by year cohort and method for female groups.

Age Cohort (years)	Male Left Hand/Wrist Greulich and Pyle (1959)	Male Left Hand/Wrist TW3 RUS (2001)	Male Left Hand/Wrist TW3 CBA (2001)	Male Left Elbow Dimeglio *et al* (2005)	Male Left Elbow Brodeur *et al* (1981)	Male Left Knee Pyle and Hoerr (1969)	Male Left Foot Hoerr *et al.* (1962)
1	1.67 (n=3)	-	-	-	100% (n=10)		-9.00 (n=3)
2	0.0 (n=3)	-	-	-	93.33% (n=15)	-5.00 (n=2)	0.00 (n=8)
3	-5.00 (n=3)	-	-	-	100% (n=11)	5.00 (n=1)	-7.85 (n=13)
4	-6.17 (n=6)	5.0 (n=1)	6.00 (n=1)	-	89.47% (n=19)	0.00 (n=6)	-6.75 (n=8)
5	-4.43 (n=7)	-	-8.00 (n=1)	-	90% (n=20)	-3.8 (n=5)	-6.00 (n=2)
6	-10.0 (n=2)	-7.5 (n=2)	-14.33 (n=3)	-	95% (n=20)	-2.5 (n=8)	-3.11 (n=18)
7	-7.88 (n=8)	-5.6 (n=5)	-5.0 (n=5)	-	100%	-1.33 (n=6)	-3.71 (n=7)
8	-7.38 (n=8)	-12.2 (n=5)	-10.0 (n=4)	-	95% (n=20)	-0.42 (n=12)	-2.60 (n=15)
9	2.92 (n=12)	0.00 (n=5)	-5.67 (n=6)	20.67 (n=6)	93.75% (n=16)	0.53 (n=17)	-3.15 (n=13)
10	-0.2 (n=15)	0.00 (n=6)	-4.5 (n=6)	13.86 (n=7)	84.21% (n=19)	5.58 (n=19)	-0.53 (n=15)
11	-0.53 (n=17)	-2.67 (n=9)	-12.00 (n=9)	11.62 (n=16)	94.73% (n=19)	7.54 (n=22)	9.26 (n=23)
12	-0.94 (n=15)	1.91 (n=11)	1.73 (n=11)	12.77 (n=17)	95.45% (n=22)	5.05 (n=21)	5.08 (n=39)
13	1.62 (n=16)	11.29 (n=7)	11.14 (n=7)	4.41 (n=22)	79.17% (n=24)	8.81 (n=21)	-3.78 (n=18)
14	0.00 (n=18)	0.12 (n=8)	-9.11 (n=9)	1.68 (n=19)	100% (n=20)	4.23 (n=31)	0.13 (n=15)
15	7.09 (n=21)	-1.29 (n=7)	-	-8.85 (n=13)	70% (n=13)	3.44 (n=27)	-0.54 (n=11)
16	11.05 (n=19)	1.00 (n=10)	-	-18.67 (n=15)	11.76% (n=17)	0.14 (n=22)	4.10 (n=10)
17	2.52 (n=21)	-	-	-	-	-1.89 (n=19)	-1.30 (n=10)
18	-7.21 (n=19)	-	-	-	-	4.80 (n=15)	-9.00 (n=3)
19	-9.53 (n=19)	-	-	-	-	-9.6 (n=20)	0.00 (n=8)
20	-18.41 (n=17)	-	-	-	-	-	-7.85 (n=13)

Table 9.8: Mean differences between estimated age and chronological age by year cohort and method for male groups.

9.3 Discussion of comparison of all methods and skeletal areas

It is important to understand the accuracy of any age estimation method.   If a standard is to be utilised as a reference standard against which the development of the children of a population is to be judged then the accuracy of the method and its relationship to normal development is relevant. This becomes even more important when age estimations are being undertaken for forensic purposes since the ability to demonstrate the accuracy of a method and to justify its use in preference to an alternative method for court becomes important. This requirement is underlined by the Human Rights implications for the individual if an age estimation is undertaken which is inaccurate.

In 1944 Simmons argued that use of multiple areas in age estimation would increase the accuracy of any age estimation undertaken since she found that the mean standard deviation was reduced when the results of six body areas were combined (Simmons, 1944). This combination of body areas has not been taken up by practitioners who undertake age estimation in the living. This is partly because it would be necessary to take multiple images in order to examine other body areas resulting in an increase in exposure to potentially harmful radiation and partly because the case has not been proven with sufficient persuasiveness.

Garn *et al.,* (1967) compared the timings of appearance of ossification centres in order to examine the relationship between ossification timings of the hand-wrist and the remainder of the skeleton. They argue that in certain disorders there can be a large discrepancy between the maturity which is seen at the

hand-wrist and that seen in other body areas. They compared the timing of the appearance of ossification centres of the hand-wrist and those of other body areas to see if there was a correlation. They determined that there was only limited correlation between any of the ossification centres examined and those of the hand-wrist even though the hand-wrist area contributes a large number of ossification centres to those which were included in the study (Garn *et al.*, 1967). This study does however concentrate on the appearance of ossification centres and does not take into account any of the other changes which might be considered in an atlas. The authors suggest that this might increase the correlation of different body areas but also argue that it might equally have the opposite effect.

In the Brush Foundation Study, radiographic images were taken of 6 body areas; the hand-wrist, the elbow, the shoulder, the hip, knee and the foot-ankle. Todd compared these areas to assess the degree of difference in maturation between them and found that they '*all yield approximately the same rating of maturity..',* although if any area were found to be advanced it was most commonly that of the hand-wrist (Todd, 1937). In a test of these six areas he found that the hand-wrist gave the smallest standard deviation compared to the other five areas, although he did not specify what standard was used for the test. In the 1937 hand-wrist atlas he goes on to say that the use of the appearance times of ossification centres is misleading due to the extent to which they are influenced by environment and the health of the individual.

There have been a small number of other studies that have compared the development of body areas to understand the potential differences in maturation. Roche and French (1970) and Xi and Roche (1990) found that in some individuals there were large differences between the maturational stage of

the hand-wrist and the knee and that the age estimation of an individual could be considerably influenced by the body area which was assessed. In reality, since each body area is assessed using a different atlas, that is, their stage of skeletal maturation is assessed using different methods, it becomes difficult to separate out what represents a differing rate of skeletal maturation from the effects of the atlas which is used to assess that maturation. In most cases it is as much a comparison between atlases as it is a comparison between body areas, although Aircardi *et al.*(2000) recognise that this is an issue and argue that this is not the case since they found that their ages were similar in different body areas despite the use of different skeletal age assessment methods.

The comparison of the results of the linear regression analyses showed that, in addition to the positive relationship between Greulich and Pyle (1959) and TW3 (2001) atlas shown previously, for females there were two skeletal areas for which the methods do not significantly differ;

- Left elbow using the Sauvegrain *et al.,* (1962) method with the left hand-wrist using the TW3 CBA (2001) method
- Left knee using the Pyle and Hoerr (1969) atlas method with the foot-ankle using the Hoerr *et al.,* (1962).

For males there were 4 areas for which the methods do not differ significantly in addition to the positive relationship between the two hand-wrist atlases.

- Left knee using the Pyle and Hoerr atlas (1962) method and the left hand wrist using the Greulich and Pyle method (1959)
- Left foot using the Hoerr *et al.,* (1962) atlas method and the left hand wrist using the TW3 RUS method (2001)

- Left foot using the Hoerr *et al.,* (1962) atlas method and the left hand wrist using the TW3 CBA method (2001)

- Left knee using the Pyle and Hoerr atlas (1962) method and the left hand wrist using the TW3 CBA method (2001)

It is interesting that the knee has been shown to be compatible with other body areas for both sexes, although with different body areas. In common with the foot-ankle it has the lowest standard deviation of all the groups. It is possible that the fact that it agrees with different methods for each of the sexes may be due to the different rates of maturation which exist between females and males which means that different areas mature at different rates for each sex. For males the foot ankle is also compatible with the hand-wrist, albeit with the TW3 atlas method (2001). For the male group the elbow method of Sauvegrain *et al.,* (1962) is the only method which is significantly different to all of the other methods.

It should be noted that it is not possible to extrapolate these results to other age estimation methods for the same areas since the relationships are between the maturational rates which have been estimated using a specified method rather than between developments of the different body areas themselves.

One thing that stands out as a result of this comparison when looking at Table 9.7 and Table 9.8 is that for older females there is a limited choice in ageing methods. The Greulich and Pyle atlas (1959) is the only atlas method which allows age estimation up to 18 years of age. This limitation is not the same for male individuals since their growth period is generally longer.

This comparison of body areas and the methods used to age estimate individuals using the identified methods gives the forensic practitioner a starting

point from which to work and from which to decide which age estimation method is most appropriate. A number of methods, including those which appear to be more accurate, using the criteria presented in this study, have a restricted age range, especially for female individuals. The upper age ranges of the knee atlas and the foot-ankle atlases for the female groups are between 15 and 16 years of age rendering them ineffective when faced with the question of whether an individual has passed the age of 18 years of age. This is not the case with male individuals where both the knee atlas (1969) and the atlas of the foot-ankle (1962 give the same ability to age older individuals as is found in the Greulich and Pyle Hand-wrist atlas (1959).

10 Procedures and Protocols

The main aim of this study was to examine the accuracy and reliability of a number of radiographic age estimation methods, providing robust statistical data which can be applied to the use of any of these methods in forensic age estimation and subsequently placed before a court of law. It has become evident that the information from this study can be used to inform protocols which can guide good practice when forensic age estimation is undertaken using radiographic data. Schmeling *et al.,* (2001) have shown that the combination of a hand-wrist radiograph, imaging of the medial clavicles for those suspected of being over 18 years of age and an orthopantomogram provide practitioners with sufficient information to undertake an age estimation which is robust enough to place before a court of law. The information and the protocols as an output from this study do not replace these, but aim to both support and augment them. The reality which underpins age estimation practices in many countries, including the UK, are the limitations placed upon the use of radiographs and CT scans. Whilst it is legal to use these imaging modalities for age estimation the need for consent and the potential harmful effects mean that there is an understandable reluctance on the part of many to enforce this approach to age estimation.

10.1 Choice of method and image

The choice of method followed will be affected both by the sex of the individual to be age estimated and their suspected or claimed age.

10.1.1 Females

It is clear from the comparison of methods that there is a limit to the availability of effective age estimation methods for females who are over the age of 15 years of age. Up until this age this study shows that the use of radiographs of any of the skeletal areas of the body; hand-wrist, knee or foot is appropriate and use of elbow radiographs should be undertaken with the caveats listed below.

For female individuals who are suspected to be between 15 and 18 years of age the only age estimation method that can be used is that of Greulich and Pyle (1959). In the below 15 year old age groups, the knee atlas of Pyle and Hoerr (1969) and the foot-ankle atlas of Hoerr *et al* (1962) proved to be the most accurate of all the methods. For the hand-wrist both the Greulich and Pyle atlas (1959) and the RUS method from the TW3 atlas (2001) were both accurate but there are potential errors inherent in the TW3 RUS method which means that if an individual is suspected to be over 15 years of age this method should not be used.

This study found that the Greulich and Pyle (1959) and the RUS method of the TW3 atlas (2001) complement each other and it would be good practice to use both if an individual is suspected to be 15 years of age or younger. If there is any suspicion at all that the individual is older than 15 then the TW3 atlas (2001) should not be used. The TW3 CBA method (2001) should not be used for age estimation in females. The elbow method of Sauvegrain *et al* (1962) is accurate over a very limited age range. This range is so limited that this method should only be used as a support for the Brodeur *et al* (1981) atlas method if an individual is suspected to fall into the indicated age range for this method, i.e. between 9 and 13 years of age. In relation to age estimation of

female individuals the reduction in accuracy of the Broduer *et al* (1981) atlas method in the 6 and 7 year age groups and then again in the 12-14 year age groups counter-indicates the use of this method for children who are suspected to fall into these age ranges until further work has been undertaken, although for the 12-14 year old individuals the revised Sauvegrain *et al.,* (1962) method can support the age range given. As a result of these periods of reduced accuracy the use of the elbow and the methods tested here is not recommended for females if it can be avoided.

10.1.2 Males

The choice of methods for male individuals is a little different. There are three age estimation methods which are appropriate for use in individuals who are suspected to be over the age of 16 years. Up until this age, as with the female individuals any of the 4 skeletal areas could be used. There are differences in the accuracy of these methods and whilst all fall within acceptable limits, those of the lower limb are the most accurate. For the majority of the methods tested on the male groups the majority had the tendency to underage in the under 8 year old age groups and overage in the over 8 year old age groups so this has to be taken into account when any age estimation is undertaken. If hand-wrist radiographs are used, then the Greulich and Pyle atlas (1959) is appropriate but good practice indicates that age estimation should also be undertaken using the TW3 atlas (2001) if an individual is suspected of being 16 years of age or under. The TW3 atlas should never be used if there is suspicion that the individual is over 16 years of age. The recommendation is that the TW3 CBA method is not used for male individuals.

The method of choice for the analysis of elbow radiographs for the male group is the Brodeur *et al* atlas (1981) but these should not be used if an individual is suspected to be older than 15 years of age. For the analysis of elbow radiographs of an individual who is suspected to be between 10 and 15 years of age the Brodeur *et al* atlas (1981) method can be supplemented by the use of the revised Sauvegrain *et al* (1962) method.

This study has shown that the use of hand-wrist, knee and foot-ankle radiographs are all appropriate for age estimation, subject to the limitations already mentioned. If images are already in existence, the hand-wrist image specified by Schmeling *et al* (2008) can be replace by radiographs of either the knee or the foot-ankle or the elbow, although their protocols in relation to the inclusion of an orthopantomogram and image of the medial clavicles should still be followed. This leads to a recommendation that when possible, medical records should be checked to locate images which might already be in existence, both CT and X-ray. This is less pertinent to an individual who may only just be crossing the border into the country but is relevant to those who have resided in the country for any period of time. There were 46 million X-rays and 1.4 million CT scans taken in 2008 which provides a large potential archive of information (Agency, 2012). This may reduce the need to expose individuals to unnecessary imaging.

10.2 Orientation of the image

Whilst it has been shown that it is possible to analyse right images with the Greulich and Pyle atlas (1959) method this study shows that rotating the image about the vertical axis increases the accuracy of the analysis for hand/wrist

radiographs. The findings indicate that the use of images of the right side of the body is acceptable but that it is good practice to mirror the image so that it is in the same orientation as those shown in the atlas.

10.3 Protocol

- Any age estimation should only be performed by a practitioner who is familiar with the application of the age estimation method

- For an individual who is already in the country recommendations should be made to check for the existence of previous medical radiographs before radiographs are taken for the sole purpose of age estimation.

- The combination of age estimation images should follow the protocols suggested by Schmeling *et al.,* (2001) but images of the knee, foot-ankle or elbow can be substituted for that of the hand-wrist under the correct circumstances.

- Right hand-wrist images can be used with no reduction in accuracy so long as they are mirrored to lie in the same plane as the images in each atlas

- If an atlas has anterior-posterior images as well as lateral images both should be viewed when undertaking age estimation.

- The sex and 'claimed' age of the individual must be taken into account when deciding on a method. This varies between females (Table 10.1) and males (Table 10.2).

- The method adopted should be indicated clearly in any report and the age range presented should be to no less than 2 standard deviations

Female					
Age Group (years)	Greulich and Pyle (1959)	TW3 RUS (2001)	Brodeur *et al* (1981)	Pyle and Hoerr (1969)	Hoerr *et al* (1962)
0-5	√	√	√	√	√
5-10	√	√	x	√	√
10-15	√	√ [20]	√ [21]	√	√
15-20	√	x	x	x	x

Table 10.1: Choice of method for female individuals.

Male					
Age Group (years)	Greulich and Pyle (1959)	TW3 RUS (2001)	Brodeur *et al* (1981)	Pyle and Hoerr (1969)	Hoerr *et al* (1962)
0-5	√	√	√	√	√
5-10	√	√	√	√	√
10-15	√	√	√ [22]	√	√
15-20	√	x	x	√	√

Table 10.2: Choice of method for male individuals.

---

[20] (with caution if individual claims 14 years and over)
[21] (with caution if individual is suspected of being over 14 years of age and in combination with the revised Sauvegrain *et al* method for individuals who might be 11 years of age or older)
[22] (not if individual is suspected to be over 14 years of age)

11 Discussion

Age estimation in the living is receiving a higher profile and is increasing in importance, not just in the UK but on a worldwide basis. At the centre of the debate are individuals, often children, who for a large number of reasons are unable to prove their chronological age to the satisfaction of the authorities. Depending on the circumstances, this can cause problems with; appropriate resource allocation and access, age appropriate consequences for those committing criminal offences and fair access to justice for victims. An error in estimation of chronological age can have serious human rights implications for the child. It is vital that for this reason alone, work is undertaken to assess and reassess the techniques utilised in the estimation of age in the living. In the UK this imperative is further driven by the recently published Law Commission Report (2011) which emphasises that only credible expert witness testimony should be presented to the court. This places an additional responsibility on the forensic expert and drives the need to ensure that the methods that are used are regularly revisited and updated. The rationale for this project is therefore rooted in the requirement to constantly examine and assess forensic methodologies to ensure the validity of the conclusions which are placed before a court of law.

Age disputes and cases involving individuals whose age is questioned have increasingly come to the attention of the court system. This has resulted in a concomitant increase in case law in relation to the issue of age estimations and recognition by the courts that '*the reality is that there are no reliable means*

whereby an exact conclusion can be reached.[23] Because of individual variation and the effects of the environment on development and growth this remains the case, however this body of work provides information about the accuracy, reliability and validity of a series of methods which can be, and are applied to assist in forensic age estimations.

Age estimation in the living relies on the analysis of a number of skeletal areas, taking into account the factors which can affect the timing of the changes seen in the observed areas. This project takes a close look at the methods used to estimate age through the analysis of change within the skeleton as an individual progresses through childhood and into adulthood. These changes have been identified, recorded and agreed upon by researchers. Each study has demonstrated that whilst small differences might exist between individuals the pattern of the skeletal changes remains constant. It is because of this constancy that it is possible to identify sequential changes and maturity indicators which occur as an individual grows.

The original work which was undertaken to understand these changes and to identify these indicators was undertaken directly on skeletal material and as such presented a snapshot of development. Commonly the children studied had suffered illness and poor nutrition which made them susceptible to a high mortality rate, making their tissues available for study. The invention and adaptation of radiographs meant that information on skeletal changes was not reliant on the direct observation of skeletal material, indeed it meant that information could be gathered from children who were in the process of growing

---

[23] *A v London Borough of Croydon & SSHD; WK v SSHD & Kent County Council* [2009] EWHC 939

and developing. This represented a major step forward in access to relevant and current information.

Franz Boas was the first to identify the physical changes that occur within populations during the passage of time and generations (Tanner, 1959). As early as 1891 he argued that longitudinal studies were the best way to study people and the changes that they undergo. It was not until the 20th century that the will to undertake these studies came together with sufficient funding sources to enable these expensive and time consuming data gathering studies to be embarked upon. Garn describes this time as the '*growth of growth*' during which an increasing number of these studies were instigated, the majority of which were based in North America although others were undertaken in other parts of the world (Garn, 1981).

These studies took regular anthropometric data from children at set intervals. For many studies this data collection included the collection of radiographic data of one or more skeletal areas. Not only does this mass of data form an invaluable source of information on child development, a number of studies also used the radiographic data to develop radiographic atlases of skeletal development. These atlases used the radiographs of children of known chronological age to identify maturity indicators which are in turn linked to the chronological age at which they appear and disappear. This association between maturity indicators and chronological age in turn leads to the premise that these identified changes can be used to predict the age of any child who has reached the same stage of development.

The process of predicting chronological age from biological maturation therefore rests on the principle that the two are linked in such a way that one can be

extrapolated from the other. This principle is one that has led practitioners to take the radiographic atlases which were devised from the information gathered during longitudinal studies and apply them as a method of age estimation in both the living and the deceased, a process for which they were never originally designed. The original authors of the atlases created them as a means of demonstrating the skeletal changes which occur during the maturational period and which could be used as a baseline to predict and measure the maturational progress of children.

This change in application from presenting a 'norm' against which children can be compared to one of a standard for forensic age estimation, brought about by the needs of the forensic community means that the use of any of the atlases for forensic purposes is open to challenge. The Law Commission Report (2011) argues that one of the measurements of reliability which in turn allows evidence to be admitted into court is that '*the evidence is predicated on sound principles, techniques and assumptions'.* This lays the burden of proof on the expert to demonstrate that the methods that they are using are appropriate for the conclusions that are drawn from application of that technique. This is only possible through rigorous testing of each method to demonstrate that it is valid, accurate and reproducible when applied.

There are a number of reasons why there might be a discrepancy between chronological age and estimated age. These fall into two broad categories; firstly there is the influence of the individual which includes the impact of natural variation which exists between individuals in relation to their rate of skeletal development and the influence of environment on skeletal maturation and secondly the potential error introduced by the assessment method itself and the error which the observer introduces to the application of that method. In the

case of age estimation atlases which were developed using data from populations of the early to mid-20th century. There is also a third set of factors to be taken into consideration and that is the issue of secular change and population differences. These cover the changes which have occurred within a population since the time of the development of the atlas plus the issue that the atlas is used to estimate the age of children from populations which differ both geographically, ethnically and in socioeconomic background. A majority of the literature, of which there is a large amount, in which many of the atlases feature, utilise them for the purpose for which they were originally designed. The atlases form a standard against which child development is measured, often to investigate the 'health' of a population or to examine the development of a target group, such as children with a specified disorder. It is only in recent years that work has been undertaken to examine the accuracy of the atlases in relation to forensic age estimation and whilst the number of publications is increasing in response to the requirements of forensic practice there is still work that needs to be done in order to ensure that techniques can be presented in court as a method underpinned by statistical robustness. This study adds to the data which has accumulated and continues to accumulate on the accuracy of the atlas methods in relation to specific populations and in turn informs work which is presented in court.

11.1 The data

By necessity this study was undertaken through the examination of radiographic data. Anterior-posterior and lateral radiographs of four skeletal areas were examined in relation to the relevant ageing standards. Despite the seeming fluidity of this method of data collecting, until further, later radiographs are taken

of the same area and of the same person, one radiograph is '*..an objective record of the maturity status of the skeleton at a single point in time and as such represents the sum of all events prior to the time that the X-Ray was taken*' (Malina, 1971). The information therefore is cross-sectional in nature.

As Malina (1971) points out and later authors have repeated, every test of an age estimation method has to be able to describe the population upon which is it performed in order for those assessing its relevance to be able to understand the background of the individuals tested. For this study the population from which the radiographs were sourced is a modern one based in the North-East of Scotland. Whilst the data gathered was screened for disorders and previous trauma it was not possible to monitor the backgrounds of the individuals in any great detail or to gather background information on the individuals involved. The population sample was therefore formed from a cross-section of the population who only had their visit to A&E at Ninewells in common. This type of population is far removed from the ones who formed the basis of those involved in the longitudinal studies whose health and nutritional intake was monitored during the period of their participation. Despite this the dataset is arguably similar to the mixture of individuals who present for forensic age estimation and therefore is a reasonably realistic test of the methods analysed.

The restrictions placed upon the project by the data collection method have to be acknowledged. As noted this data is cross-sectional in nature, it has been shown that the examination of cross sectional data can cause issues in ageing studies since it can cause statistical errors in relation to events such as the pubertal growth spurt. This is due to the variation which exists between individuals in the timing of the start, duration of and age of cessation of the increased period of growth. Similarly the examination of cross sectional data

does not allow repeated examination of radiographs which would give an understanding of how the atlases would continue to behave in relation to the same person over time. In a forensic situation this is also the case. The analysis of a single radiograph is undertaken with no knowledge of the relevant point of development which an individual has achieved.

As with many studies there are generally a lower number of radiographs of female individuals available in comparison to the number of male individuals. This is a reflection of the data collection method which relied on the attendance of individuals at the Accident and Emergency department with suspected injuries. Boys are more likely to be involved in direct contact sports and take part in risky behaviours and are therefore more prone to the types of injury which result in a visit to A&E and investigation of potential injury through the use of radiographs. The data collection method also means that there are fewer individuals in the younger age groups due to their limited activity levels combined with higher supervision levels from adults.

11.2 Accuracy of the methods

The most commonly used age estimation atlas is the Greulich and Pyle atlas of 1959. The rationale for testing this and the other atlas methods is to begin to establish a statistically robust body of work which can inform the conclusions of forensic practitioners involved in age estimation in the living and who will be presenting these conclusions before a court of law. This call for a sound statistical underpinning to any work which is being put before the court is strengthened by the Law Commission Report (2011), although the human factor involved in age estimation of the living should never be trivialised or ignored.

Whilst the hand-wrist is the preferred image for forensic age estimation, there is no getting away from the fact that radiographic imaging is potentially harmful and required consent is mandatory in order for images to be taken for age estimation purposes. If consent is not forthcoming to avoid the ethical issue of exposure to harmful radiation it is conceivable that X-Rays which have been taken for other purposes are appropriate for use in age estimation. This study provides statistical information into other age estimation methods in addition to those which are more commonly used for age estimation from the hand-wrist. The result of this study supports the use of these radiographs and the age estimation methods which are available to predict age from these different anatomical areas.

This study aimed to prove whether a method is accurate and reliable enough to be used for forensic purposes but also to provide an idea of the relationship between skeletal age as predicted by the identified age estimation standard and the chronological age for this population. This relationship will allow any age estimation which is undertaken to take into account the differences which exist between chronological age and estimated age for a specific atlas. For example, the Greulich and Pyle hand-wrist atlas (1959) method tended to overage both females and males after the onset of puberty until the ages of 17 and 18 years of age respectively. Standard deviations have been calculated for each atlas except the Brodeur *et al* atlas (1981) for which these calculations were not possible. It was possible however to demonstrate expected accuracy rates and demonstrate the potential for agreement between observers.

Standard deviations have also been calculated for each of the methods, with the exception of the Brodeur *et al.* atlas (1981) method. Good practice suggests that any age estimation should be provided as an age range. This

age range should be given to +/- 2 standard deviations. Except in the case of the TW3 CBA scoring method (2001) the greatest standard deviation was 16.54 months, using this protocol this gives an age range of 66.16 months (5 years 6 months). This range falls well within the acceptable range for forensic age estimations whilst allowing for most normal individual variation (Rosing and Kvaal, 1997).

All of the atlas methods are based upon the identification of maturity criteria which are linked to a chronological age. The results of this study show that all of the age estimation methods with the exception of the TW3 CBA scoring method (2001) performed well when tested on this Scottish population.   This indicates that for these methods and this population the links between chronological age and the maturity criteria identified in the ageing methods tested are strong except when carpal bone age is assessed independently.

This study supports the use of all methods which have been tested with the exception of the TW3 CBA method (2001). Whilst this performed better for the male group rather than the female group it did not perform as well as the TW3 RUS method (2001) which is sufficiently accurate to stand alone.

11.3 Relationship between the methods and body areas

Despite the strong relationship between chronological age and estimated age which has been demonstrated for these atlases on this population there are limited, if any, relationships with each other. There may be a number of reasons for this but, in a study of this nature it is not possible to separate whether these results are influenced by the different methods used in the age estimations, or are the result of differing or indeed, similar rates of maturation between different body areas. There are varying views on this in the literature and this study does not assist in clarifying this. Whilst there are a limited number of atlas methods for which there are no significant differences when compared to each other, with the exception of the TW3/RUS method (2001) and the Greulich and Pyle method (1959), these are not consistent across the sexes. The results of the age estimation with the knee atlas method of Pyle and Hoerr (1969) shows no significant difference with the Dimeglio *et al.,* (2005) version of the Sauvegrain *et al.,* (1962) method of age estimation for females and for the male group it shows no significant difference in relation to the Greulich and Pyle atlas. There are limitations for both the Dimeglio *et al.,* (2005) version of the Sauvegrain *et al* (1962) method and the knee atlas of Pyle and Hoerr (1969) for the female group, since both are limited by the age ranges for which the atlases are appropriate. The methods which are appropriate for the male group do not demonstrate the same limitations since both are capable of age estimation in older individuals.   Further testing is required before a strong recommendation can or should be made to combine these analyses since unless radiographs have been taken for other reasons and are therefore already in existence the use of multiple X-rays involves extra exposure to

potentially harmful imaging techniques. Given the potential for the use of these standards on different imaging modalities in addition to radiographs such as MRI it may at some future point be possible to combine these body areas however this should be considered with care and not before further rigorous testing has taken place.

11.4 Repeatability of the methods

All of the methods underwent inter and intra-observer testing and the results were subject to statistical analysis. There were two second observers. The first undertook the inter-observer tests on the hand-wrist radiographs and the knee radiographs and the second undertook the inter-observer tests for the foot and elbow radiographs. Both observers had training in physical anthropology and anatomy and in each case had a small amount of experience in reading radiographs. Additionally the first was familiar with reading radiographs but had only a familiarity rather than an in-depth knowledge of the atlas methods whereas the second was familiar with radiographs and had experience with the foot-ankle atlas of Hoerr *et al.,* (1962)

For the inter-observer tests there were good correlations between the original observer and the second observer for all of the methods. The poorest correlations were found for the TW3 CBA scoring method. There were also good correlations between age estimations which were undertaken on different occasions by the same observer. These results indicate that these methods remain accurate between observers.

11.5 The Atlases

This study has provided an indication that the radiographic methods of assessing skeletal age which were developed in the 20th century are appropriate for use on a modern population in the early 21st century. At the forefront of this research is the fact that the outcome of any age estimation which is undertaken for forensic or humanitarian purposes has serious consequences. For this reason the research into age estimation methods must remain dynamic whilst maintaining a solid research and statistical base. It is not possible to ever recreate the data collection methods which formed the basis for the creation of many of the radiographic atlases which were tested here but this does not mean that it is not possible to collect enough data to begin to modernise and make available datasets which are appropriate for use as modern standards. Socio-economic factors are the most important for determining the rate of skeletal development. By taking a cross section of the population in a Scottish city, this study has shown that for an individual who has experienced or been experiencing access to the resources which are available in Scotland the use of these atlases for age estimation is appropriate.

The one issue which is raised repeatedly in the literature is the need for population specific standards. One of the questions raised by the examination of the standards in existence is how future standards should be presented to ensure ease of use coupled with reliability and accuracy. This study did not demonstrate that the scoring methods devised by both Tanner *et al* (2001) or Sauvegrain *et al.,* (1962) were more accurate than the available comparison methods for the relevant skeletal areas. Whilst the scoring methods took slightly longer to perform than the same age estimation undertaken using the

Greulich and Pyle atlas (1959), this was a matter of minutes and in a forensic scenario, accuracy and reliability are paramount when choosing a method and speed is subservient to accuracy. The atlas methods which combined the most user-friendly approach with the greatest accuracy were demonstrated to be the comparison method atlases created from the Brush Study. The atlas method given by Brodeur *et al.,* (1981) was time consuming and at times confusing to use and gave no appreciable increase in accuracy.

The recommendation is that the design of future standards is based on the comparison method with the presentation of the image which is 'most representative' of each stage of maturity which in turn is related to a chronological age. All of the standards studied were successful due to the robust identification of maturity criteria both in images and written description which accompanied each image and this should continue. Consideration should also be given to the inclusion of the appearance of individuals who are identified as being at either end of the developmental range identified by 2 standard deviations. For example if the standard deviation is 14 months, images which show the expected stage of maturity expected at 28 months older and younger than the identified age.

11.6 Recommendations

This study explored the validity of 6 age estimation methodologies in relation to a modern population. The results of the statistical analysis indicate that all of the methods tested, with the exception of the TW3 CBA scoring method, are appropriate for use as forensic age estimation methods on this modern population. The question will always remain however, whether or not they are

applicable to individuals who are not originally from the North-East of Scotland. Given the arguments put forward by Schmeling *et al.,* (2000; 2006d) and others in relation to the importance of socioeconomic influence on growth and age estimation techniques there is the potential that with care and due cognisance of the limitations this is possible. Many forensic age disputes occur after an individual has resided in the UK for a long period of time, often in many cases for years, giving them access to the same resources, health care and nutritional intake as is available to the children whose radiographs were included in this study. Given the plasticity of growth and the proven ability of children to experience 'catch-up' growth, albeit to varying degrees dependent on age the standards should remain applicable, added to this is the argument from Schmeling *et al.,* (*2006d)*, that since the effect of poor nutrition and high disease burden is to slow skeletal development this ensures that in forensic situations any error caused by these factors acts in the favour of the child. This is echoed in common law by Mr Justice Collins[24] who stated that in relation to age estimation techniques by experts '*..perfection is unattainable and the approach adopted by the Secretary of State that, if the decision maker is left in doubt, the claimant should receive the benefit of that doubt is undoubtedly proper'*

---

[24] *A v London Borough of Croydon & SSHD; WK v SSHD & Kent County Council* [2009] EWHC 939

12 References

Acharya, A. B. 2011. Age Estimation in Indians Using Demirjian's 8-teeth Method. *Journal of Forensic Sciences,* 56**,** 124-127.

Acheson, R. M. 1954. A method of assessing skeletal maturity from radiographs. A report from the Oxford Child Health Survey. *Journal of Anatomy,* 88**,** 498-508.

Acheson, R. M. 1957. The Oxford method of assessing skeletal maturity. *Clinical Orthopaedics* 10**,** 19.

Acheson, R. M., Fowler, G. B., Fry, E. I., Janes, M. D., Koski, K., Urbano, E. & Van der Werff, J. J. 1963. Studies in the reliability of assessing skeletal maturity from x-rays, Part I. Greulich and Pyle Atlas. *Human Biology,* 35**,** 317-349.

Acheson, R. M. & Zampa, G. A. 1961. Skeletal maturation in ovarian dysgenesis and Turner's syndrome. *The Lancet,* 277**,** 917-920.

Agency, H. P. 2012. Available: http://www.hpa.org.uk/NewsCentre/NationalPressReleases/2011PressReleases/110104scaleofxrayexposurerevealed/ [Accessed 24th February 2012].

AGFAD. 2011. *Study Group in Forensic Age Diagnostics of the Germal Association of Forensic Medicine* [Online]. [Accessed 5th February 2012].

Agnihotri, A. K., Purwar, B., Googoolye, K., Agnihotri, S. & Jeebun, N. 2007. Estimation of stature by foot length. *Journal of Forensic and Legal Medicine,* 14**,** 279-283.

Ahmed, M. L. & Warner, J. T. 2007. TW2 and TW3 bone ages: time to change? *Archives of Disease in Childhood,* 92**,** 371-372.

Aicardi, G., Vignolo, M., Milani, S., Naselli, A., Magliano, P. & Garzia, P. 2000. Assessment of skeletal maturity of the hand-wrist and knee: A comparison among methods. *American Journal of Human Biology,* 12**,** 610-615.

Akridge, M., Hilgers, K. K., Silveira, A. M., Scarfe, W., Scheetz, J. P. & Kinane, D. F. 2007. Childhood obesity and skeletal maturation assessed with Fishman's hand-wrist analysis. *American Journal of Orthodontics and Dentofacial Orthopedics,* 132**,** 185-190.

Allen, G. M. & Wilson, D. J. 2007. Ultrasound in sports medicine--A critical evaluation. *European Journal of Radiology,* 62**,** 79-85.

Allison, W. 2009. *Radiation and Reason,* York, York Publishing Services.

Altinay, R. E. 2009. "This Child , Whose Bone Age is Fourteen..." Ethical Dimensions of Skeletal Age Assessment. *The International Journal of Feminist Approaches to Bioethics,* 2**,** 165-173.

Andersen, E. 1971. Comparison of Tanner-Whitehouse and Greulich-Pyle methods in a large scale Danish survey. *American Journal of Physical Anthropology,* 35**,** 373-376.

Anderson, M., Blais, M. & Green, W. T. 1956. Growth of the normal foot during childhood and adolescence; length of the foot and interrelations of foot, stature, and lower extremity as seen in serial records of children between 1-18 years of age. *American Journal of Physical Anthropology,* 14**,** 287-308.

Attallah, N. L. & Marshall, W. A. 1989. Estimation of chronological age from different body segments in boys and girls aged 4-19 years, using anthropometric and photogrammetric techniques. *Medicine Science and Law,* 29**,** 147-55.

Baer, M. J. & Durkatz, J. 1957. Bilateral asymmetry in skeletal maturation of the hand and wrist: A roentgenographic analysis. *American Journal of Physical Anthropology,* 15**,** 181-196.

Bailey, S. M., Gershoff, S. N., McGandy, R. B., Nondasuta, A., Tantiwongse, P., Suttapreyasri, D., Miller, J. & McCree, P. 1984. A longitudinal study of growth and maturation in rural Thailand. *Human Biology,* 56**,** 539.

Bajaj, I. D., Bhardwaj, O. P. & Bhardwaj, S. 1967. Appearance and fusion of important ossification centres; a study in Delhi population. *Indian Journal of Medical Research,* 55**,** 1064.

Barrett, J. H. 1936. The union of certain epiphyses in a mixed female population in Rangoon. *Journal of Anatomy,* 70**,** 432-434.

Bassed, R. B., Briggs, C. & Drummer, O. H. 2011. Age Estimation and the Developing Third Molar Tooth: An Analysis of an Australian Population Using Computed Tomography. *Journal of Forensic Sciences,* 56**,** 1185-1191.

Baumann, U., Schulz, R., Reisinger, W., Heinecke, A., Schmeling, A. & Schmidt, S. 2009. Reference study on the time frame for ossification of the distal radius and ulnar epiphyses on the hand radiograph. *Forensic Science International,* 191**,** 15-18.

Behrents, R. G. & Broadbent, B. H. 1984. *A chronological account of the Bolton-Brush growth studies - in search of truth for the greater good of man* [Online]. Cleveland, Ohio: The Bolton-Brush Growth Study Center. Available: http://dental.case.edu/bolton-brush/background.html [Accessed 16th January 2012].

