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A THREE-DIMENSIONAL STUDY OF FACIAL CHANGES IN CHILDREN AGED 11-14 YEARS

A thesis submitted to the University of Wales for the degree of
DOCTOR OF PHILOSOPHY
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by

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[I] © Cardiff University Wales College of Medicine 3D Facial Macro Version 1.4a June 2005. Developed by Dr Alexei Zhurov

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DECLARATION

This work has not previously been accepted in substance for any degree and is not concurrently submitted in candidature for any degree.

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This thesis is dedicated to my wife Renee and son Shane who have sacrificed a great deal in order for us to be where we are today.

Do not conform any longer to the pattern of this world but be transformed by the renewing of your mind."
Romans 12: 2

ABSTRACT

Introduction: One area of constant interest to orthodontists is the developing face. This is probably a result of the region in which orthodontists work in and the belief that orthodontic treatment provided can influence the outcomes of facial growth. New three-dimensional modalities have enabled clinicians to better understand the facial changes occurring in a developing child.

Materials and Methods: 95 children were evaluated using a previously validated three-dimensional laser imaging device. Laser scanned images were taken of children at 6 monthly intervals over a 2 year period. Surface changes were evaluated using normal and average faces. These changes were seen as mean differences of surface changes shown as colour maps as well as surface area and volume changes.

Results: The results showed that there were morphological differences between males and females. Surfaces changes were seen in the children at the ages evaluated. The results suggest that the surface areas of change in the average faces were in a general downward and forward direction. This was taken with respect to the nose and soft tissue nasion. The lips also translated in a downward direction as the nose grew and there was a general increase in the vertical dimension. In addition, there were a number of subjects falling into the "significant changes" category. These were changes significantly greater in males than in females. There was asymmetric growth patterns in 35% of the children. The results suggest that orthodontic treatment did not affect facial growth to a large extent. However, some changes were seen in the female comparisons groups.

Conclusions: The following conclusions could be drawn from this study of facial morphology:

1. The three-dimensional laser capture technique described is both valid and reliable.
2. The study has shown that the use of three-dimensional imaging is a feasible method in the analyzing and perceiving of changes to the face over time.
3. Males and females show differing facial morphology.
4. The magnitudes of surface changes are larger in males than in females.
5. There is a significant difference in the timing of the surface changes in males than in females, with males exhibiting later changes.
6. There is forward growth particularly occurring in the nose, brows, lips and vertical dimensions of the face.
7. There seems to be a deepening of the eyes and flattening of the cheeks.
8. Clinicians should be aware of three-dimensional surface changes that result from growth and treatment.
9. Growth has been shown to be variable in this age group of 11-14 year olds. Some children have illustrated significant growth changes whilst others very little, and this may depend on the period of capture related to their growing period.
10. There was a difference between the facial morphology of females who received and did not receive orthodontic treatment. These differences were seen particularly in the upper and lower lip regions.
11. However, there was very little difference in individuals who received and did not receive orthodontic treatment.
12. Asymmetric growth patterns were seen occurring in 35% of the cohort studied with right sided differences being more than left sided differences.

CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

For over a century, the practice of orthodontics has evolved and continues to embrace new innovations and technologies. This can be illustrated by Andrew's refinement of Angle's classifications of occlusion (Andrews 1972; Angle 1900); the great extraction/non-extraction debate (Case 1964) with treatment planning protocols that were initially based on dental structures, but later led to the appreciation and incorporation of facial balance (facial aesthetic keys) (Ackerman et al. 1999; Arnett and Bergman 1993; Sarver 1998).

Technology has enabled innovations to map and quantify facial characteristics, beginning with Bolton-Broadbent's cephalometer (Broadbent 1931) to the present day three-dimensional hard and soft tissue imaging systems (Hajeer et al. 2004c; Kau et al. 2005d; Mah and Hatcher 2004; Papadopoulos et al. 2002). Innovations in technology and the use of powerful computer software tools over the last two decades have seen an improvement in both hard and soft tissue imaging devices. The latter are non-invasive, easy to use and do not require exposure to radiation. These "surface imaging" or "soft tissue" imaging systems, initially expensive, bulky and technique sensitive have undergone several modifications. Today these devices are easily portable and soft tissue representation of faces can be captured quickly and efficiently (Aldridge et al. 2005; Harrison et al. 2004; Kau et al. 2005c; Kau et al. 2006b). However, these three-dimensional devices are still in their infancy of development when compared to their equivalent counterparts in two-dimensional photography (Blais 2004), as realistic soft tissue simulation can be a complex task (Mah and Bumann 2001; Mah 2002; Mah and Enciso 2003).

Therefore, the challenges for the clinician are not just to capture impressive three-dimensional images, but to evaluate the issues of validity, reliability and clinical applications.

1.2 BACKGROUND

One area of interest to orthodontists is the change in the face as a result of growth/ageing and orthodontic interventions. There has been considerable debate regarding the benefits of orthodontic treatment dating back to the 1900's (Angle 1907), with more recent media programs (C4Dispatches 1999) claiming that some orthodontic treatment has a detrimental effect on facial development and growth, namely by flattening the facial profile, elongating the upper lip and increasing the prominence of the nose). This has caused a great deal of correspondence in the dental press with two opposing groups, one suggesting no effect on facial development and growth and another suggesting that it does have an effect (Dibiase and Sandler 2001; Mew 2000). The truth is that the evidence to support these claims is insufficient.

This is due partly to the fact that each individual is unique in the way that they develop. Therefore, it is important during the treatment planning process to determine whether an individual is within or outside normal variation. Variations in growth and development are particularly evident during the adolescence period (Tanner 1962). All children undergo a growth spurt in adolescence that can be clearly seen by plotting height or weight, but growth varies for each individual with girls tending to reach their growth spurt earlier than boys. Age alone is often not a good indicator of an individual's growth status and a number of other methods have been suggested as growth indicators.

Cephalometrics has been the traditional method used by the orthodontist to assess hard and soft tissue changes due to orthodontics and facial growth. These methods have some problems (For example, measuring landmarks from a two-dimensional radiograph that arguably does not exist in a three-dimensional individual)(Bjork 1963; Bjork 1969). Furthermore, landmark identification of hard and soft tissues on radiographs can be difficult. Many clinicians and researchers claim that it is at this stage that the major source of errors occurs (Baumrind and Frantz 1971a; Baumrind and Frantz 1971b). Therefore, conventional methods are limited in their ability to comprehensively describe the three-dimensional characteristics of the face as the lateral projection of the profile does not give a representation of orientation and depth. The facial surface exhibits all the characteristics of three-dimensional morphology (form and structure) where distinct facial features and landmarks have their spatial position (x, y, z co-ordinates), which inevitably alter with movement in space (Farkas 1994) (i.e. landmark nasion is an estimate on a lateral projection and varies if the subject is positioned differently in the cephalostat).

Three-dimensional imaging therefore has a role to play in determining how the face develops in the three planes of space. The literature has shown that three-dimensional imaging techniques have been used to create databases for normative populations (Yamada et al. 2002), analyze growth changes cross-sectionally (Nute and Moss 2000), and also in the assessment of clinical outcomes for surgical (Ayoub et al. 1996; Ayoub et al. 1998; Ji et al. 2002; Khambay et al. 2002a; Marmulla et al. 2003; McCance et al. 1992a; McCance et al. 1997d) and non-surgical treatments (Ismail et al. 2002a; McDonagh et al. 2001; Moss et al. 2003a) in the head and neck region. A better knowledge and a comprehensive database of three-dimensional facial changes in a growing individual may also lead to:

(a) A better understanding of soft tissue facial form and topography

(b) Creation of normative databases and facial templates

(c) A better understanding of facial growth

To date there have been no studies reported in the literature on three-dimensional facial changes as a result of growth. This study evaluates the feasibility of using surface imaging on a cohort of school children to evaluate facial change and serves as a reference for future evaluations of soft tissue in the growing face.

CHAPTER 2
LITERATURE REVIEW

2.1 INTRODUCTION

The study of cranio-facial growth has been of interest to orthodontists for almost a century. There have been a number of reported methods to evaluate facial change and many opinions on the facial changes that occur. This section gives a brief overview of these discussions.

2.2 CRANIO-FACIAL GROWTH

2.2 (a) Definition and Concepts of Growth

The lay person's understanding of the term "growth" implies that something has changed in magnitude (Donald and Hans 1996). However, "growth" applied in the context of the developing child and in particular that of the changing face is much more complex than the definition implies. It has to take into account the direction of growth, encompassing the shape and surface changes of part of the face. For example, the face not only changes in magnitude, it also appears to grow in a "downward and forward" direction in relation to the base of the skull (Proffit 2000a). This overall process incorporates "rotations" and "displacements" of the facial bones (Björk 1969; Björk 1984; Björk 1991). As a result, the term "development" seems more appropriate to describe these changes. There is constant change occurring throughout an individual's lifetime, commonly termed growth or ageing. Most structures of the face do not remain stable and the rates of these changes differ from individual to individual.

2.2 (b) Stages of Growth

In order to understand craniofacial growth it is easier to describe it in two phases; pre- and post-natal.

(i) Pre-Natal Growth

The pre-natal period is defined as the time from conception of the foetus to the birth of the baby and normally lasts for 38 weeks. From the minute the ovum is fertilised, the process is initiated. A series of complex molecular processes interact with one another to create vital organs and physical characteristics that are distinctively human. However, due to the confined intra-uterine environment, the upper third of the head bearing the cranium is given priority, as it accommodates the brain as an important organ in overall development. As a result, the lower two-thirds of the face is proportionally smaller than the cranium at birth. This is approximately 60% and 40% complete, for the cranium and face respectively (Ranly 1988; Ranly 2000).

(ii) Post-Natal Growth

Post-natal growth by definition forms part of the continuation of pre-natal growth interrupted by birth. After birth, the constraints of the womb are lifted from the face and the individual is subjected to genetically pre-programmed growth and the effects of the general environment. These processes alter the external form and the internal architecture of a bone or a complex of bones within the face. There are different stages of post-natal growth and these will be discussed under the following sub-headings: The early years, adolescent years and adulthood.

- ***The Early years (0-12 years)***

In general, the brain dictates the pace of growth of the head in the early years. The brain reaches nearly 50% of its total weight by the age of 1 year, 75% by the age of 3 years and 90% by 7 years of age. It reaches full development normally around 11-12 years (Israel 1978). Therefore as the brain mass increases, the surrounding cranium expands to accommodate it. The complex sutural systems present within the cranial vault have a fast rate of growth in the early years and then begins to slow down during puberty. It has been postulated that sutures allow the brain to expand (functional matrix theory) whilst surface deposition and resorption create unique facial characteristics. The anterior forehead region is no exception and is remodelled under the influence of the frontal sinuses. These changes on the surfaces result in the prominence of the brow areas, especially in males later in life. The base of the skull plays an important role in facial growth in terms of the position of the maxilla and mandible.

The cranial base is divided into the anterior and posterior portions by the spheno-occipital suture. The anterior cranial base follows a neural pattern of growth and is stable by the age of 8 years (Stamrud 1959). Therefore, many researchers favour using this area as a reference for evaluating growth. The posterior cranial base contains the spheno-occipital synchondrosis, a cartilaginous site that follows a somatic pattern of growth. Flexion of this synchondrosis influences the relative positions of the maxilla and mandible (i.e. an obtuse flexion produces a skeletal Class II pattern and an acute flexion produces a skeletal Class III pattern). Therefore, facial changes in the adolescent years are closely related to this synchondrosis and the facial bones continue to enlarge markedly for many years to accommodate the airway and masticatory growth and functions. At 3 years of age, the cranium is 90% of the adult size, whereas the lower face is only 65% complete (Ranly 2000).

The orbits of the face attain transverse stability in the early years and have been shown to attain full development (between the inner corners of the eyes) at 8 years for females and 11 years for males (Farkas et al. 1992).

- ***The Adolescent Years (12-18 years)***

This period is normally when a child attains puberty and is characterized by dramatic physical changes associated with an individual maturing (Proffit 2000a). There are dramatic increases in both height and weight. This occurs typically two years earlier in girls than boys. In addition, there are changing secondary characteristics, such as menarche, breast development in females and facial hair, deepening of the voice in males, due to greater influence of sex hormones, oestrogen and testosterone. The major adolescent events occurring in the cranio-facial region are the development of the lower two-thirds of the face, an increase in definition of the facial structures and a change from the mixed to the permanent dentition.

In describing the external changes of the face, much of the research data shows acceleration in growth of the maxillary complex and the mandible, both of which are attached to the posterior cranial base. These changes make the face noticeably deeper in an anterior posterior plane studied by super-imposition techniques on lateral cephalograms on the anterior cranial base. There are also the following changes (Enlow 1966; Enlow 1979) when the cranial base is used as a reference and when two-dimensional evaluations are used;

1. Forward growth of the upper and lower jaws,
2. Forward elongation of the nose,
3. Backward shift of the lateral orbits,
4. Posterior movement of the zygoma allow the zygomatico-maxillary suture,
5. Posterior extension of the dental arches in the tuberosity region of the maxilla.

- ***Adulthood***

In the past, it was assumed that growth of the facial skeleton ceased in the late teens or early twenties. In the early 1980's, Behrents succeeded in recalling over 100 individuals who had participated in the Bolton-Brush growth studies in the 1930's and 1940's (Behrents 1984). This sample consisted of patients who were in their 40's and most had never had orthodontic treatment previously. Interestingly, the results showed that facial growth continued throughout adult life. There was an increase in all of the facial dimensions over the recall period. Vertical changes in the face during adulthood were more prominent than anterior-posterior changes, whereas width changes were least evident and so the alterations observed in the adult facial skeleton seem to be a continuation of the pattern seen during maturation. A point of particular interest was an apparent deceleration of growth in females in the late teens were followed by a resumption of growth in the late twenties. It appears that the woman's first pregnancy often produces some growth of her jaws. Although the annual magnitude of adult growth changes measured in millimetres was quite small the cumulative effects over the decades was surprisingly large in all dimensions of space.

In the light of these findings, it seems that the view of facial growth as a process that ended in the late teens had to be revised. It is however correct to assume that the growth process is one that diminishes after the attainment of sexual maturity. However, mandibular rather than maxillary changes continue in adult life. The study showed that the rates and timing of growth can be determined in adulthood although these were difficult to quantify due to small sample sizes and individuals lost to follow-up (Lewis and Roche 1988).

2.2 (c) Traditional methods of assessing facial growth

A number of three-dimensional methods on the analysis of facial changes have been reported in the literature. Basically, the x, y, z coordinate defines a point in space and a series of points provides an accurate representation of the object studied. The techniques used to capture these coordinates are numerous.

Examples of the early studies using direct methods which included the use of vernier callipers and angular dividers. These methods were often described as craniometry (Enlow et al. 1969), anthroposcopy and anthropometry (Farkas 1994). These physical measurements had many inaccuracies, due to the methods of data capture, operator variability and landmark identification. These methods were also often time consuming at the primary research sites and not based on a Cartesian or-ordinate system.