Belli, D. C., Seidman, E., Bouthillier, L., Weber, A. M., Roy, C. C., Pletincx, M., Beauliei, M. & Morin, C. L. 1988. Chronic intermittent elemental diet improves growth failure in children with Crohn's disease. *Gastoenterology,* 94**,** 603-610.

Berst, M. J., Dolan, L., Bogdanowicz, M. M., Stevens, M. A., Chow, S. & Brandser, E. A. 2001. Effect of knowledge of chronological age on the variability of pediatric bone age determined using the Greulich and Pyle standards. *American Journal of Roentgenology,* 176**,** 507-510.

Bhabha, J. & Finch, N. 2006. Seeking Asylum Alone. *In:* RIGHTS, H. C. O. H. (ed.) *Refugee Council.*

Bhat, V. J. & Kamath, G. P. 2007. Age Estimation From Root Development of Mandibular Third Molars in Comparison With Skeletal Age of Wrist Joint. *American Journal of Forensic Medicine and Pathology.,* 28**,** 238-241.

Billmann, F. & Minor, J. M. L. 2007. Secondary centers of ossification of the human toes: Exceptional polymorphism and evolutionary perspectives. *American Journal of Physical Anthropology,* 132**,** 110-118.

Black, S. M., Aggrawal, A. & Payne-James, J. 2010. *Age Estimation in the Living: The Practitioner's Guide,* Oxford, Wiley-Blackwell.

Blankenship, J. A., Mincer, H. H., Anderson, K. M., Woods, M. A. & Burton, E. L. 2007. Third Molar Development in the Estimation of Chronologic Age in American Blacks as Compared With Whites. *Journal of Forensic Sciences,* 52**,** 428-433.

Bogin, B. 1988. *Patterns of Human Growth,* Cambridge, Cambridge University Press.

Bogin, B. & Macvean, R. B. 1982. Ethnic and secular influences on the size and maturity of seven year old children living in Guatemala City. *American Journal of Physical Anthropology,* 59**,** 393-398.

Bogin, B. & Rios, L. 2003. Rapid morphological change in living humans: implications for modern human origins. *Comparative Biochemistry and Physiology - Part A: Molecular & Integrative Physiology,* 136**,** 71-84.

Bolton, S. 2011. 'Best interests': safeguarding and promoting the welfare of children in immigration law and practice. *In:* WOODALL, L. (ed.) *Working with Refugee Children.* London: Immigration Law Practitioners' Association.

Brabston, E. W., Genuario, J. W. & Bell, J. E. 2009. Anatomy and physcial examination of the elbow. *Operative Techniques in Orthopeadics,* 19**,** 190-198.

Brenner, D. J., Doll, R., Goodhead, D. T., Hall, E. J., Land, C. E., Little, J. B., Lubin, J. H., Preston, D. L., Preston, R. J., Puskin, J. S., Ron, E., Sachs, R. K., Samet, J. M., Setlow, R. B. & Zaider, M. 2003. Cancer risks attributable to low doses of ionizing radiation: Assessing what we really know. *Proceedings of the National Academy of Sciences of the United States of America,* 100**,** 13761-13766.

British Broadcasting Corporation. 2008a. *Canada Coroner Condemns Foot Hoax* [Online]. Available: http://news.bbc.co.uk/1/hi/world/americas/7462953.stm [Accessed 5th January 2012 2012].

British Broadcasting Corporation. 2008b. *Fifth Human Foot Found in Canada* [Online]. Available: http://news.bbc.co.uk/1/hi/world/americas/7458468.stm [Accessed 5th January 2012 2012].

British Broadcasting Corporation. 2008c. *'Foot' Discovered on Canada Shore* [Online]. Available: http://news.bbc.co.uk/1/hi/world/americas/7726165.stm [Accessed 5th January 2012 2012].

Brodeur, A. E., Silberstein, M. J. & Gravis, E. R. 1981. *Radiology of the Pediatric Elbow,* Boston, G.K. Hall Medical Publishers.

Brogdon, B. G. & Lichtenstein, J. E. 1998. Forensic Radiology in Historical Perspective. *In:* BROGDON, B. G. (ed.) *Forensic Radiology.* Bacon Rouge: CRC Press.

Bűken, B., Bűken, E., Safak, A. A., Yazici, B., Erkol, Z. & Mayda, A. S. 2008. Is the "Gok Atlas" sufficiently reliable for forensic age determination of Turkish children? *Turkish Journal of Medical Sciences,* 38**,** 319-327.

Büken, B., Erzengin, Ö. U., Büken, E., Safak, A. A., YazIcI, B. & Erkol, Z. 2009. Comparison of the three age estimation methods: Which is more reliable for Turkish children? *Forensic Science International,* 183**,** 103.e1-103.e7.

Büken, B., Safak, A. A., YazIcI, B., Büken, E. & Mayda, A. S. 2007. Is the assessment of bone age by the Greulich-Pyle method reliable at forensic age estimation for Turkish children? *Forensic Science International,* 173**,** 146-153.

Bull, R. K., Edwards, P. D., Kemp, P. M., Fry, S. & Hughes, I. A. 1999. Bone age assessment: a large scale comparison of the Greulich and Pyle, and Tanner and Whitehouse (TW2) methods. *Archives of Disease in Childhood,* 81**,** 172-173.

Calfee, R., Sutter, M., Steffen, J. & Goldfarb, C. 2010. Skeletal and chronological ages in American adolescents: current findings in skeletal maturation. *Journal of Children's Orthopaedics,* 4**,** 467-470.

Cameriere, R., Ferrante, L., Mirtella, D. & Cingolani, M. 2006. Carpals and epiphyses of radius and ulna as age indicators. *International Journal of Legal Medicine,* 120**,** 143-146.

Cameron, N. 1982. Age Estimation. Estimation of chronological age in children. *Science and Public Policy.***,** 20-27.

Cameron, N. 2002. Assessment of maturation. *In:* CAMERON, N. (ed.) *Human Growth and Development.* London: Academic Press.

Cameron, N. 2007. Growth patterns in adverse environments. *American Journal of Human Biology,* 19**,** 615-621.

Cameron, N., Kgamphe, J. S. & Levin, Z. 1991. Age at menarche and an analysis of secular trends in menarcheal age of South African urban and rural black females. *Am J Hum Biol,* 3**,** 251.

Canavese, F., Charles, Y. & Dimeglio, A. 2008. Skeletal age assessment from elbow radiographs. Review of the literature. *La Chirurgia degli Organi di Movimento,* 92**,** 1-6.

Cardoso, H. F. V. 2007. Environmental Effects on Skeletal Versus Dental Development: Using a Documented Subadult Skeletal Sample to Test a Basic Assumption in Human Osteological Research. *American Journal of Physical Anthropology,* 132**,** 223-233.

Cardoso, H. F. V. 2008. Epiphyseal union at the innominate and lower limb in a modern Portuguese skeletal sample, and age estimation in adolescent and young adult male and female skeletons. *American Journal of Physical Anthropology,* 135**,** 161-170.

Cardoso, H. F. V. & Severino, R. S. S. 2010. The chronology of epiphyseal union in the hand and foot from dry bone observations. *International Journal of Osteoarchaeology,* 20**,** 737-746.

CEOP 2009. Strategic Threat Assessment Child Trafficking in the UK. Child Exploitation and Online Protection.

CEOP 2011. *Child Trafficking Update,* London, Child Exploitation and Online Protection Centre.

Chan, S. T., Chang, K. S. F. & Hsu, F. K. 1961. Growth and skeletal maturation of Chinese children in Hong Kong. *American Journal of Physical Anthropology,* 19**,** 289-300.

Charles, Y. P., Dimeglio, A., Canavese, F. & Daures, J. P. 2007. Skeletal age assessment from the olecranon for idiopathic scoliosis at Risser grade 0. *Journal of Bone and Joint Surgery,* 89**,** 2737-2744.

Chaumoitre, K., Colavolpe, N., Sayegh-Martin, Y., Pernoud, N., Dutour, O. & Panuel, M. 2006. Reliability of the Sauvegrain and Nahum method to assess bone age in a contemporary population. *Journal of Radiology,* 87**,** 1679-82.

Cheng, J. C. Y., Wing-Man, K., Shen, W., Yurianto, H., Xia, G., Lau, J. T. & Cheung, A. Y. 1998. A new look at the sequential development of elbow-ossification centers in children. *Journal of Pediatric Orthopaedics March/April,* 18**,** 161-167.

Chiang, K.-H., Chou, A. S.-B., Yen, P.-S., Ling, C.-M., Lin, C.-C., Lee, C.-C. & Chang, P.-Y. 2005. The reliability of using Greulich-Pyle method to determine children's bone age in Taiwan. *Tzu Chi Medical Journal,* 17**,** 417-420.

Christoforidis, A., Badouraki, M., Katzos, G. & Athanassiou-Metaxa, M. 2007. Bone age estimation and prediction of final height in patients with β-thalassaemia major: a comparison between the two most common methods. *Pediatric Radiology,* 37**,** 1241-1246.

Chumlea, C., Roche, A. F. & Thissen, D. 1989. The Fels method of assessing the skeletal maturity of the hand-wrist. *American Journal of Human Biology,* 35**,** 385-386*.*

Clarke, S. 2011. Young Lives in Limbo. *In:* COUNCIL, W. R. (ed.). Welsh Refugee Council.

Clarkin, P. F. 2008. Adiposity and height of adult Hmong refugees: Relationship with war-related early malnutrition and later migration. *American Journal of Human Biology,* 20**,** 174-184.

Cole, A. J. L., Webb, L. & Cole, T. J. 1988. Bone age estimation: a comparison of methods. *British Journal of Radiology,* 61**,** 683-686.

Cole, T. J. 2000. Secular Trends in Growth. *Proceedings of the Nutrition Society,* 59**,** 317-324.

Cole, T. J. 2003. The secular trend in human physical growth: a biological view. *Economics & Human Biology,* 1**,** 161-168.

Convention., E. 2000. The Charter of Fundamental Rights of the European Union. European Parliament.

Coqueugniot, H. & Weaver, T. D. 2007. Brief Communication: Infracranial Maturation in the Skeletal Collection from Coimbra, Portugal: New Aging Standards for Epiphyseal Union *American Journal of Physical Anthropology,* 134**,** 424-437.

Crawley, H. 2007. When is a child not a child? *In:* IMMIGRATION LAW PRACTITIONERS' ASSOCIATION (ed.). London: Immigration Law Practitioners' Association.

Cronk, C. E. & Stallings, V. A. 1989. Relationship of disease characteristics and nutritional status to patterns of growth in children with Chron disease. *American Journal of Human Biology,* 100**,** 13761-13766.

Crowder, C. & Austin, D. 2005. Age ranges of epiphyseal fusion in the distal tibia and fibula of contemporary males and females. *Journal of Forensic Sciences,* 50**,** 1001-1007.

Danker-Hopfe, H. 1986. Menarcheal age in Europe. *American Journal of Physical Anthropology,* 29**,** 81-112.

Das Gupta, S. M., Prasad, V. & Singh, S. 1974. A roentgenologic study of epiphyseal union around elbow, wrist and knee joints and the pelvis in boys and girls of Uttar Pradesh. *Journal of the Indian Medical Association,* 62**,** 10-12.

Davies, D. A. & Parsons, F. G. 1927. The age order of the appearance and union of the normal epiphyses as seen by X-Rays. *Journal of Anatomy,* 62**,** 58-71.

De Roo, T. & Scröder, H. J. 1976. *Pocket Atlas of Skeletal Age,* The Hague, Martinus Nijhoff Medical Division.

De Salvia, A., Calzetta, C., Orrico, M. & De Leo, D. 2004. Third mandibular molar radiological development as an indicator of chronological age in a European population. *Forensic Science International,* 146**,** S9-S12.

De Vasconcellos, H. A. & Ferreira, E. 1998. Metatarsal growth during the second trimester: a predictor of gestational age? *Journal of Anatomy,* 193**,** 145-149.

DEFRA 2004. The Justification of Practices Involving Ionising Radiation Regulations 2004 (SI 2004 No 1769). Department for Environment, Food and Rural Affairs.

Demirjian, A., Goldstein, H. & Tanner, J. M. 1973. A new system of dental age assessment. *Human Biology,* 45**,** 211.

Department of Health 2000. Ionising Radiation (Medical Exposure) Regulations IS 1999/3232. Norwich: Stationery Office.

Dhanjal, K. S., Bhardwaj, M. K. & Liversidge, H. M. 2006. Reproducibility of radiographic stage assessment of third molars. *Forensic Science International,* 159**,** S74-S77.

Dimeglio, A., Charles, Y. P., Daures, J.-P., de Rosa, V. & Kabore, B. 2005. Accuracy of the Sauvegrain method in determining skeletal age during puberty. *The Journal of Bone and Joint Surgery,* 87-A**,** 1689-1696.

Directgov. 2009. *Angus Council Area-Demographic Factsheet,,* Edinburgh, Scottish Administration.

Dittmar, M. 1998. Secular growth changes in the stature and weight of Amerindian schoolchildren and adults in the Chilean Andes, 1972-1987. *American Journal of Human Biology,* 10**,** 607-617.

Donne, H. D., Jr., Faundes, A., Tristao, E. G., de Sousa, M. H. & Urbanetz, A. A. 2005. Sonographic identification and measurement of the epiphyseal ossification centers as markers of fetal gestational age. *Journal of Clinical Ultrasound,* 33**,** 394-400.

Dreizen, S., Snodgrass, R. M., Parker, G. S., Currie, C. & Spies, T. D. 1954. Maturation of bone centres in hand and wrist of children with chronic nutritive failure. Effects of dietary supplements of reconstituted milk solids. *American Journal of Diseases of Children,* 87**,** 429.

Dreizen, S., Snodgrass, R. M., Webb-Peploe, H., Parker, G. S. & Spies, T. D. 1957. Bilateral symmetry of skeletal maturation in the human hand and wrist. *Journal of Diseases in Children,* 93**,** 122-127.

Dreizen, S., Spirakis, C. N. & Stone, R. E. 1964. Chronic undernutrition and postnatal ossification. Effect on time and sequence of appearance of the postnatal ossification centres in the human hand skeleton. *American Journal of Diseases of Children,* 108**,** 44.

Dreizen, S., Spirakis, C. N. & Stone, R. E. 1967. A comparison of skeletal growth and maturation in undernourished and well-nourished girls before and after menarche. *The Journal of Pediatrics,* 70**,** 256-263.

Duckworth, W. L. H. 1919. The international agreement for the unification of anthropometric measurements to be made of the living subject. *American Journal of Physical Anthropology,* 2**,** 61-67.

Dvorak, J., George, J., Junge, A. & Hodler, J. 2007a. Age determination by magnetic resonance imaging of the wrist in adolescent male football players. *British Journal of Sports Medicine,* 41**,** 45-52.

Dvorak, J., George, J., Junge, A. & Hodler, J. 2007b. Application of MRI of the wrist for age determination in international U-17 soccer competitions. *British Journal of Sports Medicine,* 41**,** 497-500.

Engebretsen, L., Steffen, K., Bahr, R., Broderick, C., Dvorak, J., Janarv, P.-M., Johnson, A., Leglise, M., Mamisch, T. C., McKay, L., Schamasch, P., Singh, G. D., Stafford, D. E. J. & Steen, H. 2010. The International Olypmic Committee Consensus Statement on age determination in high-level young athletes. *British Journal of Sports Medicine,* 44**,** 476-484.

Engstrom, C., Engstrom, H. & Sagne, S. 1983. Lower Third Molar Development In Relation To Skeletal Maturity and Chronological Age. *The Angle Orthodontist,* 53**,** 97-106.

Ernst, C., Schmid, G. & Angst, J. 1992. The Zurich study. *European Archives of Psychiatry and Clinical Neuroscience,* 242**,** 142-151.

European Migration Network 2010. Policies on reception, return and integration arrangements for, and numbers of, Unaccompanied Minors - an EU comparative study. *In:* NETWORK, E. M. (ed.). European Migration Network.

Eveleth, P. B., Bowers, E. J. & Schall, J. I. 1979. Secular change in the growth of Philadelphia black adolescents. *Human Biology,* 51**,** 213.

Eveleth, P. B. & Tanner, J. M. 1976. *Worldwide Variation in Human Growth,* Cambridge, Cambridge University Press.

Even, L., Bronstein, V. & Hochberg, Z. 1998. Bone Maturation in Girls with Turner's Syndrome. *European Journal of Endocrinology,* 138**,** 59-62.

Facchini, F., Fiori, G., Bedogni, G., Galletti, L., Ismagulov, O., Ismagulova, A., Sharmanov, T., Tsoy, I., Becastro, M. G., Rissoli, S. & Goldoni, M. 2008. Puberty in Modernizing Kazakhstan: A comparison of rural and urban children. *Annals of Human Biology,* 35**,** 50-64.

Fernandez, T. J. M., Santiago, R. F., Perez, C. A., Tanner, L. G., Cordero, A. M. J. & Torreblanca, C. F. 2007. The influence of nutrition and social environment on the bone maturation of children. *Nutricion Hospitalaria,* 22**,** 417-24.

Fishman, L. S. 1982. Radiographic avaluation of skeletal maturation. *Angle Orthodontist,* 52**,** 88-112.

Flecker, H. 1932. Roentgenographic observations of the times of appearance of epiphyses and their fusion with the diaphyses. *Journal of Anatomy,* 67**,** 118-164.

Flecker, H. 1942. Time of appearance and fusion of ossification centers as observed by roentgenographic methods. *The american Journal of Roentgenology and Radium Therapy,* 47**,** 97-159.

Fleshman, K. 2000. Bone age determination in a paediatric population as an indicator of nutritional status. *Tropical Doctor,* 30**,** 16-18.

Flood, S. J., Mitchell, W. J., Oxnard, C. E., Turlach, B. A. & McGeachie, J. 2011. A Comparison of Demirjian's Four Dental Development Methods for Forensic Age Assessment. *Journal of Forensic Sciences***,** no-no.

Frush, D. 2009. Radiation safety. *Pediatric Radiology,* 39**,** S385-S390.

Garamendi, P. M., Landa, M. I., Ballesteros, J. & Solano, M. A. 2005. Reliability of the methods applied to assess age minority in living subjects around 18 years old. A survey on a Moroccan origin population. *Forensic Science International,* 154**,** 3-12.

Gardner, E., Gray, D. J. & O'Rahilly, R. 1959. The prenatal development of the skeleton and joints of the human foot. *Journal of Bone and Joint Surgery,* 41-A**,** 847-876.

Garn, S. M. 1981. The growth of growth. *American Journal of Physical Anthropology,* 56**,** 521-530.

Garn, S. M. 1982. Book Review. Radiology of the Pediatric Elbow. *Radiology,* 142**,** 366.

Garn, S. M. 1987. The secular trend in size and maturational timing and its implication for nutritional assessment. *Journal of Nutrition,* 117**,** 817-823.

Garn, S. M. & Rohmann, C. G. 1966. Communalities in the ossification timing of the growing foot. *American Journal of Physical Anthropology,* 24**,** 45-50.

Garn, S. M., Rohmann, C. G., Blumenthal, T. & Silverman, F. N. 1967. Ossification communalities of the hand and other body parts: Their implication to skeletal assessment. *American Journal of Physical Anthropology,* 27**,** 75-82.

Garn, S. M., Rohmann, C. G. & Silverman, F. N. 1965. Missing secondary ossification centres of the foot. Inheritance and developmental meaning. *Annales de Radiologie (Paris),* 8**,** 629-644.

Gentili, P., Trasimeni, A. & Giorlandino, C. 1984. Fetal ossification centers as predictors of gestational age in normal and abnormal pregnancies. *Journal of Ultrasound Medicine,* 3**,** 193-197.

Georgopoulos, N., Markou, K., Theodoropoulou, A., Paraskevopoulou, P., Varaki, L., Kazantzi, Z., Leglise, M. & Vagenakis, A. G. 1999. Growth and Pubertal Development in Elite Female Rhythmic Gymnasts. *Journal of Clinical Endocrinology and Metabolism,* 84**,** 4525-4530.

Georgopoulos, N. A., Markou, K. B., Theodoropoulou, A., Vagenakis, G. A., Benardot, D., Leglise, M., Dimopoulos, J. C. A. & Vagenakis, A. G. 2001. Height velocity and skeletal maturation in elite female rhythmic gymnasts. *Journal of Clinical Endocrinology and Metabolism,* 86**,** 5159-5164.

Gilbert, S. R., Gilbert, A. C. & Henderson, R. C. 2004. Skeletal maturation in children with quadriplegic cerebral palsy. *Journal of Pediatric Orthopaedics,* 24**,** 292-7.

Gilsanz, V. & Ratib, O. 2005. Hand Bone Age. *A Digital Atlas of Skeletal Maturity.* Los Angeles: Springer.

Girdany, B. R. & Golden, R. 1952. Centers of Ossification of the Skeleton. *American Journal of Roentgenography,* 68**,** 922-924.

Godoy, R., Nyberg, C., Eisenberg, D. T. A., Magvanjav, O., Shinnar, E., Leonard, W. R., Gravlee, C., Reyes-Garcia, V., McDade, T. W., Huanca, T. & Tanner, S. 2010. Short but catching up: Statural growth among native Amazonian Bolivian children. *American Journal of Human Biology,* 22**,** 336-347.

Gȍk, S., Erolcer, N. & Ozen, C. 1985. *Age Determination in Forensic Medicine [in Turkish],* Istanbul, Council of Forensic Medicine Press.

Goldstein, I., Reece, E. A. & Hobbins, J. C. 1988. Sonographic appearance of the fetal heel ossification centers and foot length measurements provide independent markers for gestational age estimation. *American Journal of Obstetrics and Gynecology,* 159**,** 923-6.

Greulich, W. W. 1951. The growth and developmental status of Guamanian school children in 1947. *American Journal of Physical Anthropology,* 9**,** 55-70.

Greulich, W. W. 1957. A comparison of the physical growth and development of American-born and native Japanese children. *American Journal of Physical Anthropology,* 15**,** 489.

Greulich, W. W. & Pyle, S. I. 1959. *Radiographic Atlas of Skeletal Development of the Hand and Wrist,* Stanford, Stanford University Press.

Griffith, J. F., Cheng, J. C. Y. & Wong, E. 2007. Are Western skeletal age standards applicable to the Hong Kong Chinese population? A comparison of the Greulich and Pyle method and the Tanner and Whitehouse method. *Hong Kong Medical Journal,* 13**,** S28-32.

Groell, R., Lindbichler, F., Riepl, T., Gherra, L., Roposch, A. & Fotter, R. 1999. The reliability of bone age determination in central European children using the Greulich and Pyle method. *British Journal of Radiology,* 72**,** 461-464.

Gunn, I. 2008. *Foot Find Confuses Canadian Police* [Online]. Vancouver. Available: http://news.bbc.co.uk/1/hi/world/americas/7418239.stm [Accessed 5th January 2012].

Gunst, K., Mesotten, K., Carbonez, A. & Willems, G. 2003. Third molar root development in relation to chronological age: a large sample sized retrospective study. *Forensic Science International,* 136**,** 52-57.

Guo, S. S., Chumlea, C., Roche, A. F. & Siervogal, R. M. 1997. Age and maturity related changes in body composition during adolescence into adulthood: The Fels Longitudinal Study. *International Journal of Obesity* 21**,** 1167-1175.

Gustafsson, A., Werdelin, L., Tullberg, B. S. & Lindenfors, P. 2007. Stature and sexual stature dimorphism in Sweden, from the 10th to the end of the 20th century. *American Journal of Human Biology,* 19**,** 861-870.

Hagg, U. & Taranger, J. 1992. Pubertal growth and maturity pattern in early and late maturers. A prospective longitudinal study of Swedish urban children. *Swedish Dental Journal,* 16**,** 199-209.

Haiter-Neto, F., Kurita, L. M., Menezes, A. V. & Casanova, M. S. 2006. Skeletal age assessment: A comparison of 3 methods. *American Journal of Orthodontics and Dentofacial Orthopedics,* 130**,** 435.e15-435.e20.

Hall, E. J. 1991. Scientific view of low-level radiation risks. *Radiographics,* 11**,** 509-518.

Hans, M. G. & Broadbent, B. H. 2008. *Bolton-Brush Growth Study Centre* [Online]. Cleveland: Case Western Reserve University. Available: http://dental.case.edu/bolton-brush/ [Accessed 12th February 2012].

Hans, S. D., Sanders, J. & Cooperman, D. R. 2008. Using the Sauvegrain method to predict peak height velocity in boys and girls. *Journal of Pediatric Orthopaedics. ,* 28**,** 836-839.

Hauspie, R., Cameron, N. & Molinari, L. 2004. *Methods in Human Growth Research,* Cambridge, Cambridge University Press.

Hawley, N. L., Rousham, E. K., Norris, S. A., Pettifor, J. M. & Cameron, N. 2009. Secular trends in skeletal maturity in South Africa: 1962–2001. *Annals of Human Biology,* 36**,** 584-594.

Hellman, M. 1928. Ossification of epiphysial cartilages in the hand. *American Journal of Physical Anthropology,* 11**,** 223-257.

Henderson, R. C., Gilbert, S. R., Clement, M. E., Abbas, A., Worley, G. & Stevenson, R. D. 2005. Altered skeletal maturation in moderate to severe cerebral palsy. *Developmental Medicine and Child Neurology,* 47**,** 229-36.

Hess, A. F. & Weinstock, M. 1925. A comparison of the evolution of carpal centres in White and Negro newborn infants. *American Journal of Diseases of Children,* 29**,** 347.

Hill, C., Riaz, M., Mozzam, A. & Brennen, M. D. 1998. A regional audit of hand and wrist injuries: A study of 4873 injuries. *The Journal of Hand Surgery: Journal of the British Society for Surgery of the Hand,* 23**,** 196-200.

Hillewig, E., De Tobel, J., Cuche, O., Vandemaele, P., Piette, M. & Verstraete, K. 2011. Magnetic resonance imaging of the medial extremity of the clavicle in forensic bone age determination: a new four-minute approach. *European Radiology,* 21**,** 757-767.

Hillingdon, L. B. 2005. *Practice Guidelines for Age Assessment of Young Unaccompanied Asylum Seekers* [Online]. London: London Borough of Hillingdon. Available: http://www.proceduresonline.com/hillingdon/childcare/pdfs/Master%20Age%20assessment%20%28August%202005%29%20.pdf [Accessed 10th February 2012].

HMSO 1984. Police and Criminal Evidence Act (c.60). HMSO; London.

HMSO 1989. Children Act 1989 (c.41). London: HMSO.

HMSO 2000. The Ionising Radiation (Medical Exposure) Regulations No. 1059. London: HMSO.

HMSO 2005. Mental Capacity Act (c.9). HMSO, London.

HMSO 2009. Borders, Citizenship and Immigration Act (c.11). HMSO, London.

Hoerr, N. L., Pyle, S. I. & Francis, C. C. 1962. *Radiographic Atlas of Skeletal Development of the Foot and Ankle.,* Springfield, Illinois., Charles C. Thomas.

Home Office 2008a. Asylum Statistics United Kingdom 2007. *In:* HOME OFFICE STATISTICAL BULLETIN (ed.).

Home Office 2008b. Supplementary tables for 2008, including applications recieved for asylum in the UK from unaccompanied children. Table 2.k. *In:* HOME OFFICE STATISTICAL BULLETIN (ed.).

Home Office 2009. Control of Immigration: Statistics United Kingdom 2008. *In:* BULLETIN, H. O. S. (ed.).

Home Office. 2010. Control of Immigration: Statistics. Available: http://webarchive.nationalarchives.gov.uk/20110218135832/rds.homeoffice.gov.uk/rds/pdfs10/hosb1510.pdf [Accessed 19th February 2012].

Home Office 2011. Policy Bulletin 75. *Section 55 Guidance*.

Hubbard, A. M., Meyer, J. S., Davidson, R. S., Mahboubi, S. & Harty, M. P. 1993. Relationship between the ossification centre and cartilaginous anlage in the normal hindfoot in children: study with MR imaging. *American Journal of Roetgenography,* 161**,** 849-853.

Hubbard, J. 2007. Letter in Response to Planning Better Outcomes and Support for Asylum Seekers. Royal College of Radiologists (RCR).

Humphrey, L. T. 1998. Growth patterns in the modern human skeleton. *American Journal of Physical Anthropology,* 105**,** 57-72.

Huxley, A. K. 1998. Comparability of gestational age values derived from diaphyseal length and foot length from known forensic foetal remains. *Medicine Science and Law,* 38**,** 42-51.

I.L.O 2002. *Every Child Counts: New Global Estimates on Child Labour,* Geneva, International Labour Office.

ILPA. 2012. *Immigration Law Practitioners' Association* [Online]. London: Immigration Law Practitioners' Association. Available: http://www.ilpa.org.uk/ [Accessed 20th February 2012].

Jenni, O. G., Fuhrer, H. Z., Iglowstein, I., Molinari, L. & Largo, R. H. 2005. A longitudinal study of bed sharing and sleep problems among Swiss children in the first 10 years of life. *Pediatrics,* 115**,** 233-240.

Jit, I. & Kulkarni, M. 1976. Times of Appearance and Fusion of Epiphysis at the Medial End of the Clavicle. *Indian Journal of Medical Research,* 64**,** 773-782.

Jnanesh, R. S., Thomas, S. T. & Gowd, H. S. 2011. Estimation of age by roentgenologic study of epiphyseal union at the lower end of humerus in Karnataka. *Anatomica Karnataka,* 5**,** 6-10.

Johnston, F. E. 2002. Social and Economic Influences on Growth and Secular Trends. *In:* CAMERON, N. (ed.) *Human Growth and Development.* London: Academic Press.

Johnston, F. E. & Jahina, S. B. 1965. The contribution of the carpal bones to the assessment of skeletal age. *American Journal of Physical Anthropology,* 23**,** 349-354.

Jones, L. L., Griffiths, P. L., Norris, S. A., Pettifor, J. M. & Cameron, N. 2009. Age at menarche and the evidence for a positive secular trend in urban South Africa. *American Journal of Human Biology,* 21**,** 130.

Kanbur, N. O., Kanli, A., Derman, O., Eifan, A. & Atac, A. 2006. The relationships between dental age, chronological age and bone age in Turkish adolescents with constitutional delay of growth. *Journal of Pediatric Endocrinology and Metabolism,* 19**,** 979-85.

Kasper, K. A., Austin, D., Kvanli, A. H., Rios, T. R. & Senn, D. R. 2009. Reliability of Third Molar Development for Age Estimation in a Texas Hispanic Population: A Comparison Study. *Journal of Forensic Sciences,* 54**,** 651-657.

Kellinghaus, M., Schulz, R., Vieth, V., Schmidt, S. & Schmeling, A. 2010. Forensic age estimation in living subjects based on the ossification status of the medial clavicular epiphysis as revealed by thin-slice multidetector computed tomography. *International Journal of Legal Medicine,* 124**,** 149-154.

Kelts, D. G., Grand, R. J., Shen, G., Watkins, J. B., Werlin, S. L. & Boehme, C. 1979. Nutritional basis of growth failure in children and adolescents with Crohn's disease. *Gastroenterology,* 76**,** 720-727.

Khan, K. M., Miller, B. S., Hoggard, E., Somani, A. & Sarafoglou, K. 2009. Application of Ultrasound for Bone Age Estimation in Clinical Practice. *The Journal of Pediatrics,* 154**,** 243-247.

Kim, S. Y., Oh, Y. J., Shin, J. Y., Rhie, Y. J. & Lee, K. H. 2008. Comparison of the Greulich-Pyle and Tanner Whitehouse (TW3) mehtods in bone age assessment. *Journal of Korean Society of Pediatric Endocrinology,* 13**,** 50-55.

Kimmerle, E. H., Jantz, R. L., Konigsberg, L. W. & Baraybar, J. P. 2008. Skeletal Estimation and Identification in American and East European Populations. *Journal of Forensic Sciences,* 53**,** 524-532.

Kimura, K. 1983. Skeletal Maturity and Bone Growth in Twins. *American Journal of Physical Anthropology,* 60**,** 491-497.

Kjar, I. 1974. Skeletal maturation of the human fetus assessed radiographically on the basis of ossification sequences in the hand and foot. *American Journal of Physical Anthropology,* 40**,** 257-276.

Koc, A., Karaoglanoglu, M., Erdogan, M., Kosecik, M. & Cesur, Y. 2001. Assessment of bone ages: is the Greulich-Pyle method sufficient for Turkish boys? *Pediatric International,* 43**,** 662-665.

Koski, K., Haataja, J. & Lappaleinen, M. 1961. Skeletal development of the hand and wrist in Finnish children. *American Journal of Physical Anthropology,* 19**,** 379.

Kovacs, R., Bartok, M., Toth, I., Bitvai, K. & Wollak, I. 1999. Ultrasound examination of the wrist in order to determine bone age of healthy children (ages 0-7 Years). *Yearbook of Pediatric Radiology***,** 1-5.

Krailassiri, S., Anuwongnukroh, N. & Dechkunakorn, S. 2002. Relationships between dental calcification stages and skeletal maturity indicators in Thai individuals. *Angle Orthodontist,* 72**,** 155-166.

Kreitner, K. F., Schweden, F. J., Riepert, T., Nafe, B. & Thelen, M. 1998. Bone Age Determination Based on the Study of the Medial Extremity of the Clavicle. *European Radiology.,* 8**,** 1116-1122.

Krogman, W. M. & Iscan, M. Y. 1986. *The Human Skeleton in Forensic Medicine,* Springfield, CC Thomas.

Kvittingen, A. V. 2010. Negotiating childhood: Age assessment in the UK asylum system. *Working Paper Series.* Oxford: Refugee Studies Centre.

Lampl, M. 2002. Saltation and Stasis. *In:* CAMERON, N. (ed.) *Human Growth and Development* Oxford Academic Press.

Lampl, M. & Jeanty, P. 2003. Timing is everything: A reconsideration of fetal growth velocity patterns identifies the importance of individual and sex differences. *American Journal of Human Biology,* 15**,** 667-680.

Lampl, M., Johnston, F. E. & Malcolm, L. A. 1978. The effects of protein supplementation on the growth and skeletal maturation of New Guinean school children. *Annals of Human Biology,* 5**,** 219-227.

Lampl, M. & Thompson, A. L. 2007. Growth chart curves do not describe individual growth biology. *American Journal of Human Biology,* 19**,** 643-653.

Langley-Shirley, N. & Jantz, R. L. 2010. A Bayesian Approach to Age Estimation in Modern Americans from the Clavicle. *Journal of Forensic Sciences,* 55**,** 571-583.

Laor, T. & Jaramillo, D. 2009. MR Imaging Insights into Skeletal Maturation: What is Normal? *Radiology,* 250**,** 29-38.

Largo, R. H. & Prader, A. 1983a. Pubertal development in Swiss boys. *Helvetica Paediatrica Acta,* 38**,** 211.

Largo, R. H. & Prader, A. 1983b. Pubertal development in Swiss girls. *Helvetica Paediatrica Acta,* 38**,** 229.

Laska-Mierzejewska, T. & Olszewska, E. 2004. The maturation of girls living in rich and poor rural regions of Poland before and after the transformation of 1989. *HOMO-Journal of Comparative Human Biology,* 55**,** 129-142.

Law, H., Mensah, L., Bailey, S. & Nelki, J. 2010. Imigration, Asylum Seekers and Undocumented Identity. *In:* BLACK, S., AGGRAWAL, A. & PAYNE-JAMES, J. (eds.) *Age Estimation in the Living.* Oxford: Wiley-Blackwell.

Lee, S.-H., Lee, J.-Y., Park, H.-K. & Kim, Y.-K. 2009. Development of third molars in Korean juveniles and adolescents. *Forensic Science International,* 188**,** 107-111.

Legovi, M., Sasso, A., Legovi, I., Brumini, G., abov, T., laj, M., Van010Dura, I. & Lapter, M. 2010. The Reliability of Chronological Age Determination by Means of Mandibular Third Molar Development in Subjects in Croatia. *Journal of Forensic Sciences,* 55**,** 14-18.

Lejarraga, H., Sanchirico, F. & Cusminsky, M. 1980. Age of menarche in urban Argentinian children. *Annals of Human Biology,* 67**,** 579.

Levenson, R. & Sharma, A. 1999. *The Health of Refugee Children - Guidelines for Paediatricians,* London, Royal College of Paediatrics and Child Health.

Lewis, A. B. 1991. Comparisons between Dental and Skeletal Ages. *The Angle Orthodontist,* 61**,** 87-92.

Lewis, C. P., Lavy, C. B. D. & Harrison, W. J. 2002. Delay in skeletal maturity in Malawian children. *Journal of Bone and Joint Surgery,* 84-B**,** 732-734.

Lewis, W. H. 1901. The development of the arm in man. *American Journal of Anatomy,* 1**,** 145-183.

Liversidge, H. M., Lyons, F. & Hector, M. P. 2003. The accuracy of three methods of age estimation using radiographic measurements of developing teeth. *Forensic Science International,* 131**,** 22-29.

Loder, R., Estle, D. T., Morrison, K., Eggleston, D., Fish, D., Greenfield, M. & Guire, K. E. 1993. Applicability of the Greulich and Pyle skeletal age standards to black and white children today. *American Journal of Diseases of Children,* 147**,** 1329-1333.

Loesch, D. Z., Hopper, J. L., Rogucka, E. & Huggins, R. M. 1995. Timing and Genetic Rapport between Growth in Skeletal Maturity and Height around Puberty: Similarities and Differences between Girls and Boys. *American Journal of Human Genetics,* 56**,** 753-759.

Loesch, D. Z., Stokes, K. & Huggins, R. M. 2000. Secular trend in body height and weight of Australian children and adolescents. *American Journal of Physical Anthropology,* 111**,** 545-556.

Lopez-Blanco, M., Izaguirre-Espinoza, I., Macias-Tomei, C. & Saab-Verardy, L. 1995. Growth in stature in early, average, and late maturing children of the Caracas mixed-longitudinal study. *American Journal of Human Biology,* 7**,** 517-527.

Luh, S. S., Sandhu, B., Y., & Yazdani, Z. 2011. Best Practice in Age Dispute Challenges. *In:* WOODALL, L. (ed.) *Working with Refugee Children. .* London: Immigration Law Practitioners' Association.

Lynnerup, N., Belard, E., Buch-Olsen, K., Sejrsen, B. & Damgaard-Pedersen, K. 2008. Intra- and interobserver error of the Greulich-Pyle method as used in a Danish forensic sample. *Forensic Science International,* 179**,** 242.e1-242.e6.

MacKay, D. 1952. Skeletal Maturation in the Hand: A Study of Development in East African Children. *Transactions of the Royal Society of Tropical Medicine and Hygiene,* 46**,** 135-151.

Magnússon, T. E. 1978. Age at menarche in Iceland. *American Journal of Physical Anthropology,* 48**,** 511.

Malina, R. M. 1971. A consideration of factors underlying the selection of methods in the assessment of skeletal maturity. *American Journal of Physical Anthropology,* 35**,** 341-346.

Malina, R. M., Chamorro, M., Serratosa, L. & Morate, F. 2007. TW3 and Fels skeletal ages in elite youth soccer players. *Annals of Human Biology,* 34**,** 265-272.

Malina, R. M., Chumlea, C., Stepick, C. D. & Gutierez, L. F. 1977. Age at menarche in Oaxaca, Mexico, schoolgirls, with comparative data for other areas of Mexico. *Annals of Human Biology,* 4**,** 551.

Malina, R. M. & Little, B. B. 1981. Comparison of TW1 and TW2 skeletal age differences in American Black and White and in Mexican children 6-13 years of age. *Annals of Human Biology,* 8**,** 543.

Malina, R. M., Pea Reyes, M. E., Eisenmann, J. C., Horta, L., Rodrigues, J. & Miller, R. 2000. Height, mass and skeletal maturity of elite Portuguese soccer players 11-16 years. *Journal of Sports Sciences,* 18**,** 685.

Maresh, M. M. & Deming, J. 1939. The growth of the long bones in 80 infants. Roentgenograms versus anthropometry. *Child Development,* 10**,** 91-106.

Marshall, W. & Tanner, J. 1970. Variations in the pattern of pubertal changes in boys. *Archives of Disease in Childhood,* 45**,** 13.

Marshall, W. A. & Tanner, J. M. 1969. Variation in the pattern of pubertal changes in girls. *Archives of Disease in Childhood,* 44**,** 291.

Martin-de las Heras, S., García-Fortea, P., Ortega, A., Zodocovich, S. & Valenzuela, A. 2008. Third molar development according to chronological age in populations from Spanish and Magrebian origin. *Forensic Science International,* 174**,** 47-53.

Matsuoka, H., Sato, K., Sugihara, S. & Murata, M. 1999. Bone maturation reflects the secular trend in growth. *Hormone Research.,* 52**,** 125-130.

Matthews, J. G. 1998. The developmental anatomy of the foot. *The Foot,* 8**,** 17-25.

Mays, S., Brickley, M. & Ives, R. 2008. Growth in an English population from the Industrial Revolution. *American Journal of Physical Anthropology,* 136**,** 85-92.

Mazrani, W., McHugh, K. & Marsden, P. J. 2007. The radiation burden of radiological investigations. *Archives of Disease in Childhood,* 92**,** 1127-1131.

McCarthy, S. M. & Ogden, J. A. 1982. Radiology of postnatal skeletal development. *Skeletal Radiology,* 9**,** 17-26.

McKern, T. W. & Stewart, T. D. 1957. *Skeletal age changes in young American males, analysed from the standpoint of age identification.* , Headquarters Quatermaster Research and Development Command, Technical Report EP-45. Natwick, M. .

Meijerman, L., Maat, G. J. R., Schulz, R. & Schmeling, A. 2007. Variables affecting the probability of complete fusion of the medial clavicular epiphysis. *International Journal of Legal Medicine,* 121**,** 463-468.

Melsen, B., Wenzel, A., Miletic, T., Andreasen, J., Vagn-Hansen, P. L. & Terp, S. 1986. Dental and skeletal maturity in adoptive children: assessments at arrival and after one year in the admitting country. *Annals of Human Biology,* 13**,** 153-159.

Mentzel, H. J., Vilser, C., Eulenstein, M., Schwartz, T., Vogt, S., Bottcher, J., Yaniv, I., Tsoref, L., Kauf, E. & Kaiser, W. A. 2005. Assessment of skeletal age at the wrist in children with a new ultrasound device. *Pediatric Radiology,* 35**,** 429-33.

Mercer, B. M., Sklar, S., Shariatmadar, A., Gillieson, M. S. & D'Alton, M. E. 1987. Fetal foot length as a predictor of gestational age. *American Journal of Obstetrics and Gynecology,* 156**,** 350-5.

Merz, E., Oberstein, A. & Wellek, S. 2000. Age-related reference ranges for fetal foot length. *Ultraschall Medicine,* 21**,** 79-85.

Mhaskar, R., Agarwal, N., Takkar, D., Buckshee, K., Anandalakshmi & Deorari, A. 1989. Fetal foot length - a new parameter for assessment of gestational age. *International Journal of Gynecology & Obstetrics,* 29**,** 35-38.

Midtbø, M. & Halse, A. 1992. Skeletal maturity, dental maturity, and eruption in young patients with Turner syndrome. *Acta Odontologica Scandinavica,* 50**,** 303-312.

Milner, G. R., Levick, R. K. & Kay, R. 1986. Assessment of bone age: a comparison of the Greulich and Pyle, and the Tanner and Whitehouse methods. *Clinical Radiology,* 37**,** 119-121.

Moorrees, C. F. A., Fanning, E. A. & Hunt, E. E. 1963. Age Variation of Formation Stages for Ten Permanent Teeth. *Journal of Dental Research,* 42**,** 1490-1502.

Mora, S., Boechat, M., Pietka, E., Huang, H. K. & Gilsanz, V. 2001. Skeletal Age Determinations in Children of European and African Descent: Applicability of the Greulich and Pyle Standards. *Pediatric Research,* 50**,** 624-628.

Moss, M. L. & Noback, C. R. 1958. A Longitudinal Study of Digital Epiphyseal Fusion in Adolescence. *Anatomical Record,* 131**,** 19-32.

Muhler, M., Schulz, R., Schmidt, S., Schmeling, A. & Reisinger, W. 2006. The influence of slice thickness on assessment of clavicle ossification in forensic age diagnostics. *International Journal of Legal Medicine,* 120**,** 15-17.

Nahid, G., Abdorrahim, A., Gharib, S. M. & Anvar, E. 2010. Assessment of bone age in Kurdish children in Iran. *Pakistan Journal of Medical Science,* 26**,** 36-39.

Noback, C. R. 1954. The appearance of ossification centers and the fusion of bones. *American Journal of Physical Anthropology,* 12**,** 63-70.

Nyati, L. H., Norris, S. A., Cameron, N. & Pettifor, J. M. 2006. Effect of ethnicity and sex on the growth of the axial and appendicular skeleton of children living in a developing country. *American Journal of Physical Anthropology,* 130**,** 135-141.

O'Connor, J. E., Bogue, C., Spence, L. D. & Last, J. 2008. A method to establish the relationship between chronological age and stage of union from radiographic assessment of epiphyseal fusion at the knee: an Irish population study. *Journal of Anatomy,* 212**,** 198-209.

O'Rahilly, R. 1973. The Human Foot. *In:* GIANNESTRAS, N. J. (ed.) *Foot disorders: medical and surgical management.* Philadelphia: Lea and Febiger.

O'Rahilly, R. & Gardner, E. 1975. The timing and sequence of events in the development of the limbs in the human embryo. *Anatomy and Embryology,* 148**,** 1-23.

O'Rahilly, R., Gardner, E. & Gray, D. J. 1960. The skeletal development of the foot. *Clinical Orthopaedics,* 16**,** 7-14.

Ontell, F. K., Ivanovic, M., Ablin, D. S. & Barlow, T. W. 1996. Bone age in children of diverse ethnicity. *American Journal of Roentgenology,* 167**,** 1395-1398.

Ortega, A. I., Haiter-Neto, F., Ambrosano, G. M. B., Boscolo, F. N., Almeida, S. M. & Casanova, M. S. 2006. Comparison of TW2 and TW3 Skeletal Age Differences in a Brazilian Population. *Journal of Applied Oral Science,* 14**,** 142-146.

Ozer, B. K. 2008. Secular trend in body height and weight of Turkish adults. *Anthropological Science,* 116**,** 191-199.

Patel, B., Reed, M. & Patel, S. 2009. Gender-specific pattern differences of the ossification centres in the pediatric elbow. *Pediatric Radiology,* 39**,** 226-231.

Pickett, K. E., Haas, J. D., Murdoch, S., Rivera, J. A. & Martorell, R. 1995. Early Nutritional Supplementation and Skeletal Maturation in Guatemalan Adolescents. *Journal of Nutrition,* 125**,** 1097S-1103S.

Platt, L. D., Medearis, A. L., DeVore, G. R., Horenstein, J. M., Carlson, D. E. & Brar, H. S. 1988. Fetal foot length: relationship to menstrual age and fetal measurements in the second trimester. *Obstetrics and Gynecology,* 71**,** 526-531.

Poland, J. 1898. *Skiagraphic Atlas showing the Development of the Bones of the Wrist and Hand,* London, Smith, Elder & Co.

Prader, A., Largo, R. H., Molinari, L. & Issler, C. 1989. Physical growth of Swiss children from birth to 20 years of age. *Helvetica Paediatrica Acta,* 52 (Suppl.)**,** 1-11.

Prentice, A., Scheonmakers, I., Laskey, M. A., de Bono, S., Ginty, F. & Goldberg, G. R. 2006. Nutrition and bone growth and development. *Proceedings of the Nutritional Society,* 65**,** 348-360.

Proos, L. A. 2009. Growth and development of Indian children adopted in Sweden. *Indian Journal of Medical Research,* 130**,** 646-650.

Pryor, J. W. 1907. The hereditary nature of variation in the ossification of bones *Anatomical Record,* 1**,** 84-88.

Pryor, J. W. 1923. Differences in the time of development of centres of ossification in the male and female skeleton. *The Anatomical Record,* 25**,** 257-273.

Pryor, J. W. 1925. Time of ossification of the bones of the hand of the male and female. *American Journal of Physical Anthropology,* 8**,** 401-410.

Pyle, S. I. & Hoerr, N. L. 1969. *A Radiographic Standard of Reference for the Growing Knee,* Springfield, Charles C. Thomas.

Pyle, S. I., Waterhouse, A. M. & Greulich, W. W. 1971. *A Radiographic Standard of Reference for the Growing Hand and Wrist,* Cleveland, Ohio, The Press of Case Western Reserve University.

Quirmbach, F., Ramsthaler, F. & Verhoff, M. A. 2009. Evaluation of the ossification of the medial clavicular epiphysis with a digital ultrasonic system to determine the age threshold of 21 years. *International Journal of Legal Medicine,* 123**,** 241-245.

Ramsthaler, F., Proschek, P., Betz, W. & Verhoff, M. 2009. How reliable are the risk estimates for X-ray examinations in forensic age estimations? A safety update. *International Journal of Legal Medicine,* 123**,** 199-204.

RCPCH. 2007. *X-Rays and Asylum Seeking Children: Policy Statement.* [Online]. Royal College of Paediatrics and Child Health. Available: http://www.rcpch.ac.uk/Policy/X-Rays-and-Asylum-Seeking-Children-Policy-Statement [Accessed 6th January 2012].

Resnick, C. S. & Hartenberg, M. A. 1986. Ossification centres of the pediatric elbow: a rare normal variant. *Pediatric Radiology,* 16**,** 254-256.

Reyes, M. E. P., Tan, S. K. & Malina, R. M. 2003. Urban–rural contrasts in the growth status of school children in Oaxaca, Mexico. *Annals of Human Biology,* 30**,** 693-713.

Reynolds, D. 1981. Growth changes in fractured long-bones: a study of 126 children. *Journal of Bone and Joint Surgery. British Volume,* 63-B**,** 83-88.

Rikhasor, R. M., Qureshi, A. M., Rathi, S. L. & Channa, N. A. 1999. Skeletal maturity in Pakistani children. *Journal of Anatomy,* 195**,** 305-308.

Ritz-Timme, S., Cattaneo, C., Collins, M. J., Waite, E. R., Schutz, H. W., Kaatsch, H. J. & Borrman, H. I. M. 2000. Age Estimation: The state of the art in relation to the specific demands of forensic practise. *International Journal of Legal Medicine,* 113**,** 129-136.

Roberts, D., F. 1994. Secular trends in growth and maturation in British girls. *American Journal of Human Biology,* 6**,** 13-18.

Roche, A. F. 1992. *Growth, Maturation, and Body Composition: the Fels Longitudinal Study 1929-1991,* Cambridge, Cambridge Univresity Press.

Roche, A. F., Chumlea, C. & Thissen, D. 1988. *Assessing the Skeletal Maturity of the Hand-Wrist: FELS Method,* Springfield, Illinois, Charles C. Thomas.

Roche, A. F. & French, N. Y. 1970. Differences in Skeletal Maturity Levels Between the Knee and Hand. *American Journal of Roentgenology,* 109**,** 307-312.

Roche, A. F., Rohmann, C. G., French, N. Y. & Davila, G. H. 1970. Effect of Training on Replicability of Assessments of Skeletal Maturity (Greulich-Pyle). *American Journal of Roentgenology,* 108**,** 511-515.

Roche, A. F., Thissen, D. & Wainer, H. 1976. *Skeletal Maturity: The Knee Joint as a Biological Indicator,* New York, Plenum Medical Book Company.

Rosberg, H. E. & Dahlin, L. B. 2004. Epidemiology of hand injuries in a middle-sized city in southern Sweden: A retrospective comparison of 1989 and 1997. *Scandinavian Journal of Plastic and Reconstructive Surgery and Hand Surgery,* 38**,** 347-355.

Rosenbloom, A. L. & Tanner, J. M. 1998. Misuse of Tanner puberty stages to estimate chronological age. *Pediatrics,* 102**,** 1494.

Rosing, F. W. & Kvaal, S. I. 1997. Dental age in adults. A review of estimation methods. *In:* ALT, K. W*.,* ROSING, F. W. & TESCHLER-NICOLA, M. (eds.) *Dental anthropology. Fundamentals, limits and prospects.* New York: Springer.

Sahni, D., Jit, I. & Sanjeev. 1995. Time of fusion of epiphyses at the elbow and wrist joints on girls of Northwest India*. Forensic Science International,* 74**,** 47-55.

Saksena, J. S. & Vyas, S. K. 1969. Epiphyseal union at the wrist, knee and iliac crest in residents of Madhya Pradesh. *Journal of the Indian Medical Association,* 53**,** 67-68.

Sangma, W. B., Marak, F. K., Singh, M. S. & Kharrubon, B. 2007. Age Determination in Girls of North-Eastern Region of India. *journal of Indian Academy of Forensic Medicine,* 29**,** 102-108.

Sauvegrain, J., Nahum, H. & Bronstein, H. 1962. [Study of bone maturation of the elbow]. *Annales Radiologie (Paris),* 5**,** 542-550.

Schaefer, M. C. & Black, S. M. 2005. Comparison of ages of epiphyseal union in North American and Bosnian skeletal material. *Journal of Forensic Sciences,* 50**,** 777-784.

Scheuer, J. L. & Black, S. 2000a. Development and ageing of the juvenile skeleton. *In:* COX, M. & MAYS, S. (eds.) *Human Osteology. In Archaeology and Forensic Science.* Cambridge: Cambridge University Press.

Scheuer, L. & Black, S. 2000b. *Developmental Juvenile Osteology,* London, Academic Press.

Schmeling, A., Baumann, U., Schmidt, S., Wernecke, K.-D. & Reisinger, W. 2006a. Reference data for the Thiemann-Nitz method of assessing skeletal age for the purpose of forensic age estimation. *International Journal of Legal Medicine,* 120**,** 1-4.

Schmeling, A., Garamendi, P. M., Prieto, J. L. & Landa, M. I. 2011. Forensic age estimation in unaccompanied minors and young living adults. *InTech* [Online]. Available: http/www.intechopen.com/articles/show/title/forensic-age-estimation-in-unaccompanied-minors-and-young-adults.

Schmeling, A., Grundmann, C., Fuhrmann, A., Kaatsch, H. J., Knell, B., Ramsthaler, F., Reisinger, W., Riepert, T., Ritz-Timme, S., Rösing, F., Rötzscher, K. & Geserick, G. 2008. Criteria for age estimation in living individuals. *International Journal of Legal Medicine,* 122**,** 457-460.

Schmeling, A., Muhler, M. R., Reisinger, W., Geserick, G. & Olze, A. 2006b. Using Forensic Age Diagnostics to Determine Criminal Libility of Living Subjects. *Scandinavian Journal of Forensic Sciences,* 1**,** 1-24.

Schmeling, A., Olze, A., Reisinger, W. & Geserick, G. 2001. Age estimation of living people undergoing criminal proceedings. *The Lancet,* 358**,** 89-90.

Schmeling, A., Olze, A., Reisinger, W. & Geserick, G. 2005. Forensic Age Estimation and Ethnicity. *Legal Medicine,* 7**,** 134-137.

Schmeling, A., Reisinger, W., Geserick, G. & Olze, A. 2006c. Age estimation of unaccompanied minors. Part I. General considerations. *Forensic Science International,* 159S**,** S61-S64.

Schmeling, A., Reisinger, W., Loreck, D., Vendura, K., Markus, W. & Geserick, G. 2000. Effects of ethnicity on skeletal maturation: consequences for forensic age estimations. *International Journal of Legal Medicine,* 113**,** 253-258.

Schmeling, A., Schmidt, S., Schulz, R., Olze, A., Reisinger, W. & Vieth, V. 2010. Practical Imaging Techniques for Age Evaluation. *In:* BLACK, S. M., AGGRAWAL, A. & PAYNE-JAMES, J. (eds.) *Age Estimation in the Living.* Chichester: Wiley-Blackwell.

Schmeling, A., Schulz, R., Danner, B. & Rosing, F. W. 2006d. The impact of economic progress and modernization in medicine on the ossification of hand and wrist. *International Journal of Legal Medicine,* 120**,** 121-126.

Schmeling, A., Schulz, R., Reisinger, W., Muhler, M., Wernecke, K. D. & Geserick, G. 2004. Studies on the time frame for ossification of the medial clavicular epiphyseal cartilage in conventional radiography. *International Journal of Legal Medicine,* 118**,** 5-8.

Schmidt, S., Baumann, U., Schulz, R., Reisinger, W. & Schmeling, A. 2008a. Study of age dependence of epiphyseal ossification of the hand skeleton. *International Journal of Legal Medicine,* 122**,** 51-54.

Schmidt, S., Koch, B., Muhler, M., Reisinger, W. & Schmeling, A. 2007. Optimizing the Thiemann-Nitz method for skeletal age determination for forensic age diagnostics in live subjects. *Scandinavian Journal of Forensic Sciences,* 1**,** 5-7.

Schmidt, S., Koch, B., Schulz, R., Reisinger, W. & Schmeling, A. 2008b. Studies in use of the Greulich–Pyle skeletal age method to assess criminal liability. *Legal Medicine,* 10**,** 190-195.

Schmidt, S., Nitz, I., Schulz, R. & Schmeling, A. 2008c. Applicability of the skeletal age determination method of Tanner and Whitehouse for forensic age diagnostics. *International Journal of Legal Medicine,* 122**,** 309-314.

Schmidt, S., Schmeling, A., Zwiesigk, P., Pfeiffer, H. & Schulz, R. 2011. Sonographic evaluation of apophyseal ossification of the iliac crest in forensic age diagnostics in living individuals. *International Journal of Legal Medicine,* 125**,** 271-276.

Schulz, R., Muhler, M., Mutze, S., Schmidt, S., Reisinger, W. & Schmeling, A. 2005. Studies on the time frame for ossification of the medial epiphysis of the clavicle as revealed by CT scans. *International Journal of Legal Medicine,* 119**,** 142-145.

Schulz, R., Muhler, M., Reisinger, W., Schmidt, S. & Schmeling, A. 2008. Radiographic staging of ossification of the medial clavicular epiphysis. *International Journal of Legal Medicine,* 122**,** 55-58.

Schulze, D., Rother, U., Fuhrmann, A., Richel, S., Faulmann, G. & Heiland, M. 2006. Correlation of age and ossification of the medial clavicular epiphysis using computed tomography. *Forensic Science International,* 158**,** 184-189.

Scrimshaw, N. S. & Guzman, M. A. 1953. The effect of dietary supplementation and the administration of vitamin B1 and aureomycin on the growth of schoolchildren. *Nutrition Symposia***,** 101-108.

Silberstein, M. J., Brodeur, A. E. & Graviss, E. R. 1979. Some vagaries of the capitellum. *The Journal of Bone and Joint Surgery* 61-A**,** 244-247.

Silberstein, M. J., Brodeur, A. E. & Graviss, E. R. 1981. Some vagaries of the medial epicondyle. *Journal of Bone and Joint Surgery,* 63-A**,** 524-528.

Silberstein, M. J., Brodeur, A. E. & Graviss, E. R. 1982. Some vagaries of the radial head and neck. *Journal of Bone and Joint Surgery,* 64-A**,** 1153-1157.

Silva, H. P. & Padez, C. 2006. Secular trends in age at menarche among Caboclo populations from Para, Amazonia, Brazil: 1930–1980. *American Journal of Human Biology,* 18**,** 83.

Silva, S. P., Freitas, D. L., Beunen, G. P. & Maia, J. A. R. 2010. The relevance of training in the TW3 method for the evaluation of biological maturation. *Revista Brasileira de Cineantropometria e Desempenho Humano,* 12**,** 352-358.

Simmons, K. 1944. The Brush Foundation study of child growth and development. II. Physical growth and development. *Monographs of the Society for Research in Child Development,* 9**,** 1-113.

Skład, M. 1977. Skeletal maturation in monozygotic and dizygotic twins. *Journal of Human Evolution,* 6**,** 145-149.

Smith, C. 1947. The effect of wartime starvation in Holland upon pregnancy and its product. *American Journal of Obstetrics and Gynecology,* 53**,** 599-608.

Smith, T. & Brownlees, L. 2011. Age assessment practices: a literature review & annotated bibliography. *In:* UNITED NATIONS CHILDREN'S FUND (UNICEF) (ed.). New York.

Stini, W. A. 1971. Evolutionary implications of changing nutritional patterns in human populations. *American Anthropologist,* 73**,** 1019-1030.

Stinson, S. 1985. Sex differences in environmental sensitivity during growth and development. *American Journal of Physical Anthropology,* 28**,** 123-147.

Stuart, H. C., Pyle, S. I., Cornoni, I. & Reed, R. B. 1962. Onsets completions and spans of ossification in the 29 bone-growth centers of the hand and wrist. *Pediatrics,* 29**,** 237.

Symonds, S. 2011. *Age Disputes and Detention* [Online]. London. Available: http://www.ilpa.org.uk/data/resources/13345/11.06-Age-Disputes-and-Detention.pdf [Accessed 20th February 2012].

Tanner, J. M. 1959. Boas' Contribution to Knowledge of Human Growth. *In:* GOLDSMITH, W. (ed.) *The Anthropology of Franz Boas-Essays on the Centennial of his Birth.* Menasha, Wis: American Anthropological Association.

Tanner, J. M. 1962. *Growth at Adolescence,* Oxford, Blackwell Scientific Publications.

Tanner, J. M. 1978. *Foetus into Man,* London, Open Books Publishing Ltd.

Tanner, J. M., Healy, M. J. R., Goldstein, H. & Cameron, N. 2001. *Assessment of Skeletal Maturity and Prediction of Adult Height (TW3 method).* London, Saunders.

Tanner, J. M., Whitehouse, R. H. & Healy, M. J. R. 1962. *A New System for Estimating Skeletal Maturity from the Hand and Wrist with Standards Derived from a Study of 2600 Healthy British Children. Part II. The Scoring System.,* Paris, International Child Centre.

Tanner, J. M., Whitehouse, R. H., Marshall, W. A., Healy, M. J. R. & Goldstein, H. 1975. *Assessment of Skeletal Maturity and Prediction of Adult Height.,* London, Academic Press.

Tanner, J. M., Whitehouse, R. H. & Takaishi, M. 1966. Standards from birth to maturity for height, weight, height velocity, and weight velocity: British children, 1965. *Part I. Archives of Disease in Childhood,* 41**,** 454-471.

The Law Commission 2011. *Expert Evidence in Criminal Proceedings in England and Wales,* London, The Law Commission (Law Com. No 325).

Thiemann, H.-H., Nitz, I. & Schmeling, A. 2006. *Rontgenatlas der Normalen Hand im Kindesalter,* Leipzig, Stuttgart, New York, Thieme.

Thompson, G. W., Popovich, I. & Luks, E. 1973. Sexual dimorphism in hand and wrist ossification. *Growth.,* 37**,** 1-11.

Tisè, M., Mazzarini, L., Fabrizzi, G., Ferrante, L., Giorgetti, R. & Tagliabracci, A. 2011. Applicability of Greulich and Pyle method for age assessment in forensic practice on an Italian sample. *International Journal of Legal Medicine,* 125**,** 411-416.

Todd, T. W. 1930. The Anatomical Features of Epiphysial Union. *Child Development,* 1**,** 186-194.

Todd, T. W. 1937. *Atlas of Skeletal Maturation,* St. Louis, The C.V. Mosby Company.

Tristan-Vega, A. & Arribas, J. I. 2008. A radius and ulna TW3 bone age assessment system. *Biomedical Engineering, IEEE Transactions on,* 55**,** 1463-1476.

UKBA 2010. Assessing Age. 2012.

Ulijaszek, S. L. 2001. Secular Trends in Growth: the narrowing of ethnic differences in stature. *Nutrition Bulletin,* 26**,** 43-51.

UNHCR. 1997. Guidelines on Policies and Procedures in Dealing with Unaccompanied Children Seeking Asylum. *In:* REFUGEES, U. N. H. C. F. (ed.). Geneva.

UNICEF. 2012. *UNICEF. United Kingdom* [Online]. London: UNICEF. Available: www.unicef.org.uk [Accessed 29th February 2012].

United Nations 1989. U.N. Convention on the Rights of the Child,. Office of the High Commissioner for Human Rights,.

Van Lenthe, F. J., Kemper, H. C. & Van Mechelen, W. 1998. Skeletal maturation in adolescence: a comparison between the Tanner-Whitehouse II and the Fels method. *European Journal of Pediatrics,* 157**,** 798-801.

Van Lenthe, F. J. & Van Mechelen, W. 1996. Rapid maturation in adolescence results in greater obesity in adulthood: The Amsterdam Growth and Health Study. *American Journal of Clinical Nutrition,* 64**,** 18-24.

Van Rijn, R. R., Lequin, M. H., Robben, S. G. F., Hop, W. C. J. & Van Kuijk, C. 2001. Is the Greulich and Pyle atlas still valid for Dutch Caucasian children today? *Pediatric Radiology,* 31**,** 748-752.

Venning, P. 1956. Radiological studies of variation in the segmentation and ossification of the digits of the human foot. Variation in length of the digit segments correlated with difference of segmentation and ossification of the toes. *American Journal of Physical Anthropology,* 14**,** 129-151.

Vignolo, M., Milani, S., DiBattista, E., Naselli, A., Mostert, M. & Aicardi, G. 1990. Modified Greulich-Pyle, Tanner-Whitehouse, and Roche-Wainer-Thissen (knee) methods for skeletal age assessment in a group of Italian children and adolescents. *European Journal of Pediatrics,* 149**,** 314-317.

Vignolo, M., Naselli, A., Magliano, P., Di Battista, E., Aicardi, M. & Aicardi, G. 1999. Use of the New US90 Standards for TW-RUS Skeletal Maturity Scores in Youths from the Italian Population. *Hormone Research,* 51**,** 168-172.

Wagner, U. A., Diedrich, V. & Schmitt, O. 1995. Determination of Skeletal Maturity by Ultrasound: A Preliminary Report. *Skeletal Radiology,* 24**,** 417-420.

Walker, J. S. 2000. *Permissible dose: A history of radiation protection in the Twentieth Century,* California, University of California Press.

Walker, S. 1997. The controversy over radiation safety. *The Journal of the American Medical Association,* 262**,** 664-668.

Wall, B. F. & Hart, D. 1997. Revised radiation doses for typical X-ray examinations. *The British Journal of Radiology,* 70**,** 437-439.

Watt, I. 1996. Letter ref. BFCR (96) 9 to all Home Clinical Radiology Fellows and Members. *In:* RADIOLOGISTS, R. C. O. (ed.). Royal College of Radiologists.

Webb, P. A. O. & Suchey, J. M. 1985. Epiphyseal Union of the Anterior Iliac Crest and Medial Clavicle in a Modern Multiracial Sample of American Males and Females. *American Journal of Physical Anthropology., 68***, 457-466.

Whitaker, J. M., Rousseau, L., Williams, T., Rowan, R. A. & Hartwig, W. C. 2002. Scoring system for estimating age in the foot skeleton. *American Journal of Physical Anthropology,* 118**, 385-392.

Wolff, P. 1971. Mirror-image confusability in adults. *Journal of Experimental Psychology,* 91**, 268-272.

Xi, H. & Roche, A. F. 1990. Differences between the hand–wrist and the knee in assigned skeletal ages. *American Journal of Physical Anthropology,* 83**, 95-102.

Zafar, A. M., Nadeem, N., Husen, Y. & Ahmad, M. N. 2010. An appraisal of Greulich-Pyle Atlas for skeletal age assessment in Pakistan. *Journal Pakistan Medical Assocation,* 60**, 552-555.

Zhang, A., Sayre, J. W., Vachon, L., Liu, B. J. & Huang, H. K. 2009. Racial differences in growth patterns of children assessed on the basis of bone age. *Radiology,* 250**, 228-235.

Zhang, S.-Y., Liu, L.-J., Wu, Z.-L., Liu, G., Ma, Z.-G., Shen, X.-Z. & Xu, R.-L. 2008. Standards of TW3 skeletal maturity for Chinese children. *Annals of Human Biology,* 35**, 349-354.

Zhang, Y.-Y. & Wang, S.-R. 2009. Secular trends in growth and body proportion among children and adolescents from 1985 to 2005 in Shandong, China. *Anthropological Science,* 117**, 69-76.

Appendix 1

Due to the size of the Bibliography it can be found as a pdf on the

accompanying disc.

Appendix 2

List of growth studies

Study (USA)	Period of time
University of Iowa Child Welfare Research Station	1917-1970
Harvard Growth Study	1922-1934
University of California Institute of Child Welfare Berkley Growth Study	1928-1954
University of California Institute of Child Welfare Child Guidance Study	1930-1950
University of California Institute of Child Welfare Adolescence Growth Study	1932-1939
Denver Growth Study. University of Oklahoma	1927-1967
Harvard School of Public Study	1929-1954
Fels Research Institute	1929-current
Child Research Council, University of Colorado	1930-1971
University of Toronto Burlington Growth Study	1952-1971
Brush Foundation, Western Reserve University	1926-1971 (now combined with the Bolton study)
Philadelphia Centre for Research on Growth	1948-current
Michigan Growth Study, University of Michigan	1953-1970
Oregon Growth Study, Oregon Health and Science University	1950-1975
Medford Boys Growth Study, University of Oregon	1956-1968
Saskatchewan Growth and Development Study, University of Saskatchewan	1964-1973
Motor Performance Study of Michigan State University	1967-1999
Leuven Growth Study of Belgian Boys	

Study (Non-USA)	Period of time
International Children's Centre Co-ordinated Studies London	1949-1969
International Children's Centre Co-ordinated Studies Paris	1953-1975
International Children's Centre Co-ordinated Studies Zurich	1954-1980
International Children's Centre Co-ordinated Studies Stockholm	1955-1975
International Children's Centre Co-ordinated Studies Brussels	1955-1975
International Children's Centre Co-ordinated Studies Louisville	1962- current
International Children's Centre Co-ordinated Studies Dakar	1954-1966
Prague Growth Study	1956-1981
Brno Growth Study	1961-1981
Lublin Growth Study	1964-1980
Harpenden Growth Study	1948-1971
Oxford Child Health Survey	1944-1964
Stockholm School of Education Study	1954-1966
Helsinki Growth Study	1955-1975
Wroclaw Growth Study	1961-1971
Budapest Growth Study	1970-1988
Edinburgh Growth Study	1972-1995
SLU, Swedish Longitudinal Growth Study	1964-1971
Newton Longitudinal Growth Study, Massachusetts	1965-1975
Newcastle upon Tyne, UK	1971-1979
Leuven Growth Study of Belgian Boys	1968-1974
Amsterdam Growth and Health Longitudinal Study	1976-1996

Appendix 3

Please see accompanying disc which contains all data.

Appendix 4

Ethics

Hunter Stewart (NHS Tayside) [Stewart.Hunter:nhs.net]

Steve/Luciana
I confirm that as the images used were fully anonymised the use of the x rays for research purposes was permissable.
Stewart Hunter
Information Governance Coordinator
01382 660111 x 33472
0782 568 0599

From: Menhinick Stephen (NHS TAYSIDE)
Sent: 11 January 2011 09:06
To: Lucina Hackman; Hunter Stewart (NHS TAYSIDE)
Subject: RE: hello

Hi Stewart,

A couple of years ago Lucina, who works at the department of forensic anthropology with Professor Sue Black, started a research project looking at x-rays of wrists and ankles of people under the age of 20 to look at the correlation between bone development and age. At that time I asked you if this would be acceptable and you agreed providing that all patient information was removed and any images to be used would be fully anonymised. As you will see below Lucina has now completed her research and would like to have a note to say that the information has been obtained legitimately. Would you be able to provide this?

Many thanks,

Steve

Stephen Menhinick
Senior Radiographer
Department of Clinical Radiology
Ninewells Hospital
Dundee
DD1 9SY

Appendix 5

Peer Reviewed Publications in support of this thesis

Hackman, L. and Black, S. (accepted) Does mirror imaging a radiograph affect reliability of age assessment using the Greulich and Pyle atlas. *Journal of Forensic Sciences.* (accepted Aug 2011)

Hackman, L. and Black, S. (accepted) The reliability of the Greulich and Pyle Atlas when applied to a modern Scottish population. *Journal of Forensic Sciences* (accepted Dec 2011)

Hackman, L., Davis, C. and Black, S. (accepted) Age estimation using foot radiographs from a modern Scottish population. *Journal of Forensic Sciences.* (accepted Jan 2012)

Hackman, L. and Black, S. (accepted) Age estimations from radiographic images of the knee. *Journal of Forensic Sciences* (accepted March 2012)

Conference papers presented in support of this thesis

Hackman, L. The Applicability of the Greulich and Pyle Atlas to a Scottish Population. BABAO (British Association for Biological Anthropology and Osteoarchaeology) 2011 Conference.

Hackman, L. A Comparison of the accuracy of Right Hand-Wrist Radiographs and Left Hand/Wrist Radiographs for Age Assessment in the Living. AGFAD (Study Group of Forensic Age Diagnostics) 2011 Annual Meeting.

Scholarships and awards pertaining to the research presented in this thesis

SIET (Scottish International Education Trust) Travel Grant. Awarded 2009 for travel to New Delhi, India.

BIBLIOGRAPHY

Book

Black, S. M., Aggrawal, A. & Payne-James, J. 2010. *Age Estimation in the Living: The Practitioner's Guide,* Oxford, Wiley-Blackwell.

Bleich, A. R. 1960. *The Story of X-Rays from Rontgen to Isotopes.,* New York Dover Publications Ltd.

Bogin, B. 1988. *Patterns of Human Growth,* Cambridge, Cambridge University Press.

Brodeur, A. E., Silberstein, M. J. & Gravis, E. R. 1981. *Radiology of the Pediatric Elbow,* Boston, G.K. Hall Medical Publishers.

De Roo, T. & Scröder, H. J. 1976. *Pocket Atlas of Skeletal Age,* The Hague, Martinus Nijhoff Medical Division.

Eveleth, P. B. & Tanner, J. M. 1976. *Worldwide Variation in Human Growth,* Cambridge, Cambridge University Press.

Gȍk, S., Erolcer, N. & Ozen, C. 1985. *Age Determination in Forensic Medicine [in Turkish],* Istanbul, Council of Forensic Medicine Press.

Greulich, W. W. & Pyle, S. I. 1950. *Radiographic Atlas of Skeletal Development of the Hand and Wrist,* Stanford, Stanford University Press.

Greulich, W. W. & Pyle, S. I. 1959. *Radiographic Atlas of Skeletal Development of the Hand and Wrist,* Stanford, Stanford University Press.

Hoerr, N. L., Pyle, S. I. & Francis, C. C. 1962. *Radiographic Atlas of Skeletal Development of the Foot and Ankle.,* Springfield, Illinois., Charles C. Thomas.

Lee, M. (ed) 2007. *Human Trafficking*. Devon. Willan Publishing,

Poland, J. 1898. *Skiagraphic Atlas showing the Development of the Bones of the Wrist and Hand,* London, Smith, Elder & Co.

Bibliography: A test of six radiographic age estimation methods on a modern population

Pyle, S. I. & Hoerr, N. L. 1969. *A Radiographic Standard of Reference for the Growing Knee,* Springfield, Charles C. Thomas.

Pyle, S. I., Waterhouse, A. M. & Greulich, W. W. 1971. *A Radiographic Standard of Reference for the Growing Hand and Wrist,* Cleveland, Ohio, The Press of Case Western Reserve University.

Roche, A. F. 1992. *Growth, Maturation, and Body Composition: the Fels Longitudinal Study 1929-1991,* Cambridge, Cambridge Univresity Press.

Roche, A. F., Chumlea, C. & Thissen, D. 1988. *Assessing the Skeletal Maturity of the Hand-Wrist: FELS Method,* Springfield, Illinois, Charles C. Thomas.

Roche, A. F., Thissen, D. & Wainer, H. 1976. *Skeletal Maturity: The Knee Joint as a Biological Indicator,* New York, Plenum Medical Book Company.