The introduction of radiographic cephalometry in 1934, by Hofrath in Germany and Broadbent in the United States (Broadbent et al. 1975), provided a clinical tool for the study of malocclusion and skeletal relationships and a means of researching treatment responses and growth which surpassed the techniques of craniometry and anthropometry used previously. Broadbent emphasized the three-dimensional nature of facial relationships and recommended that postero-anterior and lateral views of the skull should be taken for cephalometric analysis. However, as the facial variations of greatest orthodontic importance are in the sagittal plane and other views are difficult to interpret and measure, cephalometric radiology has come to mean, almost exclusively, the measurement of lateral cephalomteric radiographs. Lateral cephalometric radiographs are taken under standardized conditions so that measurements can be compared between patients and for the same patient on different occasions. Analysis is commonly carried out on a tracing of the radiograph, which reduces the amount of information on the film to a manageable level, or on a computer that analyses the x-y coordinates of cephalometric landmarks. Both the validity and reproducibility of certain landmarks used in cephalometric analysis have been called into question and these points do not necessarily depict the true anatomical landmark. These considerations have to be made when evaluating the role of cephalometric lateral radiographs in orthodontics in clinical diagnosis and evaluating treatment results.

- ***Errors in cephalometry***

The traditional measurement tool to assess facial growth is by lateral cephalograms measuring two-dimensional landmarks that arguably do not exist in a three-dimensional individual (Björk 1963; Björk 1969). The major problem in cephalometry is landmark identification of hard and soft tissue on radiographs. It is at this stage that the major sources of cephalometric error occurs (Baumrind and Frantz 1971a; Baumrind and Frantz 1971b). Many factors are involved in uncertainty of the results that are obtained from these images. These may be attributed to:

1. Quality of the radiographic image
2. Precision of landmark definition and the reproducibility of landmark location
3. Operator and registration procedure
4. Registration of landmarks in two-dimensions of a three-dimensional structure

Changes in skeletal assessment using radiographic techniques are relatively small but tend to be much greater in the soft tissues (Nute and Moss 2000). Sagittal recordings of midline points or lateral skulls radiographs and optical surface scanning have shown to be consistent (McDonagh et al. 2001). Whilst ethical approval is unlikely in this day and age for radiographic growth studies, these precious databases are still used from time to time for analysis of data (Palomo et al. 2005).

Due to the radiation risks of radiographic techniques, alternative methods using three-dimensional devices have been developed and these will be discussed later.

2.2 (d) Soft Tissue Growth

The number of papers focusing on and analysing soft tissue morphology and growth are comparatively small in relation to the general orthodontic literature (Riolo et al. 1987). Yet the external profile is by far the most visible entity that clinicians and lay people perceive, and on which they formulate judgments. With a greater emphasis being placed on the balance between the hard and soft tissues, it is important to have reliable and readily available data on the facial soft tissues. At present, there is a lack of information on the longitudinal development of the nose, lips and soft tissues at the chin (Sarver 1998). Most of the available data on the changing soft tissue profile has been obtained from cephalometric data with a small number of case reports from limited three-dimensional studies. These studies have placed an emphasis on the following three areas: the nose, lips and soft tissue chin (Burke and Beard 1979; Burke 1980; Burke and Hughes-Lawson 1988a; Meredith et al. 1958; Sarver 1998; Subtelny 1959; Subtelny 1961).

(i) Development of the nose

Out of the three, the development of the nose is the one that an orthodontist has the least control of. Yet in terms of facial balance and profile it is arguably the most important! One of the first studies of the nose was carried out by Subtelny who used 30 records of male and female cephalometric data from the Bolton and Brush longitudinal data sets (Subtelny 1959). He was the first to describe the downward and forward growth of the nose that occurred during maturity. In addition, the growth of the nose in the vertical dimension is more than the anterior-posterior dimensions. The nose plays such an important role that when the convexity of the facial profile was analyzed using hard and soft tissue landmarks, the hard tissue readings recorded a more prognathic profile whilst the soft tissue readings were more convex (Subtelny

1959). He also found that there was a sizeable growth of the nose between the ages of 10-16 years for males and females. This growth was more marked in boys with a tendency for accelerated growth changes from the ages of 13-14 years whilst the growth in the female nose was gradual and seen around the age of 12 years. A further study on 46 children between 10-16 years confirmed some of the original findings (Manera and Subtelny 1961). In addition, they found the magnitude of growth in the boys to be much larger than that of girls. Using two-dimensional analysis on stereo-photogrammetric method, the downward movement was also confirmed as being more pronounced than the lateral aspect dimensions in 52 same sexed twins obtained from a mixed longitudinal study (Burke and Hughes-Lawson 1988b; Burke and Hughes-Lawson 1989).

Another study investigated sexual dimorphism and potential differences in skeletal profiles (Genecov et al. 1990). 64 lateral cephalograms (32 Class I and 32 Class II) were obtained from the Bolton Brush sample and analyzed over three time frames: mixed dentition (7-9 years), early permanent (11-13 years) and early adulthood (16-18 years). They found the following, based on the sample investigated:

- Growth of the nose in an anterior posterior direction continued in both males and females after skeletal growth had subsided.
- Females had completed or finished a large proportion of soft tissue development by age 12 years whilst males continued until 17 years.
- Growth of the nose was independent of skeletal classification.

(ii) Soft tissue Lip Changes

The lips will be discussed broadly under two general headings: soft tissue changes associated with normal growth and secondly under treatment effects. In

Subtelny's studies described earlier (Subtelny 1959), he found that the upper lips increased in length rapidly from the ages of 1-3 years, but the rate of increase was markedly reduced from ages 3-6 years. There was also a progressive increase for children at the ages of 8, 10, 12, 14, 16 and 18 years. He found that most of the maxillary lip lengths in females were reached by 14 years and in males this tended to be complete by 18 years. Furthermore, vertical mandibular lip length growth persisted longer than maxillary lip length in females. The incremental percentage was greater in males than females, and was not complete at age 18 years (Mamandras 1988). In another study using a different growth sample, Genecov et al. (1990) found that males between the ages of 7-17 years had a greater increase in upper lip length than females in the same period. The males experienced a little more than 2mm in vertical height of the upper lip and females experienced less than 1mm in vertical height

(iii) Soft tissue chin

The last in the three segments of soft tissue analysis and probably the most difficult to study is the soft tissue chin. Past evidence seems to suggest that the increased chin projection in males during growth is due to mandibular growth rather than to soft tissue changes (Nanda et al. 1990). Genecov (1990) also found that there was a gender difference in the soft tissue thickness during the growing period; the thickness of the soft tissue chin in comparison to the hard tissue counterpart was more or less the same at the age of 17 years.

2.2 (f) Soft tissue profile and Body Mass Index

Published sources relating soft tissue thickness to the bony structures have also been reported (Smith and Buschang 2001; Smith and Buschang 2002) and used in forensic science (Tyrrell et al. 1997). However, the basis of associating soft tissue profiles to body parameters like BMI, can be questionable as a relationship hardly presents between the two. Probably the only reference relating BMI to soft tissue profile was carried out by Riolo and co-workers on a pre-selected sample taken from the Michigan growth study (Riolo et al. 1987). He used data collected from the ages of 6-16 years (Riolo and TenHave 1986) and found that the BMI had a significant effect on the relationship between growth changes in the hard and soft tissue profiles. Children with a higher BMI had thicker soft tissue profile measurements and greater horizontal profile measurements but no differences were found in other sample groups. In addition, there was a significant difference in vertical facial heights for high BMI children. A higher BMI had no effect on the measures of profile convexity. However, soft tissue changes in normal BMI children were present but were less significant than the high BMI groups.

2.2(g) Growth Studies

- ***Longitudinal Studies***

The longitudinal method of analysis involves repeated measurements on a cohort of individuals over a period of time. The advantage lies in the fact that patterns of growth and variations within groups can be analyzed (Persson and Thilander 1985). Longitudinal studies however are expensive, labour intensive and time consuming to run. Furthermore, the drop out rate in this type of studies can be significant, weakening the statistical inference. There have been a number of high profile studies that have made significant contributions to the understanding of facial growth. A few examples will be cited.

The Bolton-Brush Studies (1930-1973 at Case Western Reserve University) included 5000 individuals of European descent were studied between 1-18 years of age (Broadbent et al. 1975). Population averages exceeding 1000 were carefully selected to represent the average face or "Bolton Facial Template". These were used in clinical research to analyze facial growth and to predict treatment changes. Evaluations of gender differences have also been carried out in recent times (Ursi et al. 1993).

The Michigan Study was started in 1930 by Drs W Olson and B Hughes at the School of Education, University of Michigan. The exact sample size was not mentioned but children from 3-18 years were enrolled and extensive data was collected which include dental records, lateral radiographs and dental casts. In 1953, yearly radiographs were discontinued. In 1974, Riolo published an atlas of craniofacial growth, from a sample of 87 subjects, depicting annual hard tissue increments as seen from these longitudinal records (Riolo et al. 1979). These readings have been carefully evaluated and analyzed and serve as a useful reference for hard tissue changes.

Radiographs and dental casts were collected at the Kings College School of Medicine and Dentistry over a period of 18 years. These sample consisted of 528 British subjects of Caucasian origin examined at birth and six months and thereafter annually. Two hundred and eight siblings were later added to the sample. These subjects were followed till they were 18 years of age. At the age of 18 years, 142 or 19.3% of the original sample were retained. Facial norms were created and the average changes in soft tissue and hard tissues were recorded and published (Bhatia and Leighton 1993).

The Belfast growth study was carried out in the 1960's and 1970's. The study included 300 orthodontically untreated individuals who had Posterior Anterior Cephalograms (PA) and lateral Cephalograms taken annually (Adams 1971). Interestingly, a selected Class I sample of these original subjects were studied again recently, and the results showed that the percentage increase in growth was most pronounced in the vertical compared to the sagittal and transverse dimensions (Lux et al. 2004). One criticism of this study is the retention of subjects by the end of the study, 37 from a total of 300.

Several other longitudinal growth studies have also been reported in the literature (Ekstrom 1982), but these studies suffer from retention of subjects, lack of full control and a variety of other non-investigator related factors. As a result they were less famous and not often cited.

- ***Mixed longitudinal***

A mixed longitudinal approach is another useful methodology to obtain growth data. For example a cohort of individuals aged 11, 14 and 17 years are followed for 5 years (there is an overlap of 2 years). Studies such as this obtain 10 years of data in 5 years, facilitating growth curves to be created and allowing for matching between cohorts (Kowalski and Prahl-Andersen 1979).

The Nymegen growth study comprised a sample of 467 children with six overlapping cohorts studied over a 5 year period from 1971-1976. The aim of the study was to provide information on the growth and development of normal Dutch children from the age of 4-14 years. A host of medical, psycho-social and dental parameters were analyzed. Part of this study included the use of lateral cepaholgrams in its analysis, and was further compared to the studies at Michigan (Riolo et al. 1979) and Groningen (Boersma 1966). The Nymegen studies were an interesting addition to the literature but reading and analyzing the data was often difficult and tedious, as there were multiple data sets.

The Burlington study was started and completed by Dr F Popovich from 1952 and 1972. An original sample consisted of 1,380 children (aged 3, 6, 8, 10, 12 years), representing 90% of all the children in Burlington, Ontario Canada. Only the records of the 3 year olds were recorded annually. To date 8,000 sets of records and 46, 746 cephalograms are on the database. The methodology undertaken was similar to a mixed longitudinal study.

- ***Cross-sectional studies***

These studies utilize different populations for each year and some researchers believe that the data collected in these types of studies are likely to produce the same basic information as longitudinal growth studies (Tanner 1962). The collective results are pooled and compared across a range. These studies are relatively easier to perform and are usually more cost effective (Farkas 1994; Ferrario et al. 1998a).

Marcus Goldstein (1936) at New York University carried one of the earliest cross-sectional studies out. Fifty males were examined at each age beginning at 2.5 to 3.5 years, and continuing every other year until and including 20.5 and 21.5 years. A further group of 50 males at the age of 74 years were also studied. Detailed anthropological data was collected in an attempt to describe the growth of the face in three-dimensions. These data sets gave a better understanding of the dynamics of facial growth, i.e. growth of the face was greatest in the vertical dimension.

A cross-sectional study of facial growth was carried out at the Craniofacial Measurement Laboratory, University of Toronto, Canada involving 1,594 Caucasians subjects aged 1 to 18 years (Farkas et al. 1992; Farkas and Posnick 1992). The analysis of the material was done of the basis of means values, growth increments and percentage changes.

Ferrario and co-workers (DATE) used facial landmark identifications to study 1,347 healthy Caucasian children aged 6-18 years and young adults aged 19-32 years. Their general findings were in line with current literature showing that males had a strong tendency to continue growing and for a longer period of time.

2.3 THREE-DIMENSIONAL SURFACE ACQUISITION TECHNOLOGY

The introduction of sophisticated three-dimensional devices has meant that the soft tissues of the face can be evaluated in a quicker, non-invasive manner to conventional anthropometric techniques. Furthermore, a comprehensive qualitative and quantitative analysis can be performed with the appropriate three-dimensional analytical software. A number of reviews have been written on the use of three-dimensional technology in orthodontics (Hajeer et al. 2004b; Hajeer et al. 2004c; Kau et al. 2005d; Papadopoulos et al. 2002).

This section will focus on imaging devices that have been used to capture facial morphology, exploring their advantages and disadvantages. The three-dimensional imaging devices can be classified as set out in Table 2.1.

Table 2.1 Tabular representation of surface imaging devices

1)	Direct Contact	a) Polhemus 3Space Digitizer b) Digi-graph c) ELITE
2)	Photogrammetry	a) Stereo-photogrammetry
3)	Lasers	a) Fixed Units • Medical Graphics and Imaging Group, UCL • Cyberware Laboratory 3030 / SP • Others
		b) Portable and Mobile • Minolta Systems (Model models 700, 900, 910, 9i) • Polhemus hand-held (FASTSCAN)
4)	Structured Light	a) Single Camera b) Multiple Camera • Moire patterns • OGIS Range Finder RFX-IV • CAM, three-dimensional Shape system • C3D-dimensional Stereo-photogrammetry (Glasgow) – Computer aided • 3dMD™ Face System • Others
5)	Video-Imaging	a) Motion-Analysis™
6)	Radiation Sources	a) Three-dimensional cephalometry b) CT Scans c) Cone Beam Computerised Tomography (CBCT)
7)	Others	a) MRI b) Ultra-sound

2.3 (a) Direct Contact Devices

As the name implies, direct contact systems obtain three-dimensional co-ordinates directly from "touching" the surfaces of the physical object. A reference framework is established first by marking fiducial points of known co-ordinates and finally by landmarking the surfaces of the face, within this framework, with an electronic probe. The locations of these landmarks were obtained based on previous direct anthropometric techniques described by Farkas in 1994. A number of these systems were described in the 1970's and 1980's.

(i) Polhemus 3Space Digitizer

Validated in the late 1980s by Hildebolt and Vannier, the Polhemus 3Space digitizer[II] was a tabletop model interfaced with a computer. It also consisted of a hand held stylus, a key pad and a foot pad (Kohn et al. 1995). The hand held stylus contacted each landmark on the face of a clinical subject, and an electronic magnetic field generated within the unit determined the location of the stylus. All subjects were placed supine and in the middle of the table. When each landmark was located, the foot pad was depressed to record the data. All data was made up of points and coordinates were recorded in centimetres (cm).

(ii) Digi-Graph Work Station

The Digi-graph workstation[III] was a system that combined non-radiographic cephalometric and video-imaging with a manual digitizing hand piece used to record cephalometric data. Three-dimensional coordinates were recorded when the button on the digitizing handpick was depressed. An audible sound was created and picked up by an array of four microphones on the system. The time it took for the sound to reach the microphones determined the landmark location. The landmarks were systematically recorded and corresponded to video images captured by two mounted video cameras. This represented a crude but initial step towards three-dimensional photographic co-ordinate capture (Chaconas et al. 1990a).

This system was validated for clinical management and patient education and found to be clinically compatible (Tsang and Cooke 1999). Studies to compare cephalometric readings and Digigraph showed that the results were not statistically significant at the 0.5 level (Chaconas et al. 1990b). It was also used to evaluate the

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[II] 3SPACE digitizer, Kaiser Aerospace and Elctronics, Polhemus Division, Colchester VT
[III] Dolphin Imaging Systems, Valcenia, CA

various soft tissue relationships in balanced young adult faces (Nanda and Ghosh 1995).

(iii) ELaboratore di Immagini TElevisive (ELITE) and Three-Dimensional Facial Morphometry (3DFM)

Ferrario and co-workers (Ferrario et al. 1993; Ferrario et al. 1996) described a more complex anthropometric technique using direct digitized measurements in combination with video images. In one of the first reported studies using the ELITE system[IV], three-dimensional facial soft tissue data was obtained from a sample of 40 men and 40 women. For each subject, 16 soft tissue facial landmarks were automatically collected using two infra-red charged coupled devices (CCD). Fifteen linear and ten angular measurements, and four linear distance ratios were computed and averaged for gender. Ferrario reported that for all angular values, both samples showed a narrow variability and no significant gender differences were demonstrated. The highest inter-sample variability was observed for the measurements of facial height (prevalent vertical dimension), and the lowest for the measurements of facial depth (prevalent horizontal dimension). The proportions of upper and lower face height relative to the anterior face height showed a significant gender difference. Mean values were in good agreement with literature data collected using traditional methods.

The group also reported that this new method allowed the direct and non-invasive calculation of linear and angular measurements that would be usefully applied in clinics as a supplement to the traditional radiographic cephalometric analyses. The technique was later given the title "Three-Dimensional Facial Morphometry (3DFM)" and was used for linear and volumetric analysis based very

[IV] Laboratorio di Anatomia Funzionale dell'Apparato, Dipartimento di Anatomia Umana, Univerita degli Studi, via Mangiagalli 31, 2013333 Milan, Italy much on geometrical principles (Ferrario et al. 1998b). This technique has also been used for a variety of orthodontic applications that include craniofacial anomalies (Sforza et al. 2004), creation of facial normals (Ferrario et al. 1997b), facial growth in cross-sectional cohorts (Ferrario et al. 1998a; Ferrario et al. 1999b; Ferrario et al. 2000; Ferrario et al. 2003), facial attractiveness studies (Ferrario et al. 1997a) and different treatment groups (Ferrario et al. 1999a; Ferrario et al. 2002).

The weakness of the system is the recording of points as three-dimensional coordinates in space and it fails to take into account surface topography.

2.3 (b) Stereo-Photogrammetry

Different systems were introduced by superimposing grid projections onto objects. Sassouni used a standardized millimetre grid, a cephalostat and profile photos *(physioprints)* (Sassouni 1957). The subsequent analyses were made on carefully drawn out contour maps. These procedures were time consuming and often distorted by perspective (Volp 1979). A similar technique, Morphanalysis was introduced by Rabey (1968). This technique also used a grid system for three-dimensional coordinate transfer. Again the issues of magnification and distortion were not addressed (Robertson 1976; Robertson and Volp 1981). This system uses 2 images (radiographs and photographs) in 2 planes on a centimetre scale and maps the common points on both to create x, y, z coordinates.

Photogrammetry is the science of measurements of photographs, and reconstructs the measurements of two- or three-dimensional structures from photographic reproductions (Richmond 1984), and it has been used in medicine and dentistry from the 1940's (Berghagen 1951). Tanner and Weiner (1949) modified and standardized this technique so that certain anthropometric dimensions could be measured to a degree of accuracy similar to direct methods . Stereo-photogrammetry is a technique that uses two or more cameras configured as a stereo-pair to obtain three-dimensional co-ordinates of facial morphology.

Early photogrammetric methods utilized techniques used by cartographers that incorporated contour mappings with varying sub-intervals. Therefore it was often laborious, tedious and expensive to map the facial structures in three-dimensions (Burke and Beard 1967; Burke 1983; Burke 1984). These techniques have also been applied to volumetric analysis and biostereometric analysis of surgically corrected abnormal faces (Berkowitz and Cuzzi 1977; Björn et al. 1953).

Stereophotogrammetry as explained, refers to combining multiple views of photos to form a three-dimensional image. For the purposes of this thesis, if a light pattern is projected on to the face it will be classified as a structured light system. Beard and Tee introduced a method in 1980 that projected a radial grid onto the face. This gave numerous points of intersection measurements and correspondence. Two stereo-metric cameras and a special flash unit mounted between the lens systems were required. This system was widely published and a number or early three-dimensional reports utilized this system.

- ***Rolleiflex® 6060 SLX***

Ras and co-workers (Ras et al. 1995a; Ras et al. 1996) described the use of two semi-metric cameras mounted on frame with a distance of 50cm between them and a positioned convergence angle of 15 degrees. A flash spot was positioned between the cameras and a grid was projected on to the face. This grid facilitates the registration of the two photographs and creates a perception of depth. These systems were checked for reliability and validity and used for analysis of patients with cleft lip and palate (Ras et al. 1994a; Ras et al. 1994b) and facial asymmetry (Ras et al. 1995a; Ras et al. 1995b).

- ***Others***

Several other systems have been described in the literature. One such system utilized special head frames to match up facial photographs and seemed to be useful in diagnosing abnormalities like foetal alcoholic syndrome (Meintjes et al. 2002).

*3.2 (c) **Laser scanning***

Laser scanning is a commonly used technique in acquiring three-dimensional data from objects in the engineering industry (Blais 2004). It is a valid and reliable technique that is used to detect minute and microscopic defects in the automotive and aerospace industries.

Laser technology utilizes optical principles and essentially is an active stereoscopic technique where the distance of the object is computed by means of a directional light source and detector. A laser beam is "deflected" from a mirror onto a scanning object. The resultant deflection angle of the laser beam may be calculated by simple trigonometry. As the laser beam is projected on the physical object, the beam is scattered which is then captured onto a detector. The distance between the object and the detector and source can be calculated by geometric principles. This may be translated into simple *x, y, z* coordinates.

There are two broad classifications of laser devices for three-dimensional acquisition according to the source of the beam. These are commonly known as single point and slit scanners. Due to the time required to scan the object, as well as the optical and mechanic simplicity, a slit scanner (projection of a plane line) is the practical solution for capturing facial morphology (Blais 2004).

(i) Fixed Units

- ***The Medical Graphics Imaging Group (MGI) System by University College London***

Moss and co-workers (1989) , were one of the first groups to describe the use of lasers in facial imaging. The MGI system[V] uses a low power, helium neon laser beam, which is projected onto the face and viewed from an oblique angle by a television camera. The laser light has a wavelength of 632.8 mm and a power not exceeding 1mW. Subjects are scanned every 2.8 degrees of rotation except over the central portion where 1.4 degrees are used. 20,000 co-ordinate points are obtained and the quoted precision was 0.5mm. There was a skin exposure time of less than 10 minutes (Moss 1989). This system was independently validated to within 0.9 mm (Aung et al. 1995) (over the entire facial surface) and had a 1 mm facial morphology reproducibility of adult facial averages (Ismail et al. 2002b). A variety of applications have been described for this imaging system as follows.

McCance and co-workers employed this technique to evaluate surgical and cleft patients (McCance et al. 1992a; McCance et al. 1997a; McCance et al. 1997b; McCance et al. 1997c; McCance et al. 1997d). Facial averages were created from controls and were used to evaluate surgical outcomes. Laser scans were taken prior to surgery, 3 months post-surgery, and at least 1 year after retention. Colour maps were used to describe the changes in facial morphology.

Ismail and co-workers employed the same technique to investigate the effects on the face of treatment involving extractions (Ismail and Moss 2002a; Ismail et al. 2002a; Moss and Linney 1990). The study initially started with 16 non-extraction and 18 extraction orthodontic patients (Moss et al. 2003b) but was reduced in another

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[V] University College London – Malet Place Engineering Building, Gower Street London WC1E 6BT report to 12 in each group (Ismail et al. 2002b). Each of the patients was scanned using the MGI scanner and the scans were analyzed using registration and surface shape analysis programs. The computer program registered the scans over the forehead and colour deviation maps highlighted differences between the groups. The surface shape analysis mathematically differentiates the surface into nine different surface shapes. The results indicated that there was a difference between the two groups at the start of treatment but there were no differences in the effect on the face of treatment in the two groups. The surface morphology was similar at the end of treatment in both groups. The MGI system has also been used to evaluate facial growth in children with clefts (Duffy et al. 2000), surgical evaluation (Soncul and Bamber 1999; Soncul and Bamber 2000) and facial profile changes after functional appliances (Morris et al. 1998).

The main problem associated with the technique was the time to complete a scan which was reported as 20 seconds. Reliability studies to test the reproducibility of facial morphology were carried out on adults although the number of subjects was small (n=10). Furthermore, all measurements recorded had to be pooled together to form averages to make comparisons. Finally, the landmarks used to make measurements were questionable and possible inaccuracies could occur (i.e 15 landmarks were identified in the studies. Five points were mathematically constructed across the forehead. Points joined across the eyes and nasion were joined to form a constructed line, using best fit least squared method. The face was then orientated to the mid sagittal plane at 90 degrees to this line. Five further landmarks were then automatically constructed on the forehead. The first point was a perpendicular projection from the canthal constructed line at a distance 30 mm up from nasion. Two pairs of points were constructed at 15mm intervals across the forehead perpendicular to mid sagittal plane. Registration was undertaken using the points on the forehead.

- ***Cyberware Laboratory 3030/SP***

This is a commercially available surface laser scanner produced by Cyberware laboratories[VI]. The Cyberware projects a low intensity laser on an object to create a highlighted profile. A high quality video sensor captures this profile from two view points. The system can digitize thousands of these profiles in a few seconds to capture the shape of the entire object. Simultaneously, a second video sensor acquires colour information. The scanner is able to capture 262,144 points each defined by an x, y, z and R, G, B (Red, Green and Blue) value.

Bush and co-workers reported on the validity of measuring anthropometric landmarks using this device (Bush and Antonyshyn 1996). He reported that a number of potential errors could occur:

(1) motion artefacts

(2) biological variation

(3) inaccuracy in digitization

(4) poor landmark identification

However, optimal positions were obtained when the head was in the centre of the scanning gantry and with the Frankfort horizontal plane elevated at 10 degrees from the horizontal. Under these conditions, all measured landmarks were visualized ideally and the variance in landmark localization was less than 0.6 mm in x, y and z axes. Girod and co-workers (Girod et al. 1995) used the system as a photo-realistic surface superimposed onto spiral CT images. The authors did not however, report on the accuracy associated with this technique.

[VI] Cyberware Inc, 2110 Del Monte Avenue, California 93940, United States

In another study, Okada used this method to create facial contours, facial units and subunits (Okada 2001). He did so by defining highlights, shadows and borderlines between the areas based on a technique described by Barnett and Whitaker (Barnett and Whitaker 1986).

Another team of researchers, using the same system as a Play Station (PS) motion platform, measured area and volumetric data on patients with facial swellings (Ji et al. 2002). Data was then translated to a CAD program in a Microsoft® Windows system. Using the CAD software, the midline of the patient's face was set as the symmetry axis, and the reference point symmetry was taken from both sides of the face. The area of the patient's face was calculated with a triangulation mechanism. The methods of calculations were however not clear. Guest and co-workers (2002) also used the scanner to evaluate methods of superimposing soft tissue changes after orthognathic surgery.

- ***Other fixed unit lasers***

Some prototype laser based systems are described in this sub-section. The Surflacer three-dimensional-VMR201 (UNISN Inc, Osaka Japan) combined three-dimensional reconstructed cephalometric skeletal images and laser-scanned facial images to produce computer generated models. This preliminary study did not state the accuracy of the system.

A research team in China also manufactured a prototype fixed laser system for trials on human subjects. The system emitted a standard laser with a wavelength of 650 nm and had a manufacturer's precision of 0.5 mm. The system had a scanning range of 0-180° and a radius of 30 cm. Clinical tests showed acceptable results but the system had a long scanning time of one minute.

(ii) Portable and Mobile

- ***Minolta laser scanners***

In 1997, Minolta (now known globally as Konica Minolta)[VII] introduced a series of VI-digitizers and, according to the manufacturers, was "going to revolutionalise the way surface imaging was carried out" (Minolta 2001). These non-contact systems enabled rapid three-dimensional acquisition that could be used in medical applications that included orthodontics and maxillofacial surgery.

The VI-700 was the first in a series of this generation of digitizers. By triangulating distances between the reflecting laser beam and the scanned surface, the surface laser scanner could detect not only an object's length and width but also its depth. The reliability of generating three-dimensional object reconstructions was assessed independently in Chicago (Kusnoto and Evans 2002). Accuracy and reproducibility were tested on a geometrical calibrated cylinder, a dental study model, and a plaster facial model. Tests were conducted at varying distances between the object and the scanner. It was found that in the calibrated cylinder tests, spatial distance measurement was accurate to 0.5 mm (+/- 0.1 mm) in the vertical dimension and 0.3 mm (+/- 0.3 mm) in the horizontal dimension. In the study model test, molar width was accurate to 0.2 mm (+/- 0.1 mm, $P > .05$), and palatal vault depth could be measured to 0.7 mm (+/- 0.2 mm, $P > 0.05$). The facial model had an accuracy of 1.9 +/- 0.8 mm. The findings suggest that the surface laser scanner has great research potential because of its accuracy and ease of use (Da Silveira et al. 2003). The VI-700 has been used for the integration of three-dimensional shapes of the dentition and face (Nagao et al. 2001) and also for idiopathic scoliosis (Hill et al. 2002).

[VII] Minolta Co, Ltd 3-13, 2-Chrome, Azuchi-Machi, Chuo-Ku, Osaka 541-8556, Japan

In 2001, Minolta released the VI-900 as an improvement to the VI-700 series. This camera had a reported manufacturing accuracy of 0.1mm. These cameras emit an eye safe Class I laser (FDA) λ=690 nm at 30 mW with an object to scanner distance of 600 to 2500 mm and a fast mode scan time of 0.3 seconds. The system uses a one-half-frame transfer CCD and could acquire 307,000 data points. The scanner's output data is 640 X 480 pixels for three-dimensional and RGB colour data. The Minolta VI-900 has been used in a host of applications as reported in the literature. These include combining laser surface scans with CT scans for computer-assisted surgery (Marmulla et al. 2003), understanding morphological differences in twins (Kau et al. 2005c), adult templates (Kau et al. 2006c), evaluation of post-operative facial swelling (Kau et al. 2006d) and understanding adult facial morphology (Kau et al. 2006b).

The VI-910 and 9i are newer systems that were introduced to the market in 2004 and 2005 respectively. They work on a similar technology to the VI-700 and VI-900, but have add on features which allow faster scanning times, higher image resolutions and better photo-realistic quality. These systems have not currently been evaluated in the literature.

- ***Fastscan™***

This new generation light weight hand held scanner held scanner[VIII], Fastscan™, emits a 670nm wavelength laser and is manually swept across the target object in a manner similar to spray painting. Two optical cameras arranged symmetrically on either side of the laser generator received the distortions of the laser beam. An electromagnetic tracker device measures the position in space and removes the need for rigid fixation or tripods. The scanning time is normally 10-15

[VIII] Polhemus Inc. 40 Hercules Drive PO Box 560, Colchester Vermont 05446-0560, USA seconds and the device has been used to evaluate facial swelling in patients after 3rd molar surgery. The initial reports showed that the device had a 4% scanning error in volumetric swelling and had some patient positional problems (Harrison et al. 2004).