Scheuer, L. & Black, S. 2000. *Developmental Juvenile Osteology,* London, Academic Press.

Sinclair, D. 1969. *Human Growth After Birth,* London, Oxford University Press.

Tanner, J. M. 1962. *Growth at Adolescence,* Oxford, Blackwell Scientific Publications.

Tanner, J. M. 1978. *Foetus into Man,* London, Open Books Publishing Ltd.

Tanner, J. M., Healy, M. J. R., Goldstein, H. & Cameron, N. 2001. *Assessment of Skeletal Maturity and Prediction of Adult Height (TW3 method).* London, Saunders.

Tanner, J. M., Whitehouse, R. H. & Healy, M. J. R. 1962. *A New System for Estimating Skeletal Maturity from the Hand and Wrist with Standards Derived from a Study of 2600 Healthy British Children. Part II. The Scoring System.,* Paris, International Child Centre.

Tanner, J. M., Whitehouse, R. H., Marshall, W. A., Healy, M. J. R. & Goldstein, H. 1975. *Assessment of Skeletal Maturity and Prediction of Adult Height.,* London, Academic Press.

Tanner, J.M. 1981. *A History of the Study of Human Growth,* Cambridge, Cambridge University Press.

The Law Commission 2011. *Expert Evidence in Criminal Proceedings in England and Wales,* London, The Law Commission (Law Com No 325).

Thiemann, H.-H., Nitz, I. & Schmeling, A. 2006. *Rontgenatlas der Normalen Hand im Kindesalter,* Leipzig, Stuttgart, New York, Thieme.

Todd, T. W. 1937. *Atlas of Skeletal Maturation,* St. Louis, The C.V. Mosby Company.

Walker, J. S. 2000. *Permissible dose: A history of radiation protection in the Twentieth Century,* California, University of California Press.

Beh, P. & Payne-James, J. 2010. Clinical and Legal Requirements for Age Determination in the Living. *In:* BLACK, S. M., AGGRAWAL, A. & PAYNE-JAMES, J. (eds.) *Age Estimation in the Living.* Oxford: Wiley-Blackwell.

Bibliography: A test of six radiographic age estimation methods on a modern population

Bolton, S. 2011. 'Best interests': safeguarding and promoting the welfare of children in immigration law and practice. *In:* WOODALL, L. (ed.) *Working with Refugee Children.* London: Immigration Law Practitioners' Association.

Brogdon, B. G. & Lichtenstein, J. E. 1998. Forensic Radiology in Historical Perspective. *In:* BROGDON, B. G. (ed.) *Forensic Radiology.* Bacon Rouge: CRC Press.

Cameron, N. 2002. Assessment of Maturation. *In:* CAMERON, N. (ed.) *Human Growth and Development.* London: Academic Press.

Fernie, G. & Payne-James, J. 2010. Legal Implications of Age Determination: Consent and Other Issues. *In:* BLACK, S. M., AGGRAWAL, A. & PAYNE-JAMES, J. (eds.) *Age Estimation in the Living.* Chichester: Wiley-Blackwell.

Johnston, F. E. 2002. Social and Economic Influences on Growth and Secular Trends. *In:* CAMERON, N. (ed.) *Human Growth and Development.* London: Academic Press.

Kemkes-Grottenthaler, A. 2002. Aging Through the Ages. *In:* HOPPA, R. D. & VAUPEL, J. W. (eds.) *Paleodemography: Age distributions from skeletal samples.* Cambridge: Cambridge University Press.

Kosa, F. 1989. Age Estimation from the fetal skeleton. *In:* ISCAN, M. Y. (ed.) *Age Markers in the Human Skeleton.* Springfield: Charles C Thomas.

Lampl, M. 2002. Saltation and Stasis. *In:* CAMERON, N. (ed.) *Human Growth and Development* Oxford Academic Press.

Law, H., Mensah, L., Bailey, S. & Nelki, J. 2010. Imigration, Asylum Seekers and Undocumented Identity. *In:* BLACK, S., AGGRAWAL, A. & PAYNE-JAMES, J. (eds.) *Age Estimation in the Living.* Oxford: Wiley-Blackwell.

Luh, S. S., Sandhu, B., Y., & Yazdani, Z. 2011. Best Practice in Age Dispute Challenges. *In:* WOODALL, L. (ed.) *Working with Refugee Children. .* London: Immigration Law Practitioners' Association.

Martrille, L., Baccino, E. & Jason, P.-J. 2005. Age Estimation in the Living. *Encyclopedia of Forensic and Legal Medicine.* Oxford: Elsevier.

Moccia, P., Anthony, D., Brazier, C., Dettori, E., Di Noia, M., Gebre-Egziabher, H., Lai, A., Leston, N., Maitre, C., Mekonnen, M., Moehlmann, K., Nayak, B., Rutgers, C., Shankar, S. & Yemane, J. (eds.) 2009. *The State of the World's Children,* New York: UNICEF.

Noël, C. 2002. 17 - Assessment of Maturation. *Human Growth and Development.* San Diego: Academic Press.

Ogden, J. A. 2000. Anatomy and Physiology of Skeletal Development. *Skeletal Injury in the Child.* 3rd ed. ed. New York: Springer.

O'Rahilly, R. 1973. The Human Foot. *In:* GIANNESTRAS, N. J. (ed.) *Foot disorders: medical and surgical management.* Philadelphia: Lea and Febiger.
.

Bibliography: A test of six radiographic age estimation methods on a modern population

Robert M, M. 2002. 15 - Exercise and Growth: Physical Activity as a Factor in Growth and Maturation. *Human Growth and Development.* San Diego: Academic Press.

Rosing, F. W. & Kvaal, S. I. 1997. Dental age in adults. A review of estimation methods. *In:* ALT, K. W., ROSING, F. W. & TESCHLER-NICOLA, M. (eds.) *Dental anthropology. Fundamentals, limits and prospects.* New York: Springer.

Scheuer, J. L. & Black, S. 2000. Development and ageing of the juvenile skeleton. *In:* COX, M. & MAYS, S. (eds.) *Human Osteology. In Archaeology and Forensic Science.* Cambridge: Cambridge University Press.

Schmeling, A., Schmidt, S., Schulz, R., Olze, A., Reisinger, W. & Vieth, V. 2010. Practical Imaging Techniques for Age Evaluation. *In:* BLACK, S. M., AGGRAWAL, A. & PAYNE-JAMES, J. (eds.) *Age Estimation in the Living.* Chichester: Wiley-Blackwell.

Spoor, F., Jeffrey, N. & Zonneveld, F. 2000. Development, Growth and Evolution. *In:* O'HIGGINS, P. & COHN, M. J. (eds.) *Development, Growth and Evolution: Implications for the Study of the Hominid Skeleton.* London: The Linnean Society of London.

Stoney, D. T. 2001. Measurement of Fingerprint Individuality. *In:* LEE, H. C. & GAENSSLEN, R. E. (eds.) *Advances in Fringerprint Technology.* Boca Rouge: CRC Press.

Tanner, J. M. 1959. Boas' Contribution to Knowledge of Human Growth. *In:* GOLDSMITH, W. (ed.) *The Anthropology of Franz Boas-Essays on the Centennial of his Birth.* Menasha, Wis: American Anthropological Association.

Ubelaker, D. H. 2002. Taphonomy Applications in Forensic Anthropology. *In:* HAGLUND, W. D. A. S., M.H. (ed.) *Advances in Forensic Taphonomy.* Boca Raton: CRC Press.

Ulijaszek, S. L., Johnston, F. E. & Preece, M. A. (eds.) 1998. *The Cambridge Encyclopedia of Human Growth and Development,* Cambridge: Cambridge University Press.

Whittaker, D. 2000. Ageing from the Dentition. *In:* COX, M. & MAYS, S. (eds.) *Human Osteology in Archaeological and Forensic Science.* London: Greenwich Medical Media Ltd.

Electronic Article

Aggrawal, A. 2000. Age estimation in the living - some medicolegal considerations. *Anil Aggrawal's Internet Journal of Forensic Medicine and Toxicology.* [Online], 1. Available: http://www.geradts.com/anil/ij/vol_001_no_002/ug001.html [Accessed 25th November 2009].

Home Office. 2010. Control of Immigration: Statistics. Available: http://webarchive.nationalarchives.gov.uk/20110218135832/rds.homeoffice.gov.uk/rds/pdfs10/hosb1510.pdf [Accessed 19th February 2012].

Munro, E. 1996. Avoidable and unavoidable mistakes in child protection work. *LSE Research Articles Online* [Online]. Available: http://eprints.lse.ac.uk/archive/00000348/ [Accessed 29.02.2008].

Bibliography: A test of six radiographic age estimation methods on a modern population

Schmeling, A., Garamendi, P. M., Prieto, J. L. & Landa, M. I. 2011. Forensic age estimation in unaccompanied minors and young living adults. *InTech* [Online]. Available: http/www.intechopen.com/articles/show/title/forensic-age-estimation-in-unaccompanied-minors-and-young-adults.

Gilsanz, V. & Ratib, O. 2005. Hand Bone Age. *A Digital Atlas of Skeletal Maturity.* Los Angeles: Springer.

Legislation

DEFRA. 2004. The Justification of Practices Involving Ionising Radiation Regulations 2004 (SI 2004 No 1769). Department for Environment, Food and Rural Affairs.

Department of Health 2000. Ionising Radiation (Medical Exposure) Regulations IS 1999/3232. Norwich: Stationery Office.

HMSO 1984. Police and Criminal Evidence Act (c.60). HMSO; London.

HMSO 2004. Children Act 2004 (c.31). London.

HMSO. 1989. Children Act 1989 (c.41). London: HMSO.

HMSO. 2000. The Ionising Radiation (Medical Exposure) Regulations No. 1059. London: HMSO.

HMSO. 2005. Mental Capacity Act (c.9). HMSO, London.

HMSO. 2009. Borders, Citizenship and Immigration Act (c.11). HMSO, London.

India Government 1969. Registration of Births and Deaths Act. India.

Articles

Abbie, A. A. & Adey, W. R. 1953. Ossification in a Central Australian tribe. *Human Biology,* 25**,** 265-278.

Acheson, R. M. 1952. Radiographs of the hand as an index of skeletal maturity in infants. *Archives of Disease in Childhood,* 27**,** 382-385.

Acheson, R. M., Fowler, G. B. & Janes, M. D. 1962. Effect of improved care on the predicted adult height of undernourished children. *Nature,* 194**,** 735

Acheson, R. M. & Hewitt, d. 1954. Physical development in the English and the American pre-school child. *Human Biology* **,** 26, 4. 343-355

Acheson, R. M., Vicinus, J. H. & Fowler, G. B. 1966. Studies in the reliability of assessing skeletal maturity from X-rays, Part III. Greulich-Pyle atlas and Tanner Whitehouse method contrasted. *Human Biology,* 35, 317-349.

Bibliography: A test of six radiographic age estimation methods on a modern population

Aggrawal, A. & Busuttil, A. 1991. Age estimation in the living. *The Police Surgeon (Journal of the Association of Police Surgeons),* 38**,** 33-36.

Aja-Fernández, S., de Luis-García, R., Martín-Fernández, M. Á. & Alberola-López, C. 2004. A computational TW3 classifier for skeletal maturity assessment. A Computing with Words approach. *Journal of Biomedical Informatics,* 37**,** 99-107.

Ajmal, M., Mody, B. & Kumar, G. 2001. Age estimation using three established methods: A study on Indian population. *Forensic Science International,* 122**,** 150-154.

Aka, P. S., Canturk, N., Dagalp, R. & Yagan, M. 2009. Age determination from central incisors of fetuses and infants. *Forensic Science International,* 184**,** 15-20.

Akachi, Y. & Canning, D. 2007. The height of women in Sub-Saharan Africa: The role of health, nutrition, and income in childhood. *Annals of Human Biology,* 34**,4,** 397-410

Albert, A. M. & Greene, D. L. 1999. Bilateral asymmetry in skeletal growth and maturation as an indicator of environmental stress. *American Journal of Physical Anthropology,* 110**,** 341-349.

Al-Hadlaq, A., Al-Qarni, M., Al-Kahtani, A. & Al-Obaid, A. 2006. Comparative Study Between Hand-Wrist Method and Cervical Vertebral Maturation Method for Evaluation of Skeletal Maturity in Saudi Boys. *Pakistan Oral and Dental Journal,* 27**,** 187-192.

Alkhal, H. A., Wong, R. W. K., Bakr, A. & Rabie, M. 2008. Elimination of hand-wrist radiographs for maturity assessment in children needing orthodontic therapy. *Skeletal Radiology,* 37**,** 195-200.

Alkhal, H. A., Wong, R. W. K. & Rabie, A. B. M. 2008. Correlation between Chronological Age, Cervical Vertebral Maturation and Fishman's Skeletal Maturity Indicators in Southern Chinese. *Angle Orthodontist,* 78**,** 591-596.

Alvear, J., Artaza, C., Vial, M., Guerrero, S. & Muzzo, S. 1986. Physical growth and bone age of survivors of protein energy malnutrition. *Archives of Disease in Childhood.,* 61**,** 257-262.

Andersen, E. 1968. Skeletal maturation of Danish school children in relation to height, sexual development, and social conditions. *Acta Paediatrica Scandinavica Supplement,* 185**,** 102-110

Anderson, M. 1971. Use of the Greulich-Pyle "Atlas of skeletal development of the hand and wrist" in a clinical context. *American Journal of Physical Anthropology,* 35**,** 347-351.

Anderson, M., Green, W. T. & Messner, M. 1963. Growth and Predictions of Growth in the Lower Extremetries. *The Journal of Bone and Joint Surgery,* 45-A**,** 1-14.

Arabi, A., Nabulsi, M., Maalouf, J., Choucair, M., Khalife, H., Vieth, R. & Fuleihan, G. E.-H. 2004. Bone Mineral Density by Age, Gender, Pubertal Stages and Socioeconomic Status in Healthy Lebanese Children and Adolescents. *Bone,* 35**,** 1169-1179.

Argemi, J. & Badia, J. 1997. A New Computerised Method for the Assessment of Skeletal Maturity in the Newborn Infant. *Pediatric Radiology,* 27**,** 309-314.

Ashcroft, M. T., Buchanan, I. C., Lovell, H. G. & WElsh, B. 1966. Growth of Infants and Preschool Children in St. Christopher-Nevis-Anguilla, West Indies. *American Journal of Clinical Nutrition,* 19**,** 37-45.

Ashizawa, K. 1994. TW2 skeletal maturation, growth and age at menarche in Tokyo girls. *Human Biology Budapest,* 25**,** 261-266

Ashizawa, K., Asami, T., Anzo, M., Matsuo, N., Matsuoka, H., Murata, M., Ohtsuki, F., Satoh, M., Tanaka, T., Tatara, H. & Tsukagoshi, K. 1996. Standard RUS skeletal maturation of Tokyo children. *Annals of Human Biology,* 23**,** 457-469.

Ashizawa, K., Kumakura, C., Kato, S., Kawabe, T., Hauspie, R. C. & Eto, M. 2005. Adolescent height growth of girls in Tokyo. *Anthropological Science,* 113**,** 245-252.

Ashizawa, K., Kumakura, C., Zhou, X., Jin, F. & Cao, J. 2005. RUS skeletal maturity of children in Beijing. *Annals of Human Biology,* 32**,** 316-325.

Ashizawa, K., Takahashi, H. & Eto, M. 1995. Individual TW2 skeletal maturity in Tokyo Girls. *Anthropological Science,* 103**,** 61.

Atamturk, D. & Duyar, I. 2008. Age-Related Factors in the Relationship Between Foot Measurements and Living Stature and Body Weight. *Journal of Forensic Sciences,* 53**,** 1296-1300.

Auerbach, B. M. & Ruff, C. B. 2006. Limb bone bilateral asymmetry: variability and commonality among modern humans. *Journal of Human Evolution,* 50**,** 203-218.

Aynsley-Green, A. 2009. Unethical age assessment. *British Dental Journal,* 206**,** 337-337.

Baber, F. M., Field, C. E., Billewicz, W. Z. & Thomson, A. M. 1974. Variations in the growth pattern of Chinese children in Hong Kong in the first three years. *Asian Journal of Modern Medicine,* 10**,** 312.

Baccetti, T., Franchi, L., De Lisa, S. & Giuntini, V. 2008. Eruption of the maxillary canines in relation to skeletal maturity. *American Journal of Orthodontics and Dentofacial Orthopedics,* 133**,** 748-751.

Baccetti, T., Franchi, L., De Toffol, L., Ghiozzi, B. & Cozza, P. 2006. The diagnostic performance of chronologic age in the assessment of skeletal maturity. *Prog Orthod,* 7**,** 176-88.

Bagnall, K. M., Harris, P. F. & Jones, P. R. M. 1982. A Radiographic Study of the Longitudinal Growth of Primary Ossification Centres in Limb Long Bones of the Human Fetus. *The Anatomical Record,* 203**,** 293-299.

Balaraj, B. M. & Nithin, M. D. 2010. Determination of adolescent ages 14-16 years by radiological study of permanent mandibular second molars. *Journal of Forensic and Legal Medicine,* 17**,** 329-332.

Banerjee, K. K. & Agarwal, B. B. L. 1998. Estimation of age from epiphyseal union at the wrist and ankle joints in the capital city of India. *Forensic Science International,* 98**,** 31-39.

Bibliography: A test of six radiographic age estimation methods on a modern population

Banik, N., Datta, D., Nayar, S., Krishna, P., Raj, L. & Gadekar, N. G. 1970. Skeletal maturation of Indian children. *Indian Journal of Paediatrics,* 37**,** 249.

Barnewolt, C. E., Shapiro, F. & Jaramillo, D. 1997. Normal gadolinium-enhanced MR images of the developing appendicular skeleton: Part I. Cartilaginous epiphysis and physis. *AJR. American Journal of Roentgenology,* 169**,** 183-9.

Baroncelli, G. I., Bertelloni, S., Vierucci, F., Ghione, S. & Saggese, G. 51 Delayed Growth and Skeletal Maturation Affect Bone Mineral Status Assessed by Phalangeal Quantitative Ultrasound. *Journal of Clinical Densitometry,* 12**,** 115-116.

Baroncelli, G. I., Federico, G., Bertelloni, S., De Terlizzi, F., Cadossi, R. & Saggese, G. 2001. Bone Quality Assessment by Quantitative Ultrasound of Proximal Phalanxes of the Hand in Healthy Subjects Aged 3-21 Years. *Pediatric Research,* 49**,** 713-718.

Barr, L. L. & Babcock, D. S. 1991. Sonography of the Normal Elbow. *American Journal of Roentgenology,* 157**,** 793-798.

Baughan, B., Dermirjian, A. & Levesque, G.-Y. 1979. Skeletal maturity standards for French-Canadian children of school-age with a discussion of the reliability and validity of such measures. *Human Biology,* 51**,** 353.

Baxter-Jones, A. D. G. 1995. Growth and development of young athletes: should competition levels be age related. *Sports Medicine,* 20**,** 59.

Baxter-Jones, A. D. G., Mirwald, R. L., McKay, H. A. & Bailey, D. A. 2003. A longitudinal analysis of sex differences in bone mineral accrual in healthy 8-19-year-old boys and girls. *Annals of Human Biology,* 30**,** 160-175.

Bayley, N. 1940. Skeletal X-Rays as Indicators of Maturity. *Journal of Consuling Psychology***,** 69-73.

Bayley, N. 1943. Size and body build of adolescents in relation to rate of skeletal maturing. *Child Development,* 14**,** 47.

Bayley, N. 1943. Skeletal maturity in adolescence as a basis for determining percentage of completed growth. *Child Development,* 14**,** 5.

Bayley, N. & Pinneau, S. R. 1952. Tables for predicting adult height from skeletal age: revised for use with the Greulich-Pyle hand standards: erratum. *Journal of Pediatrics,* 41**,** 371.

Beals, R. K. & Skyhar, M. 1984. Growth and Development of the Tibia, Fibula and Ankle Joint. *Clinical Orthopaedics and Related Research,* 182**,** 289-292.

Becroft, T. & Bailey, K. V. 1965. Supplementary feeding trial in New Guinea highland infants. *Journal of Tropical Pediatrics,* 11**,** 28.

Benson, J. 2008. Age Determination in Refugee Children. *Australian Family Physician,* 37**,** 821-824.

Bibliography: A test of six radiographic age estimation methods on a modern population

Beresowski, A. & Lundie, J. K. 1952. Sequence in the time of ossification of the carpal bones in 705 African children from birth to 6 years of age. *South African Journal of Medical Science,* 17**,** 25.

Bergensen, E. O. 1972. The male adolescent facial growth spurt: Its prediction and relation to skeletal maturation. *Angle Orthodontist,* 42**,** 319.

Bermudez de la Vega, J. A., Vasquez, M. A., Bernal, S., Gentil, F. J., Gonzalez-Hachero, J., Montoya, M. J. & Perez-Cano, R. 2007. Anthropometric Bone Age, and Bone Mineral Density Changes after a Family-Based Treatment for Obese Children. *Calicification Tissue International,* 81**,** 279-284.

Bernaards, C. M., Kemper, H. C. G., Twisk, J. W. R., Mechelen, W. v. & Snel, J. 2001. Smoking behaviour and biological maturation in males and females: a 20-year longitudinal study. Analysis of data from the Amsterdam Growth and Health Longitudinal Study. *Annals of Human Biology,* 28**,** 634-648.

Bertaina, C., Staslowska, B., Benso, A. & Vannelli 2007. Is TW3 Height Prediction More Accurate than TW2? *Hormone Research.,* 67**,** 220-223.

Beunen, G. 1975. Skeletal maturation and a simplified Tanner, Whitehouse, and Healy method for boys aged 12 through 15. *Hermes (Leuven),* 9**,** 393-399

Beunen, G. & Cameron, J. M. 1980. The Reproducibility of TW2 Skeletal Age Assessments by a Self - Taught Assessor. *Annals of Human Biology,* 7**,** 155-162.

Beunen, G. & Cameron, N. 1980. The reproducibility of TW2 skeletal age assessment by a self-taught assessor. *Annals of Human Biology,* 7**,** 155-162

Beunen, G., De Beul, G., Ostyn, M., Renson, R., Simons, J. & Van Gerven, D. 1978. Age of menarche and motor performance in girls aged 11 through 18. *Medicine and Sport,* 11**,** 118-125.

Beunen, G., Lefevre, J., Ostyn, M., Renson, R., Simons, J. & Van Gerven, D. 1990. Skeletal maturity in Belgian youths assessed by the Tanner-Whitehouse method (TW2). *Annals of Human Biology,* 17**,** 355-376.

Beunen, G., Malina, R. M., Claessens, A. L., Lefevre, J. & Thomas, M. 1999. Ulnar Variance and Skeletal Maturity of Radius and Ulna in Female Gymnasts. *Medicine and Science in Sports and Exercise,* 31**,** 653-657.

Beunen, G., Malina, R. M., Ostyn, M., Renson, R., Simons, J. & Gerven, D. 1982. Fatness and skeletal maturity of Belgian boys 12 through 17 years of age. *American Journal of Physical Anthropology,* 59**,** 387.

Beunen, G., Ostyn, M., Renson, R., Simons, J. & Van Gerven, D. 1979. Growth and maturity as related to motor ability. *S. A. Journal for Research in Sport, Physical Education and Recreation,* 2**,** 9.

Beunen, G., Ostyn, M., Renson, R., Simons, J. & Van Gerven, D. 1983. Patterns of TW-1 and TW-2 skeletal age differences in 12-19-year-old Belgian boys. *Annals of Human Biology,* 10**,** 479-482.

Beunen, G., Ostyn, M., Simons, J., Renson, R. & Van Gerven, D. 1981. Chronological and biological age as related to physical fitness in boys 12 to 19 years. *Annals of Human Biology,* 8**,** 321.

Bibliography: A test of six radiographic age estimation methods on a modern population

Beunen, G. P., Malina, R. M., Lefevre, J., Claessens, A. L., Renson, R., Vanden Eynde, B. & Simons, J. 1997. Skeletal maturation, somatic growth and physical fitness in girls aged 6- 16 years. *International Journal of Sports Medicine,* 18**,** 413.

Beunen, G. P., Ostyn, M., Simons, J., Renson, R. & VanGerven, D. 1981. Chronological age and biological age as related to physical tness in boys 12 to 19 years. *Annals of Human Biology,* 8**,** 321.

Beunen, G. P., Rogol, A. D. & Malina, R. M. 2006. Indicators of biological maturation and secular changes in biological maturation. *Food and Nutrition Bulletin,* 27**,** S244-S256.

Bielicki, T. 1975. Interrelationships between various measures of maturation rate in girls during adolescence. *Studies in Physical Anthropology,* 1**,** 51.

Bielicki, T., Koniarek, J. & Malina, R. M. 1984. Interrelationships among certain measures of growth and maturation rate in boys during adolescence. *Annals of Human Biology,* 11**,** 201-210.

Bilgili, Y., HIzel, S., Kara, S. A., Sanli, C., Erdal, H. H. & Altinok, D. 2003. Accuracy of skeletal age assessment on children from birth to 6 years of age with the ultrasonographic version of the Greulich-Pyle atlas. *Journal of Ultrasound Medicine,* 22**,** 683-390.

Bilkey, W., Marak, F. K. & Singh, S. 2007. Age Determination in Girls of North - Eastern Region of India. *Journal of Indian Academy of Forensic Medicine,* 29**,** 102-108.

Billewicz, W. Z., Fellowes, H. M. & Thompson, A. M. 1981. Pubertal changes in boys and girls in Newcastle upon Tyne. *Annals of Human Biology,* 8**,** 211.

Birkbeck, J. A. & Herbert, C. M. 1980. Skeletal maturity in seven year old Dunedin children. *New Zealand Medical Journal,* 92**,** 312-3.

Bjork, A. & Helm, S. 1967. Prediction of the Age of Maximum Puberal Growth in Body Height. *The Angle Orthodontist,* 37**,** 134-143.

Blair, E., Liu, Y. & Cosgrove, P. 2004. Choosing the best estimate of gestational age from routinely collected population-based perinatal data. *Paediatric and Perinatal Epidemiology.,* 18**,** 270-276.

Blanco, R. A., Acheson, R. M., Canosa, Cipriano & Salomon, J. B. 1972. Retardation in appearance of ossification centers in deprived Guatamalan children. *Human Biology,* 44**,** 525.

Blanco, R. A., Acheson, R. M., Cansoa, C. & Salomon, J. B. 1974. Height, weight, and lines of arrested growth in young Guatemalan children. *American Journal of Physical Anthropology,* 40**,** 39.

Bock, R. D. 2004. Multiple prepubertal growth spurts in children of the Fels Longitudinal Study: comparison with results from the Edinburgh Growth Study. *Annals of Human Biology,* 31**,** 59-74.

Boechat, M. I. & Lee, D. C. 2007. Graphic Representation of Skeletal Maturity Determinations. *American Journal of Roentgenology,* 189**,** 873-874.

Bogin, B., Silva, M. I. V. & Rios, L. 2007. Life history trade-offs in human growth: Adaptation or pathology? *American Journal of Human Biology,* 19**,** 631-642.

Bogin, B., Sullivan, T., Hauspie, R. & MacVean, R. B. 1989. Longitudinal Growth in Height, Weight, and Bone Age of Guatemalan Latino and Indian Scholchildren. *American Journal of Human Biology.,* 1**,** 103-113.

Bolboaca, S., Denes, C. & Cardariu, A. 2003. Free Software Development. 4. Client-Server Implementation of Bone Age Assessment Calculations. *Leonardo Electronic Journal of Practices and Technologies,* 2**,** 1-19.

Borgna-Pignatti, C., Stefano, P. D., Zonta, L., Vullo, C., Sanctis, V. D., Melevendi, C., Naselli, A., Masera, G., Terzoli, S., Gabutti, V. & Piga, A. 1985. Growth and sexual maturation in thalassemia major. *The Journal of Pediatrics,* 106**,** 150-155.

Borkan, G. A., Hults, D. E. & Glynn, R. J. 1983. Role of Longitudinal Change and Secular Trend in Age Differences in Male Body Dimensions. *Human Biology,* 55**,** 629-641.

Bouchard, C., Leblanc, C., Malina, R. M. & Hollmann, W. 1978. Skeletal age and submaximal working capacity in boys. *Annals of Human Biology,* 5**,** 75.

Bouchard, C., Malina, R. M., Hollmann, W. & Leblanc, C. 1976. Relationships between skeletal maturity and submaximal working capacity in boys 8 to 18 years. *Medicine and Science in Sports,* 8**,** 186.

Boutourline, E., Tesi, G., Kerr, G. R., Ghamry, M. T. & Stare, F. J. 1973. Nutritional Correlates of Child Development in Southern Tunnisia III. Skeletal Growth and Maturation. *Growth,* 37**,** 223-247.

Bowden, B. D. 1976. Epiphyseal changes in the hand/wrist area as indicators of adolescent stage. *Australian Orthodontic Journal,* 4**,** 87.

Braga, J. & Treil, J. 2007. Estimation of pediatric skeletal age using geometric morphometrics and three-dimensional cranial size changes. *International Journal of Legal Medicine,* 121**,** 439-443.

Brailsford, J. F. 1943. Variations in the Ossification of the Bones of the Hand. *Journal of Anatomy,* 77**,** 170-175.

Braude, S. C., Henning, L. M. & Lambert, M. I. 2007. Accuracy of Bone Assessments for Verifying Age in Adolescents - Applications in Sport. *SA Journal of Radiology,* June**,** 4-7.

Brennan, P. C. & Johnston, D. 2002. Irish X-Ray departments demonstrate varying levels of adherence to European guidelines on good radiographic technique. *The British Journal of Radiology,* 75**,** 243-248.

Briers, P. J., Hoorweg, J. & Stanfield, J. P. 1975. The long-term effects of protein energy malnutrition in early childhood on bone age. Bone cortical thickness and height. *Acta Pediatrica Scandinavia [Suppl],* 64**,** 853-858.

Brinkmann, B. 2007. Hans-Heinrich Thiemann, Inna Nitz, Andreas Schmeling (eds), Röntgenatlas der normalen Hand im Kindesalter (Radiographic atlas of the normal hand at an early age). *International Journal of Legal Medicine,* 121**,** 429-429.

Broadbent, B. H. & Golden, W. H. 1971. The value of an assessment of skeletal maturity in orthodontic diagnosis. *American Journal of Physical Anthropology,* 35**,** 409-410.

Buckler, J. M. 1983. How to make the most of bone ages. *Archives of Disease in Childhood,* 58**,** 761-763.

Bibliography: A test of six radiographic age estimation methods on a modern population

Burdan, F., Szumiło, J., Korobowicz, A., Farooquee, R., Patel, S., Patel, A., Dave, A., Szumiło, M., Solecki, M., Klepacz, R. & Dudka, J. 2009. Morphology and physiology of the epiphyseal growth plate. *Folia Histochemica et Cytobiologica,* 47**,** 5-16.

Butler-Sloss, E. & Hall, A. 2002. Expert witnesses, courts and the law. *Journal of the Royal Society of Medicine,* 95**,** 431-434.

Butte, N. F., Garza, C. & de Onis, M. 2007. Evaluation of the Feasibility of International Growth Standards for School-Aged Children and Adolescents. *The Journal of Nutrition,* 137**,** 153-157.

Caffey, J., Madell, S. H., Royer, C. & Morales, P. 1958. Ossification of the Distal Femoral Epiphysis. *The Journal of Bone and Joint Surgery,* 40**,** 647-714.

Cahn, A. & Roche, A. F. 1961. Influence of illness and calcium intake on rate of skeletal maturation in children. *British Journal of Nutrition***,** 411.

Caine, D. J. & Broekhoff, J. 1987. Maturity assessment: a viable preventative measure against physical and psychological insult to the young athlete. *Physician and Sports Medicine,* 15**,** 67.

Cameriere, R., Ferrante, L., Ermenc, B., Mirtella, D. & Strus, K. 2008. Age estimation using carpals: Study of a Slovenian sample to test Cameriere's method. *Forensic Science International,* 174**,** 178-181.

Cameron, N. 1984. BASIC programs for the assessment of skeletal maturity and the prediction of adult height using the Tanner-Whitehouse method. *Annals of Human Biology,* 11**,** 261-264.

Cameron, N. 2007. Growth patterns in adverse environments. *American Journal of Human Biology,* 19**,** 615-621.

Cameron, N., Pettifor, J., De Wet, T. & Norris, S. 2003. The Relationship of Rapid Weight Gain in Infancy to Obesity and Skeletal Maturity in Childhood. *Obesity,* 11**,** 457-460.

Cao, F., Huang, H. K., Pietka, E. & Gilsanz, V. 2000. Digital Hand Atlas and Web-Based Bone Age Assessment: System Design and Implementation. *Computerized Medical Imaging and Graphics,* 24**,** 297-307.

Cardoso, H. F. 2008. Age estimation of adolescent and young adult male and female skeletons II, epiphyseal union at the upper limb and scapular girdle in a modern Portuguese skeletal sample. *American Journal of Physical Anthropology,* 137**,** 97-105.

Cardoso, H. F. V. & Severino, R. S. S. 2010. The chronology of epiphyseal union in the hand and foot from dry bone observations. *International Journal of Osteoarchaeology,* 20**,** 737-746.

Carter, B. S. 1973. A program for assessing the effect of treatment on growth and development in children with growth disorders. *Computers in Biology and Medicine,* 3**,** 443.

Carvalho, H. M., Coelho-e-Silva, M. J., Gonçalves, C. E., Philippaerts, R. M., Castagna, C. & Malina, R. M. 2011. Age-related variation of anaerobic power after controlling for size and maturation in adolescent basketball players. *Annals of Human Biology,* 38**,** 721-727.

Castilho, L. V. & Lahr, M. M. 2001. Secular trends in growth among urban Brazilian children of European descent. *Annals of Human Biology,* 28**,** 564.

Castriota-Scanderbeg, A. & De Micheli, V. 1995. Ultrasound of femoral head cartilage: a new method of assessing bone age. *Skeletal Radiology,* 24**,** 197-200.

Castriota-Scanderbeg, A., Sacco, M. C., Emberti-Gialloreti, L. & Fraracci, L. 1998. Skeletal age assessment in children and young adults: comparison between a newly developed sonographic method and conventional methods. *Skeletal Radiology,* 27**,** 271-277.

Cattaneo, C., De Angelis, D., Ruspa, M., Gibelli, D. & Grandi, M. 2008. How old am I? Age estimation in living adults: a case report. *Journal of Forensic Odontostomatology,* 27**,** 39-43.

Cattaneo, C., Porta, D., De Angelis, D., Gibelli, D., Poppa, P. & Grandi, M. 2010. Unidentified bodies and human remains: An Italian glimpse through a European problem. *Forensic Science International,* 195**,** 167.e1-167.e6.

Cattaneo, C., Ritz-Timme, S., Gabriel, P., Gibelli, D., Giudici, E., Poppa, P., Nohrden, D., Assmann, S., Schmitt, R. & Grandi, M. 2009. The difficult issue of age assessment on pedo-pornographic material. *Forensic Science International,* 183**,** e21-e24.

Chance, J. K. 1971. Kinship and urban residence: household and family organization in a suburb of Oaxaca, Mexico. *Journal of the Steward Anthropological Society,* 2.

Chang, K. S. F., Chan, S. T., Low, W. D. & Ng, C. K. 1967. Skeletal maturation of Chinese pre-school children. *Far East Medical Journal,* 3**,** 289.

Chatzigianni, A. & Halazonetis, D. J. 2009. Editor's Summary and Q&A: Geometric morphometric evaluation of cervical vertebrae shape and its relationship to skeletal maturation. *American Journal of Orthodontics and Dentofacial Orthopedics,* 136**,** 481-483.

Chen, S. T., Jee, F. C. & Mohamed, T. B. 1990. Bone age of Malaysian children aged 12 to 28 months. *Journal of the Singapore Paediatric Society,* 32**,** 97-101.

Chen, X., Zhang, Z. & Tao, L. 2008. Determination of male age at death in Chinese Han population: Using quantitative variables statistical analysis from pubic bones. *Forensic Science International,* 175**,** 36-43.

Chertkow, S. 1979. The Relationship Between Tooth Mineralization and Early Radiographic Evidence of the Ulnar Sesamoid. *The Angle Orthodontist,* 49**,** 282-288.

Chervenak, F. A., Skupski, D. W., Romero, R., Myers, M. K., Smith-Levitin, M., Rosenwaks, Z. & Thaler, H. T. 1998. How accurate is fetal biometry in the assessment of fetal age? *American Journal of Obstetrics and Gynecology,* 178**,** 678-687.

Chinn, D. H., Bolding, D. B., Callen, P. W., Gross, B. H. & Filly, R. A. 1983. Ultrasonographic Identification of Fetal Lower Extremity Epiphyseal Ossificiation Centers. *Radiology,* 147**,** 815-818.

Christensen, A. M. & Crowder, C. M. 2009. Evidentiary Standards for Forensic Anthropology. *Journal of Forensic Sciences,* 54**,** 1211-1216.

Christie, A. 1949. Prevalence and distribution of ossification centers in the newborn infant. *American Journal of Diseases of Children,* 77**,** 355.

Bibliography: A test of six radiographic age estimation methods on a modern population

Chrzastek-Spruch, H., Kozlowska, M., Hauspie, R. & Susanne, C. 2002. Longitudinal study on growth in height in Polish boys and girls. *International Journal of Anthropology,* 17**,** 153-160.

Clarke, H. H. & Hayman, N. R. 1962. Reduction of bone assessments necessary for the skeletal age determination of boys. *Research Quarterly,* 33**,** 202.

Clarot, F., Le Dosseur, P., Vaz, E. & Proust, B. 2004. Skeletal maturation and ethnicity. *Legal Medicine,* 6**,** 141-142.

Clements, E. M. B. 1953. Changes in the mean stature and weight of children over the past seventy years. *British Medical Journal,* 2**,** 897.

Cobb, W. M. 1971. Choice of Area for Assessment. *American Journal of Physical Anthropology.,* 35**,** 385-386.

Cole, T. J. 1990. The LMS method for constructing normalized growth standards. *European Journal of Clinical Nutrition,* 44**,** 45.

Cole, T. J. 2006. The International Growth Standard for Preadolescent and Adolescent Children: Statistical Considerations. *Food and Nutrition Bulletin,* 27**,** S237-S243.

Cole, T. J. & Cole, A. J. L. 1992. Bone age, social deprivation, and single parent families. *Archives of Disease in Childhood,* 67**,** 1281.

Cole, T. J., Freeman, J. V. & Preece, M. A. 1995. Body mass index reference curves for the UK, 1990. *Archives of Disease in Childhood,* 73**,** 25-29.

Cole, T. J., Freeman, J. V. & Preece, M. A. 1998. British 1990 Growth Reference Centiles for Weight, Height, Body Mass Index and Head Circumference Fitted by Maximum Penalized Likelihood. *Statistics in Medicine,* 17**,** 407-429.

Corry-Mann, H. C. 1926. Diets for boys during the school age. *Special Reports Series, Medical Research Council of London*.

Corsini, M.-M., Schmitt, A. & Bruzek, J. 2005. Aging process variability on the human skeleton: artificial network as an appropriate tool for age at death assessment. *Forensic Science International,* 148**,** 163-167.

Corson, E. R. 1900. A Skiagraphic Study of the Normal Membral Epiphyses at the Thirteenth Year. *Annals of Surgery,* 32**,** 621-647.

Cox, L. A. 1994. Preliminary report on the validation of a grammar-based computer system for assessing skeletal maturity with the Tanner-Whitehouse 2 method. *Acta Pediatrica Scandinavia [Suppl],* 406**,** 84-85.

Craig, J., Cody, D. & Holsbeeck, M. 2004. The distal femoral and proximal tibial growth plates: MR imaging, three-dimensional modeling and estimation of area and volume. *Skeletal Radiology,* 33**,** 337-344.

Csukas, A., Takai, S. & Baran, S. 2006. Adolescent Growth in Main Somatic Traits of Japanese Boys: Ogi Longitudinal Growth Study. *HOMO-Journal of Comparative Human Biology,* 57**,** 73-86.

Bibliography: A test of six radiographic age estimation methods on a modern population

Cumming, G. R., Garand, T. & Borysyk, L. 1972. Correlation of performance in track and field events with bone age. *Journal of Pediatrics,* 80**,** 970.

Cunha, E., Baccino, E., Martrille, L., Ramsthaler, F., Prieto, J., Schuliar, Y., Lynnerup, N. & Cattaneo, C. 2009. The problem of aging human remains and living individuals: A review. *Forensic Science International,* 193**,** 1-13.

Czerwinski, F., Tomasik, E., Tomasik, M. & Mahaczek-Kordowska, A. 2004. The Ossification of the Metacarpal and Phalangeal Bones in Human Foetuses. *Folia Morphologica,* 63**,** 329-332.

Danker-Hopfe, H. 1986. Menarcheal age in Europe. *American Journal of Physical Anthropology,* 29**,** 81-112.

De Leonardis, F., Orzincolo, C., Prandini, N. & Trotta, F. 2008. The Role of Conventional Radiography and Scintigraphy in the Third Millenium. *Best Practice and Research Clinical Rheumatology,* 22**,** 961-979.

De Simone, M., Danubio, M. E., Amicone, E., Verrotti, A., Gruppioni, G. & Vecchi, F. 2004. Age of onset of pubertal characteristics in boys aged 6–14 years of the Province of L'Aquila (Abruzzo, Italy). *Annals of Human Biology,* 31**,** 488-493.

De Simone, M., Farello, G., Palumbo, M., Gentile, T., Ciuffreda, M., Olioso, P., Cinque, M. & De Matteis, F. 1995. Growth charts, growth velocity and bone development in childhood obesity. *International Journal of Obesity and Related Metabolic Disorders,* 19**,** 851-7.

Demerath, E. W., Choh, A. C., Czerwinski, S. A., Lee, M., Sun, S. S., Chumlea, W. C., Duren, D., Sherwood, R. J., Blangero, J., Towne, B. & Siervogel, R. M. 2007. Genetic and environmental influences on infant weight and weight change: The Fels longitudinal study. *American Journal of Human Biology,* 19**,** 692-702.

Demerath, E. W., Jones, L. L., Hawley, N. L., Norris, S. A., Pettifor, J. M., Duren, D., Chumlea, W. C., Towne, B. & Cameron, N. 2009. Rapid Infant Weight Gain and Advanced Skeletal Maturation in Childhood. *Journal of Pediatrics,* 155**,** 355-361.

Deming, J. 1957. Application of the Gompertz curve to the observed pattern of growth in length of 48 individual boys and girls during the adolescent cycle of growth. *Human Biology,* 29**,** 83.

Demirjian, A., Buschang, P. H., Tanguay, R. & Patterson, D. K. 1985. Interrelationships among measures of somatic, skeletal, dental, and sexual maturity. *American Journal of Orthodontics,* 88**,** 433-438.

Dimeglio, A., Charles, Y. P., Daures, J.-P., de Rosa, V. & Kabore, B. 2005. Accuracy of the Sauvegrain method in determining skeletal age during puberty. *The Journal of Bone and Joint Surgery,* 87-A**,** 1689-1696.

Diz, P., Limeres, J., Salgado, A. F. P., Tomás, I., Delgado, L. F., Vázquez, E. & Feijoo, J. F. Correlation between dental maturation and chronological age in patients with cerebral palsy, mental retardation, and Down syndrome. *Research in Developmental Disabilities,* 32**,** 808-817.

Doel, G. 1948. Delayed epiphyseal union. *British Journal of Radiology,* 21**,** 99.

Bibliography: A test of six radiographic age estimation methods on a modern population

Douglas, H. 1965. Retardation of skeletal maturation and linear growth in the treatment of the simple virilizing form of adrenal hyperplasia. *The Journal of Pediatrics,* 67**,** 1025.

Drayer, N. & Cox, L. 1994. Assessment of bone ages by the Tanner-Whitehouse method using a computer-aided system. *Acta Paediatrica,* 83**,** 77-80.

Dreizen, S., Snodgrass, R. M., Webb-Peploe, H. & Spies, T. D. 1958. The retarding effect of protracted under-nutrition on the appearance of the postnatal ossification centers in the hand and wrist. *Human Biology,* 30**,** 243-263.

Dreizen, S., Snodgrasse, R. M., Webb-Peploe, H. & Spies, T. D. 1957. The effect of prolonged nutritive failure on epiphyseal fusion in the human hand and skeleton. *American Journal of Roentgenology, Radium Therapy, and Nuclear Medicine,* 78**,** 461.

Dreizen, S., Spirakis, C. N. & Stone, R. E. 1964. The influence of age and nutritional status on ldquobone scarrdquo formation in the distal end of the growing radius. *American Journal of Physical Anthropology,* 22**,** 295-305.

Dreizen, S. & Stone, R. E. 1962. Human nutritive and growth failure. *Postgraduate Medicine,* 32**,** 381.

Dreizen, S., Stone, R. E. & Spies, T. D. 1961. The influence of chronic undernutrition on bone growth in children. *Postgraduate Medicine,* 29**,** 182.

Dubina, T. L., Mints, A. Y. & Zhuk, E. V. 1984. Biological age and its estimation. III. Introduction of a correction to the multiple regression model of biological age and assessment of biological age in cross-sectional and longitudinal studies. *Experimental Gerontology,* 19**,** 133-143.

Duke, P. M., Litt, I. F. & Gross, R. T. 1980. Adolescents' self-assessment of sexual maturation. *Pediatrics,* 66**,** 918.

Duren, D. L., Sherwood, R. J., Choh, A. C., Czerwinski, S. A., Chumlea, C., Lee, M., Sun, S. S., Demerath, E. W., Siervogal, R. M. & Towne, B. 2007. Quantitative genetics of cortical bone mass in healthy 10-year-old children from the Fels Longitudinal Study. *Bone,* 40**,** 464-470.

Duyar, İ. & Özener, B. 2005. Growth and nutritional status of male adolescent laborers in Ankara, Turkey. *American Journal of Physical Anthropology,* 128**,** 693-698.

Dvorak, J., George, J., Junge, A. & Hodler, J. 2006. Age determination by MRI of the wrist in adolescent male football players. *British Journal of Sports Medicine*. 41**,** 45-52.

Dvorak, J., George, J., Junge, A. & Hodler, J. 2007. Application of MRI of the wrist for age determination in international U-17 soccer competitions. *British Journal of Sports Medicine,* 41**,** 497-500.

Edelsten, A. D., Hughes, I. A., Oakes, S., Gordon, I. R. S. & Savage, D. C. L. 1981. Height and skeletal maturity in Children with Newly-Diagnosed Juvenile-onset Diabetes. *Archives of Disease in Childhood,* 56**,** 40-44.

Ellis, F. G. & Joseph, J. 1954. Time of Appearance of the Centres of Ossification of the Fibular Epiphyses. *Journal of Anatomy,* 88**,** 533-536.

Espenschade, A. 1940. Motor performance in adolescence, including the study of relationships with measures of physical growth and maturity. *Monographs of the Society for Research in Child Development,* 5.

Eto, M. 1971. The skeletal development of the children in Tokyo. Comparative study through two kinds of the skeletal age assessed by Japanese and British methods. *Journal of Anthropological Society of Nippon,* 79**,** 9.

Euling, S. Y., Herman-Giddens, M. E., Lee, P. A., Selevan, S. G., Juul, A., Sorensen, T. I. A., Dunkel, L., Himes, J. H., Teilmann, G. & Swan, S. H. 2008. Examination of US Puberty-Timing Data from 1940 to 1994 for Secular Trends: Panel Findings. *Pediatrics,* 121**,** S172-S191.

European Union 2010. Comparative E.U. Study on Unaccompanied Minors, E.U. ref: MEMO/10/169

Evans, N., Robinson, V. P. & Lister, J. 1972. Growth and Bone Age of Juvenile Diabetics. *Archives of Disease in Childhood,* 47**,** 589-593.

Fachini, F. & Veschi, S. 2004. Age Determination on Long Bones in a Skeletal Subadults Sample (b-12 Years). *Collegium Anthropologicum,* 28**,** 89-98.

Falkner, F. 1971. Skeletal maturity indicators in infancy. *American Journal of Physical Anthropology,* 35**,** 393-394.

Fan, B. C., Hseih, C. W., Jong, T. L. & Tiu, C. M. 2001. Automatic Bone Age Estimation Based on Carpal Bone Image - A Preliminary Report. *Chinese Medical Journal,* 64**,** 203-208.

Fellingham, S. A. 1966. Statistical planning of the nutrition status surveys on Pretoria school children. *South African Medical Journal,* 2**,** 228.

Feresu, S. A., Gillespie, B. W., Sowers, M. F., Johnson, T. R. B., Welch, K. & Harlow, S. D. 2002. Improving the assessment of gestational age in a Zimbabwean population. *International Journal of Gynecology & Obstetrics,* 78**,** 7-18.

Ferguson, A. C., Murray, A. B. & Tze, W.-J. 1982. Short stature and delayed skeletal maturation in children with allergic disease. *Journal of Allergy and Clinical Immunology,* 69**,** 461-466.

Ferrante, L. & Cameriere, R. 2009. Statistical methods to assess the reliability of measurements in the procedures for forensic age estimation. *International Journal of Legal Medicine,* 123**,** 277-283.

Fields, S. J., Spiers, M., Hershkovitz, I. & Livshits, G. 1995. Reliability of reliability coefficients in the estimation of asymmetry. *American Journal of Physical Anthropology,* 96**,** 83-87.

Figueiredo, A. J., Gonçalves, C. E., Coelho E Silva, M. J. & Malina, R. M. 2009. Youth soccer players, 11–14 years: Maturity, size, function, skill and goal orientation. *Annals of Human Biology,* 36**,** 60-73.

Filipsson, R. & Hall, K. 1976. Correlation between dental maturity height development and sexual maturation in normal girls. *Annals of Human Biology,* 3**,** 205.

Fishman, L. S. 1979. Chronological versus skeletal age, an evaluation of craniofacial growth. *The Angle Orthodontist,* 49**,** 181-189.

Bibliography: A test of six radiographic age estimation methods on a modern population

Fishman, L. S. 1982. Radiographic avaluation of skeletal maturation. *Angle Orthodontist,* 52**,** 88-112.

Fishman, L. S. 1987. Maturational Patterns and Prediction During Adolescence. *The Angle Orthodontist,* 57**,** 178-193.

Flor-Cisneros, A., Roemmich, J. N., Rogol, A. D. & Baron, J. 2006. Bone age and onset of puberty in normal boys. *Molecular and Cellular Endocrinology,* 254-255**,** 202-206.

Flores-Mir, C., Burgess, C. A., Champney, M., Jensen, R. J., Pitcher, M. R. & Major, P. W. 2006. Correlation of skeletal maturation stages determined by cervical vertebrae and hand-wrist evaluations. *Angle Orthodontist,* 76**,** 1-5.

Flores-Mir, C., Mauricio, F. R., Orellana, M. F. & Major, P. W. 2005. Association between growth stunting with dental development and skeletal maturation stage. *Angle Orthodontist,* 75**,** 935-40.

Flores-Mir, C., Nebbe, B. & Major, P. W. 2004. Use of Skeletal Maturation Based on Hand-Wrist Radiographic Analysis as a Predictor of Facial Growth: A Systematic Review. *Angle Orthodontist,* 74**,** 118-124.

Floyd, B. 2008. Clinal Variation in Chinese Height and Weight: Evidence from the Descendants of Emigrants to Taiwan. *HOMO-Journal of Comparative Human Biology,* 59**,** 47-66.

Forbes, A. P., Ronaghy, H. A. & Majd, M. 1971. Skeletal maturation of children in Shiraz, Iran. *American Journal of Physical Anthropology,* 35**,** 449-454.

Foti, B., Lalys, L., Adalian, P., Giustiniani, J., Maczel, M., Signoli, M., Dutour, O. & Leonetti, G. 2003. New forensic approach to age determination in children based on tooth eruption. *Forensic Science International,* 132**,** 49-56.

Francis, C. C., Werle, P. P. & Behm, A. o. A. 1939. The appearance of centers of ossification from birth to 5 years. *American Journal of Physical Anthropology,* 24**,** 273-299.

Franklin, D. 2010. Forensic age estimation in human skeletal remains: Current concepts and future directions. *Legal Medicine,* 12**,** 1-7.

Franklin, D. & Cardini, A. 2007. Mandibular Morphology as an Indicator of Human Subadult Age: Interlandmark Approaches. *Journal of Forensic Sciences,* 52**,** 1015-1019.

Freitas, D., Maia, J., Beunen, G., Lefevre, J., Claessens, A., Marques, A., Rodrigues, A., Silva, C., Crespo, M., Thomis, M., Sousa, A. & Malina, R. 2004. Skeletal maturity and socio-economic status in Portugues children and youths: the Madiera Growth Study. *Annals of Human Biology,* 31**,** 408-420.

Frisancho, A. R., Garn, S. M. & Ascoli, W. 1970. Childhood retardation resulting in retardation of adult body size due to lesser adolescent skeletal delay. *American Journal of Physical Anthropology***,** 325.

Frisancho, A. R., Garn, S. M. & Ascolli, W. 1970. Unequal Influences of Low Dietary Intakes on Skeletal Maturation during Childhood and Adolescence. *The American Journal of Clinical Nutrition.,* 23**,** 1220-1227.

Frisancho, A. R., Sanchez, J., Pallardel, D. & Yanez, L. 1973. Adaptive significance of small body size under poor socioeconomic conditions in southern Peru. *American Journal of Physical Anthropology,* 39**,** 255.

Fritsch, H., Brenner, E. & Debbage, P. 2001. Ossification in the Human Calcaneus: A Model for Spatial Bone Development and Ossification. *Journal of Anatomy,* 199**,** 609-616.

Frucht, S., Schneglelsberg, C., Sculte-Monting, J., Rose, E. & Jonas, I. 2000. Dental Age in Southwest Germany. *Journal of Orofacial Orthopedics,* 61**,** 318-329.

Frush, D. 2009. Radiation safety. *Pediatric Radiology,* 39**,** S385-S390.

Fry, E. I. 1971. Tanner-Whitehouse and Greulich-Pyle skeletal age velocity comparisons. *American Journal of Physical Anthropology,* 35**,** 377-379.

Fry, P. C. 1965. Nutritive values of diets in Hong Kong children. *Journal of Tropical Paediatrics,* 10**,** 100.

Fry, P. C., Leverton, R. M. & Goksu, S. 1967. Growth of Hong Kong children on diets containing rice, or rice and wheat mixtures with and without nutritional supplements. *American Journal of Clinical Nutrition,* 20**,** 954.

Fryer, J. G. & Karlberg, J. 1985. An approach to the estimation of growth standards. *Annals of Human Biology,* 12**,** 83.

Gandini, P., Mancini, M. & Andreani, F. 2006. A comparison of hand-wrist bone and cervical vertebral analyses in measuring skeletal maturation. *Angle Orthodontist,* 76**,** 984-9.

Garamendi, P. M., Landa, M. I., Ballesteros, J. & Solano, M. A. Forensic estimation of age in a group of immigrants of Moroccan origin, supposedly under 18.

Gardner, E. & O'Rahilly, R. 1968. The early development of the knee joint in staged human embryos. *Journal of Anatomy,* 102**,** 289-299.

Garn, S. M., Rohmann, C.G., and Apfelbaum, B. 1961. Complete Epiphyseal Union of the Hand. *American Journal of Physical Anthropology.,* 19**,** 365-372.

Garn, S. M., Behar, M., Rohmann, C., Viteri, F. & Wilson, D. 1964. Catch-up bone development during treatment of kwashiorkor. *Federation Proceedings,* 23**,** 338.

Garn, S. M. & Clark, D. C. 1975. Nutrition, growth, development and maturation: Findings from the ten-state nutrition survey of 1968–1970. *Pediatrics,* 56**,** 306.

Garn, S. M., Hempy, H. O. & Schwager, P. M. 1968. Measurement of Localized Bone Growth Employing Natural Markers. *American Journal of Physical Anthropology,* 28**,** 105-108.

Garn, S. M., Lewis, A. B. & Kerewsky, R. S. 1965. Genetic, Nutritional, and Maturational Correlates of Dental Development. *Journal of Dental Research,* 44**,** 228-242.

Garn, S. M., Mayor, G. H. & Shaw, H. A. 1976. Paradoxical bilateral asymmetry in bone size and bone mass in the hand. *American Journal of Physical Anthropology,* 45**,** 209-210.

Garn, S. M., Poznanski, A. K. & Larson, K. E. 1975. Magnitude of sex differences in dichotomous ossification sequences of the hand and wrist. *American Journal of Physical Anthropology,* 42**,** 85-89.

Garn, S. M., Poznanski, A. K. & Nagy, J. M. 1971. The Operational Meaning of Maturity Criteria. *American Journal of Physical Anthropology,* 35**,** 319-326.

Garn, S. M. & Rohmann, C. G. 1960. Variability in the order of ossification of the bony centers of the hand and wrist. *American Journal of Physical Anthropology,* 18**,** 219.

Garn, S. M., Rohmann, C. G. & Blumenthal, T. 1966. Ossification sequence polymorphism and sexual dimorphism in skeletal development. *American Journal of Physical Anthropology,* 24**,** 101.

Garn, S. M., Rohmann, C. G. & Davis, A. A. 1963. Genetics of Hand-wrist Ossification. *American Journal of Physical Anthropology,* 21**,** 33-40.

Garn, S. M., Sandusky, S., Nagy, J. M. & McCann, M. 1972. Advanced Skeletal Development in Low-Income Negro Children. *Journal of Pediatrics,* 80**,** 965-969.

Garn, S. M., Sandusky, S. T., Miller, R. L. & Nagy, J. M. 1972. Developmental implications of dichotomous ossification sequences in the wrist region. *American Journal of Physical Anthropology,* 37**,** 111.

Garn, S. M., Sandusky, S. T., Rosen, N. N. & Trowbridge, F. 1973. Economic impact on postnatal ossification. *American Journal of Physical Anthropology,* 38**,** 1.

Garn, S. M., Silverman, F. N. & Rohmann, C. G. 1964. A rational approach to the assessment of skeletal maturation. *Ann Radiol,* 7**,** 297.

Garnier, D., Simondon, K. B. & Bénéfice, E. 2005. Longitudinal estimates of puberty timing in Senegalese adolescent girls. *American Journal of Human Biology,* 17**,** 718-730.

Gasser, T., Kneip, A., Binding, A., Prader, A. & Molinari, L. 1991. The dynamics of linear growth in distance, velocity and acceleration. *Annals of Human Biology,* 18**,** 129.

Georgopoulos, N. A., Theodoropoulou, M. L., Vagenakis, A. G. & Markou, K. B. 2004. Growth and Skeletal Maturation in Male and Female Artistic Gymnasts. *The Journal of Clinical Endocrinology and Metabolism,* 89**,** 4377-4382.

Gerace, L., Aliprantis, A., Russell, M., Allison, D. B., Buhl, K. M., Wang, J., Wang, Z.-M., Pierson, R. N. & Heymsfield, S. B. 1994. Skeletal differences between black and white men and their relevance to body composition estimates. *American Journal of Human Biology,* 6**,** 255-262.

Gertych, A., Zhang, A., Sayre, J., Pospiech-Kurkowska, S. & Huang, H. K. 2007. Bone Age Assessment of Children Using a Digital Hand Atlas. *Computerized Medical Imaging and Graphics,* 31**,** 322-331.

Gilli, G. 1996. The assessment of skeletal maturation. *Hormone Research,* 45**,** 49.

Gindhart, P. S. 1973. Growth Standards for the Tibia and Radius in Children Aged One Month through Eighteen Years. *American Journal of Physical Anthropology.,* 39**,** 41-48.

Goldstein, H. 1986. Efficient Statistical Modelling of Longitudinal Data. *Annals of Human Biology,* 13**,** 129-141.

Gollapudi, K., Feeley, B. T. & Otsuka, N. Y. 2007. Advanced Skeletal Maturity in Ambulatory Cerebral Palsy Patients. *Journal of Pediatric Orthopaedics,* 27**,** 295-298.

Gracey, M. 2002. Child health in an urbanizing world. *Acta Paediatrica,* 91**,** 1-8.

Grave, K. C. & Brown, T. 1976. Skeletal Ossification and the Adolescent Growth Spurt. *American Journal of Orthodontics,* 69**,** 611-619.

Gravlee, C. C. 2009. How race becomes biology: Embodiment of social inequality. *American Journal of Physical Anthropology,* 139**,** 47-57.

Greulich, W. W. 1976. Some secular changes in the growth of American-born and native Japanese children. *American Journal of Physical Anthropology,* 45**,** 553-568.

Gross, G. W., Boone, J. M. & Bishop, D. M. 1995. Pediatric Skeletal Age: Determination with Neural Networks. *195*.

Guimarey, L., Moreno Morcillo, A., Orazi, V. & Lemos-Marini, S. H. 2003. Validity of the use of a few hand-wrist bones for assessing bone age. *Journal of Pediatric Endocrinology and Metabolism,* 16**,** 541-4.

Gunst, K., Mesotten, K., Carbonez, A. & Willems, G. 2003. Third molar root development in relation to chronological age: a large sample sized retrospective study. *Forensic Science International,* 136**,** 52-57.

Gunter, K., Baxter-Jones, A. D. G., Mirwald, R. L., Almsted, H., Fuller, A., Durski, S. & Snow, C. 2008. Jump Starting Skeletal Health: A Longitudinal Study Assessing the Effects of Jumping on Skeletal Development in Pre and Circum Pubertal Children. *Bone,* 42**,** 710-718.

Gupta, B., Anegundi, R. & Sudha, P. 2008. Comparison of Dental Age of Hubli Dharwad Children by Moore's Method With The Skeletal Age And Chronological Age. *The Internet Journal of Dental Science,* 6.

Gustafsson, A., Werdelin, L., Tullberg, B. S. & Lindenfors, P. 2007. Stature and sexual stature dimorphism in Sweden, from the 10th to the end of the 20th century. *American Journal of Human Biology,* 19**,** 861-870.

Guzman, M. A., Rohmann, C., Flores, M., Garn, S. M. & Scrimshaw, N. S. 1964. Osseous growth of Guatemalan children fed a protein-calorie supplement. *Federation Proceedings,* 23**,** 338.

Haas, J. D. & Campirano, F. 2006. Interpopulation variation in height among children 7-18 years of age. *Food and Nutrition Bulletin,* 27**,** S212-S223.

Haas, J. D., Hunt, E. E. & Buskirk, E. R. 1971. Skeletal development of non-institutionalized children with low intelligence quotients. *American Journal of Physical Anthropology,* 35**,** 455-466.

Haavikko, K. & Kilpinen, E. 1973. Skeletal development of Finnish children in the light of hand-wrist roentgenograms. *Proceedings of the Finnish Dental Society,* 69**,** 182.

Bibliography: A test of six radiographic age estimation methods on a modern population

Hadlock, F. P., Harrist, R.B. and Martinez-Poyer, J. 1991. In Utero Analysis of Fetal Growth: A Sonographic Weight Standard. *Radiology,* 181**,** 129-133.

Hadlock, F. P., Shah, Y.P., Kanon, D.J., and Lindsey, J.V. 1992. Fetal Crown-Rump Length: Reevaluation of Relation to Menstrual Age (5-18 weeks) with High-Resolution Real-Time US. *Radiology,* 182**,** 501-505.

Hadlock, F. P., Deter, R. L., Harrist, R. B. & Park, S. K. 1984. Estimating Fetal Age: Computer-Assisted Analysis of Multiple Fetal Growth Parameters. *Radiology,* 152**,** 497-501.

Hägg, U. & Hägg, E. 1986. The accuracy and precision of assessment of chronological age by analysis of tooth emergence. *J Int Ass Dent Child,* 17**,** 45.

Hägg, U. & Mattson, L. 1985. Dental maturity as an indicator of chronological age: the accuracy and precision of three methods. *European Journal of Orthodontics,* 7**,** 25.

Hägg, U. & Taranger, J. 1981. Dental emergence stages and the pubertal growth spurt. *Acta Odontologica Scandinavica,* 39**,** 295.

Hägg, U. & Taranger, J. 1982. Maturation indicators and the pubertal growth spurt. *American Journal of Orthodontics,* 82**,** 299.

Hägg, U. & Taranger, J. 1985. Dental development dental age and tooth count. *Angle Orthodontist,* 55**,** 93.

Hägg, U. & Taranger, J. 1980. Menarche and voice change as indicators of the pubertal growth spurt. *Acta Odontologica Scandinavica,* 38**,** 179-186.

Hägg, U. & Taranger, J. 1980. Skeletal stages of the hand and wrist as indicators of the pubertal growth spurt. *Acta Odontologica Scandinavica,* 38**,** 187-200.

Hägg, U. & Taranger, J. 1981. Dental emergence stages and the pubertal growth spurt. *Acta Odontologica Scandinavica,* 39**,** 295-306.

Hägg, U. & Taranger, J. 1982. Maturation indicators and the pubertal growth spurt. *American Journal of Orthodontics,* 82**,** 299-309.

Haines, R. W. 1975. The histology of epiphyseal union in mammals. *Journal of Anatomy,* 120**,** 1-25.

Halaba, Z. P. & Pluskiewicz, W. 2004. Quantitative ultrasound in the assessment of skeletal status in children and adolescents. *Ultrasound in Medicine & Biology,* 30**,** 239-243.

Halcrow, S. E. & Tayler, N.. 2008. The Bioarchaeological Investigation of Childhood and Social Age: Problems and Prospects. *Journal of Archaeological Method Theory,* 15**,** 190-215.

Halcrow, S. E., Tayles, N. & Buckley, H. R. 2007. Age Estimation of Children from Prehistoric Southeast Asia: are the dental formation methods used appropriate? *Journal of Archaeological Science,* 34**,** 1158-1168.

Hall, B. K. & Miyake, T. 2000. All for one and one for all: condensations and the initiation of skeletal development. *Bioessays,* 22**,** 138-147.

Hammar, S. L., Campbell, M. M., Campbell, V. Z., Moores, N. L., Sareen, C., Gareis, F. J. & Lucas, B. 1972. An interdisciplinary study of adolescent obesity. *Journal of Pediatrics,* 80**,** 373.

Harris, V. J., Green, L. & Seeler, R. A. 1976. Delayed skeletal maturation in young children with sickle cell anemia. *The Journal of Pediatrics,* 89**,** 855-856.

Harrison, M., Turner, M. & Jacobs, P. 1976. Skeletal immaturity in Perthes' disease. *Journal of Bone and Joint Surgery. British Volume,* 58-B**,** 37-40.

Hart, D. & Wall, B. F. 2004. UK population dose from medical X-ray examinations. *European Journal of Radiology,* 50**,** 285-291.

Hasan, M. & Narayan, A. 1963. The ossification centres of carpal bones. A radiological study of the times of appearance in U.P. Indian subjects. *Indian Journal of Medical Research,* 51**,** 917.

Hattingh, L., Ramsden, W. H., Wolfe, S. P., Conway, S. P., Truscott, J. G. & Brownlee, K. G. 2006. 276 Bone age in English children with CF using the RUS (TW2) method. *Journal of Cystic Fibrosis,* 5**,** S64-S64.

Hauspie, R., Bielicki, T. & Koniarek, J. 1991. Skeletal maturity at onset of the adolescent growth spurt and at peak velocity for growth in height: a threshold effect? *Annals of Human Biology,* 18**,** 23-29.

Hauspie, R., Das, S. R., Preece, M. A. & Tanner, J. M. 1980. A longitudinal study of the growth in height of boys and girls of West Bengal (India) aged six months to 20 years. *Annals of Human Biology,* 7**,** 429-441.

Hawley, N. L., Rousham, E. K., Johnson, W., Norris, S. A., Pettifor, J. M. & Cameron, N. Determinants of Relative Skeletal Maturity in South African Children. *Bone*. 36**,** 584-594.

Hegde, R. J. & Sood, P. B. 2002. Dental maturity as an indicator of chronological age: radiographic evaluation of dental age in 6 to 13 years children of Belgaum using Demirjian methods. *Journal of the Indian Society of Pedodontics and Preventive Dentistry,* 20**,** 132-8.

Helm, S. 1979. Skeletal maturity in Danish schoolchildren assessed by the TW2 method. *American Journal of Physical Anthropology,* 51**,** 345.

Helm, S., Siersbaek-Nielsen, S., Skieller, V. & Björk, A. 1971. Skeletal maturation of the hand in relation to maximum pubertal growth spurt in body height. *Tandlaegebladet,* 75**,** 1223.

Henderson, R. C., Grossberg, R. I., Matuszewski, J., Menon, N., Johnson, J., Kecskemethy, H. H., Vogel, L., Ravas, R., Wyatt, M., Bachrach, S. J. & Stevenson, R. D. 2007. Growth and Nutritional Status in Residential Center Versus Home-Living Children and Adolescents with Quadriplegic Cerebral Palsy. *The Journal of Pediatrics,* 151**,** 161-166.

Henneberg, M., Brush, G. & Harrison, G. A. 2001. Growth of specific muscle strength between 6 and 18 years in contrasting socioeconomic conditions. *American Journal of Physical Anthropology,* 115**,** 62-70.

Henneberg, M. & van den Berg, E. R. 1990. Test of socioeconomic causation of secular trend: Stature changes among favored and oppressed South Africans are parallel. *American Journal of Physical Anthropology,* 83**,** 459-465.

Heuzé, Y. & Braga, J. 2008. Application of non-adult Bayesian dental age assessment methods to skeletal remains: the Spitalfields collection. *Journal of Archaeological Science,* 35**,** 368-375.

Heuzé, Y. & Cardoso, H. F. V. 2008. Testing the quality of nonadult Bayesian dental age assessment methods to juvenile skeletal remains: The Lisbon collection children and secular trend effects. *American Journal of Physical Anthropology,* 135**,** 275-283.

Hewitt, D. & Acheson, R. M. 1961. Some aspects of skeletal development through adolescence. I. Variations in the rate and pattern of skeletal maturation at puberty. *American Journal of Physical Anthropology,* 19**,** 321-331.

Hill, A. H. 1939. Fetal Age Assessment by Centres of Ossification. *American Journal of Physical Anthropology,* XXIV**,** 251-272.

Hill, K. & Pynsent, P. B. 1994. A Fully Automated Bone-Ageing System. *Acta Pediatrica Supplement,* 406**,** 81-83.

Himes, J. H. 1984. An Early Hand-Wrist Atlas and its Implications for Secular Change in Bone Age. *Annals of Human Biology,* 11**,** 71-75.

Himes, J. H. 2006. Long-term longitudinal studies and implications for the development of an international growth reference for children and adolescents. *Food and Nutrition Bulletin,* 27**,** S199-S211.

Himes, J. H. & Malina, R. M. 1975. Age and secular factors in the stature of adult Zapotec males. *American Journal of Physical Anthropology,* 43**,** 367.

Honarvar, M., Allahyari, M. & Dehbashi, S. 2000. Assessment of gestational age based on ultrasonic femur length after the first trimester: a simple mathematical correlation between gestational age (GA) and femur length (FL). *International Journal of Gynecology & Obstetrics,* 70**,** 335-340.

Houston, W. T., B. 1980. Relationships Between Skeletal Maturity Estimated from Hand-Wrist Radiographs and the Timing of the Adolescent Growth Spurt. *European Journal of Orthodontics,* 2**,** 81-93.

Hsieh, C. W., Jong, T. L., Chou, Y. H. & Tiu, C. M. 2007. Computerized geometric features of carpal bone for bone age estimation. *Chinese Medical Journal,* 120**,** 767-770.

Hunt, E. E. & Gleiser, I. 1955. The estimation of age and sex of preadolescent children from bones and teeth. *American Journal of Physical Anthropology,* 13**,** 479-487.

Hunter, C. J. 1966. The Correlation Of Facial Growth With Body Height And Skeletal Maturation At Adolescence. *The Angle Orthodontist,* 36**,** 44-54.

Ireton, M. J., Carrillo, J. C. & Caro, L. E. 2011. Biometry and sexual maturity in a sample of Colombian schoolchildren from El Yopal. *Annals of Human Biology,* 38**,** 39-52.

Jamison, P. L. & Zegura, S. L. 1974. A univariate and multivariate examination of measurement error in anthropometry. *American Journal of Physical Anthropology,* 40**,** 197-203.

Bibliography: A test of six radiographic age estimation methods on a modern population

Jantz, R. L. & Owsley, D. W. 1984. Long bone growth variation among Arikara skeletal populations. *American Journal of Physical Anthropology,* 63**,** 13-20.

Jeanty, P., Kirkpatrick, C., Dramaix-Wilmet, M. & Struyven, J. 1981. Ultrasonic Evaluation of Fetal Limb Growth. *Radiology,* 140**,** 165-168.

Jimenez-Castellanos, J., Carmano, A., Catalina-Herrera, C. J. & Vinuales, M. 1996. Skeletal Maturation of Wrist and Hand Ossification Centres in Normal Spanish Boys and Girls: A Study Using the Greulich-Pyle Method. *British Journal of Radiology,* 72**,** 461-464.

Jit, I. & Singh, B. 1971. A radiological study of the time of fusion of certain epiphyses in Punjabees. *Journal of Anatomical Society of India,* 20**,** 1.

Johnson, G. F., Dorst, J. P., Kuhn, J. P., Roche, A. F. & Davila, G. H. 1973. Reliability of Skeletal Age Assessments. *American Journal of Roentgenology,* 118**,** 320-464.

Johnston, D. A. & Brennan, P. C. 2000. Reference dose levels for patients undergoing common diagnostic X-ray examinations in Irish hospitals. *The British Journal of Radiology,* 73**,** 396-402.

Johnston, F. E. 1962. Growth of the Long Bones of Infants and Young Children at Indian Knoll. *American Journal of Physical Anthropology,* 20**,** 249-254.

Johnston, F. E. 1964. The relationship of certain growth variables to chronological and skeletal age. *Human Biology,* 36**,** 16.

Johnston, F. E. 1971. The use of the Greulich-Pyle method in a longitudinal growth study. *American Journal of Physical Anthropology,* 35**,** 353-357.

Johnston, F. E., Bogin, B., MacVean, R. B. & Newman, B. C. 1984. A comparison of International standards versus local reference data for the triceps and subscapular skinfolds of Guatemalan children and Youth. *Human Biology,* 57**,** 157.

Johnston, F. E., Wainer, H., Thissen, D. & MacVean, R. B. 1976. Heredity and environmental determinants of growth in height in a longitudinal sample of children and youth of Guatemalan and European ancestry. *American Journal of Physical Anthropology,* 44**,** 469.

Jones, G. & Ma, D. 2005. Skeletal age deviation by the Tanner-Whitehouse 2 method is associated with bone mass and fracture risk in children. *Bone,* 36**,** 352-357.

Jones, H. E. 1946. Skeletal maturing as related to strength. *Child Development,* 17**,** 173.

Jones, H. E. & Bayley, N. 1941. The Berkeley Growth Study. *Child Development,* 12**,** 167-173.

Jones, M. A., Hitchen, P. J. & Stratton, G. 2000. The importance of considering biological maturity when assessing physical fitness measures in girls and boys aged 10 to 16 years. *Annals of Human Biology,* 27**,** 57-65.

Jones, P. R. M. & Dean, R. F. A. 1956. The effects of kwashiorkor on the development of the bones of the hand. *Journal of Tropical Pediatrics,* 2**,** 51.

Jordan, J., Ruben, M., Hernandez, J., Bebelagua, A. & Goldstein, H. 1975. The 1972 Cuban Child Growth Study as an Example of Population Health Monitoring: Design and Methods. *Annals of Human Biology, 2***,** 153-171.

Joseph, J. 1951. The Sesamoid Bones of the Hand and the Time of Fusion of the Epiphyses of the Thumb. *Journal of Anatomy***,** 230-241.