3.2 (d) Structured Light Techniques

The structured light technique is another broad category of systems used for capturing three-dimensional information based on the triangulation principles. Normally, a projector shines a pattern of "structured" light (that may be composed of elliptical patterns, random texture maps, etc) onto a targeted surface to be scanned. When the light illuminates the surface, the light pattern distorts and bends. A system of cameras at a known distance captures the reflected and distorted pattern under an angle and translates the information into three-dimensional co-ordinates.

(i) Single Camera Systems

Tuncay and co-workers (2001) developed a series of 25 different high density structured light patterns and evaluated the system on a mannequin made up of a skull embedded in latex. The imaging system consisted of a black and white CCD camera and a monochrome LCD projector connected to a Macintosh computer. The cameras and projectors were positioned at 30 degree angles to each other and the mannequin was rotated on a turntable at 10 degree increments over 180 degrees. The technique produced satisfactory results but this accuracy was reduced when a human face was utilized (Nguyen 1999).

Enciso and co-workers (2003) also reported on a single camera system, consisting of a slide projector, a digital camera and a calibration pattern. Using a digitizer for validation purposes, landmarks were plotted and the linear distances calculated between real physical distances and image produced distances. The errors found ranged between 0.48 to 1.55mm.

(ii) Two or more camera Systems

- ***Moiré Fringe Patterns***

One of the earliest methods using the "structured" light technique utilized "Moiré" fringe patterns and was first described in 1970 (Takasaki 1970). Moire topography imaging is a contour mapping technique that involves positioning a "grating" close to an object and observing its shadow on the object through the grating. The resultant "Moire" Fringes correspond to a contour line system of the object under certain conditions.

One study reported the use of a similar technique using a three-directional camera (Motoyoshi et al. 1992). The cameras were placed "straight-on" and at 45 degrees to the patient. The facial features were illuminated with a grating system and the surface was captured by controlling the three shutters simultaneously. The images produced however, did not produce photorealistic surface texture and surface reproduction around sharp features was questionable (Hajeer et al. 2004c). These methods have also been used in whole body imaging, cleft studies and facial growth imaging (Ohta et al. 1982; Soh 1983).

As mentioned earlier, most non-contact devices will require some form of photography followed by complex mathematics to obtain a three-dimensional image.

- ***OGIS Range Finder RFX-IV* (Yamada et al. 1999; Yamada et al. 2002)**

Another three-dimensional measurement and evaluation system for facial forms was developed with a liquid crystal range finder (LCRF- OGIS Range Finder RFX-IV, OGIS Research). This is essentially a light based system with a resolution of approximately 0.4 mm. It is capable of measuring >30000 points from the entire facial surface in one second. A program was developed to identify facial landmarks using not only linear distances, but also three-dimensional curvatures and discriminant analysis of the RGB data. The programming language was C and the graphical interface was based on the following 3 methods of extracting data:

(1) Extraction by A-P x, y, z distances from the face,

(2) Extraction of the three-dimensional curvature,

(3) Extraction by discriminant analysis of the RGB data.

Only beta versions of this system were built and reported.

- ***CAM*** ^{3D} ***Systems***

The CAM^{3D} (Nkenke et al. 2003a; Nkenke et al. 2003b) is another structured light system[IX]. A sequence of phase shifted fringe patterns of structured light are projected onto the region of interest. Data is recorded from 2 CCD cameras and evaluated by means of a four-shift algorithm to receive three-dimensional information based on the shape of the object's surface.

- ***C3D systems***

A team of orthodontists and oral maxillofacial surgeons have carried out extensive research on the C3D system (Ayoub and Stirrups 1993; Ayoub et al. 1996; Ayoub et al. 1997; Ayoub et al. 1998; Ayoub et al. 2003; Bourne et al. 2001; Hajeer et al. 2002a; Hood et al. 2003). The technique utilizes two stereo pairs of cameras positioned on each side of the patient's face. Under computer control a random texture pattern is projected onto the face or a natural un-textured illumination. This is used as a means to find corresponding points to line up images. The task of finding corresponding points between stereo-images is called image matching, and is performed by the computer using automatic correlation. Image matching generates a set of parallel measurements for each point with each of the stereo pairs of images. These parallels are then converted into distances from the surfaces imaged by the

[IX] CamSorik GmbH Bienroderweg 53 D-38108 Braunschweig stereo-pairs by a process based on triangulation known and mentioned from photogrammetric principles. This is known as space re-sections and is a fundamental step in recovering depth of stereo-images. Before this camera calibration must occur. This is a process known as space intersection. The authors have successfully tested the three-dimensional device on infants, patients in surgical orthodontics and also on study models.

- ***3dMDface™ System***

In the last two years, 3dMD[X] has launched a structured light system combining stereo-photogrammetry and the structured light technique. This system uses multiple cameras, three on each side (one colour and two infra-red) to capture the photo-realistic quality pictures. Briefly, the system works by projecting a random light pattern on a subject and an is image captured with multiple precisely synchronized digital cameras set as various angles in an optimum configuration. The capture time of the system is 1.5 milliseconds at the highest resolution, making it ideal for documentation of children. It has a manufacturers quoted accuracy of less than 0.5mm (Root Mean Square) and clinical accuracy of 1.5% of the total observed variance (Aldridge et al. 2005).

- ***Others***

Some other newer machines include the Fiore 3_D Range camera[XI] (Yip et al. 2004) and the Genex 3D Rainbow Systems[XII] (Lee et al. 2004; Weinberg et al. 2004; Weinberg and Kolar 2005).

2.3 (e) Video-imaging

Some other light based systems make use of video camera technology and because of the number of frames captured per second. Some researchers have

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[X] 3dMD, 100 Galleria Parkway, Suite 1070 Atlanta GA 30339, USA
[XI] NEC Italia – Via leonardo da Vinci, 97 – 20090 Trezzano S/N - MI
[XII] Genex Technologies, Inc, 10605 Concord Street, Suite 500, Kensington, MD 20895

attempted to study three-dimensional motion. One of the early studies was carried out by Caruso and he demonstrated the feasibility of obtaining three-dimensional trajectories of lip and jaw landmarks during chewing movements (Caruso et al. 1989).

Trotman and co-workers (Trotman et al. 1996) successfully validated a motion system and applied this technique to measure facial animation, soft tissue mobility (Gross et al. 1996b) and facial expression (Trotman and Faraway 2004a; Trotman and Faraway 2004b). Facial motions were captured by Motion-Analysis™ (Motion Analysis Corporation, Santa Roas, CA) essentially made up of three 60-Hz video cameras. Reflective markers were placed on facial landmarks and the subjects were told to carry out a number of pre-assigned facial movements. Three-dimensional maximum motion amplitudes were calculated and were significantly more than two-dimensional data, some up to 43% (Gross et al. 1996a). Student's *t*-test and Pearson product-moment correlation coefficients were used to test for significant differences between repetitions. The results show moderate to excellent reliability of the amplitude of motion for the landmarks over all animations according to the authors. This system was also utilized for vector and inter-landmark variations (Nooreyazdan et al. 2004; Trotman and Faraway 2004a) and sex and facial shape comparisons (Weeden et al. 2001). Some recent innovations have added on sound and virtual animation as well (Deng et al. 2006).

In a further modification of the video based technique, Eian (Eian and Poppele 2002) was able to use just a single video camera system to capture three-dimensional motion using complex algorithms.

2.3 (f) Radiographic techniques

(i) Conventional Computed Tomography (CT)

CT was developed by Godfrey Hounsfield in 1967 and since the first prototype, there has been a gradual evolution to produce five generations of CT. The method of classification for each system is based on the organization of the individual parts of the device and the physical motion of the beam in capturing the data.

First generation scanners consisted of a single radiation source and a single detector and information was obtained slice by slice. The second generation was introduced as an improvement and multiple detectors were incorporated within the plane of the scan. However, these detectors were not necessarily continuous nor did they span the diameter of the object. The third generation was made possible by the advancement in detector and data acquisition technology. These large detectors reduced the need for the beam to translate around the object to be measured and were often known as the "fan-beam" CTs. Ring artefacts were often seen on the images captured, distorting the three-dimensional image and obscuring certain anatomical landmarks. The fourth generation was developed to counter this problem. A moving radiation source and a fixed detector ring were introduced. This meant that modifications to the angle of the radiation source had to be taken into account and more scattered radiation was seen. Finally, the fifth (sometimes known as the sixth) generation scanners were introduction to reduced "motion" or "scatter" artefacts. As with the previous two generations, the detector is stationary and the electron beam is electronically swept along a semicircular tungsten strip anode. The radiation is produced at the point where the electron beam hits the anode and results in a source of x-rays that rotates about the patient with no translation components moving parts.

Projections of the X-rays are so rapid that even the heart beat may be captured. This has led some clinicians to hail it as a 4D motion capture device.

There are a number of limitations of these systems. They require a dedicated facility and are very expensive. The images captured on the detector screens are made up of multiple slices that are "stacked" to obtain a final complete image, making it time consuming and less cost efficient. Furthermore the radiation exposure to the patient has limited its usage to complex craniofacial problems and for specialized diagnostic information only.

(ii) Cone Beam Computerized Tomography (CBCT)

Craniofacial CBCTs were designed to counter some of the limitations of the conventional CT scanning devices. The radiation source consists of a conventional low-radiation X-ray tube and the resultant beam is projected onto a panel detector. The cone beam produces a more focused beam and much less radiation scatter compared to the conventional fan-shaped CT devices (Mah and Hatcher 2003). This significantly increases the X-ray utilization and reduces the X-ray tube capacity required for volumetric scanning (Sukovic 2003). It has been reported that the total radiation is approximately 20% of conventional CTs and equivalent to a full mouth periapical radiographic exposure (Mah et al. 2003b).

These component innovations are significant and allow the CBCT to be less expensive and smaller. Furthermore, the exposure chamber (i.e. head), is custom built and hence reduces the amount of radiation. The images are comparable to the conventional CTs and may be a displayed as a full head view, as a skull view or regional components. There are currently 4 main system providers in the world market. As clinical research in this technology escalates and as the costs reduces, there is no doubt that more providers will start to invest in and promote this technology.

The four machines currently available produce high quality three-dimensional skeletal and soft tissue information. However, there are differences in size, area of image capture and clinical usage. These will be discussed under each device sub-heading.

- ***Newtom 3G***

The family of Newtom 3G devices was introduced recently as part of an evolutionary process from its predecessor the, Newtom 9000, and is developed by Quantitative Radiology in Verona, Italy. The latter was the first device in the dental market to use CBCT technology.

The system operates similarly to the device set-up mentioned earlier for conventional CBCTs. The imaging positioning of the patient in the Newtom 3G is with the patient lying supine on a custom built table. Three-dimensional scans of the head and neck are completed within 36 seconds and the system is able to obtain 3 different fields of view depending on the device specification and clinical information needed. The manufacturer claim that the system is able to produce a voxel resolution of 0.125mm, but this may vary according to the speed of the scan.

Custom built software allows volumetric and surface area analysis of soft and hard tissues. These datasets may be exported into a standard Digital Imaging and Communications in Medicine (DICOM) three-dimensional format for image manipulation.

- ***i-CAT***

The i-CAT cone beam three-dimensional imaging system is developed by Imaging Sciences International. The three-dimensional image is captured with the patient sitting upright as in any standard OPT machine and the scan time varies from 20 seconds to cover chin to brow and 40 seconds for a full head scan. In the initial prototypes, only the maxillo-mandibular regions could be imaged, but with new improvements and modifications, the manufacturers now claim that a field of view of 19 cm may be obtained. This is sufficient to capture a standard facial image equivalent to that of a three-dimensional lateral cephalogram. The manufacturers also claim that the novel amorphous silicon flat panel detector provides no distortion, a 12-bit grayscale and a pixel size resolution of 0.125 mm. It also claims that it has a good small area contrast and a long panel life, thus making it more clinically and cost effective. The images produced may also be exported as a standard DICOM format for image manipulation.

One early criticism of the system was the distortion of the facial tissues produced by the chin rest when the patient was positioned in the device. This feedback has led the company to improve the patient posturing device and no such problems arise in the later versions of the system.

- ***CB MercuRay***

The CB MercuRay is the latest addition to the full view head and neck imaging CBCT and is developed by Hitachi Corporation, Japan. Most clinicians and radiologists describe this device as the "Rolls Royce" of CBCT devices, because of the mammoth size and sophisticated technology. It occupies the largest physical footprint of all the 4 devices and also requires a separate viewing room.

The x-ray source is also made of a low energy fixed anode tube producing a cone shaped x-ray beam that is captured on an image intensifier and a solid state CCD. The manufacturers claim a scan time of 10 seconds through a rotation of 360 degrees that provides 288 views that can be seen either 2D or three-dimensional.

- ***3D Accuitomo***

This machine was developed as collaboration with the School of Dentistry, Nihon University and J Morita MfG Corp and it provides three-dimensional regional information to the clinician. This does limit the application for the clinician and only allows specific anatomical investigation. This small and compact unit has the advantage of only requiring 1.6 times the space of a dental panoramic X-ray unit (1,620mm X 1,200mm).

The machine delivers an X-ray tube voltage of 80kV and acquires an image in 18 seconds or less. It has an excellent resolution with a voxel size of 0.125 x 0.125 x 0.125mm and a slice width of 0.125 -2 mm. The size of the imaging volume however is small compared to the other machines described and therefore information provided is only regional and pathology or investigation specific.

- ***Radiation Issues***

Despite the CBCT device's capability in producing excellent high quality three-dimensional skeletal and soft tissue images, clinicians must be cautious about managing the risk/benefits to the patient as part of the process of obtaining the images. Though research has shown that the radiation exposure is comparable to conventional CT, there is still a small risk in orthodontics due to the age of patients involved. Probably 80% of the patients seen are children who have 2-3 times multiplication factor for risk of cancer below the age of 20 years (Faculty of General Dental Practioners, 1998). The British Orthodontic Society Guidelines suggests that: "Radiographs should only be justified when the management of patient is dependent on the information obtained" (Isaacson and Thom 2001). Often there is a temptation to exploit new technology to the fullest but clinicians must take the responsibility of protecting the patient first and then explore the science.

- ***Soft tissues and photographic colour contrast***

The CBCT is excellent in imaging hard tissues structures and most soft tissue components. However, it does not have the ability to map out exactly the muscle structures and their attachments. These intricate structures would have to image using conventional magnetic resonance imaging (MRI) technology that incidentally does not predispose the patient to radiation exposure.

Another point to note relates to the way in which the patient is positioned. This will ultimately affect the quality of the soft tissue structures because of the "pull" of gravity on the soft tissues and the different resting position of the jaws when the patient is supine and sitting upright. A clinically reproducible position will lead to a more accurate picture of the jaws and soft tissues at the time of image capture (Kau et al. 2005b). Patients are positioned as they would be in an OPT machine for all devices mentioned, with the exception of the Newtom 3G which has the patient supine. This may lead to a slightly distorted facial image, though this has not been documented in the literature.