Kalichman, L., Malkin, I. & Kobyliansky, E. 2005. Association Between Physique Characteristics and Hand Skeletal Aging Status. *American Journal of Physical Anthropology, 128***,** 889-895.

Kalichman, L., Malkin, I., Livshits, G., Pavlovsky, O., Batsevich, V. & Kobyliansky, E. 2007. Variation of skeletal biomarkers of biological aging in a Chuvashian population: A longitudinal study. *American Journal of Human Biology, 19***,** 74-81.

Kalichman, L., Malkin, I., Seibel, M. J., Kobyliansky, E. & Livshits, G. 2008. Age-related Changes and Secular Trends in Hand Bone Size. *HOMO-Journal of Comparative Human Biology, 59***,** 301-315.

Kalish, R. B., Thaler, H. T., Chasen, S. T., Gupta, M., Berman, S. J., Rosenwaks, Z. & Chervenak, F. A. 2004. First- and second-trimester ultrasound assessment of gestational age. *American Journal of Obstetrics and Gynecology, 191***,** 975-978.

Kanchan, T., Mohan Kumar, T. S., Pradeep Kumar, G. & Yoganarasimha, K. 2008. Skeletal asymmetry. *Journal of Forensic and Legal Medicine, 15***,** 177-179.

Kant, S. G., Grote, F., de Ru, M. H., Oostdijk, W., Zonderland, H. M., Breuning, M. H. & Wit, J. M. 2007. Radiographic Evaluation of Children with Growth Disorders. *Hormone Research., 68***,** 310-315.

Karasik, D., Shimabuku, N. A., Zhou, Y., Zhang, Y., Cupples, L. A., Kiel, D. P. & Demissie, S. 2008. A genome wide linkage scan of metacarpal size and geometry in the Framingham Study. *American Journal of Human Biology, 20***,** 663-670.

Karlberg, J. 1989. A Biologically-Oriented Mathematical Model (ICP) for Human Growth. *Acta Paediatrica, 78***,** 70-94.

Karlberg, J., Albertsson-Wikland, K., Baber, F., Low, L. & Yeung, C. 1996. Born small for gestational age: consequences for growth. *Acta Paediatrica, 85***,** 8-13.

Karlberg, P., Klackenberg, G., Engström, I., Klackenberg-Larsson, I., Lichtenstein, H., Stenson, J. & Svennberg, I. 1968. The development of children in a Swedish urban community. A prospective longitudinal study. *Acta Paediatrica Scandinavica***,** 187.

Karlberg, P., Taranger, J., Engström, I., Karlberg, J., Landström, T., Lichtenstein, H., Lindström, B. & Svennberg-Redegren, I. 1976. Physical growth from birth to 16 years and longitudinal outcome of the study during the same age period. *Acta Paediatrica Scandinavica. Supplement, 258***,** 7.

Karlberg, P., Taranger, J., Engström, I., Karlberg, J., Landström, T., Lichtenstein, H., Lindström, B. & Svennberg-Redegren, I. 1976. The somatic development of children in a Swedish urban community. I. Physical growth from birth to 16 years and longitudinal outcome of the study. *Acta Paediatrica Scandinavica***,** 7.

Karpati, A. M., Rubin, C. H., Kieszak, S. M., Marcus, M. & Troiano, R. P. 2002. Stature and pubertal stage assessment in American boys: the 1988-1994 Third National Health and Nutrition Examination Survey. *Journal of Adolescent Health, 30***,** 205-212.

Bibliography: A test of six radiographic age estimation methods on a modern population

Katzmarzyk, P. T., Malina, R. M. & Beunen, G. P. 1997. The contribution of biological maturation to the strength and motor fitness of children. *Annals of Human Biology,* 24**,** 493.

Kaur, B. & Singh, R. 1994. One year follow-up study of stature, weight, emergence of dentition, and sexual maturation of well-nourished indian girls from birth to 20 years. *American Journal of Human Biology,* 6**,** 425-436.

Kawashima, M., Nanjo, F., Sakura, H. & Ohta, S. 1972. Skeletal age estimated by the Tanner-Whitehouse-Healy method. Comparison with the Sugiura and Nakazawa method. *Clinical Orthopedic Surgery,* 7**,** 350.

Keen, J. A. 1950. Age determination; conflicting evidence presented by anatomical and radiological data of the skeleton. *South African Medical Journal,* 24**,** 1086-9.

Keith, A. 1939. In Memoriam. Thomas Wingate Todd (1885-1938). *Journal of Anatomy,* 73**,** 350-353.

Kellinghaus, M., Schulz, R., Vieth, V., Schmidt, S., Pfeiffer, H. & Schmeling, A. 2010. Enhanced possibilities to make statements on the ossification status of the medial clavicular epiphysis using an amplified staging scheme in evaluating thin-slice CT scans. *International Journal of Legal Medicine,* 124**,** 321-325.

Kelly, A. M., Shaw, N. J., Thomas, A. M. C., Pynsent, P. B. & Baker, D. J. 1997. Growth of Pakistani Children in Relation to the 1990 Growth Standards. *Archives of Disease in Childhood.,* 77**,** 401-405.

Kemp, S. F. & Sy, J. P. 1999. Analysis of bone age data from national cooperative growth study substudy VII. *Pediatrics,* 104**,** 1031-6.

Kemper, H. C. G. & Verschuur, R. 1974. Relationship between biological age, habitual physical activity and morphological, physiological characteristics of 12 and 13 year old boys. *Acta Paediatrica Belgica,* 28**,** 191.

Khadilkar, V. V., Frazer, F. L., Skuse, D. H. & Stanhope, R. 1998. Metaphyseal growth arrest lines in psychosocial short stature. *Archives of Disease in Childhood,* 79**,** 260-262.

Kim, J.-Y., Oh, I.-H., Lee, E.-Y., Choi, K.-S., Choe, B.-K., Yoon, T.-Y., Lee, C.-G., Moon, J.-S., Shin, S.-H. & Choi, J.-M. 2008. Anthropometric changes in children and adolescents from 1965 to 2005 in Korea. *American Journal of Physical Anthropology,* 136**,** 230-236.

Kimura, K. 1971. On the skeletal maturation of the Japanese-American hybrid—a preliminary report. *Journal of the Anthropological Society, Nippon,* 79**,** 21.

Kimura, K. 1972. Skeletal maturation in Japanese as assessed by the Oxford and Tanner-Whitehouse methods. *Acta Anatomica Nipponica,* 47**,** 358.

Kimura, K. 1972. Skeletal maturation in Japanese—a new analytical method. *Journal of Anthropological Society of Nippon,* 80**,** 319.

Kimura, K. 1973. An introduction to the comparative studies of physical growth in Okinawa islanders. *Bulletin of Department of Physical Education, Tokyo University of Education,* 14**,** 103.

Kimura, K. 1975. Comparative studies on the physical growth and development of the children in Okinawa. *Journal of Anthropological Society of Nippon,* 83**,** 151.

Kimura, K. 1976. Growth of the second metacarpal according to chronological age and skeletal maturation. *Anatomical Record,* 184**,** 147-57.

Kimura, K. 1976. On the skeletal maturation of Japanese-American hybrids. *American Journal of Physical Anthropology.*

Kimura, K. 1976. Skeletal maturation of children in Okinawa. *Annals of Human Biology,* 3**,** 149-155.

Kimura, K. 1977. Skeletal maturity of the hand and wrist in Japanese children by the TW2 method. *Annals of Human Biology,* 4**,** 353-356.

Kimura, K. 1977. Skeletal maturity of the hand and wrist in Japanese children in Sapporo by the TW2 method. *Annals of Human Biology,* 4**,** 449.

Kimura, K. 1984. Studies on Growth and Development in Japan. *Yearbook of Physical Anthropology,* 27**,** 179-214.

Kjaer, M. S. & Kjaer, I. 1998. Human fetal hand size and hand maturity in the first half of the prenatal period. *Early Human Development,* 50**,** 193-207.

Klepinger, L. L. 2001. Stature, Maturational Variation and Secular Trends in Forensic Anthropology. *Journal of Forensic Sciences,* 46**,** 788-790.

Knell, B., Ruhstaller, P., Prieels, F. & Schmeling, A. 2009. Dental age diagnostics by means of radiographical evaluation of the growth stages of lower wisdom teeth. *International Journal of Legal Medicine,* 123**,** 465-469.

Koniarek, J. 1971. Skeletal age and other indices of biological development in girls. *Materialy i Prace Antropologiczne,* 82**,** 69.

Konie, J. C. 1964. Comparative Value of X-Rays of the Spheno-occipital Synchondrosis And of the Wrist for Skeletal Age Assessments. *The Angle Orthodontist,* 34**,** 303-313.

Kopecky, G. R. & Fishman, L. S. 1993. Timing of cervical headgear treatment based on skeletal maturation. *American Journal of Orthodontics and Dentofacial Orthopedics,* 104**,** 162-169.

Koshy, S. & Tandon, S. 1998. Dental age assessment: The applicability of Demirjian's method in South Indian children. *Forensic Science International,* 94**,** 73-85.

Krekmanova, L., Carlstedt-Duke, J., Marcus, C. & Dahllöf, G. 1999. Dental maturity in children of short stature-a two-year longitudinal study of growth hormone substitution. *Acta Odontologica Scandinavica,* 57**,** 93-96.

Kristmundsdottir, F., Burwell, R. G. & Harrison, M. H. M. 1987. Delayed skeletal maturation in Perthes' disease. *Acta Orthopaedica,* 58**,** 277-279.

Kristmundsdottir, F., Burwell, R. G., Marshall, W. A. & Small, P. 1982. Skeletal maturation in normal children: a recognition of normality. *Annals of the Royal College of Surgeons of England,* 64**,** 198.

Kristmundsdottir, F., Burwell, R. G., Marshall, W. A. & Small, P. 1984. Cross-sectional study of skeletal maturation in normal children from Nottingham and London. *Annals of Human Biology,* 11**,** 133.

Krogman, W. M. 1959. Maturation age of 55 boys in the Little League World Series, 1957. *Research Quarterly,* 30**,** 54.

Krogman, W. M. 1971. William Walter Greulich. *American Journal of Physical Anthropology,* 35**,** 316-317.

Krook, P. M., Wawrukiewicz, A. S. & Hackethorn, J. C. 1985. Caveats in the Sonographic Determination of Fetal Femur Length for Estimation of Gestational Age. *Radiology,* 154**,** 823-824.

Kulin, H. E. 1974. The physiology of adolescence in man. *Human Biology,* 46**,** 133.

Kullman, L. 1995. Accuracy of two dental and one skeletal age estimation method in Swedish adolescents. *Forensic Science International,* 75**,** 225-236.

Lacroix, B., Wolff-Quenot, M.-J. & Haffen, K. 1984. Early human hand morphology: an estimation of fetal age. *Early Human Development,* 9**,** 127-136.

Lai, E. H.-H., Chang, J. Z.-C., Yao, C.-C. J., Tsai, S.-J., Liu, J.-P., Chen, Y.-J. & Lin, C.-P. 2008. Relationship Between Age at Menarche and Skeletal Maturation Stages in Taiwanese Female Orthodontic Patients. *Journal of the Formosan Medical Association,* 107**,** 527-532.

Lai, E. H.-H., Liu, J.-P., Chang, J. Z.-C., Tsai, S.-J., Yao, C.-C. J., Chen, M.-H., Chen, Y.-J. & Lin, C.-P. 2008. Radiographic Assessment of Skeletal Maturation Stages for Orthodontic Patients: Hand-wrist Bones or Cervical Vertebrae? *Journal of the Formosan Medical Association,* 107**,** 316-325.

Lampl, M. & Johnston, F. E. 1996. Problems in the aging of skeletal juveniles: Perspectives from maturation assessments of living children. *American Journal of Physical Anthropology,* 101**,** 345-355.

Landewe, R. & van Der Heijde, D. 2005. Presentation and analysis of Radiographic Data in Clinical Trials and Observational Studies. *Annals of the Rheumatic Diseases,* 64**,** 48-51.

Largo, R. H., Gasser, T., Prader, A., Stuetzle, W. & Huber, P. J. 1978. Analysis of the adolescent growth spurt using smoothing spline functions. *Annals of Human Biology,* 5**,** 421.

Lee, M. M. C. 1971. Maturation disparity between hand-wrist bones in Hong Kong Chinese children. *American Journal of Physical Anthropology,* 34**,** 385-395.

Lee, M. M. C. 1971. Problems in Combining Skeletal Age for an Individual. *American Journal of Physical Anthropology.,* 35**,** 395-398.

Lee, M. M. C., Chan, S. T., Low, W. D. & Chang, K. S. F. The relationship between dental and skeletal maturation in Chinese children. *Archives of Oral Biology,* 10**,** 883-891.

Lee, S.-H., Modi, H., Song, H.-R., Hazra, S., Suh, S. & Modi, C. 2009. Deceleration in maturation of bone during adolescent age in achondroplasia—a retrospective study using RUS scoring system. *Skeletal Radiology,* 38**,** 165-170.

Lee, S.-T., Vaidya, S. V., Song, H.-R., Lee, S.-H., Suh, S.-W. & Telang, S. S. 2007. Bone Age Delay Patterns in Legg-Calve-Perthes Disease. *Journal of Pediatric Orthopedics,* 27**,** 198-203.

Leif, K. 1995. Accuracy of two dental and one skeletal age estimation method in Swedish adolescents. *Forensic Science International,* 75**,** 225-236.

Leighton, G. & Clark, C. L. 1929. Milk consumption and the growth of schoolchildren. *Lancet,* i**,** 40.

Leite, H. R., O'Reilly, M. T. & Close, J. M. 1987. Skeletal age assessment using the first, second, and third fingers of the hand. *American Journal of Orthodontics and Dentofacial Orthopedics,* 92**,** 492-498.

Lejarraga, H., Cusminsky, M. & Castro, E. 1976. Age of onset of puberty in urban Argentinian children. *Annals of Human Biology,* 3**,** 379.

Lejarraga, H., Guimarey, L. & Orazi, V. 1997. Skeletal maturity of the hand and wrist of healthy Argentinian children aged 4-12 years, assessed by the TW2 method. *Annals of Human Biology,* 24**,** 257.

Leonard J, S. 1959. The relationship of dentofacial growth and skeletal maturation to malocclusion. *American Journal of Orthodontics,* 45**,** 801-816.

Levine, E. 1972. The skeletal development of children of four South African populations. *Human Biology,* 44**,** 399.

Lewis, A. B. 1991. Comparisons between Dental and Skeletal Ages. *The Angle Orthodontist,* 61**,** 87-92.

Lewis, C. P., Lavy, C. B. D. & Harrison, W. J. 2002. Delay in skeletal maturity in Malawian children. *Journal of Bone and Joint Surgery,* 84-B**,** 732-734.

Li, L., Dangour, A. D. & Power, C. 2007. Early life influences on adult leg and trunk length in the 1958 British birth cohort. *American Journal of Human Biology,* 19**,** 836-843.

Liao, X.-P., Zhang, W.-L., he, J., Sun, J.-H. & huang, P. 2005. Bone Measurements of Infants in the First 3 Months of Life by Quantitative Ultrasound: the Influence of Gestational Age, Season, and Postnatal Age. *Pediatric Radiology,* 35**,** 847-853.

Lieverse, A. R., Metcalf, M. A., Bazaliiskii, V. I. & Weber, A. W. 2008. Pronounced bilateral asymmetry of the complete upper extremity: a case from the early Neolithic Baikal, Siberia. *International Journal of Osteoarchaeology,* 18**,** 219-239.

Lin, N. H., Ranjitkar, S., Macdonald, R., Hughes, T., Taylor, J. A. & Townsend, G. C. 2006. New growth references for assessment of stature and skeletal maturation in Australians. *Australian Orthodontic Journal,* 22**,** 1-10.

Lin, P., Zhang, F., Yang, Y. & Zheng, C.-X. 2004. Carpal-Bone Feature Extraction Analysis in Skeletal Age Assessment Based on Deformable Model. *JCS&T,* 4**,** 152-156.

Lindgren, G. 1978. Growth of schoolchildren with early, average and late ages of peak height velocity. *Annals of Human Biology,* 5**,** 253.

Lindsten, J., Filipsson, R., Hall, K., Leikrans, S., Glis-Tavson, K.-H. & Ryman, N. 1974. Body height and dental development in patients with Turner's syndrome. *Helv Paediat Acta,* 34**,** 34.

Linhares, E. D. R., Round, J. M. & Jones, D. A. 1986. Growth, Bone Maturation, and Biochemical Changes in Brazilian Children from Two Different Socioeconomic Groups. *The american Journal of Clinical Nutrition,* 44**,** 552-558.

Lintsi, M., Kaarma, H., Saluste, L. & Vasar, V. 2002. Systematic Changes in Body Structure of 17-18-year-old Schoolboys. *HOMO-Journal of Comparative Human Biology,* 53**,** 157-169.

Little, B. B. & Malina, R. M. 2005. Familial similarity in body size in an isolated Zapotec-speaking community in the Valley of Oaxaca, southern Mexico: Estimated genetic and environmental effects. *Annals of Human Biology,* 32**,** 513.

Little, B. B. & Malina, R. M. 2007. Gene-environment interaction in skeletal maturity and body dimensions of urban Oaxaca Mestizo schoolchildren. *Annals of Human Biology,* 34**,** 216-225.

Little, B. B., Malina, R. M. & Buschang, P. H. 1989. Natural selection is not related to reduced body size in a rural subsistence agricultural community in southern Mexico. *Human Biology,* 61**,** 287.

Little, B. B., Malina, R. M., Buschang, P. H. & DeMoss, J. H. 1986. Genetic and environmental influences on the growth status of school children from a rural subsistence agricultural community in southern Mexico. *American Journal of Physical Anthropology,* 71**,** 81.

Little, B. B., Malina, R. M., Buschang, P. H. & DeMoss, J. H. 1987. Sibling correlations for growth status in a rural community in southern Mexico. *Annals of Human Biology,* 14**,** 11.

Little, B. B., Malina, R. M., Buschang, P. H. & DeMoss, J. H. 1990. Sibling similarity in annual growth increments in school children from southern Mexico. *Annals of Human Biology,* 17**,** 41.

Liu, B., Chu, B. & Tang, X. 1983. Bone-age study on the growth and development of school-age children. *Journal of Harbin Medical University,* 17**,** 41.

Liu, B., Guan, C. & Tang, X. 1983. A study on skeletal ages in infants and children. *Chinese Journal of Pediatrics,* 12**,** 210.

Liu, J., Qi, J., Liu, Z., Ning, Q. & Luo, X. 2008. Automatic bone age assessment based on intelligent algorithms and comparison with TW3 method. *Computerized Medical Imaging and Graphics,* 32**,** 678-684.

Liversidge, H. M. & Speechly, T. 2001. Growth of permanent mandibular teeth of British children aged 4 to 9 years. *Annals of Human Biology,* 28**,** 256-262.

Loesch, D. Z., Huggins, R., Rogucka, E., Hoang, N. H. & Hopper, J. L. 1995. Genetic correlates of menarcheal age: a multivariate twin study. *Annals of Human Biology,* 22**,** 479-490.

Lohman, T. G. & Going, S. B. 2006. Body Composition Assessment for Development of an International Growth Standard for Preadolescent and Adolescent Children. *Food and Nutrition Bulletin,* 27**,** S314-S326.

Louis C, G. A primer on radiographic assessment of skeletal growth: Endocrine Control of Skeletal Maturation: Annotations to Bone Age Readings by Ze'ev Hochberg. Karger, 2003 CHF 84.00/EUR 60.00/US$73.25 (111 pages) ISBN 3 8055 7313 8. *Trends in Endocrinology & Metabolism,* 15**,** 5.

Low, W. D. 1972. Relation between socio-economic status and skeletal maturation of Chinese children. *Zeitschrift fur Morphologie und Anthropologie,* 64**,** 1.

Low, W. D., Chan, S. T., Chang, K. S. F. & Lee, M. M. C. 1968. Skeletal maturation of Southern Chinese Children. *Child Development,* 35**,** 1313.

Low, W. D. & Ng, C. K. 1976. Assessing skeletal maturity by Greulich Pyle and Tanner Whitehouse methods. *Journal of Western Pacific Orthopaedic Association*.

Lurie, L. A., Levy, S. & Lurie, M. L. 1943. Determination of bone age in children: A method based on a study of 1,129 white children. *The Journal of Pediatrics,* 23**,** 131-140.

Maat, G. J. R. 1987. Practising Methods of Age Determination. Comments on Methods Combining Multiple Age Indicators. *International Journal of Anthropology,* 2**,** 293-299.

Maber, M., Liversidge, H. M. & Hector, M. P. 2006. Accuracy of age estimation of radiographic methods using developing teeth. *Forensic Science International,* 159**,** S68-S73.

MacWilliams, K. V. & Dean, R. F. A. 1965. The growth of malnourished children after hospital treatment. *East African Medical Journal,* 42**,** 297.

Mafulli, M. 1996. Children in sport: Towards the year 2000. *Sports Exercise and Injury,* 63**,** 96.

Magarey, A., Boulton, T., Chatterton, B., Schultz, C. & Nordin, B. 1999. Familial and environmental influences on bone growth from 11–17 years. *Acta Paediatrica,* 88**,** 1204-1210.

Magarey, A., Boulton, T., Chatterton, B., Schultz, C., Nordin, B. & Cockington, R. 1999. Bone growth from 11 to 17 years: relationship to growth, gender and changes with pubertal status including timing of menarche. *Acta Paediatrica,* 88**,** 139-146.

Magarey, A. M., Boulton, T. J. C., Chatterton, B. E., Schultz, C. & Nordin, B. E. C. 1999. Familial and environmental influences on bone growth from 11-17 years. *Acta Pediatrica Scandinavia [Suppl],* 88**,** 1204-1210.

Magnusson, T. E. 1979. Skeletal maturation of the hand in Iceland. *Acta Odontologica Scandinavica,* 37**,** 21.

Magnússon, T. E. 1976. An epidemiologic study of occlusal anomalies in relation to development of the dentition in Icelandic children. *Community Dentistry and Oral Epidemiology,* 4**,** 121.

Mahony, B. S., Callen, P. W. & Filly, R. A. 1985. The Distal Femoral Epiphyseal Ossification Center in the Assessment of Third-Trimester Menstrual Age: Sonosgraphic Identification and Measurement. *Radiology,* 155**,** 201-204.

Malcolm, L. A. 1970. Growth retardation in a New Guinea boarding school and its response to supplementary feeding. *British Journal of Nutrition,* 24**,** 297.

Malina, R. M. 1970. Skeletal maturation studied longitudinally over one year in American Whites and Negroes six through thirteen years of age. *Human Biology,* 42**,** 377.

Malina, R. M. 1972. Weight, height and limb circumferences in American Negro and White children: Longitudinal observations over a one year period. *Journal of Tropical Pediatrics and Environmental Child Health,* 18**,** 280.

Bibliography: A test of six radiographic age estimation methods on a modern population

Malina, R. M. 1978. Adolescent growth and maturation: selected aspects of current research. *Yearbook of Physical Anthropology,* 21**,** 63.

Malina, R. M. 1983. Menarche in athletes: a synthesis and hypothesis. *Annals of Human Biology,* 10**,** 1.

Malina, R. M. 1994. Longitudinal observations on physical growth and TW2 skeletal maturation of girls in Tokyo: Radiographic atlas of hand and wrist. By Moriharu Eto and Kumi Ashizawa. 640 pp. Tokyo: Therapeia Co. Ltd., 1992, 69,000 Yen ($680.00) (cloth). *American Journal of Human Biology,* 6**,** 408.

Malina, R. M. 1994. Physical growth and biological maturation of young athletes. *Exercise and Sports Science Reviews,* 22**,** 389.

Malina, R. M., Beunen, G., Wellens, R. & Claessens, A. 1986. Skeletal maturity and body size of teenage Belgian track and field athletes. *Annals of Human Biology,* 13**,** 331-339.

Malina, R. M. & Bielicki, T. 1996. Retrospective longitudinal growth study of boys and girls active in sport. *Acta Pediatrica Scandinavia [Suppl],* 85**,** 570-576.

Malina, R. M., Chumlea, C., Stepick, C. D. & Gutierez, L. F. 1977. Age at menarche in Oaxaca, Mexico, schoolgirls, with comparative data for other areas of Mexico. *Annals of Human Biology,* 4**,** 551.

Malina, R. M., Dompier, T. P., Powell, J. W., Barron, M. J. & Moore, M. T. 2007. Validation of a Noninvasive Maturity Estimate Relative to Skeletal Age in Youth Football Players. *Clinical Journal of Sport Medicine,* 17**,** 362-368.

Malina, R. M., Himes, J. H. & Stepick, C. D. 1976. Skeletal maturity of the hand and wrist in Oaxaca school children. *Annals of Human Biology,* 3**,** 211-219.

Malina, R. M. & Katzmarzyk, P. T. 2006. Physical Activity and Fitness in an International Growth Standard for Preadolescent and Adolescent Children. *Food and Nutrition Bulletin,* 27**,** S295-S313.

Malina, R. M., Pena Reyes, M. E., Tan, S. K., Buschang, P. H., Little, B. B. & Koziel, S. 2004. Secular change in height, sitting height and leg length in rural Oaxaca, southern Mexico: 1968-2000. *Annals of Human Biology,* 31**,** 615.

Malina, R. M., Reyes, M. E. P. & Little, B. B. 2009. Socioeconomic variation in the growth status of urban school children 6-13 years in Oaxaca, Mexico, in 1972 and 2000. *American Journal of Human Biology,* 21**,** 805-816.

Maniar, B. M., Kapur, P. L. & Seervai, M. H. 1974. Effect of malnutrition on bones of hand in children. *Indian Pediatrics,* 11**,** 213.

Maniar, B. M., Seervai, M. H. & Kapur, P. L. 1974. A study of ossification centres in the hand and wrist of Indian children. *Indian Pediatrics,* 11**,** 203.

Maresh, M. M. 1971. Single versus serial assessment of skeletal age: Either, both or neither? *American Journal of Physical Anthropology,* 35**,** 387-392.

Maresh, M. M. 1972. A Forty-five Year Investigation for Secular Changes in Physical Maturation. *American Journal of Physical Anthropology.,* 36**,** 103-109.

Bibliography: A test of six radiographic age estimation methods on a modern population

Mariotti, V., Facchini, F. & Belcastro, G. 2007. The study of entheses: proposal of a standardised scoring method for twenty-three entheses of the postcranial skeleton. *Collegium Antropologium,* 31**,** 291-313.

Marques da Silva, A. M., Olabarriaga, S. D., Dietrich, C. A. & Schmitz, C. A. A. 2001. On Determining a Signature for Skeletal Maturity. *PRoceedings of the 14th Brazilian Symposium on Computer Graphics and Image Processing. IEEE Computer Society***,** 246-251.

Marques-Vidal, P., Madeleine, G., Romain, S., Gabriel, A. & Bovet, P. 2008. Secular trends in height and weight among children and adolescents of the Seychelles, 1956-2006. *BMC Public Health,* 8**,** 166.

Marshall, W. A. 1974. Interrelationships of skeletal maturation, sexual development and somatic growth in man. *Annals of Human Biology,* 1**,** 29-40.

Marshall, W. A. 1981. Geographical and Ethnic Variations in Human Growth. *British Medical Bulletin,* 37**,** 273-279.

Marshall, W. A., Ashcroft, M. T. & Bryan, G. 1970. Skeletal maturation of the hand and wrist in Jamaican children. *Human Biology,* 42**,** 419.

Marshall, W. A. & De Limongi, Y. 1976. Skeletal maturity and the prediction of age at menarche. *Annals of Human Biology,* 3**,** 235-243.

Marshall, W. A. & Tanner, J. M. 1969. Variation in the pattern of pubertal changes in girls. *Archives of Disease in Childhood,* 44**,** 291.

Martin, D., Deusch, D., Schweizer, R., Binder, G., Thodberg, H. & Ranke, M. 2009. Clinical application of automated Greulich-Pyle bone age determination in children with short stature. *Pediatric Radiology,* 39**,** 598-607.

Martin-Fernandez, M. A., Martin-Fernandez, M. & Alberola-Lopez, C. 2003. Automatic bone age assessment: a registration approach. *Medical Imaging,* 5032**,** 1765-1776.

Martorell, R., Yarbrough, C., Klein, R. E. & Lechtig, A. 1979. Malnutrition, Body Size and Skeletal Maturation: Interrelationships and Implications for Catch Up Growth. *Human Biology,* 51**,** 371-389.

Marx, M., Schoof, E., Grabenbauer, G. G., Beck, J. D. & Doerr, H. G. 1999. Effects of puberty on bone age maturation in a girl after medulloblastoma therapy. *Journal of Pediatric and Adolescent Gynecology,* 12**,** 62-66.

Masoud, M. I., Masoud, I., Kent Jr, R. L., Gowharji, N., Hassan, A. H. & Cohen, L. E. 2009. Relationship between blood-spot insulin-like growth factor 1 levels and hand-wrist assessment of skeletal maturity. *American Journal of Orthodontics and Dentofacial Orthopedics,* 136**,** 59-64.

Massé, G. & Hunt, E. E. 1963. Skeletal maturation of the hand and wrist in West African children. *Human Biology,* 35**,** 3.

Mathiasen, M. S. 1972. Determination of bone age and recording of minor skeletal hand anomalies in normal children. *Danish Medical Bulletin,* 20**,** 80.

Matsudo, S. M. M. & Matsudo, V. K. R. 1993. Physical fitness behaviour among girls at different levels of sexual maturation. *Pediatric Exercise Science, Conference Abstracts,* 5**,** 440.

Matsudo, S. M. M. & Matsudo, V. K. R. 1994. Self-assessment and physician assessment of sexual maturation in Brazilian boys and girls: concordance and reproducibility. *American Journal of Human Biology,* 6**,** 451.

Matton, L., Duvigneaud, N., Wijndaele, K., Philippaerts, R., Duquet, W., Beunen, G., Claessens, A. L., Thomis, M. & Lefevre, J. 2007. Secular trends in anthropometric characteristics, physical fitness, physical activity, and biological maturation in Flemish adolescents between 1969 and 2005. *American Journal of Human Biology,* 19**,** 345-357.

Mays, S., Ives, R. & Brickley, M. 2009. The effects of socioeconomic status on endochondral and appositional bone growth, and acquisition of cortical bone in children from 19th century Birmingham, England. *American Journal of Physical Anthropology,* 140**,** 410-416.

Mazess, R. B. & Cameron, J. R. 1971. Skeletal growth in school children: Maturation and bone mass. *American Journal of Physical Anthropology,* 35**,** 399-407.

McCormack, M. K., Katz, S. H. & Dicker, L. 1975. Delayed skeletal maturation in sickle cell trait. *The Journal of Pediatrics,* 87**,** 489-490.

McIntyre, M. H., Cohn, B. A. & Ellison, P. T. 2006. Sex dimorphism in digital formulae of children. *American Journal of Physical Anthropology,* 129**,** 143-150.

McKern, T. W. 1957. Estimation of Skeletal Age from Combined Maturational Activity. *American Journal of Physical Anthropology,* 15**,** 399-408.

McLean, F. C. & Bloom, W. 1940. Calcification and Ossification. Calcification in Normal Growing Bone. *The Anatomical Record,* 178**,** 333-359.

Medicus, H., Grøn, A. M. & Moorrees, C. F. A. 1971. Reproducibility of rating stages of osseous development. Tanner-Whitehouse system. *American Journal of Physical Anthropology,* 35**,** 359.

Megyesi, M. S., Tubbs, R. M. & Sauer, N. J. 2009. An Analysis of Human Skeletal Remains with Cerebral Palsy: Associated Skeletal Age Delay and Dental Pathologies. *Journal of Forensic Sciences,* 54**,** 270-274.

Meinl, A., Tangl, S., Huber, C., Maurer, B. & Watzek, G. 2007. The chronology of third molar mineralization in the Austrian population--a contribution to forensic age estimation. *Forensic Science International,* 169**,** 161-167.

Meinl, A., Tangl, S., Pernicka, E., Fenes, C. & Watzek, G. 2007. On the Applicability of Secondary Dentin Formation to Radiological Age Estimation in Young Adults. *Journal of Forensic Sciences,* 52**,** 438-441.

Mellits, E. D., Dorst, J. P. & Cheek, D. B. 1971. Bone age: Its contribution to the prediction of maturational or biological age. *American Journal of Physical Anthropology,* 35**,** 381-384.

Mérida-Velasco, J. A., Sánchez-Montesinos, I., Espín-Ferra, J., Rodríguez-Vázquez, J. F., Mérida-Velasco, J. R. & Jiménez-Collado, J. 1997. Development of the human knee joint. *The Anatomical Record,* 248**,** 269-278.

Mesotten, K., Gunst, K., Carbonez, A. & Willems, G. 2002. Dental age estimation and third molars: a preliminary study. *Forensic Science International,* 129**,** 110-115.

Michelson, N. 1946. A method for assessing the development of the hand skeleton. *American Journal of Physical Anthropology,* 4**,** 235-242.

Michie, C. A. 2005. Age Assessment: time for progress? *Archives of Disease in Childhood.,* 90**,** 612-613.

Miloglu, O., Celikoglu, M., Dane, A., Cantekin, K. & Yilmaz, A. B. 2011. Is the Assessment of Dental Age by the Nolla Method Valid for Eastern Turkish Children? *Journal of Forensic Sciences,* 56**,** 1025-1028.

Mitchell, J. C., Roberts, G. J., Donaldson, A. N. A. & Lucas, V. S. 2009. Dental age assessment (DAA): Reference data for British caucasians at the 16 year threshold. *Forensic Science International,* 189**,** 19-23.

Modi, H. N., Modi, C., Suh, S. W., Yang, J.-H. & Hong, J.-Y. 2009. Correlation and Comparison of Risser Sign Versus Bone Age Determination (TW3) Between Children with and without Scoliosis in Korean Population. *Journal of Orthopaedic Surgery,* 4**,** 1-8.

Moeller, S., Berger, L., Salvador, J. G. & Helitzer, D. 2002. How old is that child? Validating the accuracy of age assignments in obesrvational surveys of vehicle restraint use. *Injury Prevention,* 8**,** 248-251.

Molinari, L., Gasser, T. & Largo, R. H. 2004. TW3 bone age: RUS/CB and gender differences of percentiles for score and score increments. *Annals of Human Biology,* 31**,** 421-35.

Molinari, L. & Hermanussen, M. 2005. The effect of variability in maturational tempo and midparent height on variability in linear body measurements. *Annals of Human Biology,* 32**,** 679-682.

Mooney, M. P. 2005. Human osteology & skeletal radiology: An atlas and guide. *American Journal of Human Biology,* 17**,** 665-666.

Moore, R. N., Moyer, B. A. & DuBois, L. M. 1990. Skeletal maturation and craniofacial growth. *American Journal of Orthodontics and Dentofacial Orthopedics,* 98**,** 33-40.

Moore, T., Hindley, C. B. & Falkner, F. 1954. A longitudinal research in child development and some of its problems. *British Medical Journal,* 11**,** 1132.

Moore, W. M. 1971. Comparability in skeletal maturation research. *American Journal of Physical Anthropology,* 35**,** 411-415.

Moraes, M. E. L. d., Tanaka, J. L. O., Moraes, L. C. d., Filho, E. M. & Castilho, J. C. d. M. 2008. Skeletal age of individuals with Down syndrome. *Special Care in Dentistry,* 28**,** 101-106.

Morris, H. G. 1975. Growth and Skeletal Maturation in Asthmatic Children: Effect of Corticosteroid Treatment. *Pediatric Research,* 9**,** 579-583.

Morris, L. L. 2003. Book Review: Assessment of Skeletal Maturity and Prediction of Adult Height (TW3 Method). *Australasian Radiology,* 47**,** 340-341.

Murray, J. R., Bock, R. D. & Roche, A. F. 1971. The Measurement of Skeletal Maturity. *American Journal of Physical Anthropology,* 35**,** 327-330.

Nambi, T. G. 2008. Radiological Bone Age Assessment by Appearance of Ossification Centers in Pediatric Age Group by Using X-Rays. *Anil Aggrawal's Internet Journal of Forensic Medicine and Toxicology.,* 9.

Nelson, D. A. & Barondess, D. A. 2000. A Noninvasive Measure of Physical Maturity as a Predictor of Bone Mass in Children. *Journal of the American College of Nutrition,* 19**,** 38-41.

Newland, C. J., Swift, P. G. & Lamont, A. C. 1991. Congenital hypothyroidism--correlation between radiographic appearances of the knee epiphyses and biochemical data. *Postgraduate Medical Journal,* 67**,** 553-6.

Newman, M. T. & Collagos, C. 1957. Growth and skeletal maturation in malnourished Indian boys from the Peruvian sierra. *American Journal of Physical Anthropology,* 15**,** 431.

Nicoletti, I., Cheli, D., Cocco, E., Salvi, A. & Socci, A. 1978. Individual skeletal profile based on the percentiles of the bone stages: a method for estimating skeletal maturity. *Acta Medica Auxologica,* 10**,** 19.

Nicolson, A. B. & Hanley, C. 1953. Indices of physiological maturity: derivation and interrelationships. *Child Development,* 24**,** 3.

Niedzielska, I. A., Drugacz, J., Kus, N., Kre & ska, J. 2006. Panoramic radiographic predictors of mandibular third molar eruption. *Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiology, and Endodontology,* 102**,** 154-158.

Nietosvaara, Y., Hasler, C., Helenius, I. & Cundy, P. 2005. Marked initial displacement predicts complications in physeal fractures of the distal radius: An analysis of fracture characteristics, primary treatment and complications in 109 patients. *Acta Orthopaedica,* 76**,** 873-877.

Niklasson, A. & Albertsson-Wikland 2008. Continuous Growth Reference from 24th Week of Gestation to 24 Months by Gender. *BMC Pediatrics,* 8.

Nilsson, O. & Baron, J. 2004. Fundamental limits on longitudinal bone growth: growth plate senescence and epiphyseal fusion. *Trends in Endocrinology and Metabolism,* 15**,** 370-374.