Finally, CBCT external soft tissue images do not capture the true colour texture of the skin. Therefore in order to obtain photograph quality resolution, manipulation of the images is still required. Successful attempts to map tissue texture maps onto conventional CTs have been reported and may be similarly applied to this new technology (Khambay et al. 2002b). Therefore, three-dimensional devices like stereo-photogrammetry and laser scanning are still the main stay in soft tissue texture capture. Some centres have started to test the radiological doses of the machines but the actual way in which the tests have been carried out has been a subject of debate (Kau et al. 2005d).

2.3 (g) Others

(i) Magnetic Resonance Imaging

MRIs have traditionally been used as a technique for two-dimensional imaging of body structures. Most systems are made up of a large cylindrical shaped electromagnet, equipped with coils along with transmitters and receivers of radio waves. A subject to be studied is placed within the system and a powerful magnetic field generated. This causes a polarization of the hydrogen atoms contained in the tissues and the subsequent depolarization emits radiation (similar to radio waves). The subsequent data collected is generated into three-dimensional images for analysis. It has been shown to be useful in a variety of head and neck applications and is a relatively safe but costly procedure (Papadopoulos et al. 2002). It has been applied to the analysis of temporo-mandibular joints (Hamada et al. 2000), pre-operative planning of tumour resection (Grevers et al. 1991) and maxillary sinus evaluation (Gray et al. 2000). These images have also been combined with traditional three-dimensional scans for surgical treatment planning (Takacs et al. 2004).

(ii) Three-dimensional ultrasound (ultrasound holography)

This technique has been used mainly in foetal visualization and obstetrics but applications have also been developed for the head and neck. A high frequency wave between 3.5 to 7.0 MHz is emitted from a special probe placed in contact with the area of interest. Repeated ultra-sound beams are able to scan thin slices of an area and reflect back to the same transducer. The production of a three-dimensional hologram is not time consuming and has been used by maxillofacial surgeons for visualization of the soft tissues and organs. These include the tongue, nose and salivary glands (Sadar et al. 1997).

2.3 (h) Combination techniques

In recent year, a number of combination techniques with surface scans and hard tissue scans have been tried and tested (Vanezi et al. 2000; Xia et al. 2000a; Xia et al. 2000b; Xia et al. 2000c; Xia et al. 2000d).

2.4 CHALLENGES

Every available system provides a representation of the object imaged. Due to inherent faults in technology and the distortion of light, none of the three-dimensional imaging systems are accurate over the full field of view. Furthermore, all systems suffer from potential for patient movement and alterations of facial expression between multiple views needed to construct a three-dimensional model of the face (Mah and Bumann 2001; Mah 2002; Mah and Enciso 2003). However, the challenges to re-create the virtual environment for better clinical care and assessment of outcomes cannot be ignored The continuous improvements in technology and software mean that researchers and clinicians are closer to realistic three-dimensional imaging though it may never be fully attainable. Table 2.2 outlines the advantages and disadvantages of the various systems.

Therefore the challenges of surface acquisition systems are to create normative three-dimensional craniofacial images that are age, gender and race specific. These are required to facilitate advancements in diagnosis and treatment planning (Mah and Bumann 2001; Mah and Sachdeva 2001; Mah 2002; Mah and Ritto 2002; Mah and Enciso 2003; Mah et al. 2003a; Mah et al. 2003b; Mah and Hatcher 2003).

2.5 JUSTFICATION FOR THE STUDY

A review of the literature has shown that no longitudinal study has been performed to evaluate three-dimensional facial change in a cohort of 11-12 year old children. Laser scanning technology has been the gold standard for imaging objects and detecting defects in the engineering and automotive industries for many years (Blais 2004). Some biomedical companies have tried to introduce this technique into the medical field but early attempts have produced cumbersome and relatively slow (1 to 30 minutes) imaging times. Furthermore, laser safety has also been a raised concerned (Mah and Bumann 2001; Mah 2002; Mah and Enciso 2003).

However, in early 2000, the Minolta VI-900 laser imaging device with a Class I (eye-safe) FDA approved device was introduced. This system has an accuracy up to 0.5mm and could capture a subject in less than 2 seconds per camera. The Minolta had a superior dimensional precision, a relatively quick surface acquisition time and sufficient software support compared with other systems.

Table 2.2 Advantages and disadvantages of the different three-dimensional imaging systems

	Device	Advantages	Disadvantages
(1)	Direct Contact	Inexpensive set-up costs Quick landmark point capture	Poor resolution Pseudo three-dimensional image Geometric shapes only
(2)	Photo-grammetry	Cheap and easy to set up	Magnification errors Tedious work to map surfaces Pseudo three-dimensional image
(3)	Lasers	High resolution Quick capture Non-invasive Contour topology and surfaces Medium photorealistic quality	Expensive equipment Technique sensitive
(4)	Computer-aided Structured Light	Very rapid capture Photorealistic Non-invasive	Technique sensitive Varying resolution quality
(5)	Video-imaging	Multiple motion capture Photorealistic Speech and animation capture	Low resolution Processing capabilities required
(6)	Radiation	Reasonable resolution Good correlation to hard tissues	Radiation dosage not feasible for multiple exposures Expensive equipment Long scan time

CHAPTER 3

AIMS

3.1 AIM:

The aim of this study is to assess and quantify growth changes in children aged 12-14 years old.

The objectives of the study are:

(a) To quantify the accuracy and validity of a three-dimensional laser capture system

(b) To compare facial morphology in males and females

(c) To highlight different rates of growth in children

(d) To identify differences in facial morphology in children who did and did not receive orthodontic treatment

CHAPTER 4

SUBJECTS AND METHODS

4.1 LONGITUDINAL GROWTH SAMPLE

4.1 (a) Sample recruitment and ethical approval

The subjects for the study were Caucasian children drawn from the Year 7 (approximately 11-12 years of age) in two large comprehensive schools[XIII,XIV] in the South Wales Valleys Area in the United Kingdom. All subjects with craniofacial anomalies and facial disfigurement were excluded.

Ethical approval for the study design was obtained from the relevant ethics committees [Appendix 1] and permission for the subjects to participate was sought from the Director of Education, Head teachers and School committees. An introductory letter was sent to the parents by the School's head teachers, inviting the subjects to participate and written informed consent was obtained prior to obtaining the three-dimensional facial scans.

4.1 (b) Sample distributions

A total of 95 children agreed to participate in the study. It was anticipated that around 35% (20-30 subjects) of the study group would receive complex orthodontic treatment in line with contemporary studies undertaken in the England and Wales (Richmond et al. 1993).

4.1 (c) Sample size estimation

No longitudinal study analyzing three-dimensional facial changes has been reported in the literature prior to this study. This study was designed to be exploratory in nature and the primary aim of the study was to assess and quantify growth changes in children aged 11-14 years old. Hypothesis testing was not

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[XIII] Cardinal Newman Catholic School, Dynea Road, Rhydyfelin, Pontypridd, Rhondda Cynon Taff CF37 5DP

[XIV] Coed-y-lan Comprehensive School, Albion Site, Cilfynydd, Pontypridd, Rhondda Cynon Taff CF37 4SF undertaken as it is anticipated that this exploratory study would enable sample size calculations for future studies.

4.2 THREE-DIMENSIONAL IMAGING SYSTEM

The imaging system used in this project consisted of a pair of commercially available laser scanners. The system was set-up in a standardized way to capture the facial morphology of clinical subjects in an effective and efficient manner.

4.2 (a) Camera System and Theory of Operation

The laser scanning system consisted of two high-resolution Minolta Vivid VI900[XV] three-dimensional cameras, with a reported manufacturing accuracy of 0.1 mm, operating as a stereo-pair. Each camera dimension was 213 (W) x 413 (H) and 271 (D) mm and a weight of 11.0 kilograms. In this study, the f=14 mm focal length lens (middle of three types available) was used. This set-up had a maximum resolution of 0.068 mm and accuracy to the z reference plane as $x = \pm$ 0.38 mm; $y = \pm$ 0.31 mm and $z = \pm$ 0.35 mm [Appendix 2].

The principle theory of image capture was by laser light triangulation. Each of these cameras emitted an eye safe Class I light-striped laser (FDA) λ=690 nm at 30 mW [Appendix 3] with an object to scanner distance of 600 to 2500 mm. The camera had two scan modes (fast and fine) with scan times of 0.3 seconds and 2.5 seconds respectively. The system used a one-half-frame transfer charged couple device (CCD) and was able to acquire 307,000 data points. Each subject to be measured was placed in the path of the camera and a plane of laser light emitted from the VI-900's source aperture. The plane of light was projected across the field of view (FOV) by an in-built mirror and rotated precisely by a galvanometer. The

[XV] Minolta Co, Ltd 3-13, 2-Chrome, Azuchi-Machi, Chuo-Ku, Osaka 541-8556, Japan distortion of the projected laser light on the subject was captured by a CCD within the camera (Fig 4.1). The contour of the subject was obtained by the reflected laser light and the three-dimensional image was mathematically constructed from a series of point clouds.

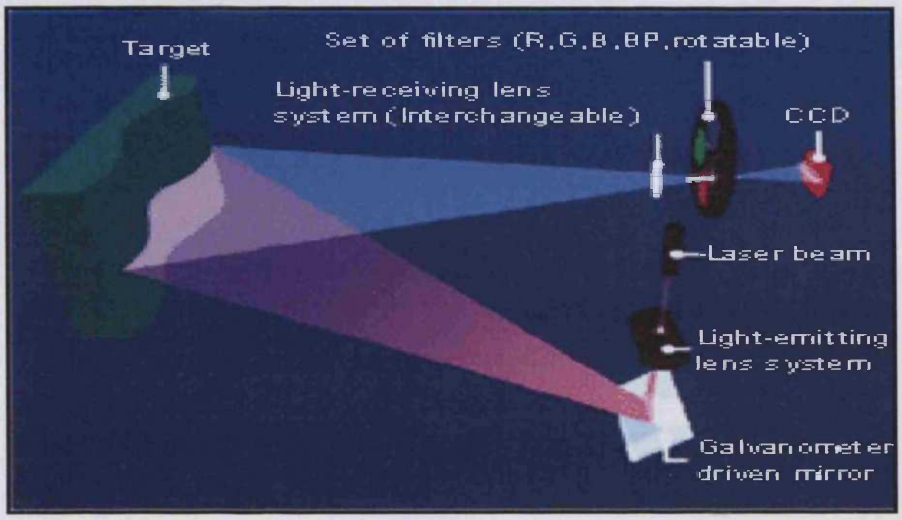

Fig 4.1 Representation of the laser light triangulation within the Minolta VI900 system (Courtesy of Minolta, UK)

The scanner's output data was 640 X 480 pixels for three-dimensional coordinates and red, green and blue (RGB) colour data. Data was recorded on a desktop workstation (Dell 8200 Inspirion) with a 2GHz Pentium 4 processor. The two cameras were placed at a distance of 1350 mm from the subjects (Fig 4.2).

The scanners were controlled with Multi-scan™ software[XVI] and data coordinates were saved as a Minolta document known as a vivid file format (vvd). Each data file possessed up to 40,000 coordinate points that could be transformed into a data mesh and different textures were applied to generate a highly accurate three-dimensional representation. Information was transferred to a reverse modelling

[XVI] Cebas computer GmBH, Lilienthalstr. 19, 69214 Eppelheim, Germany software package Rapidform™ 2004 Plus Pack 2 – RF4 PP2[XVII] for analysis. This software provided nine different three-dimensional work activities that included:

- Three-dimensional scan data processing
- Polygon cleaning, editing and optimization
- Rapid prototyping work preparation
- Curve modelling and editing
- Polygon-to-NURBS conversion, modelling and editing
- Freeform inspection and geometric dimensioning and tolerance
- Three-dimensional reconstruction of MRI / CT DICOM data
- Customized application development in VB, VBA, C++, and Java

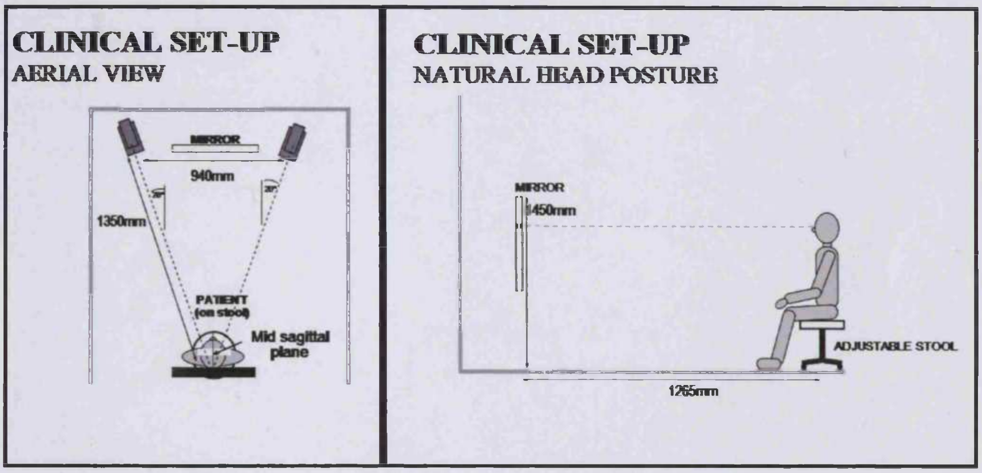

Fig 4.2 **(a)** Imaging System acting as a stereo-pair, **(b)** Patient positioned in natural head posture

Together these functions allowed high quality polygon meshes, accurate freeform Non-Uniform Rationale B-Spline (NURBS) surfaces and geometrically perfect solid models to be created. RF4 PP2 generated data as absolute mean shell deviations,

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[XVII] Global Headquarters, INUS Technology Inc 601-20 Yeoksam-dong Gangnam-gu Seoul 135-080, Korea standard deviations of errors during shell-to-shell overlaps, maximum and minimum range maps, histogram plots and finally colour maps.

4.2 (b) Camera Calibration

In order to determine the real three-dimensional position and rotation of each entity, a process known as camera calibration was carried out at the start of each scanning session. A calibration cube, of known fixed dimensions and coloured surfaces, was used. The cameras were placed in the set-up described earlier and "fired" off individually using the Multi-scan™ software. At least 3 surfaces of the cube need to be visible for the three-dimensional data to be accurately captured. This calibration process allows the software to use a series of complex mathematical algorithms to calculate the three-dimensional co-ordinates of the cube and subsequent objects to be measured. This is a crucial step, without which the cameras were unable to function together and to compute the "full face" three-dimensional images.

4.2 (c) Software for image processing

Each set of scanned images (Fig 4.3a and b) was imported into RF4 PP2. The initial raw images had a semi-rough image texture due to the irregularity of the surface contours and the way in which the light was reflected off the surfaces of different objects (Fig 4.4a and b). Further data processing was required to obtain a workable image that preserved shape, surface and volume (Fig 4.4c and d). This is known as the rendering process. These computer methods had to be carefully developed as part of the project and involved close co-operation with colleagues in the research group. The shape preservation technique consisted of a mathematical formula known as the *la Place* method with volume preservation for smoothing and cleaning the raw image distortions. This method has been shown to be reliable and accurate in producing high quality three-dimensional images (Zhurov et al. 2005).

Fig 4.3 Left and right photo snap shots of the patient in nature head posture

Fig 4.4 Raw data images of left and right scans pre-processed and "cleaned" to produce workable left and right images. Further applications were also created to standardize the image captured and the localization of the centre of mass of the object. These "*in house*" developed tools are now available as simple sub-routines within customized macros[XVIII] in RF2004 PP2.

[XVIII] © Cardiff University Wales College of Medicine 3D Facial Macro Version 1.4a June 2005. Developed by Dr Alexei Zhurov

4.2 (d) Data processing of left and right facial scans

After the image processing stage, the left and right scans were aligned to one another using the iterative closest point algorithm (ICP), based on the areas of overlap of the faces and point clouds.

The pre-merged scans were carefully checked individually and unwanted areas that could not be automatically removed were done so manually by dividing the unwanted areas from the main shell before proceeding to the next stage. The fit of the two facial meshes was checked by determining the degree of overlap error derived from a colour contour map (Fig 4.5). In general, the error of overlap generally did not exceed a mean value of 0.5mm (Zhurov et al. 2005). Surface meshes with "defects" or "holes" were filled-in automatically by RF4 PP2. These were generally located in areas of the eye and eye sockets, where the reflection of the laser light was lost and therefore not recorded. Finally, one composite whole face, per individual subject, for every time frame was generated (Fig 4.6).

4.2 (e) Data capture technique

In order to standardize the lighting conditions a custom made portable studio was created (Fig 4.7). The studio is sufficiently compact to fit into a corner of a classroom or medical room without difficulty and housed all the necessary equipment. Two Bowen's tri-lite lamps were used to ensure consistent lighting conditions in the neutral white light zone with a wavelength varying from 400-800nm.

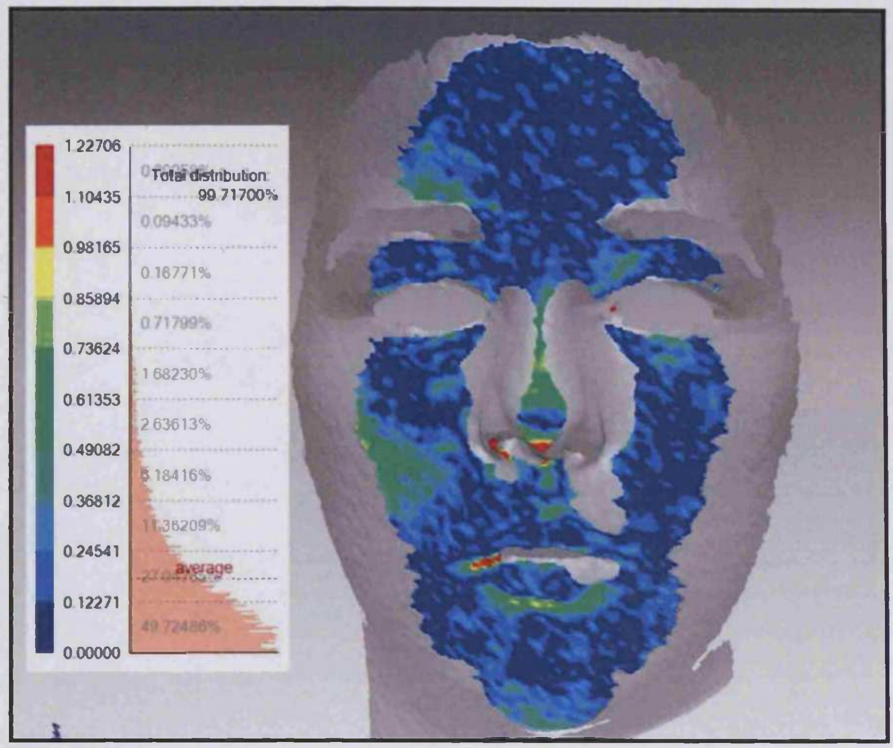


Fig 4.5 Colour map showing the surface differences when two shells are aligned together. The error is approximately 0.15mm.

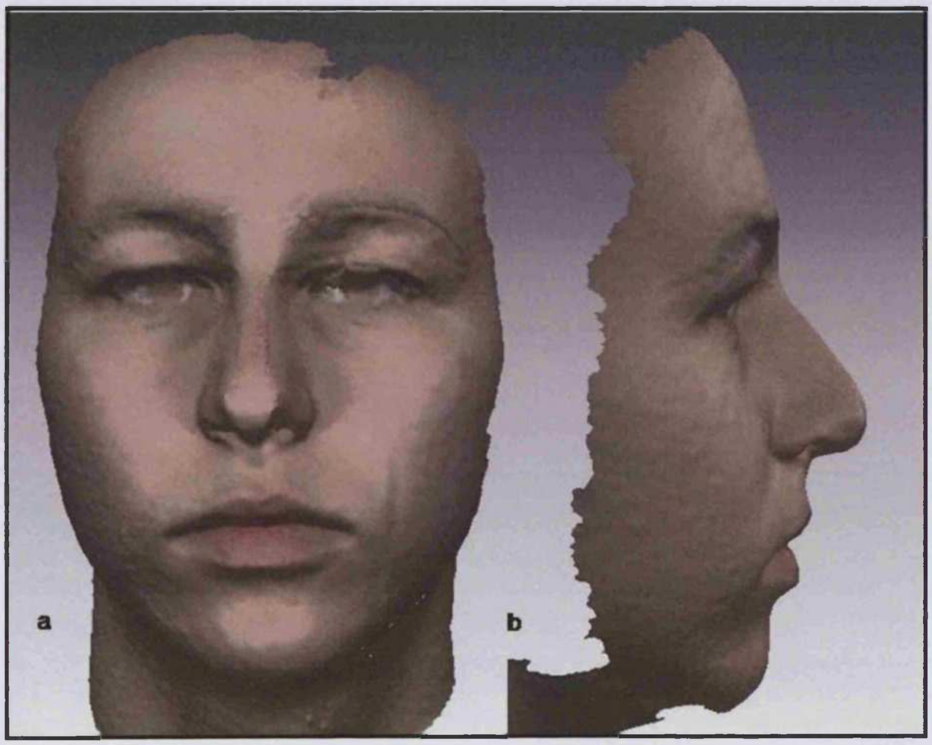


Fig 4.6 Final merged image. Facial shell is ready for evaluation and superimposition.

Natural Head Posture (NHP) was adopted for all studies which involved patients, as this has been shown to be clinically reproducible (Chiu and Clark 1991; Kau et al. 2005a). The subjects sat on a self-adjustable stool and were asked to look into a mirror with a horizontal and vertical line marked on it. They were asked to level their eyes to the horizontal line and the midline of the face is aligned to the vertical line. Adjustments to seating heights were made to assist the subjects in achieving NHP. The subjects were also instructed to swallow hard and to keep their jaws in a relaxed position just before the scans were taken. The scans were taken at the same time and the total scan time was approximately 7.5 seconds.

Fig 4.7 Light controlled environment

4.3 METHODS AND PARAMETERS FOR ANALYSIS

The following parameters and methods of analysis were carried out in the analysis of three-dimensional data in the longitudinal study.

4.3 (a) Demographic Evaluation

Each child was assigned a specific code number based on the school and the order in which they were scanned. For example – T1CN001 was the first child scanned at the first period in Cardinal Newman School. The gender and dates of birth were also recorded. In addition, a history of orthodontic intervention was taken. If the child indicated that a history of appliance treatment had been carried out then the name of orthodontist was obtained. A sample form is enclosed in Appendix 4.

4.3 (b) Body Mass Index (BMI)

Height and weight measurements were recorded in metres and kilograms for each patient respectively. The BMI score was calculated using a formula that divided the weight in kilograms by the square of the height in meters.

4.3 (c) Linear Measurements and Histogram plots

Linear measurements representing the mean differences between two surface shells were recorded in millimetres. This value represents the sum total of all differences recorded between overlapping surfaces of two shells and the value could be used as an indicator of the best fit between two shells. Furthermore, it could also show the changes in surface fit or regions of changes on the full faces as the time intervals increased.

Colour deviation maps, as previously mentioned, were produced using the software tool RF4 PP2. The colour maps gave an indication of the areas of change that occurred between two time intervals. In this study, blue areas showed "negative" changes and red areas showed "positive" changes (Fig 4.8).

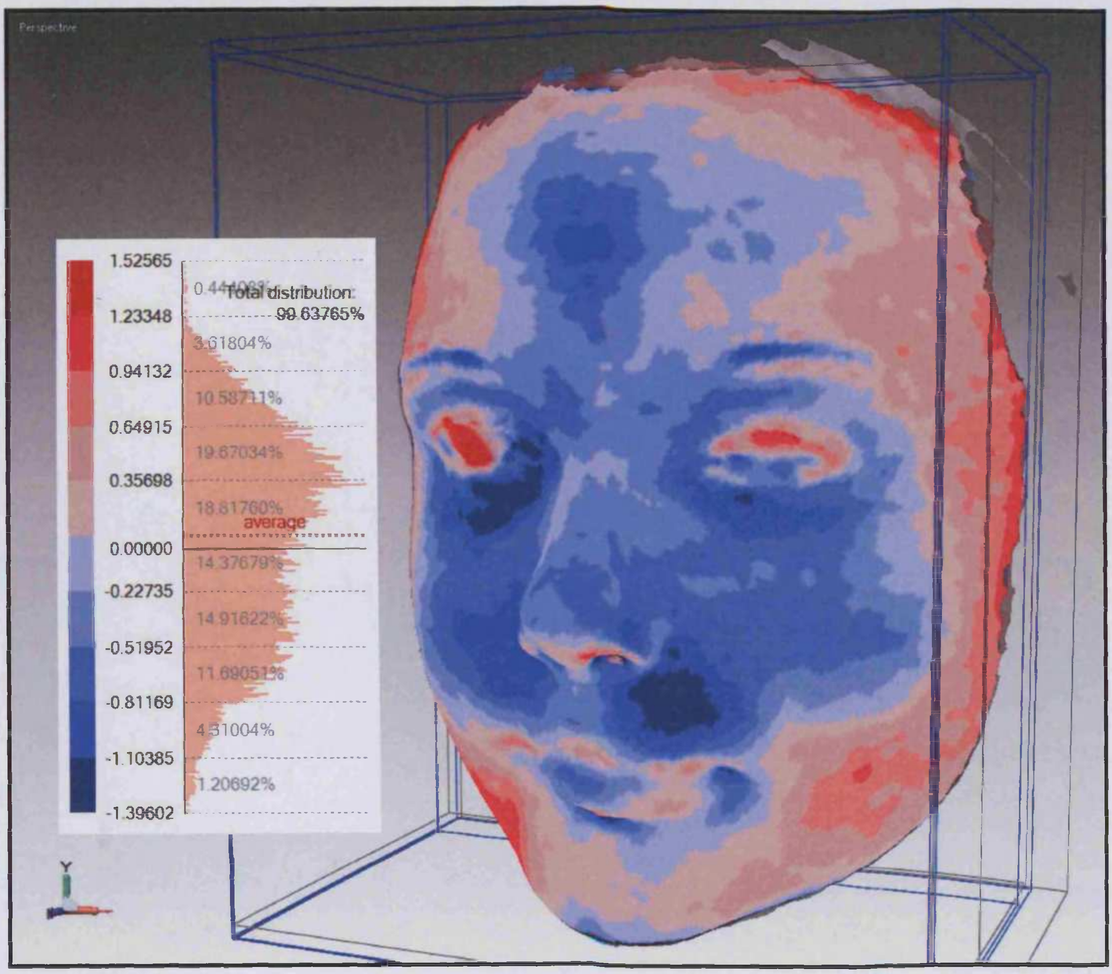


Fig 4.8 This figure represents two surface shells of the same patient at two different time intervals, 1 year apart, superimposed onto one another using the best fit algorithm. The colour maps shows the areas of positive (blue) and negative changes. The maximum and minimum values were approximately 1.53 mm and -1.40 mm respectively. Furthermore, a histogram plot gave the percentages changes as a range over 100%. For example, a positive change between 1.23mm and 1.53mm was seen in approximately 0.44% of the surface changes.

4.3 (d) Average Face Constructions

Average faces were constructed in this study to represent the average and their variations based on the facial morphology of a cohort of children. This method produces a final average surface mesh that is age and gender specific to each cohort of children (For example, an average male face and an average female face indicating T1, T2, etc respectively).

This *in-house* sub-routine was created from tools available within RF4 PP2 and produced as a separate computer macro[XIX]. The steps required to produce an average face has been reported on previously (Kau et al. 2006a) and may be summarized as follows:

(i) Pre-alignment of images by determining the principal axes of rotation, based on computing the tensor of inertia of each three-dimensional image (Fig 4.9).

(ii) Manual positioning, when necessary, to improve the previous stage.

(iii) Best fit alignment using the built-in algorithm in RF4 PP2 (Fig 4.10).

(iv) Averaging of "z" coordinates of the images based on normals to a facial template.

(v) Point cloud is triangulated to obtain an average face.

(vi) The average face is improved by filling in small holes and removing possible mesh defects.

(vii) Colour texture is applied.

(viii) Shells with one positive and one negative standard deviation are created.

The averaging procedure may be further outlined mathematically as follows (Kau et al. 2006a): suppose there are K facial masks appropriately aligned at steps (1) to (3). All of them are bounded within a box $\{x_{\min} \le x \le x_{\max},\ Y_{\min} \le Y \le Y_{\max},\ Z_{\min} \le Z \le Z_{\max}\}$. Suppose that all the faces "look" in the *z*-direction, with the *y*-axis pointing vertically from chin to forehead and the *x*-axis pointing horizontally from right eye to left eye. Each face is considered to a function $Z = f_k(X,Y)$, where

[XIX] Cardiff University Wales College of Medicine (CUWCM) 3D Facial: Averaging Macro V1.1c. Developed by Drs Alexei Zhurov, Chung How Kau and Stephen Richmond.

k represents the number of the face. In order to perform the averaging, the functions f_k are evaluated at nodes (i, j) of a rectangular mesh, so that

$$\begin{aligned} &Z_{ij}^k = f_k(X_i, Y_j), \qquad k = 1,\dots,K, \quad i = 0,\dots,M, \quad j = 0,\dots,N; \\ &X_i = X_{\min} + i\,\Delta X, \quad \Delta X = \frac{X_{\max} - X_{\min}}{M}, \quad X_0 = X_{\min}, \quad X_M = X_{\max}; \\ &Y_j = Y_{\min} + j\,\Delta Y, \quad \Delta Y = \frac{Y_{\max} - Y_{\min}}{N}, \quad Y_0 = Y_{\min}, \quad Y_N = Y_{\max}. \end{aligned} \tag{1}$$

The averaging is performed along the Z-coordinate and hence,

$$Z_{ij}^{\text{ave}} = \frac{1}{K}\sum_{k=1}^{K} Z_{ij}^k. \tag{2}$$

The average face is thus defined by the point cloud $\{X_i, Y_j, Z_{ij}^{\text{ave}}\}$ (Fig 4.11). The point cloud is then triangulated to obtain an average facial surface. Then +/- 1 standard deviation (SD) shells are created. The respective z-coordinates are evaluated by:

$$(a) \quad Z_{ij}^{\text{ave+1SD}} = Z_{ij}^{\text{ave}} + \frac{1}{K-1}\sqrt{\sum_{k=1}^{K}(Z_{ij}^{\text{ave}} - Z_{ij}^k)^2}, \tag{3}$$

$$(b) \quad Z_{ij}^{\text{ave-1SD}} = Z_{ij}^{\text{ave}} - \frac{1}{K-1}\sqrt{\sum_{k=1}^{K}(Z_{ij}^{\text{ave}} - Z_{ij}^k)^2}, \tag{4}$$

The respective point clouds are defined by the sets $\{X_i, Y_j, Z_{ij}^{\text{ave+1SD}}\}$ and $\{X_i, Y_j, Z_{ij}^{\text{ave-1SD}}\}$. The point clouds are then triangulated. The constructed average faces are illustrated in Fig 4.12.