Nilsson, O. & Baron, J. 2005. Impact of grwoth plate sensence on catch-up growth and epiphyseal fusion. *Pediatric Nephrology,* 20**,** 319-322.

Noback, C. R., Moss, M. L. & Leszczynska, E. 1960. Digital Epiphyseal Fusion of the Hand in Adolescence: A Longitudinal Study. *American Journal of Physical Anthropology,* 18**,** 13-18.

Nordentoft, E. L. 1964. Completion of Growth in the Lower Limbs in Relation to Biological Development Menarche, and Inherited Factors. *Acta Orthopaedica,* 34**,** 213-224.

Nyström, M., Haataja, J., Kataja, M., Evälahti, Peck, L. & Kleemola-Kujala, E. 1986. Dental maturity in Finnish children estimated from the development of seven permanent mandibular teeth. *Acta Odontologica Scandinavica,* 44**,** 193.

Odusanya, S. A. & Abayomi, I. O. 1991. Third molar eruption among rural Nigerians. *Oral Surgery, Oral Medicine, Oral Pathology,* 71**,** 151-154.

Ogden, J. A., Conlogue, G.J. and Bronson, M.L. 1979. Radiology of Postnatal Skeletal Development. *Skeletal Radiology,* 4**,** 196-203.

Ohtani, S. & Yamamoto, T. 2011. Comparison of Age Estimation in Japanese and Scandinavian Teeth Using Amino Acid Racemization. *Journal of Forensic Sciences,* 56**,** 244-247.

Olivieri, F., Semproli, S., Pettener, D. & Toselli, S. 2008. Growth and malnutrition of rural Zimbabwean children (6-17 years of age). *American Journal of Physical Anthropology,* 136**,** 214-222.

Olsen, Ø. E. 2006. Radiography Following Perinatal Death: A Review. *Acta Radiologica,* 47**,** 91-99.

Olsen, O. E., Lie, R. T., Lachman, R. S., Maartmann-Moe, H. & Rosendahl, K. 2002. Ossification Sequence in Infants Who Die During the Perinatal Period: Population-based References. *Radiology,* 225**,** 240-244.

Olze, A., Bilang, D., Schmidt, S., Wernecke, K.-D., Geserick, G. & Schmeling, A. 2005. Validation of Common Classification Systems for Assessing the Mineralization of Third Molars. *International Journal of Legal Medicine,* 119**,** 22-26.

Olze, A., Niekerk, P., Schulz, R. & Schmeling, A. 2007. Studies of the Chronological Course of Wisdom Tooth Eruption in a Black African Population. *Journal of Forensic Sciences,* 52**,** 1161-1163.

Olze, A., Reisinger, W., Geserick, G. & Schmeling, A. 2006. Age estimation of unaccompanied minors: Part II. Dental aspects. *Forensic Science International,* 159**,** S65-S67.

Olze, A., Schmeling, A., Taniguchi, M., Maeda, H., Niekerk, P., Wernecke, K.-D. & Geserick, G. 2004. Forensic age estimation in living subjects: the ethnic factor in wisdom tooth mineralization. *International Journal of Legal Medicine,* 118**,** 170-173.

Olze, A., Taniguchi, M., Schmeling, A., Zhu, B.-L., Yamada, Y., Maeda, H. & Geserick, G. 2003. Comparative study on the chronology of third molar mineralization in a Japanese and a German population. *Legal Medicine,* 5**,** S256-S260.

Olze, A., Taniguchi, M., Schmeling, A., Zhu, B.-L., Yamada, Y., Maeda, H. & Geserick, G. 2004. Studies on the chronology of third molar mineralization in a Japanese population. *Legal Medicine,* 6**,** 73-79.

Olze, A., van Niekerk, P., Ishikawa, T., Zhu, B., Schulz, R., Maeda, H. & Schmeling, A. 2007. Comparative study on the effect of ethnicity on wisdom tooth eruption. *International Journal of Legal Medicine,* 121**,** 445-448.

Olze, A., Van Niekerk, P., Schulz, R. & Schmeling, A. 2007. Studies of the Chronological Course of Wisdom Tooth Eruption in a Black African Population. *Journal of Forensic Sciences,* 52**,** 1161-1163.

Olze, A., van Nierke, P., Schmidt, S., Wernecke, K.-D., Rosing, F. W., Geserick, G. & Schmeling, A. 2006. Studies on the Progress of Third-molar Mineralisation in a Black African Population. *HOMO-Journal of Comparative Human Biology,* 57**,** 209-217.

Oman, S. D. & Wax, Y. 1984. Estimating Fetal Age by Ultrasound Measurements: An Example of Multivariate Calibration. *Biometrics,* 40**,** 947-960.

Onat, T., Haluk, Idot, scedil & er 1995. Rate of skeletal maturation in relation to secondary sexual development during female adolescence. *American Journal of Human Biology,* 7**,** 751-755.

Onat, T. & Numan-Cebeci, E. 1976. Sesamoid bones of the hand: relationship to growth skeletal and sexual development in girls. *Human Biology,* 48**,** 659.

Orhan, K., Ozer, L., Orhan, A. I., Dogan, S. & Paksoy, C. S. 2007. Radiographic evaluation of third molar development in relation to chronological age among Turkish children and youth. *Forensic Science International,* 165**,** 46-51.

Ott, W. J. 2006. Sonographic Diagnosis of Fetal Growth Restriction. *Clinical Obstetrics and Gynecology.,* 49**,** 295-307.

Ouml & Zer, B. K. 2008. Secular trend in body height and weight of Turkish adults. *Anthropological Science,* 116**,** 191-199.

Ounsted, M. K., Chalmers, C. A. & Yudkin, P. L. 1978. Clinical assessment of gestational age at birth: the effects of sex, birthweight, and weight for length of gestation. *Early Human Development,* 2**,** 73-80.

Özener, B. 2010. Fluctuating and directional asymmetry in young human males: Effect of heavy working condition and socioeconomic status. *American Journal of Physical Anthropology,* 143**,** 112-120.

Ozer, B. K. 2007. Growth Reference Centiles and Secular Changes in Turkish Children and Adolescents. *Economics and Human Biology,* 5**,** 280-301.

Ozer, T., Kama, J. D. & Ozer, S. Y. 2006. A practical method for determining pubertal growth spurt. *American Journal of Orthodontics and Dentofacial Orthopedics,* 130**,** 131 e1-6.

Ozerovic, B. 1980. Correlation of dental and skeletal age in children with cerebral palsy. *European Journal of Orthodontics,* 2**,** 193-195.

Padez, C., Varela-Silva, M. I. & Bogin, B. 2009. Height and relative leg length as indicators of the quality of the environment among Mozambican juveniles and adolescents. *American Journal of Human Biology,* 21**,** 200-209.

Paesano, P. L., Vigone, M. C., Siragusa, V., Chiumello, G., Del Maschio, A. & Mora, S. 1998. Assessment of skeletal maturation in infants: comparison between two methods in hypothyroid patients. *Pediatric Radiology,* 28**,** 622-626.

Pangrazi, R. P. & Corbin, C. B. 1990. Age as a factor relating to physical fitness test performance. *Research Quarterly for Exercise and Sport,* 61**,** 410.

Parfitt, A. M. 2002. Misconcetions (1): Epiphyseal Fusion Causes Cessation of Growth. *Bone,* 30**,** 337-339.

Park, E., Bailey, J. D. & Cowell, C. A. 1983. Growth and Maturation of Patients with Turner's Syndrome. *Pediatric Research,* 17**,** 1-7.

Parsons, P. A. 1992. Fluctuating asymmetry: a biological monitor of environmental and genomic stress. *Heredity,* 68**,** 361-364.

Bibliography: A test of six radiographic age estimation methods on a modern population

Pasquet, P. 1999. Age at menarche and urbanisation in Cameroon: Current status and secular trends. *Annals of Human Biology,* 26**,** 89.

Pathak, A., Bala, M. & Jain, R. 2010. Assessment of skeletal age using MP3 and hand-wrist radiographs and its correlation with dental and chronological ages in children. *Journal Indian Society for Preventative Dentistry* 28, 2, 95-99

Paterson, R. S. 1929. A Radiological Investigation of the Epiphyses of the Long Bones. *Journal of Anatomy,* 64**,** 28-46.

Pathmanathan, G. & Raghavan, P. 2006. Bone Age Based Linear Growth and Weight of Under Privileged North west Indian Children Compared with their Well-Off North west Indian Peers. *Journal of Anatomical Society India,* 55**,** 34-42.

Patil, S. T., Parchand, M. P., Meshram, M. M. & Kamdi, N. Y. Applicability of Greulich and Pyle skeletal age standards to Indian children. *Forensic Science International*.

Pazzaglia, U. E., Beluffi, G., Benetti, A., Bondioni, M. P. & Zarattini, G. 2011. A Review of the Actual Knowledge of the Processes Governing Growth and Development of Long Bones. *Fetal & Pediatric Pathology,* 30**,** 199-208.

Pea Reyes, M. E., Cardenas-Barahona, E. & Malina, R. M. 1994. Growth, physique, and skeletal maturation of soccer players 7-17 years of age. *Humanbiologia Budapestinensis,* 25**,** 453.

Peiris, T. S., Roberts, G. J. & Prabhu, N. 2009. Dental Age Assessment: a comparison of 4- to 24-year-olds in the United Kingdom and an Australian population. *International Journal of Paediatric Dentistry,* 19**,** 367-376.

Peritz, E. & Sproul, A. 1970. Some Aspects of the Analysis of the Hand-Wrist Bone-Age Readings. *American Journal of Physical Anthropology,* 35**,** 441-448.

Peter, I., Yakovenko, K. & Livshits, G. 2002. Relationship Between Parameters of Early Growth in Isreali Infants. *HOMO-Journal of Comparative Human Biology,* 53**,** 146-156.

Pettinato, A. A., Loud, K. J., Bristol, S. K., Feldman, H. A. & Gordon, C. M. 2006. Effects of Nutrition, Puberty, and Gender on Bone Ultrasound Measurements in Adolescents and Young Adults. *Journal of Adolescent Health,* 39**,** 828-834.

Pfau, R. O.& Sciulli., P.W. 1994. A Method for Establishing the Age of Subadults. *Journal of Forensic Sciences,* 39**,** 165-176.

Piercecchi-Marti, M. D., Adalian, P., Bourliere-Najean, B., Gouvernet, J., Maczel, M., Dutour, O. & Leonetti, G. 2002. Validation of a Radiographic Method to Establish New Fetal Growth Standards: Radio-Anatomical Correlation. *Journal of Forensic Sciences,* 47**,** 328-331.

Pietka, E. 2003. Computer-assisted bone age assessment--database adjustment. *International Congress Series,* 1256**,** 87-92.

Bibliography: A test of six radiographic age estimation methods on a modern population

Pietka, E., Gertych, A., Pospiech, S., Cao, F., Huang, H. K. & Gilsanz, V. 2001. Computer-assisted bone age assessment: image preprocessing and epiphyseal/metaphyseal ROI extraction. *IEEE Transactions on Medical Imaging,* 20**,** 715-29.

Pietka, E. & Huang, H. K. 1995. Epiphyseal fusion assessment based on wavelets decomposition analysis. *Computerized Medical Imaging and Graphics,* 19**,** 465-72.

Pietka, E., Pospiech, S., Gertych, A., Cao, F., Huang, H. K. & Gilsanz, V. 2001. Computer Automated Approach to the Extraction of Epiphyseal Regions in Hand Radiographs. *Journal of Digital Imaging,* 14**,** 165-172.

Pietka, E., Witko, K. & Gertych, A. 2005. Remotely accessible e-atlas for bone age assessment. *International Congress Series,* 1281**,** 260-265.

Pileski, R. C. A. & Woodside, D. G. 1973. Relationship of the ulnar sesamoid bone and maximum mandibular growth velocity. *Angle Orthodont.,* 43**,** 162.

Pinhasi, R., Shaw, P., White, B. & Ogden, A. R. 2006. Morbidity, rickets and long-bone growth in post-medieval Britain—a cross-population analysis. *Annals of Human Biology,* 33**,** 372-389.

Plato, C. C., Wood, J. L. & Norris, A. H. 1980. Bilateral asymmetry in bone measurements of the hand and lateral hand dominance. *American Journal of Physical Anthropology,* 52**,** 27-31.

Platt, L. D., Medearis, A. L., DeVore, G. R., Horenstein, J. M., Carlson, D. E. & Brar, H. S. 1988. Fetal foot length: relationship to menstrual age and fetal measurements in the second trimester. *Obstetrics and Gynecology,* 71**,** 526-31.

Pludowski, P., Lebiedowski, M. & Lorenc, R. S. 2004. Evaluation of the possibility to assess bone age on the basis of DXA derived hand scans-preliminary results. *Osteoporosis International.,* 15**,** 317-322.

Pludowski, P., Lebiedowski, M. & Lorenc, R. S. 2005. Evaluation of Practical Use of Bone Age Assessments Based on DXA-Derived Hand Scans in Diagnosis of Skeletal Status in Healthy and Diseased Children. *Journal of Clinical Densitometry,* 8**,** 48-56.

Pludowski, P., Litwin, M. & Lorenc, R. 2009. Skeletal maturation and body composition in primary hypertension. *Bone,* 45, Supplement 2**,** S67.

Powell, C. 2003. Early Indicators of Child Abuse and Neglect: A Multi-Professional Delphi Study. *Child Abuse Review,* 12**,** 25-40.

Poznanski, A. K., Garn, S. M., Kuhns, L. R. & Sandusky, S. T. 1971. Dysharmonic maturation of the hand in the congenital malformation syndromes. *American Journal of Physical Anthropology,* 35**,** 417-432.

Prakash, S. 1975. Age and order of appearance of elbow and hand-wrist ossific centres in Punjabee children from Rohtak. *Indian Journal of Medical Research,* 63**,** 640.

Prakash, S. 1975. Time of appearance of ossific centres of foot bones in Punjabee children from Rohtak. *The Anthropologist,* 20**,** 1.

Bibliography: A test of six radiographic age estimation methods on a modern population

Prakash, S. & Bala, K. 1979. Skeletal maturation in deprived pre-school children of Chandigarh. *Indian Journal of Medical Research,* 70**,** 242.

Prakash, S. & Cameron, N. 1981. Skeletal maturity of well-off children in Chandigarh, North India. *Annals of Human Biology,* 8**,** 175-180.

Prakash, S. & Chopra, S. R. K. 1978. Hand-wrist ossification timing delay in Punjabee pre-school children from Rohtak. *Indian Journal of Medical Research,* 68**,** 531.

Prakash, S. & Pathmanathan, G. 1991. Tempo-unconditional 1-year bone score velocities in well-off north-west Indian children. *Annals of Human Biology,* 18**,** 303.

Preece, M. A. & Baines, M. J. 1978. A new family of mathematical models describing the human growth curve. *Annals of Human Biology,* 5**,** 1.

Pretorius, D. H., Nelson, T. R. & Manco-Johnson, M. L. 1984. Fetal Age Estimation by Ultrasound: The Impact of Measurement Errors. *Radiology,* 152**,** 763-766.

Pretty, I. A. 2003. The Use of Dental Aging Techniques in Forensic Odontological Practice. *Journal of Forensic Sciences,* 48.

Price, B., Cameron, N. & Tobias, P. V. 1987. A Further Search for a Secular Trend of Adult Body Size in South Africa in Blacks: Evidence from the Femur and Tibia. *Human Biology,* 59**,** 467-475.

Prieto, J. L., Barberia, E., Ortega, R. & Magana, C. 2005. Evaluation of chronological age based on third molar development in the Spanish population. *International Journal of Legal Medicine,* 119**,** 349-54.

Pruvost, M.-O., Boraud, C. & Chariot, P. 2010. Skeletal age determination in adolescents involved in judicial procedures: from evidence-based principles to medical practice. *Journal of Medical Ethics,* 36**,** 71-74.

Pryse-Davies, J., Smitham, J. H. & Napier, K. A. 1974. Factors Influencing Development of Secondary Ossification Centres in the Fetus and Newborn. *Archives of Disease in Childhood,* 49**,** 425-431.

Pyle, S. I., Mann, A. W., Dreizen, S., Kelly, H. J., Macy, I. G. & Spies, T. D. 1948. A substitute for skeletal age (Todd) for clinical use: the red graph method. *Journal of Pediatrics,* 32**,** 125.

Pyle, S. I., Waterhouse, A. M. & Greulich, W. W. 1971. Attributes of the Radiographic Standard of Reference for the National Health Examination Survey. *American Journal of Physical Anthropology,* 35**,** 331-338.

Rai, B. & Anand, S. C. 2007. Relationship of Different Radiograph: Maturity Indicator. *Advances in Medical and Dental Sciences,* 1**,** 15-18.

Rai, B., Kaur, J. & Jafarzadeh, H. 2010. Dental age estimation from the developmental stage of the third molars in Iranian population. *Journal of Forensic and Legal Medicine,* 17**,** 309-311.

Rajan, R., Swindells, M., Metcalfe, J. & Konstantoulakis, C. 2011. Can orthopaedic clinicians learn to read skeletal bone age? An inter- and intra observer study between specialties. *Journal of Children's Orthopaedics,* 5**,** 69-72.

Bibliography: A test of six radiographic age estimation methods on a modern population

Ranjitkar, S., Lin, N. H., Macdonald, R., Taylor, J. A. & Townsend, G. C. 2006. Stature and skeletal maturation of two cohorts of Australian children and young adults over the past two decades. *Australian Orthodontic Journal,* 22**,** 47-58.

Rarick, G. L. & Oyster, M. 1964. Physical maturity, muscular strength, and motor performance of young school age children. *Research Quarterly of the American Association for Health, Physical Education and Recreation,* 35**,** 522.

Rauch, F. & Schoenau, E. 2001. The Developing Bone: Slave or Master of Its Cells and Molecules. *Pediatric Research,* 50**,** 309-314.

Rauch, F. a. S., E. 2002. Skeletal development in premature infants: a review of bone physiology beyond nutritional aspects. *Archives of Disease in Childhood Fetal Neonatal Ed.,* 86**,** F82-F85.

Reuland, P. & Werz, R. 2000. Investigations on skeletal growth zones via bone scans as base of determination of optimal time for surgery in mandibular asymmetry. *Nuklearmedizin,* 39**,** 121-6.

Reyes, M. E. P., Tan, S. K. & Malina, R. M. 2003. Urban–rural contrasts in the growth status of school children in Oaxaca, Mexico. *Annals of Human Biology,* 30**,** 693-713.

Reynolds, E. L. & Wines, J. V. 1948. Individual differences in physical changes associated with adolescence in girls. *American Journal of Disease of Children,* 75**,** 329.

Richey, H. G. 1937. The relation of accelerated, normal and retarded puberty to the height and weight of school children. *Monographs of the Society for Research in Child Development,* 2.

Richter, J. & Kern, G. 1987. Secular Changes in the Development of Children Born in Goerlitz, German Democratic Republic, 1956 to 1967 *Human Biology,* 2.

Richter, L., Norris, S., Pettifor, J., Yach, D. & Cameron, N. 2007. Cohort profile: Mandela's children: The 1990 birth to twenty study in South Africa. *International Journal of Epidemiology,* 36**,** 504.

Riddoch, C. J. & Boreham, C. A. G. 1995. The health-related physical activity of children. *Sports Medicine,* 19**,** 86.

Rissech, C., Schaeffer, M., and Malgosa, A. 2008. Development of the femur-Implications for age and sex determination. *Forensic Science International,* 180**,** 1-9.

Ritschl, E., Wehmeijer, K., de Terlizzi, F., Wipfler, E., Cadossi, R., Douma, D., Urlesberger, B. & Muller, W. 2005. Assessment of Skeletal Development in Preterm and Term Infants by Qunatitative Ultrasound. *Pediatric Research,* 58**,** 341-346.

Rivas, R. & Shapiro, F. 2002. Structural stages in the development of the long bones and epiphyses: a study in the New Zealand white rabbit. *Journal of Bone and Joint Surgery,* 84-A**,** 85-100.

Rivera, J. A., Barquera, S., Campirano, F., Campos, I., Safdie, M. & Tovar, V. 2002. Epidemiological and nutritional transition in Mexico: Rapid increase of non-communicable chronic diseases and obesity. *Public Health Nutr,* 5**,** 113.

Rizzoli, R. 2008. Nutrition: its role in bone health. *Best Practice & Research Clinical Endocrinology & Metabolism,* 22**,** 813-829.

Bibliography: A test of six radiographic age estimation methods on a modern population

Robert L, R. 1995. Skeletal maturation in children with hemiplegia. *The Journal of Pediatrics,* 127**,** 161.

Roberts, C. D., Vogtle, L. & Stevenson, R. D. 1994. Effect of hemiplegia on skeletal maturation. *The Journal of Pediatrics,* 125**,** 824-828.

Roberts, G. J., Parekh, S., Petrie, A. & Lucas, V. S. 2007. Dental Age Assessment (DAA): A Simple Method for Children and Emerging Adults. *British Dental Journal,* 204.

Roberts, L. J., Blair, R., Lenning, B. & Scott, M. 1938. Effect of a milk supplement on the physical status of institutional children. 1. Growth in height and weight. *American Journal of Diseases of Children,* 56**,** 287.

Robinow, M. & Chumlea, W.C. 1982. Standards for Limb Bone Length Ratios in Children. *Radiology,* 143**,** 433-436.

Robinson, R. A. & Cameron, D. A. 1956. Electron Microscopy of Cartilage and Bone Matrix at the Distal Epiphyseal Line of the Femur in the Newborn Infant. *Journal of Biophysical and Biochemical Cytology,* 2**,** 253-263.

Roche, A. & Himes, J. 1980. Incremental growth charts. *American Journal of Clinical Nutrition,* 33**,** 2041-2052.

Roche, A. F. 1970. Associations between the rates of maturation of the bones of the hand-wrist. *American Journal of Physical Anthropology,* 33**,** 341.

Roche, A. F. 1971. Summary of discussion. *American Journal of Physical Anthropology,* 35**,** 467-469.

Roche, A. F. 1989. Relative utility of carpal skeletal ages. *American Journal of Human Biology,* 1**,** 479-482.

Roche, A. F. & Davila, G. H. 1976. The reliability of assessments of the maturity of individual hand-wrist bones. *Human Biology,* 48**,** 585.

Roche, A. F., Davila, G. H. & Eyman, S. L. 1971. A comparison between Greulich-Pyle and Tanner-Whitehouse assessments of skeletal maturity. *Radiology,* 98**,** 273.

Roche, A. F., Davila, G. H., Pasternack, B. A. & Walton, M. J. 1970. Some Factors Influence the Replicability of Assessments of Skeletal Maturity (Greulich-Pyle) *American Journal of Roentgenography,* 109**,** 299-306.

Roche, A. F., Eyman, S. L. & Davila, G. H. 1971. Skeletal age prediction. *The Journal of Pediatrics,* 78**,** 997-1003.

Roche, A. F. & French, N. Y. 1970. Differences in Skeletal Maturity Levels Between the Knee and Hand. *American Journal of Roentgenology,* 109**,** 307-312.

Roche, A. F. & Hermann, R. F. 1970. Associations between the rates of elongation of the short bones of the hand. *American Journal of Physical Anthropology,* 32**,** 83.

Roche, A. F. & Hermann, R. F. 1970. Rates of change in width and length-width ratios of the diaphyses of the hand. *American Journal of Physical Anthropology,* 32**,** 89.

Roche, A. F. & Johnson, J. M. 1969. A comparison between methods of calculating skeletal age (Greulich-Pyle). *American Journal of Physical Anthropology,* 30**,** 221-229.

Roche, A. F., Roberts, J. & Hamill, V. V. 1975. Skeletal maturity of children 6–11 years: racial, geographic area, and socioeconomic differentials. *Vital and Health Statistics*.

Roche, A. F., Roberts, J. & Hamill, V. V. 1979. Skeletal maturity of children 12–17 years: racial, geographic area, and socioeconomic differentials. *Vital and Health Statistics*.

Roche, A. F. & Sunderland, S. 1959. Multiple ossification centres in the epiphyses of the long bones of the human hand and foot. *Journal of Bone and Joint Surgery,* 41B**,** 375-383.

Rochelle, R. H., Kelliher, M. S. & Thornton, R. 1961. Relationship of maturation age to incidence of injury in tackle football. *Research Quarterly,* 32**,** 78.

Rogol, A. D., Roemmich, J. N. & Clark, P. A. 2002. Growth at Puberty. *Journal of Adolescent Health,* 31**,** 192-200.

Rona, R. J. & Altman, D. G. 1977. National Study of Health and Growth, standards of attained height, weight and triceps skinfold in English children aged 5–11 years old. *Annals of Human Biology,* 4**,** 501.

Rösing, F. W., Graw, M., Marré, B., Ritz-Timme, S., Rothschild, M. A., Rötzscher, K., Schmeling, A., Schröder, I. & Geserick, G. 2007. Recommendations for the forensic diagnosis of sex and age from skeletons. *HOMO - Journal of Comparative Human Biology,* 58**,** 75-89.

Rotch, T. M. 1908. Chronological and anatomical age early in life. *Journal American Medical Association,* 51**,** 1197.

Rotch, T. M. 1909. A study of the development of the bones in childhood by the Roentgen method, with the view of establishing a development index for the grading of and the protection of early life. *Transactions of the Association of American Physicians,* 24**,** 603.

Rothenberg, L. H., Hintz, R. & VanCamp, M. 1977. Assessment of physical maturation and somatomedin levels during puberty. *American Journal of Orthodontics,* 71**,** 666-677.

Roy, T. A., Ruff, C. B. & Plato, C. C. 1994. Hand dominance and bilateral asymmetry in the structure of the second metacarpal. *American Journal of Physical Anthropology,* 94**,** 203-211.

Rózylo-Kalinowska, I., Kiworkowa-Raczkowska, E. & Kalinowski, P. 2008. Dental age in Central Poland. *Forensic Science International,* 174**,** 207-216.

Rudlin, C. R. 1989. A Three-Dimensional Representation of Linear Growth and Skeletal Maturation. *Acta Pediatrica Scandinavia [Suppl],* 356**,** 46-50.

Ruff, C. 2002. Variations in Human Body Size and Shape. *Annual Review in Anthropology,* 31**,** 211-232.

Ruff, C. 2003. Growth in Bone Strength, Body Size, and Muscle Size in a Juvenile Longitudinal Sample. *Bone,* 33**,** 317-329.

Russell, D. L., Keil, M. F., Bonat, S. H., Uwaifo, G. I., Nicholson, J. C., McDuffie, J. R., Hill, S. C. & Yanovski, J. A. 2001. The relation between skeletal maturation and adiposity in African American and Caucasian children. *The Journal of Pediatrics,* 139**,** 844-848.

Saenz de Rodriguez, C. A., Bongiovanni, A. M. & Conde de Borrego, L. 1985. An epidemic of precocious development in Puerto Rican children. *Journal of Pediatrics,* 107**,** 393.

Salardi, S., Tonioli, S., Tassoni, P., Tellarini, M., Mazzanti, L. & Cacciari, E. 1987. Growth and Growth Factors in Diabetes Mellitus. *Archives of Disease in Childhood,* 62**,** 57-62.

Salpou, D., Kiserud, T., Rasmussen, S. & Johnsen, S. L. 2008. Fetal age assessment based in 2nd trimester ultrasound in Africa and the effect of ethnicity. *BMC Pregnancy and Childbirth,* 8.

San Roman, P., Palma, J. C., Oteo, M. D. & Nevado, E. 2002. Skeletal maturation determined by cervical vertebrae development. *European Journal of Orthodontics,* 24**,** 303-11.

Sanders, J. O., Khoury, J. G., Kishan, S., Browne, R. H., Mooney, J. F., Arnold, K. D., McConnell, S. J., Mauman, J. A. & Finegold, D. N. 2008. Predicting Scoliosis Progression from Skeletal Maturity: A Simplified Classification During Adolescence. *The Journal of Bone and Joint Surgery (American),* 90**,** 540-553.

Sandhu, S. & Kaur, T. 2005. Radiographic Evaluation of the Status of Third Molars in the Asian-Indian Students. *Journal of Oral and Maxillofacial Surgery,* 63**,** 640-645.

Sangma, W. B., Marak, F. K., Singh, M. S. & Kharrubon, B. 2007. Age Determination in Girls of North-Eastern Region of India. *journal of Indian Academy of Forensic Medicine,* 29**,** 102-108.

Santoro, V., De Donno, A., Marrone, M., Campobasso, C. P. & Introna, F. 2009. Forensic age estimation of living individuals: A retrospective analysis. *Forensic Science International,* 193**,** 129.e1-129.e4.

Santoro, V., Lozito, P., Mastrorocco, N. & Introna, F. 2008. Morphometric Analysis of Third Molar Root Development by an Experimental Method Using Digital Orthopantomographs. *Journal of Forensic Sciences,* 53**,** 904-909.

Satake, T., Okajima, Y., Atomi, Y., Asami, T. & Kuroda, Y. 1986. Effect of physical exercise on growth and maturation. *J Phys Fit Japan,* 35**,** 104.

Sato, K., Ashizawa, K., Anzo, M., Otsuki, F., Kaneko, S., Tanaka, T., Tsukagoshi, K., Nimura, A., Matsuok, H., Matsuo, N., Mitani, H. & Murata, M. 1999. Setting up an automated system for evaluation of bone age. *Endocrine Journal,* 46 Suppl**,** S97-100.

Sato, M. & Kitagawa, C. 1983. Physical characteristics of young people in the Amami archipelago. *Human Biology,* 55**,** 615.

Satoh, M., Tanaka, T., Ashizawa, K., Ohtsuki, F., Anzo, M., Matsuo, N., Tatara, H. & Murata, M. 1993. Inter- and intra-observer errors on estimation of the bone age by Tanner-Whitehouse II method. *Clinical Pediatric Endocrinology,* 2**,** 160.

Savaridas, S. L., and Huntely, J.S., Porter, D.E., Williams, L., and Wilkinson, A.G 2007. The Rate of Skeletal Maturation in the Scottish Population. *A Comparison Across 25 Years (1980-2005). Journal of Pediatric Orthopaedics,* 27**,** 952-954.

Scammon, R. E. 1927. The First Seriatim Study of Human Growth. *American Journal of Physical Anthropology,* X**,** 329-336.

Schaefer, M. C. 2008. A summary of epiphyseal union timings in Bosnian males. *International Journal of Osteoarchaeology,* 18**,** 536-545.

Schaefer, M. C. & Black, S. M. 2007. Epiphyseal union sequencing: aiding in the recognition and sorting of commingled remains. *Journal of Forensic Sciences,* 52**,** 277-85.

Scheck, R. J., Coppenrath, E. M., Kellner, M. W., Lehmann, K. J., Rock, C., Rieger, J., Rothmeier, L., Schweden, F., Bauml, A. A. & Hahn, K. 1998. Radiation Dose and Image Quality in Spiral Computed Tomography: Multicentre Evaluation at Six Institutions. *The British Journal of Radiology,* 71**,** 734-744.

Schell, L. M., Johnston, F. E., Smith, D. R. & Paolone, A. M. 1985. Directional asymmetry of body dimensions among white adolescents. *American Journal of Physical Anthropology,* 67**,** 317-322.

Schmeling, A., Baumann, U., Schmidt, S., Wernecke, K.-D. & Reisinger, W. 2006. Reference data for the Thiemann-Nitz method of assessing skeletal age for the purpose of forensic age estimation. *International Journal of Legal Medicine,* 120**,** 1-4.

Schmeling, A., Geserick, G., Reisinger, W. & Olze, A. 2007. Age estimation. *Forensic Science International,* 165**,** 178-181.

Schmeling, A., Olze, A., Reisinger, W., König, M. & Geserick, G. 2003. Statistical analysis and verification of forensic age estimation of living persons in the Institute of Legal Medicine of the Berlin University Hospital Charité. *Legal Medicine,* 5**,** S367-S371.

Schmeling, A., Olze, A., Reisinger, W., Rosing, F. W. & Geserick, G. 2003. Forensic age diagnostics of living individuals in criminal proceedings. *HOMO,* 54**,** 162-169.

Schmeling, A., Reisinger, W., Geserick, G. & Olze, A. 2005. The Current State of Forensic Age Estimation of Live Subjects for the Purpose of Criminal Prosecution. *Forensic Science, Medicine and Pathology.,* 1**,** 239-246.

Schmeling, A., Schulz, R., Danner, B. & Rosing, F. W. 2006. The impact of economic progress and modernization in medicine on the ossification of hand and wrist. *International Journal of Legal Medicine,* 120**,** 121-126.

Schmeling, A., Schulz, R., Reisinger, W., Muhler, M., Wernecke, K. D. & Geserick, G. 2004. Studies on the time frame for ossification of the medial clavicular epiphyseal cartilage in conventional radiography. *International Journal of Legal Medicine,* 118**,** 5-8.

Schmidt, S. Forensic age determination in living individuals at the Institute of Legal Medicine in Berlin (Charité): analysis of the expert reports from 2001 to 2007. *Archiv fur Kriminologie,* 224**,** 168-76.

Schmidt, S., Baumann, U., Schulz, R., Reisinger, W. & Schmeling, A. 2008. Study of age dependence of epiphyseal ossification of the hand skeleton. *International Journal of Legal Medicine,* 122**,** 51-54.

Schmidt, S., Koch, B., Muhler, M., Reisinger, W. & Schmeling, A. 2007. Optimizing the Thiemann-Nitz method for skeletal age determination for forensic age diagnostics in live subjects. *Scandinavian Journal of Forensic Sciences,* 1**,** 5-7.

Bibliography: A test of six radiographic age estimation methods on a modern population

Schmidt, S., Koch, B., Schulz, R., Reisinger, W. & Schmeling, A. 2007. Comparative Analysis of the Applicability of the Skeletal Age Determination Methods of Greulich-Pyle and Thiemann-Nitz for Forensic Age Estimation in Living Subjects. *International Journal of Legal Medicine,* 121**,** 293-296.

Schmidt, S., Muhler, M., Schmeling, A., Reisinger, W. & Schulz, R. 2007. Magnetic resonance imaging of the clavicular ossification. *International Journal of Legal Medicine,* 121**,** 321-324.

Schmidt, S., Nitz, I., Schulz, R., Tsokos, M. & Schmeling, A. 2009. The digital atlas of skeletal maturity by Gilsanz and Ratib: a suitable alternative for age estimation of living individuals in criminal proceedings? *International Journal of Legal Medicine,* 123**,** 489-494.

Schoenau, E., Fricke, O. & Rauch, F. 2003. The Regulation of Bone Development as a Biological System. *HOMO-Journal of Comparative Human Biology,* 54**,** 113-118.

Schultz, S. P., Anner, J. & Hills, A. P. 2009. Paediatric Obesity, Physical Activity and the Musculoskeletal System. *Obesity Reviews,* 10**,** 576-582.

Schulze, D., Rother, U., Fuhrmann, A., Richel, S., Faulmann, G. & Heiland, M. 2006. Correlation of age and ossification of the medial clavicular epiphysis using computed tomography. *Forensic Science International,* 158**,** 184-189.

Schwarze, C. P., Arens, D., Haber, H. P., Wollmann, H. A., Binder, G., Mayer, E. I. & Ranke, M. B. 1998. Bone age in 116 untreated patients with Turner's syndrome rated by a computer-assisted method (CASAS). *Acta Paediatrica,* 87**,** 1146-50.

Sciulli, P. W. 2007. Relative Dental Maturity and Associated Skeletal Maturity in Prehistoric Native Americans of the Ohio Valley Area. *American Journal of Physical Anthropology,* 132**,** 545-557.

Scrimshaw, N. S. & Guzman, M. A. 1953. The effect of dietary supplementation and the administration of vitamin B1 and aureomycin on the growth of schoolchildren. *Nutrition Symposia***,** 101.

Seeman, E. & D., M. 1998. Growth in Bone Mass and Size-Are Racial and Gender Differences in Bone Mineral Density More Apparent than Real? *Journal of Clinical Endocrinology and Metabolism,* 83**,** 1414-1419.

Seidell, J. C., Doak, C. M., de Munter, J. S. L., Kuijper, L. D. J. & Zonneveld, C. 2006. Cross-sectional growth references and implications for the development if an international growth standard for school-aged children and adolescents. *Food and Nutrition Bulletin,* 27**,** S189-S198.

Semproli, S. & Gualdi-Russo, E. 2007. Childhood malnutrition and growth in a rural area of Western Kenya. *American Journal of Physical Anthropology,* 132**,** 463-469.

Serinelli, S., Panetta, V., Pasqualetti, P. & Marchetti, D. 2011. Accuracy of three age determination X-ray methods on the left hand-wrist: A systematic review and meta-analysis. *Legal Medicine,* 13**,** 120-133.

Shaikh, A. H., Rikhasor, R. M. & Qureshi, A. M. 1998. Determination of skeletal age in children aged 8-18 years. *J Pak Med Assoc,* 48**,** 104-6.

Shakir, A. 1971. The age at menarche in girls attending schools in Baghdad. *Human Biology,* 43**,** 265.

Bibliography: A test of six radiographic age estimation methods on a modern population

Shakir, A. & Zaini, S. 1974. Skeletal maturation of the hand and wrist of young children in Baghdad. *Annals of Human Biology,* 1**,** 189-199.

Shapiro, F. 1982. Legg-Calvé-Perthes Disease: A Study of Lower Extremity Length Discrepancies and Skeletal Maturation. *Acta Orthopaedica,* 53**,** 437-444.

Sherwood, R. J., Meindl, R. S., Robinson, H. B. & May, R. L. 2000. Fetal age: Methods of estimation and effects of pathology. *American Journal of Physical Anthropology,* 113**,** 305-315.

Shimura, N., Koyama, S., Arisaka, O., Imataka, M., Sato, K. & Matsuura, M. 2005. Assessment of Measurement of Children's Bone Age Ultrasonically with Sunlight BonAge. *Clinical Pediatric Endocrinology,* 14(suppl. 24)**,** 17-20.