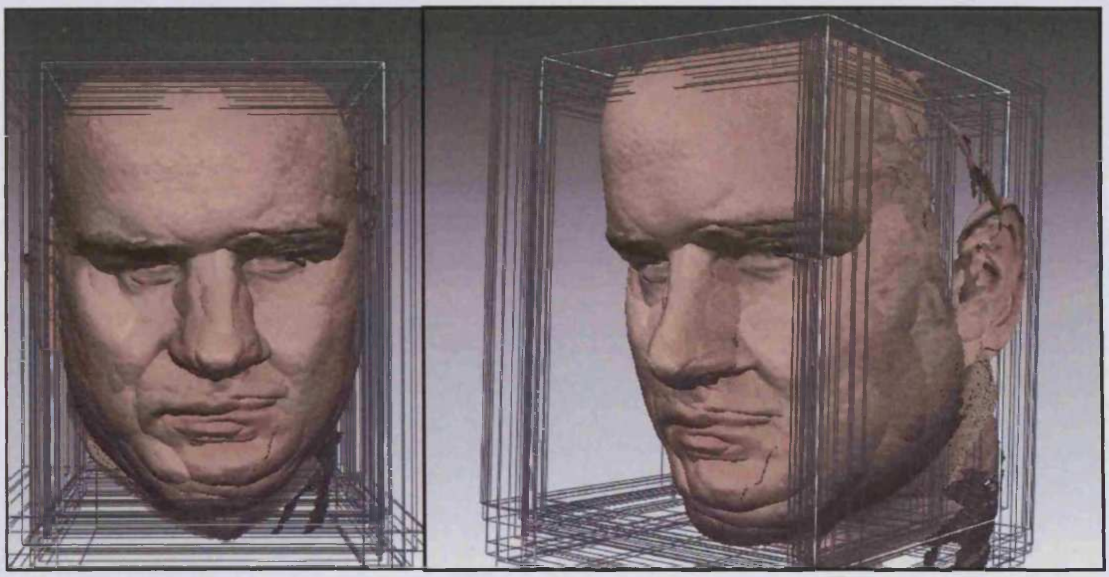


Fig 4.9 Frontal view and three-quarter views of thirty-three male faces lined up on the principal axis.

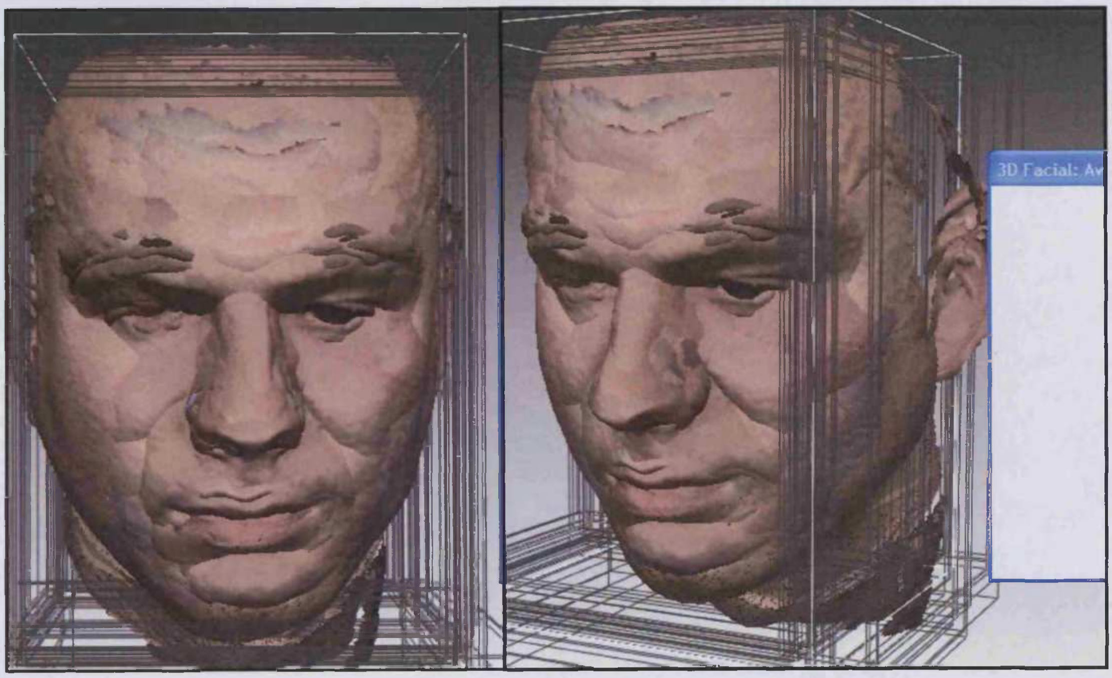


Fig 4.10 Frontal view and three-quarter views of thirty-three male faces after the faces have been automatically aligned on best fit using the "fine" registration function in RF4 PP2.

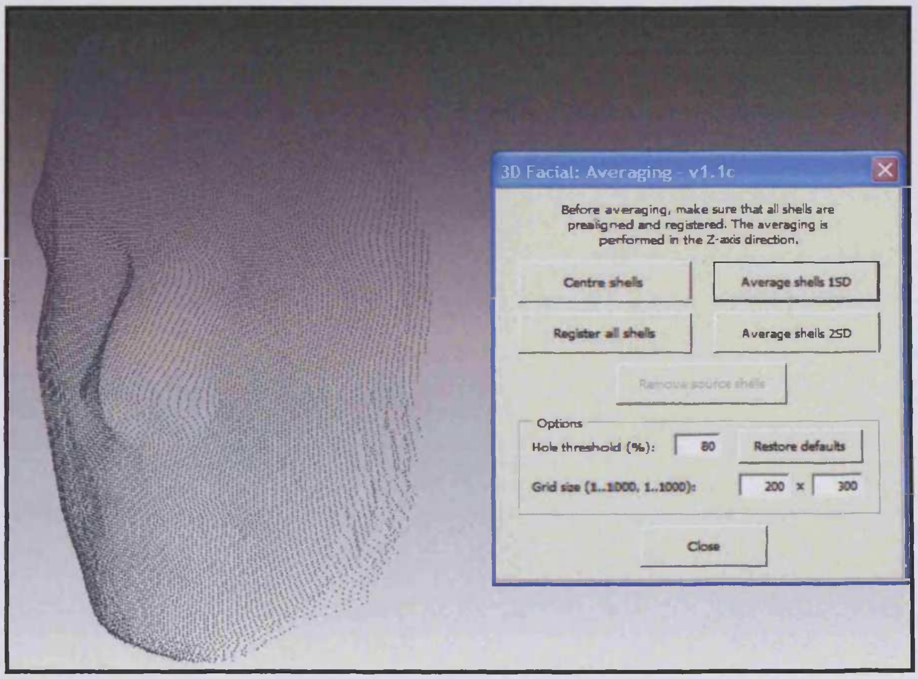


Fig 4.11 Point cloud generated after the averaging procedure. These points are tri-angulated to create a meshed surface. A surface texture is applied to produce a life like face.

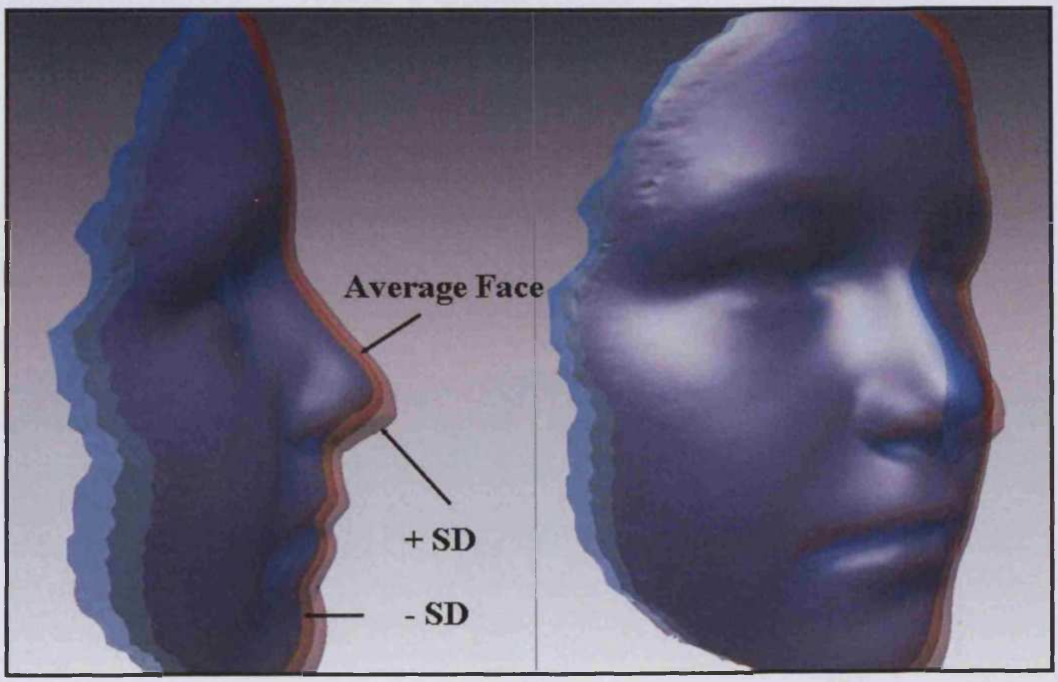


Fig 4.12 Figure shows an average face of a cohort of 12 year old males +/- standard deviation shells.

4. 3 (e) Surface Shapes and Volume Changes

A procedure for measuring three-dimensional volume changes between two selected facial shells was also developed using in-house software[XX]. The procedure involved the following stages;

(i) The two selected shells were checked and appropriately aligned.

(ii) Areas where the two shells diverged from each other were determined (i.e. diverge by more than a prescribed distance, which can be set by the user. In this case the threshold was set at 0.425 mm). Each of the shells was treated as a collection of vertices. The software scanned each facial shell vertex, looking for and removing the pairs of vertices that are closer to each other than the selected threshold. This resulted in two facial shells with only essentially divergent areas remaining.

(iii) Small areas of no or little importance were removed. This was set manually at 200 vertices and often required further manual selection to remove such areas.

(iv) The resulting divergence maps were separated individually by connecting the regions mathematically for further analysis. This was equivalent to the surface area maps.

(v) Finally, volumes representing three-dimensional shape changes were created. This was done by manually selecting two matching regions and invoking the appropriate software function in the macro.

(vi) This procedure of creating a volume difference shell involves the following. A selected surface region, which refers to one of the two facial shells being compared, is extruded towards the other reference shell by a distance of

[XX] Cardiff University Wales College of Medicine (CUWCM) 3D Facial: Volume and Area Changes Macro V1.2b. Developed by Drs Alexei Zhurov, Chung How Kau and Stephen Richmond.

$1.2d_{max}$, where d_{max} is the maximum distance between the selected region and the reference shell. This creates an extruded volume shell. Then the reference shell is extruded towards the selected region by $1.2d_{max}$ to produce another volume shell. The Boolean difference between the two extruded volume shells is further determined resulting in a desired volume difference shell.

The entire analysis of three-dimensional surface shape and volume changes was extremely time-consuming and took several hours per pair of shells. In addition, due to the technical complexities at this stage of software development, only surface shapes and volume recordings could be made of the average composite faces (Fig 4.13). These were recorded in mm^2 for surface areas and mm^3 for volumes.

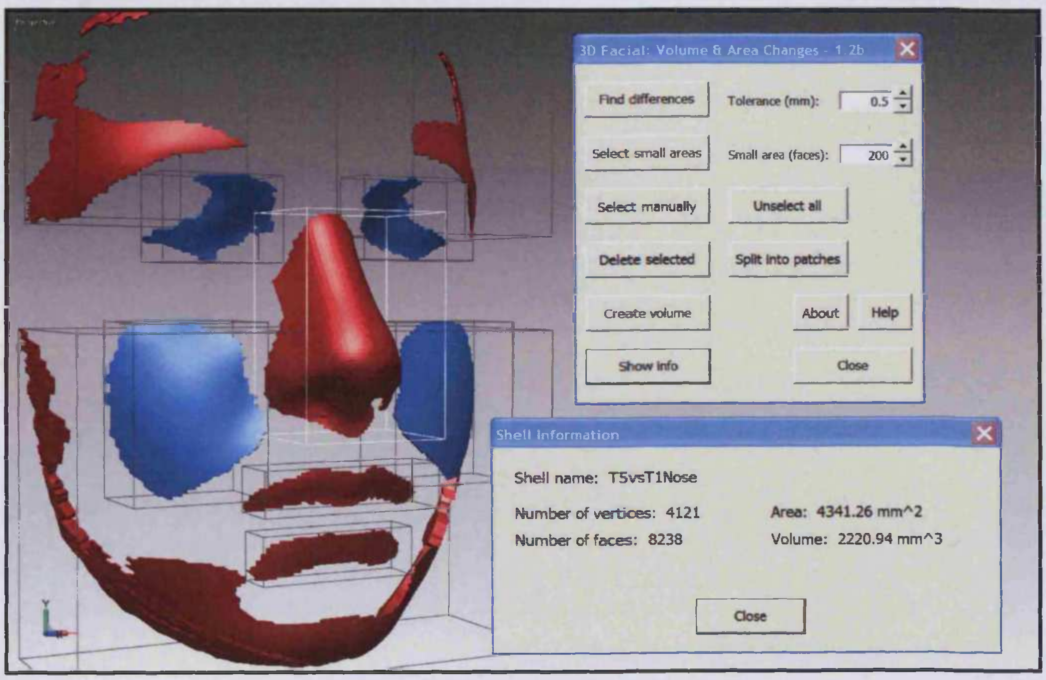


Fig 4.13 Changes between two average faces are shown. A tolerance of 0.5mm was set in the example and small areas of 200 vertices or less were excluded from the final calculations. The negative (blue) areas are seen in the cheek areas and the positive (red) areas in the brows, lips and mandible. The volume calculated for the nose was $2220.94mm^3$.

4.4 VALIDITY AND RELIABILITY

Before actual three-dimensional data collection could be carried out on the longitudinal cohort, a number of evaluations were undertaken to test the validity of the soft tissue morphology in children. Unlike the evaluation of hard tissue data, often reported in cephalometric studies, soft tissue image capture could be potentially variable due to changes in muscle tone, head posture and facial movements (Kau et al. 2006e).

4.4 (a) System Validation and Reliability

Different manufacturers claim that their systems are accurate and produce reliable results accurate to less than 1mm. However, these systems are normally tested and reported by the manufacturer rather than in a clinical research environment. As a result, the Minolta scanning system was validated for accuracy in a clinically reproducible environment. Validity was assessed by scanning a number of objects of known dimensions and clinical reliability by repeated measurements on subjects.

(i) Calibrated Cube

Nine dimensions representing the lengths, breadths and depths of the cube were evaluated. The mean error for the actual cube measurements versus the three-dimensional image produced was calculated by subtracting the physical length against the length measured on the computer generated image. This error was expressed as a percentage and calculated as [(Mean Error / Physical length) X 100%].

(ii) Phantom Head

Applying a similar method to the calibrated cube, a life sized phantom head was obtained. The phantom head investigations had the following aims:

- Determine the errors associated with producing a final scanned full-face image when two laser imaging devices were used.
- Determine the mean errors present when linear measurements were obtained of known physical objects from three-dimensional laser scans.