Shultz, S. P., Anner, J. & Hills, A. P. 2009. Paediatric obesity, physical activity and the musculoskeletal system. *Obesity Reviews,* 10**,** 576-582.

Sidhom, G. & Derry, D. E. 1931. The Dates of Union of some Epiphyses in Egyptians from X-ray Photographs. *Journal of Anatomy,* 65**,** 196-211.

Siegling, J. A. 1941. Growth of the Epiphyses. *The Journal of Bone and Joint Surgery,* 23**,** 23-36.

Silvertoinen, K., Kapiro, J., Lahelma, E. & Koskenvuo, M. 2000. Relative effect of genetic and environmental factors on body height: Differences across birth cohorts among Finnish men and women. *Am J Pub Health,* 90**,** 627.

Simmons, K. & Greulich, W. W. 1943. Menarcheal age and the height, weight and skeletal age of girls, age 7 to 17 years. *Journal of Pediatrics,* 22**,** 518.

Singer, R. & Kimura, K. 1981. Body height, weight, and skeletal maturation in Hottentot (Khoikhoi) children. *American Journal of Physical Anthropology,* 54**,** 401-413.

Singh, A. & Gorea, R. K. 2007. Use of physiological changes occurring in teeth for age estimation of living person. *Forensic Science International,* 169**,** S47-S47.

Sklad, M. 1977. Skeletal maturation in monozygotic and dizygotic twins. *Journal of Human Evolution,* 6**,** 145-149.

Smith, P. J., Potgieter, J. F. & Fellingham, S. A. 1967. Body measurement of school children of four racial groups in Pretoria. *South African Medical Journal,* 41**,** 868.

Smith, R. J. 1980. Misuse of hand-wrist radiographs. *American Journal of Orthodontics,* 77**,** 75-78.

Smith, S. L. 1996. Attribution of Hand Bones to Sex and Population Groups. *Journal of Forensic Sciences,* 41**,** 469-477.

Smith, S. L. 2007. Stature Estimation of 3–10-Year-Old Children from Long Bone Lengths. *Journal of Forensic Sciences,* 52**,** 538-546.

Smith, S. L. & Buschang, P. H. 2005. Longitudinal models of long bone growth during adolescence. *American Journal of Human Biology,* 17**,** 731-745.

Snodgrass, R. M., Dreizen, S., Parker, G. S. & Spies, T. D. 1955. Serial Sequential Development of Anomalous Metacarpal and Phalangeal Ossification Centers in the Human Hand. *Growth,* 19**,** 307-322.

So, L. L. Y. 1997. Correlation of Sexual Maturation with Skeletal Age of Southern Chinese Girls. *Australian Orthodontic Journal,* 14**,** 215-217.

Soegiharto, B. M., Cunningham, S. J. & Moles, D. R. 2008. Skeletal maturation in Indonesian and white children assessed with hand-wrist and cervical vertebrae methods. *American Journal of Orthodontics and Dentofacial Orthopedics,* 134**,** 217-226.

Soegiharto, B. M., Moles, D. R. & Cunningham, S. J. 2008. Discriminatory ability of the skeletal maturation index and the cervical vertebrae maturation index in detecting peak pubertal growth in Indonesian and white subjects with receiver operating characteristics analysis. *American Journal of Orthodontics and Dentofacial Orthopedics,* 134**,** 227-237.

Solari, A. C. & Abramovitch, K. 2002. The Accuracy and Precision of Third Molar Development as an Indicator of Chronological Age in Hispanics. *Journal of Forensic Sciences,* 47**,** 531-535.

Solheim, T. & Vonen, A. 2006. Dental age estimation, quality assurance and age estimation of asylum seekers in Norway. *Forensic Science International,* 159**,** S56-S60.

Song, J., Claessens, A., Beunen, G. & Lefevre, J. 1994. Body size, biological maturation, and sport participation related to cortical bone in adolescent girls. *American Journal of Human Biology,* 6**,** 585-592.

Sorribas, A., March, J. & Voit, E. O. 2000. Estimating age-related trends in cross-sectional studies using S-distributions. *Statistics in Medicine,* 19**,** 697-713.

Sproul, A. & Peritz, E. 1971. Assessment of Skeletal Age in Short and Tall Children. *American Journal of Physical Anthropology,* 35**,** 433-440.

Stanitski, C. L. 2006. Skeletal Maturity. *Journal of Pediatric Orthopaedics,* 26**,** 825-826.

Steele, J. & Mays, S. 1995. Handedness and directional asymmetry in the long bones of the human upper limb. *International Journal of Osteoarchaeology,* 5**,** 39-49.

Steinberg, N., Siev-Ner, I., Peleg, S., Dar, G., Masharawi, Y. & Hershkovitz, I. 2008. Growth and development of female dancers aged 8-16 years. *American Journal of Human Biology,* 20**,** 299-307.

Stevenson, P. H. 1924. Age Order of Epiphyseal Union in Man. *American Journal of Physical Anthropology,* 7**,** 53-93.

Stewart, T. D. 1934. Sequence of Epiphyseal Union, Third Molar Eruption and Suture Closure in Eskimos and American Indians. *American Journal of Physical Anthropology,* 19**,** 433-452.

Stuart, H. C., Pyle, S. I., Cornoni, I. & Reed, R. B. 1962. Onsets completions and spans of ossification in the 29 bone-growth centers of the hand and wrist. *Pediatrics,* 29**,** 237.

Stützle, W., Gasser, T. & Largo, R. H. 1976. Analysis of the adolescent growth spurt using smoothing spline functions Centre International de L'enfance. *Rennes.***,** 109.

Bibliography: A test of six radiographic age estimation methods on a modern population

Subrahmanyan, V., Joseph, K., Doraiswamy, T. R., Narayanarao, M., Sankaran, A. N. & Swarinathan, M. 1957. The effect of a supplementary multipurpose food on the growth and nutritional status of children. *British Journal of Nutrition,* 11**,** 382.

Sun, S. S., Schubert, C. M., Chumlea, W. C., Roche, A. F., Kulin, H. E., Lee, P. A., Himes, J. H. & Ryan, A. S. 2002. National Estimates of the Timing of Sexual Maturation and Racial Differences Among U.S. Children. *Pediatrics,* 110**,** 911-919.

Sunakawa, K. 1960. Studies on the physical growth of the natives of Naha City, Okinawa. *Kagoshima Medical Journal,* 33**,** 1509.

Sundick, R. I. 1978. Human Skeletal Growth and Age Determination. *HOMO,* 29**,** 228-249.

Susanne, C., Hauspie, R. C., Gyenis, G. & Wachholder, A. 1986. Skeletal maturation in a longitudinal study of Belgian boys. *Anthropoligiai Közlemenyek,* 30**,** 77.

Suttleworth, F. K. 1939. The physical and mental growth of girls and boys age six to nineteen in relation to age at maximum growth. *Monographs of the Society for Research in Child Development,* 4.

Sutton, J. B. 1883. A New Rule of Epiphyses of Long Bones. *Journal of Anatomy and Physiology,* 17**,** 479-483.

Takai, S. 1981. Sexual dimorphism in somatic growth viewed from the skeletal maturation. *Igaku Kenkyu. Acta Medica,* 51**,** 225.

Takai, S. 1990. Smoothed skeletal maturity curve of Japanese children by Tanner-Whitehouse 2 (TW2) method and its application. *Acta Anatomica Nipponica,* 65**,** 436.

Takai, S. 1993. Velocities for the Tanner-Whitehouse 2 skeletal maturity in northwest Japanese children. *Okajimas Folia Anatomica Japonica,* 70**,** 119.

Takai, S. & Akiyoshi, T. 1983. Skeletal maturity of Japanese children in Western Kyushu. *American Journal of Physical Anthropology,* 62**,** 199.

Takai, S., Akiyoshi, T. & Fuchigami, A. 1984. Skeletal maturity of Japanese children in Amami-Oshima Island. *Annals of Human Biology,* 11**,** 571-575.

Takamura, K., Ohyama, S., Yamada, T. & Ishinishi, N. 1988. Changes in body proportions of Japanese medical students between 1961 and 1986. *American Journal of Physical Anthropology,* 77**,** 17-22.

Talwar, R. M., Haug, R. H., Gonzalez, M. L. & Perrott, D. H. 2004. The AAOMS age-related third molar study. *Journal of Oral and Maxillofacial Surgery,* 62**,** 34-35.

Tanner, J. M. 1971. The essential characteristics of a rating system. *American Journal of Physical Anthropology,* 35**,** 339-340.

Tanner, J. M. 1978. A correction to the TW2 RUS-based tables for predicting adult height. *Annals of Human Biology,* 5**,** 491-492.

Tanner, J. M., Oshman, D., Bahhage, F. & Healy, M. J. R. 1997. Tanner-Whitehouse bone age reference values for North American children. *Journal of Pediatrics,* 131**,** 34.

Bibliography: A test of six radiographic age estimation methods on a modern population

Tanner, J. M. & Whitehouse, R. H. 1967. Growth response of 26 children with short stature given human growth hormone. *British Medical Journal,* 2**,** 69.

Tanner, J. M. & Whitehouse, R. H. 1973. Height and Weight Charts from Birth to 5 Years Allowing for Length of Gestation: for Use in Infant Welfare Clinics. *Archives of Disease in Childhood,* 48**,** 786-789.

Tanner, J. M. & Whitehouse, R. H. 1975. Revised standards for triceps and subscapular skinfolds in British children. *Archives of Diseases of Childhood,* 50**,** 142.

Tanner, J. M. & Whitehouse, R. H. 1976. Clinical longitudinal standards for height, weight, height velocity, weight velocity, and stages of puberty. *Archives of Disease in Childhood,* 51**,** 170-179.

Tanner, J. M., Whitehouse, R. H., Marshall, W. A. & Carter, B. S. 1975. Prediction of adult height from height, bone age and occurrence of menarche, at ages 4 to 16 with allowance for mid-parent height. *Archives of Disease in Childhood,* 50**,** 14.

Tanner, J. M., Whitehouse, R. H., Marubini, E. & Resele, L. F. 1976. The adolescent growth spurt of boys and girls of the Harpenden Growth Study. *Annals of Human Biology,* 3**,** 109.

Tanner, J. M., Whitehouse, R. H. & Takaishi, M. 1966. Standards from birth to maturity for height, weight, height velocity, and weight velocity: British children, 1965. *Part I. Archives of Disease in Childhood,* 41**,** 454.

Taranger, J. 1976. II. Evaluation of biological maturation by means of maturity criteria. *Acta Pediatrica Scandinavia [Suppl],* 258**,** 77-82.

Taranger, J., Bruning, B., Claesson, I., Karlberg, P., Landström, T. & Lindström, B. 1976. A new method for the assessment of skeletal maturity -the MAT - method (mean appearance time of bone stages). *Acta Paediatrica,* 65**,** 109-120.

Taranger, J., Bruning, D., Karlberg, P., Landström, T. & Lindström, B. 1976. Skeletal development from birth to 7 years. *Acta Paediatrica Scandinavica. Supplement,* 258**,** 98.

Taranger, J., Engström, I., Lichenstein, H. & Svennberg-Redegren, I. 1976. Somatic pubertal development. *Acta Paediatrica Scandinavica,* 258**,** 121.

Taranger, J. & Hägg, U. 1980. The timing and duration of adolescent growth. *Acta Odontologica Scandinavica,* 58**,** 57.

Taranger, J., Karlberg, J., Bruning, B. & Engström, I. 1987. Standard deviation score charts of skeletal maturity and its velocity in Swedish children assessed by the Tanner-Whitehouse method (TW2-20). *Annals of Human Biology,* 14**,** 357-365.

Taranger, J., Karlberg, P., Lichtenstein, H. & Bruning, B. 1973. 7. A method for estimation of skeletal maturity. *Acta Paediatrica,* 62**,** 82-83.

Thevissen, P. W., Alqerban, A., Asaumi, J., Kahveci, F., Kaur, J., Kim, Y. K., Pittayapat, P., Van Vlierberghe, M., Zhang, Y., Fieuws, S. & Willems, G. 2010. Human dental age estimation using third molar developmental stages: Accuracy of age predictions not using country specific information. *Forensic Science International,* 201**,** 106-111.

Thevissen, P. W., Fieuws, S. & Willems, G. 2010. Human third molars development: Comparison of 9 country specific populations. *Forensic Science International,* 201**,** 102-105.

Thevissen, P. W., Pittayapat, P., Fieuws, S. & Willems, G. 2009. Estimating Age of Majority on Third Molars Developmental Stages in Young Adults from Thailand Using a Modified Scoring Technique. *Journal of Forensic Sciences,* 54**,** 428-432.

Thodberg, H. H. 2009. An Automated Method for Determination of Bone Age. *Journal of Clinical Endocrinology and Metabolism,* 94**,** 2239-2244.

Thomis, M. A. & Towne, B. 2006. Genetic determinants of prepubertal and pubertal growth and development. *Food and Nutrition Bulletin,* 27**,** S257-S278.

Thompson, T. 2001. Legal and ethical considerations of forensic anthropological research. *Science and Justice,* 41**,** 261-270.

Tiisala, R., Kantero, R., Bäckström, L. & Hallman, N. 1969. A mixed longitudinal study on skeletal maturation in healthy Finnish children aged 1 to 5 years. *Human Biology,* 41**,** 560.

Tipton, R. E., Wilroy Jr, R. S. & Summitt, R. L. 1973. Accelerated skeletal maturation in infancy syndrome: Report of a third case. *The Journal of Pediatrics,* 83**,** 829-832.

Todd, W. 1930. Comparitive Youth. *Child Development,* 1**,** 79-89.

Tritrakarn, A. & Tansuphasiri, V. 1991. Roentgengraphic assessment of skeletal ages of Asian junior youth football players. *Journal of the Medical Association of Thailand,* 74**,** 459.

Tunc, E. S. & Koyuturk, A. E. 2008. Dental age assessment using Demirjian's method on northern Turkish children. *Forensic Science International,* 175**,** 23-26.

Tupman, G. S. 1962. A Study of Bone Growth in Normal Children and its Relationship to Skeletal Maturation. *The Journal of Bone and Joint Surgery,* 44B**,** 42-67.

Tyvalsky, F. A. 2004. Nutritional Influences Bone Growth in Children. *Journal of Nutrition,* 1345**,** 689S-690S.

Ubelaker, D. H. 1987. Estimating Age at Death from Immature Human Skeletons: An Overview. *Journal of Forensic Sciences,* 32**,** 1254-1263.

Ulbrich, J. 1971. Individual variants of physical fitness in boys from the age of 11 up to maturity and their selection for sports activities. *Medicina Dello Sport,* 24**,** 118.

Ulijaszek, S. L. 2001. Secular Trends in Growth: the narrowing of ethnic differences in stature. *Nutrition Bulletin,* 26**,** 43-51.

Ulijaszek, S. L. 2006. The International Growth Standard for Children and Adolescents Project: Environmental influences on preadolescent and adolescent growth in weight and height. *Food and Nutrition Bulletin,* 27**,** S279-S294.

Uysal, T., Ramoglu, S. I., Basciftci, F. A. & Sari, Z. 2006. Chronologic age and skeletal maturation of the cervical vertebrae and hand-wrist: is there a relationship? *American Journal of Orthodontics and Dentofacial Orthopedics,* 130**,** 622-8.

Van den Brande, J. L., Van Wyk, J. J., French, F. S., Strickland, A. L. & Radcliffe, W. B. 1973. Advancement of skeletal age of hypopituitary children treated with thyroid hormone plus cortisone. *The Journal of Pediatrics,* 82**,** 22-27.

Van Der Kamp, H. J., Otten, B. J., Buitenweg, N., De Muinck Keizer-Schrama, S. M. P. F., Oostdijk, W., Jansen, M., Delemarre-de Waal, H. A., Vulsma, T. & Wit, J. M. 2002. Longitudinal analysis of growth and puberty in 21-hydroxylase deficiency patients. *Archive of Disease in Children,* 87**,** 139-144.

Van Dusen, C. R. 1939. An anthropolometric study of the upper extremities of children. *Human Biology,* 11**,** 277-284.

Van Eck, M., Dallmeijer, A. J., Voorman, J. M. & Becher, J. G. 2008. Skeletal maturation in children with cerebral palsy and its relationship with motor functioning. *Developmental Medicine and Child Neurology,* 50**,** 515-519.

Van Loon, H., Saverys, V., Vuylsteke, J. P., Vlietinck, R. F. & Eeckels, R. 1986. Local versus universal growth standards: the effect of using NCHS as universal reference. *Annals of Human Biology,* 13**,** 347.

Van Rijn, R. R. & Lequin, M. H. 2009. Automatic Determination of Greulich and Pyle Bone Age in Healthy Dutch Children. *Pediatric Radiology,* 39**,** 591-597.

Van Valen, L. 1978. The statistics of variation. *Evolutionary Theory,* 4**,** 33.

Van Venrooij-Ysselmuiden, M. & Van Ipenburg, A. 1978. Mixed longitudinal data on skeletal age from a group of Dutch children living in Utrecht and surroundings. *Annals of Human Biology,* 5**,** 359.

Van Vlierberghe, M., Boltacz-Rzepkowska, E., Van Langenhove, L., Laszkiewicz, J., Wyns, B., Devlaminck, D., Boullart, L., Thevissen, P. & Willems, G. 2010. A comparative study of two different regression methods for radiographs in Polish youngsters estimating chronological age on third molars. *Forensic Science International,* 201**,** 86-94.

Venrooij-Ysselmuiden M.E., Van Smeets H.J.L. & Van der Werff ten Bosch J.J. 1976. The secular trend in age at menarche in the Netherlands. *Annals of Human Biology,* 3**,** 283.

Vance, V. L., Steyn, M., L'Abbé, E. N. & Becker, P. J. 2010. A cross-sectional analysis of age related changes in the osteometric dimensions of long bones in modern South Africans of European and African descent. *Forensic Science International,* In Press,

Varkkola, O., Ranta, H., Metsäniitty, M. & Sajantila, A. 2011. Age assessment by the Greulich and Pyle method compared to other skeletal X-ray and dental methods in data from Finnish child victims of the Southeast Asian Tsunami. *Forensic Science, Medicine, and Pathology***,** 1-6.

Vasconcelos, N. P. S., Caran, E. M. M., Lee, M. L., Lopes, N. N. F. & Weiler, R. M. E. 2009. Dental maturity assessment in children with acute lymphoblastic leukemia after cancer therapy. *Forensic Science International,* 184**,** 10-14.

Vejvoda, M. & Grant, D. B. 1981. Discordant bone maturation of the hand in children with precocious puberty and congenital adrenal hyperplasia. *Acta Paediatrica Scandinavica,* 70**,** 903.

Verma, D., Peltomaki, T. & Jager, A. 2009. Reliability of growth prediction with hand-wrist radiographs. *European Journal of Orthodontics,* 31**,** 438-442.

Vestlund, J., Langeborg, L., SÖRqvist, P. & Eriksson, M. 2009. Experts on age estimation. *Scandinavian Journal of Psychology,* 50**,** 301-307.

Virtanen, M. & Perheentupa, J. 1989. Bone Age at Birth; Method and Effect of Hypothyroidism. *Acta Pediatrica Scandinavia [Suppl],* 78**,** 412-418.

Vorster, H. H., Venter, C. S., Wissing, M. P. & Margetts, B. M. 2005. The nutrition and health transition in the North West Province of South Africa: a review of the THUSA (Transition and Health during Urbanisation of South Africans) study. *Public Health Nutr,* 8**,** 480.

Voss, L., Walker, J., Lunt, H., Wilkin, T. & Betts, P. 1989. The Wessex Growth Study: First Report. *Acta Pediatrica Scandinavia [Suppl],* 349**,** 65-72.

Vrijens, J. & van Cauter, C. 1985. Physical performance capacity and specific skills in young soccer players. In: Binkhorst RA, Kemper HCG, Saris WHM, editors. Children and exercise XI. *Champaign, IL: Human Kinetics. pp***,** 285.

Wachholder, A. & Hauspie, R. 1986. Clinical standards for growth in height of Belgian boys and girls, aged 2 to 18 years. *International Journal of Anthropology,* 1**,** 327-338.

Waldmann, E., Baber, F. M., Field, C. E., Billewicz, W. Z. & Thomson, A. M. 1977. Skeletal maturation of Hong Kong Chinese children in the first five years of life. *Annals of Human Biology,* 4**,** 343-352.

Waliszko, A. & Jedlińska, W. 1976. Wroclaw Growth Study. Part II. Males. *Studies in Physical Anthropology,* 3**,** 27.

Walker, P. L. 1969. The Linear Growth of Long Bones in Late Woodland Indian Children. *Proceedings of the India Academy of Science for 1968,* 78**,** 83-87.

Wang, S., Qiu, Y., Ma, Z., Xia, C., Zhu, F. & Zhu, Z. 2007. Histologic, Risser Sign, and Digital Skeletal Age Evaluation for Residual Spine Growth Potential in Chinese Female Idiophathic Scoliosis. *Spine,* 32**,** 1648-1654.

Wang, Y., Monteiro, C. & Popkin, B. M. 2002. Trends of obesity and underweight in older children and adolescents in the United States, Brazil, China, and Russia. *American Journal of Clinical Nutrition,* 75**,** 971.

Wang, Y., Moreno, L. A., Caballero, B. & Cole, T. J. 2006. Limitations of the current World Health Organization growth references for children and adolescents. *Food and Nutrition Bulletin,* 27**,** S175-S188.

Warren, M. S., Smith, K. R., Stubblefield, P. R., Martin, S. S. & Walsh-Haney, H. A. 1999. Use of Radiographic Atlases in a Mass Fatality. *Journal of Forensic Sciences,* 45**,** 467-470.

Weaver, D. D., Graham, C. B., Thomas, I. T. & Smith, D. W. 1974. A new overgrowth syndrome with accelerated skeletal maturation, unusual facies, and camptodactyly. *The Journal of Pediatrics,* 84**,** 547-552.

Webber, M. L., Puck, M. H., Maresh, M. M., Boad, W. B. & Robinson, A. 1982. Short Communication: Skeletal Maturation of Children with Sex Chromosome Abnormalities. *Pediatric Research,* 16**,** 343-346.

Webster, G. & De Saram, G. S. W. 1954. Estimation of age from bone development. Observations on a study of 567 Ceylonese school children of the ages 9-16 years. *The Journal of Criminal Law, Criminology, and Police Science,* 45**,** 96-101.

Wehkalampi, K., Silventoinen, K., Kaprio, J., Dick, D. M., Rose, R. J., Pulkkinen, L. & Dunkel, L. 2008. Genetic and environmental influences on pubertal timing assessed by height growth. *American Journal of Human Biology,* 20**,** 417-423.

Weiner, J. S. & Thambipillai, V. 1952. Skeletal maturation of West African Negroes. *American Journal of Physical Anthropology,* 10**,** 407-418.

Weise, M., De-Levi, S., Barnes, K. M., Gafni, R. I., Abad, V. & Baron, J. 2001. Effects of estrogen on growth plate senescence and epiphyseal fusion. *Proceedings of the National Academy of Sciences of the United States of America,* 98**,** 6871-6876.

Wellens, R., Malina, R. M., Beunen, G. & Lefevre, J. 1990. Age at menarche in Flemish girls: current status and secular change in the 20th century. *Annals of Human Biology,* 16**,** 145.

Welon, Z. & Bielicki, T. 1973. The adolescent growth spurt and the 'critical body weight' hypothesis. *Materialy i Prace Antropologiczne,* 86**,** 27.

Wenstrup, R. J., Roca-Espiau, M., Weinreb, N. J. & Bembi, B. 2002. Skeletal Aspects of Gaucher Disesase: a Review. *The British Journal of Radiology,* 75 (suppl. 1)**,** A1-A12.

Wenzel, A., Droschl, H. & Melsen, B. 1984. Skeletal maturity in Austrian children assessed by the GP and the TW2 methods. *Annals of Human Biology,* 11**,** 173.

Wenzel, A. & Melsen, B. 1982. Replicability of assessing radiographs by the Tanner and Whitehouse-2 method. *Human Biology*.

Wenzel, A. & Melsen, B. 1982. Skeletal maturity in 6-16-year-old Danish children assessed by the Tanner-Whitehouse-2 method. *Annals of Human Biology,* 9**,** 277.

Wenzel, A. & Melsen, B. 1982. Skeletal maturity in 6–16-year-old Danish children assessed by the Tanner-Whitehouse-2 method. *Annals of Human Biology,* 9**,** 277-281.

Wetherington, R. K. 1961. A Note on the Fusion of the Lunate and Triquetral Centers. *American Journal of Physical Anthropology,* 19**,** 251-253.

Whieldon, D. 1978. Maturity sorting: new balance for young athletes. *Physician and Sports Medicine,* 6**,** 127.

Whitaker, J. M., Rousseau, L., Williams, T., Rowan, R. A. & Hartwig, W. C. 2002. Scoring system for estimating age in the foot skeleton. *American Journal of Physical Anthropology,* 118**,** 385-92.

WHO Multicentre Growth Reference Study Group 2006. Enrolment and baseline characteristics in the WHO multicentre growth reference study. *Acta Paediatrica,* Suppl 450**,** 7-15.

Wierman, M. E., Beardsworth, D. E., Crawford, J. D., Crigler, J. F., Mansfield, M. J., Bode, H. H., Boepple, P. A., Kushner, D. C. & Crowley, W. F. 1986. Adrenache and Skeletal Maturation during Luteinizing Hormone Releasing Hormone Analogue Suppression of Gonadarche. *Journal of Clinical Investigation,* 77**,** 121-126.

Willems, G. 2001. A review of the most commonly used dental age estimation techniques. *Journal of Forensic Odonto-Stomatology,* 19**,** 9-17.

Wingerd, J., Peritz, E. & Sproul, A. 1974. Race and stature differences in the skeletal maturation of the hand and wrist. *Annals of Human Biology,* 1**,** 201-209.

Winter, R. J. & Green, O. C. 1985. Irradiation-induced growth hormone deficiency: Blunted growth response and accelerated skeletal maturation to growth hormone therapy. *The Journal of Pediatrics,* 106**,** 609-612

Wolanski, N. 1967. Basic Problems in Physical Development in Man in Relation to the Evaluation of Development of Children and Youth. *Current Anthropology,* 8**,** 35-60.

Wong, R. W. K., Alkhal, H. A. & Rabie, A. B. M. 2009. Editor's Summary: Use of cervical vertebral maturation to determine skeletal age. *American Journal of Orthodontics and Dentofacial Orthopedics,* 136**,** 484-485.

Wong, R. W. K., Alkhal, H. A. & Rabie, A. B. M. 2009. Use of cervical vertebral maturation to determine skeletal age. *American Journal of Orthodontics and Dentofacial Orthopedics,* 136**,** 484.e1-484.e6.

Wu, Y., Schreiber, G. B., Klementowicz, V., Biro, F. & Wright, D. 2001. Racial differences in accuracy of self-assessment of sexual maturation among young black and white girls. *Journal of Adolescent Health,* 28**,** 197-203.

Xu, X., Wang, W., Guo, Z. & Karlberg, J. 2002. Longitudinal Growth During Infancy and Childhood in Children from Shanghai: Predictors and Consequences of the Age at Onset of the Childhood Phase of Growth. *Pediatric Research,* 51**,** 377-385.

Yang, K. T. & Yang, A. 2006. Evaluation of Activity of Epiphyseal Plates in Growing Males and Females. *Calcified Tissue International,* 78**,** 348-356.

Yang, S. 1989. Effect of bone maturity on the morphology, function and work capacity of youngsters. *Sports Science,* 9**,** 24.

Yarbrough, C., Habicht, R. E. & Roche, A. F. 1973. Determining the biological age of the preschool child from a hand wrist radiograph. *Investigative Radiology,* 8**,** 233.

Yashar, A., Loder, R. T. & Hensinger, R. N. 1995. Determination of skeletal age in children with Osgood-Schlatter disease by using radiographs of the knee. *Journal of Pediatric Orthopedics,* 15**,** 298-301.

Ye, Y. Y., Ling, T. L. & Luo, Z. 1989. Clinical application of TW2 method for bone age evaluation in paediatrics in China. *Chinese Journal of Paediatrics,* 27**,** 84.

Ye, Y.-Y., Wang, C.-X. & Cao, L.-Z. 1992. Skeletal maturity of the hand and wrist in Chinese children in Changsha, assessed by TWII method. *Annals of Human Biology,* 19**,** 427.

Bibliography: A test of six radiographic age estimation methods on a modern population

Y'Edynak, G. 1976. Long bone growth in western Eskimo and Aleut skeletons. *American Journal of Physical Anthropology,* 45**,** 569-574.

Young, M. 1928. Age of Full Stature in Females and Epiphyseal Union in Long Bones of Lower Limbs. *American Journal of Physical Anthropology,* XII**,** 285-290.

Zachmann, M., Ferrandes, A., Mürset, G. & Preder, A. 1975. Estrogen Treatment of excessively tall girls. *Helvetia Paediatrica Acta.,* 30**,** 11.

Zadik, Z. 2009. Age and Bone Age Determinations - Inaccurate Methods at Their Best. *Journal of Pediatric Endocrinology and Metabolism,* 22**,** 479-480.

Zammit, M. P., Kalra, V., Nelson, S., Broadbent, B. H. & Hans, M. G. 1994. Growth patterns of Labrador Inuit youth: II. Skeletal age. *Arctic Medical Research,* 53**,** 176-83.

Zemel, B. S., Kawachak, D. A., Ohene-Frempong, K., Schall, J. I. & Stallings, V. A. 2007. Effects of Delayed Pubertal Development, Nutritional Status, and Disease Severity on Longitudinal Patterns of Growth Failure in Children With Sickle Cell Disease. *Pediatric Research,* 61**,** 607-613.

Zeng, D., Wu, Z. & Cui, M. 2010. Chronological age estimation of third molar mineralization of Han in southern China. *International Journal of Legal Medicine,* 124**,** 119-123.

Zhang, A., Gertych, A. & Liu, B. J. 2007. Automatic bone age assessment for young children from newborn to 7-year-old using carpal bones. *Computerized Medical Imaging and Graphics,* 31**,** 299-310.

Zhang, S.-Y., Liu, L.-J., Wu, Z.-L., Liu, G., Ma, Z.-G., Shen, X.-Z. & Xu, R.-L. 2008. Standards of TW3 skeletal maturity for Chinese children. *Annals of Human Biology,* 35**,** 349-354.

Zhen, O. & Baolin, L. 1986. Skeletal maturity of the hand and wrist in Chinese school children in Harbin assessed by the TW2 method. *Annals of Human Biology,* 13**,** 183-187.

Zhen-Wang, B. & Cheng-Ye, J. 2005. Secular growth changes in body height and weight in children and adolescents in Shandong, China between 1939 and 2000. *Annals of Human Biology,* 32**,** 650-665.

Zoetis, T., Tassinari, M. S., Bagi, C., Walthall, K. & Hurtt, M. E. 2003. Species Comparison of Postnatal Bone Growth and Development. *Birth Defects Research (Part B),* 68**,** 86-110.

Report

Bhabha, J. & Finch, N. 2006. Seeking Asylum Alone. Harvard Committee on Human Rights, Refugee Council.

CEOP. 2009. Strategic Threat Assessment Child Trafficking in the UK. Child Exploitation and Online Protection.

CEOP. 2011. *Child Trafficking Update,* London, Child Exploitation and Online Protection Centre.

Child Exploitation and Online Protection Centre 2009. Strategic Threat Assessment Child Trafficking in the UK. Child Exploitation and Online Protection.

Clarke, S. 2011. Young Lives in Limbo. *In:* COUNCIL, W. R. (ed.). Welsh Refugee Council.

Crawley, H. 2007. When is a child not a child? *In:* IMMIGRATION LAW PRACTITIONERS' ASSOCIATION (ed.). London: Immigration Law Practitioners' Association.

Easton, P. 2006. Population profile for inequalities strategy. *In:* TAYSIDE, N. (ed.). Tayside: Ninewells Hospital.

European Convention. 2000. The Charter of Fundamental Rights of the European Union. European Parliament.

European Migration Network 2010. Policies on reception, return and integration arrangements for, and numbers of, Unaccompanied Minors - an EU comparative study. *In:* NETWORK, E. M. (ed.). European Migration Network.

Greiner, T. M. & Gordon, C. C. 1990. An Assessment of Long-Term Changes in Anthropometric Dimensions: Secular Trends of U.S. Army Males. Natick, Massachusetts.

Home Office 2008. Asylum Statistics United Kingdom 2007. *In:* HOME OFFICE STATISTICAL BULLETIN (ed.).

Home Office 2008. Better Outomes: The Way Forward. Improving the care of unaccompanied asylum seeking children.: Home Office: Border and Immigration Agency.

Home Office 2008. Supplementary tables for 2008, including applications recieved for asylum in the UK from unaccompanied children. Table 2.k. *In:* HOME OFFICE STATISTICAL BULLETIN (ed.).

Home Office 2009. Control of Immigration: Statistics United Kingdom 2008. *In:* BULLETIN, H. O. S. (ed.).

Hubbard, J. 2007. Letter in Response to Planning Better Outcomes and Support for Asylum Seekers. Royal College of Radiologists (RCR).

I.L.O. 2002. *Every Child Counts: New Global Estimates on Child Labour,* Geneva, International Labour Office.

Kvittingen, A. V. 2010. Negotiating childhood: Age assessment in the UK asylum system. *Working Paper Series.* Oxford: Refugee Studies Centre.

Levenson, R. & Sharma, A. 1999. *The Health of Refugee Children - Guidelines for Paediatricians,* London, Royal College of Paediatrics and Child Health.

McKern, T. W. & Stewart, T. D. 1957. *Skeletal age changes in young American males, analysed from the standpoint of age identification.* , Headquarters Quatermaster Research and Development Command, Technical Report EP-45. Natwick, M. .

Bibliography: A test of six radiographic age estimation methods on a modern population

Serrao, A. & Sujatha, B. R. 2004. Birth Registration. A Background Note. Bangalore: Community Development Foundation, Bangalore.

Smith, T. & Brownlees, L. 2011. Age assessment practices: a literature review & annotated bibliography. *In:* (UNICEF), U. N. C. S. F. (ed.). New York.

UNHCR. 1997. Guidelines on Policies and Procedures in Dealing with Unaccompanied Children Seeking Asylum. *In:* REFUGEES, United Nations Children's Fund (ed.). Geneva.

Watt, I. 1996. Letter ref. BFCR (96) 9 to all Home Clinical Radiology Fellows and Members. Royal College of Radiologists.

Thesis

Dibnah, M. 2007/8. *Asylum Seekers and Age Determination-Professional Bodies Guidance for Unaccompanied Minors.*

Web Page

AGFAD. 2011. *Study Group in Forensic Age Diagnostics of the German Association of Forensic Medicine* [Online]. [Accessed 5th February 2012].

Behrents, R. G. & Broadbent, B. H. 1984. *A chronological account of the Bolton-Brush growth studies - in search of truth for the greater good of man* [Online]. Cleveland, Ohio: The Bolton-Brush Growth Study Center. Available: http://dental.case.edu/bolton-brush/background.html [Accessed 16th January 2012].

British Broadcasting Corporation. 2008. *Canada Coroner Condemns Foot Hoax* [Online]. Available: http://news.bbc.co.uk/1/hi/world/americas/7462953.stm [Accessed 5th January 2012 2012].

British Broadcasting Corporation. 2008. *Fifth Human Foot Found in Canada* [Online]. Available: http://news.bbc.co.uk/1/hi/world/americas/7458468.stm [Accessed 5th January 2012 2012].

British Broadcasting Corporation. 2008. *'Foot' Discovered on Canada Shore* [Online]. Available: http://news.bbc.co.uk/1/hi/world/americas/7726165.stm [Accessed 5th January 2012 2012].

Directgov. 2008. *Registering or changing a birth record* [Online]. Available: http://www.direct.gov.uk/en/Governmentcitizensandrights/Registeringlifeevents/Birthandadoption records/Registeringorchangingabirthrecord/index.htm.

Gunn, I. 2008. *Foot Find Confuses Canadian Police* [Online]. Vancouver. Available: http://news.bbc.co.uk/1/hi/world/americas/7418239.stm [Accessed 5th January 2012].

Hans, M. G. & Broadbent, B. H. 2008. *Bolton-Brush Growth Study Centre* [Online]. Cleveland: Case Western Reserve University. Available: http://dental.case.edu/bolton-brush/ [Accessed 12th February 2012].

Hillingdon, L. B. 2005. *Practice Guidelines for Age Assessment of Young Unaccompanied Asylum Seekers* [Online]. London: London Borough of Hillingdon. Available: http://www.proceduresonline.com/hillingdon/childcare/pdfs/Master%20Age%20assessment%20%28August%202005%29%20.pdf [Accessed 10th February 2012].

ILPA. 2012. *Immigration Law Practitioners' Association* [Online]. London: Immigration Law Practitioners' Association. Available: http://www.ilpa.org.uk/ [Accessed 20th February 2012].

RCPCH. 2007. *X-Rays and Asylum Seeking Children: Policy Statement.* [Online]. Royal College of Paediatrics and Child Health. Available: http://www.rcpch.ac.uk/Policy/X-Rays-and-Asylum-Seeking-Children-Policy-Statement [Accessed 6th January 2012].

Symonds, S. 2011. *Age Disputes and Detention* [Online]. London. Available: http://www.ilpa.org.uk/data/resources/13345/11.06-Age-Disputes-and-Detention.pdf [Accessed 20th February 2012].

UKBA. 2010. *Assessing Age* [Online]. London: United Kingdom Border Agency. Available: http://www.ind.homeoffice.gov.uk/sitecontent/documents/policyandlaw/asylumprocessguidance/specialcases/guidance/assessing-age?view=Binary [Accessed 10th February 2012].

WHO/India. 2009. *Core Programme Clusters. Communicable Diseases and Disease Surveillance. Tuberculosis* [Online]. Available: http://www.whoindia.org/en/Section3/Section123.htm [Accessed 3 December 2009.

Bibliography: A test of six radiographic age estimation methods on a modern population