Seven simulated landmarks were established randomly at different points on the face that created ten distances. The landmarks were made from circular plastic rings, each 2.5mm in diameter. The centres of these rings were used as the desired landmark identification points. The mean error was calculated for each distance by subtracting the three-dimensional image measurement against the real image length.

4.4 (b) Human Subjects

Three-dimensional facial scans were taken randomly of human subjects. This was done to determine the different errors associated with:

(i) Image registration and full-face shell distortion

(ii) Sequence in which left and right surface shells were superimposed to produce final full faces

(i) Image Registration and Superimposition of longitudinal data

Due to the scanning technique used in this study (i.e. Minolta system capturing a left and right facial scan), it was crucial to know whether any distortion took place due to the superimposition method used to create the final composite face.

To evaluate this, two types of scans where obtained to create the final full face. One method utilized the set-up described in Section 4.2 whilst the other method had the subject facing directly into one camera only (Fig 4.15). The latter scan produced an intact final composite not requiring a merging procedure. These two scans were selected and superimposed using the best fit method or ICP algorithms in-built within RF4 PP2. This was repeated on 5 different subjects randomly selected from within the department of Orthodontics, School of Dentistry at Cardiff University. Each set of scans was tested to determine the deviations between shells and a colour map with histogram was produced.

4.4 (c) Feasibility of using three-dimensional laser imaging for the capture of facial soft tissue morphology in children

One previously cited criticism of the laser scanning device is the ability to capture three-dimensional facial images of children (Hajeer et al. 2004c). An investigation to determine the feasibility of measuring soft tissue morphology in children versus that of an adult population was therefore carried out (Kau et al. 2004b).

Thirty adults (15 males and 15 females, with a mean age of 28.4 years) and thirty children (15 males and 15 females, with a mean age of 11.6 years) were selected to participate in this study. Positive written consent was obtained for the children and adults to participate in this evaluation.

To obtain a fuller clinical picture, coloured face maps and histograms were generated to determine the patterns within the face where the errors were considered to be high. Tolerance levels were set for mean shell deviations at levels corresponding to 0.3 mm, 0.5 mm and 0.75 mm.

The mean shell deviations were tested for normality and differences between the groups measured were analysed using the Students *t* test (SPSS, Chicago, Ill). P values less than .05 were considered significant.

4.4 (d) Reproducibility of three-dimensional laser imaging for soft tissue facial morphology in children

As mentioned before, assessing the accuracy of soft tissue simulation is a complex process (Mah and Enciso 2003). All surface acquisition systems are affected by changes in muscular tone and head posture of the subjects measured. This investigation was carried out to determine the reliability in soft tissue facial morphology of children over time. This was important as any changes that are reported in the study of facial morphology could be due to inherent errors of the technique or to actual growth or treatment changes. As part of the preliminary investigations, a randomly selected number of Year 7 children in one large school were scanned again after three minutes and invited to return for a facial scan three days later. These scans were obtained at the first time interval at the start of the longitudinal growth study.

Individual whole faces of subjects were superimposed over one another to determine changes that occurred at T1 and T2, T1 and T3. This systematic process starts by manually aligning the 5 points on the facial scans (4 points at the outer and inner cantus of the eyes and 1 point on the nasal tip) and subsequently by fine registration where the computers determined the best fit of the two scans (Fig 4.15).

In order to obtain a fuller clinical picture, coloured face maps were also generated to determine the patterns within the face where the error was considered to be high. Tolerance levels were set for shell deviations and calculated automatically by the software. Any deviations between the faces during the two time intervals that corresponded to a tolerance level above 0.85mm were shown in colour and any values below the tolerance interval showed up in black. Levels corresponding to 0.5mm, 0.85mm and 1mm were used. This helped to determine the reproducibility of the face over the periods T1 and T2, T1 and T3. A further attempt was made to quantify the errors by dividing the face into fifteen segments. Nine segments in the upper and mid facial regions represented muscular movements that would occur as a result of facial expression and six stringent segments represented movements to the lips and mandible. Whenever a patch corresponding to one third of the zone was recorded, the zone was marked as having one error score. The mean shell deviations were tested for normality and differences between the groups measured were analyzed using the Students *t* test (SPSS, Chicago, Ill). P values less than .05 were considered significant. This was undertaken for pre-merged left and right scans and also for the whole faces superimposed over one another at T1, T2 and T3.

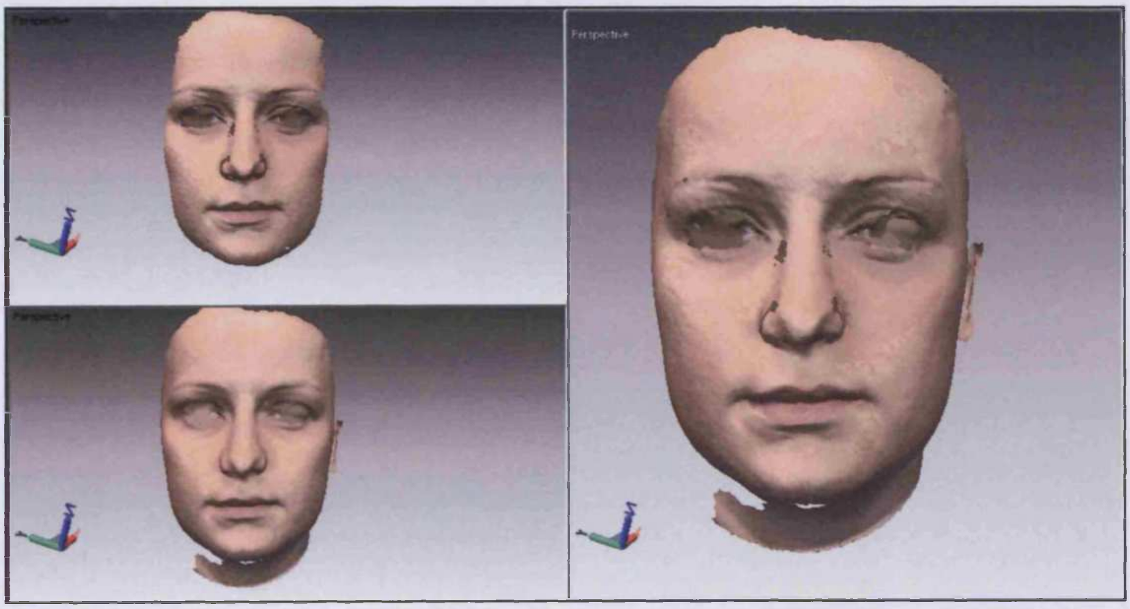


Fig 4.14 Anticlockwise beginning with the top left. Full-face image from a single scan with the subject looking directly into the camera. Full-face image from two laser scans. The two image capture techniques superimposed onto one another using the best fit algorithm.

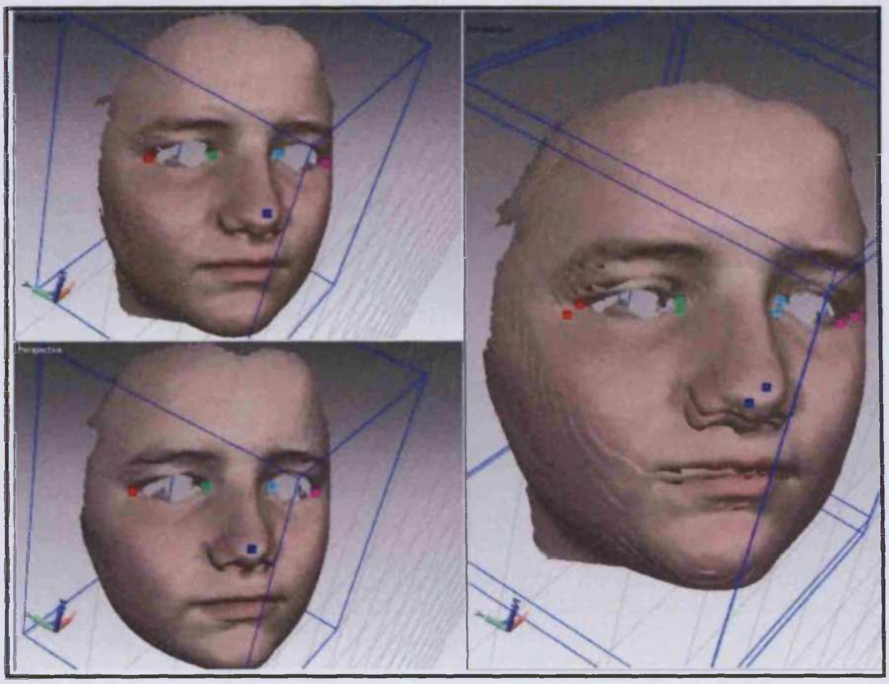


Fig 4.15 Initial facial alignment using 5 points on the face. Red points – outer cantus of right eye, Green points – inner cantus of right eye. Grey points – inner cantus of left eye, Purple points – outer cantus of left eye, Blue points – nasal tip

4.5 EVALUATION OF LONGITUDINAL GROWTH DATA

The evaluation of three-dimensional soft tissue changes in a cohort of children was performed at five time points over a two-year period. Data was collected at each school every six months with the portable three-dimensional imaging system. Each set of scans (left and right images) was saved in the raw data format and pre-processed into the final format at the Dental School in Cardiff. During the course of the study, a small number of subjects was unavailable due to leaving school on permanent basis, illness or other activities. Only subjects who had 3 or more scans were used in the final data analysis. The data was broken down into the following sub-categories for evaluation:

(i) **Demographics**

The gender and age of the subjects were recorded. Age was recorded according to the date of birth.

(ii) BMI

The sample was sub-divided into the various study groups:

(i) Males with normal BMI who received no treatment (MNT),

(ii) Females with normal BMI scores who received no treatment (FNT),

(iii) Males with normal BMI scores who received some form of orthodontic treatment (MT),

(iv) Females with normal BMI scores who received some form of orthodontic treatment (FT),

(v) Males with high BMI scores who received no treatment (MHBMI),

(vi) Females with high BMI scores who received no treatment (FHBMI).

The children were subdivided into groups with normal and high BMI scores as it was anticipated that children with high BMI scores are liable to greater variation in soft tissue due to variation in thickness and positioning of the fatty layers. Furthermore, there has also been evidence of variation in the increment growth rates of children with high BMI scores (Riolo et al. 1987).

There has been considerable debate as to how to define a high BMI in children in the literature (Cole et al. 2000; WHO 1997). For the purposes of this study, a high BMI is defined as a child in the 95th percentile of a recorded chart for his or her age [Appendix 5], indicating that the child is obese (Cole et al. 2000; WHO 1997). These figures were obtained from data resources and international respected charts available in the United States. The "cut of" score for children in the high BMI category at the age of 12 years was a BMI of more than 25.

CHAPTER 5

RESULTS

5.1.1 VALIDITY AND RELIABILITY

The following results were obtained as part of the system validation exercise carried out to determine the reliability and reproducibility of data obtained from three-dimensional surface laser scanning with the Minolta VI-900 set-up.

5.1.1 (a) Calibrated Cube

The results of the calibrated cube study are displayed in Table 5.1 as mean errors, standard deviations in millimetre and percentage errors. The average errors in measuring the true length, breadth and depth for the cube were 0.12% (0.09-0.20%), 0.29% (0.21-0.37%) and 0.87% (0.78-0.93%) respectively. Un-paired *t*-test comparing the mean differences between the true length and three-dimensional reproductions revealed no statistically significant differences between two groups ($p > .05$) (Kau et al. 2004a).

5.1.2 (b) Phantom Head

In the phantom head experiment, the sum of errors produced as a result of the shell deviations between left and right scans was 0.13 ± 0.18mm. This indicated that even for inanimate objects, a small degree of discrepancy occurred when the two halves of an image were used to construct a complete face.

The results also showed that some errors existed when measurements of landmarks were made on the three-dimensional image compared with the actual phantom head. Table 5.2 shows the distribution of errors associated with measuring distances between landmarks. The range of errors recorded was between 0.22mm and 0.83mm. The resulting mean error in linear lengths between pre-determined landmarks was 0.56 ± 0.25mm (max=0.86, min=0.22). These errors were not statistically or clinically significant.

5.1 (c) Human Subjects

In addition to inanimate object evaluation, shell to shell deviations were calculated to determine if laser scans could be captured of compliant adult subjects. The average error associated with merging a left and right scans was 0.25 ± 0.09 mm.

Table 5.1 Error difference between computer generated measurements and actual measurements of the cube expressed in mm and as a %.

Parameter	Error (mm)	SD (mm)	Error (%)
1	0.56	0.39	0.28
2	1.65	0.17	0.83
3	0.49	0.37	0.25
4	1.19	0.36	0.60
5	0.14	0.35	0.07
6	0.55	0.33	0.28
7	0.55	0.38	0.28
8	0.37	0.36	0.19
9	1.86	0.49	0.93

Table 5.2 Error difference between computer generated measurements and actual measurements of the simulated points on the phantom head expressed in mm.

Parameter	Actual (mm)	3 D Mean (mm)	Error (mm)
1	47.70	48.54	0.83
2	47.70	48.35	0.65
3	78.80	79.38	0.98
4	78.20	79.01	0.61
5	68.00	68.58	0.58
6	87.80	88.15	0.35
7	55.30	55.52	0.22
8	75.30	75.53	0.23
9	85.40	86.02	0.62
Average			0.56

5.1.2 IMAGE REGISTRATION AND SUPERIMPOSITION OF DATA

5.1.2 (a) Image Registration

The results showed there was a small difference of 0.03 mm when the two methods of registration were used. There was no difference in whether the left or right was superimposed first to reproduce a final facial image (Fig 5.1). Coloured maps produced an equal distribution in the overlap of left and right images. When the images from the two sets of automatic procedures were merged to form a final composite face, there was no difference in shell to shell deviations.

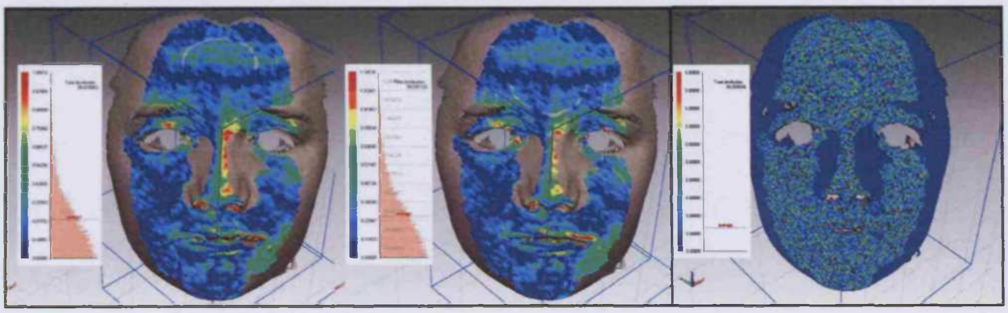


Fig 5.1(a) Coloured facial maps of left over right facial scans showing a shell deviation of 0.229 ± 0.209 mm, **(b)** Coloured facial maps of right over left facial scans showing a shell deviation of 0.256 ± 0.231 mm, **(c)** Coloured facial maps of the final merged composite faces superimposed on one another. There is no difference in the shells as shown on the figure.

5.1.2 (b) A single front-on versus paired scans

Two methods comparing a single front-on scan and a stereo method of obtaining final facial images were performed on five random subjects. These scans were processed using the normal computer methods previously described and the final composite face compared. There was no difference in the face except at the portions of the eyes. This area is difficult to capture using a laser based system (Fig 5.2).

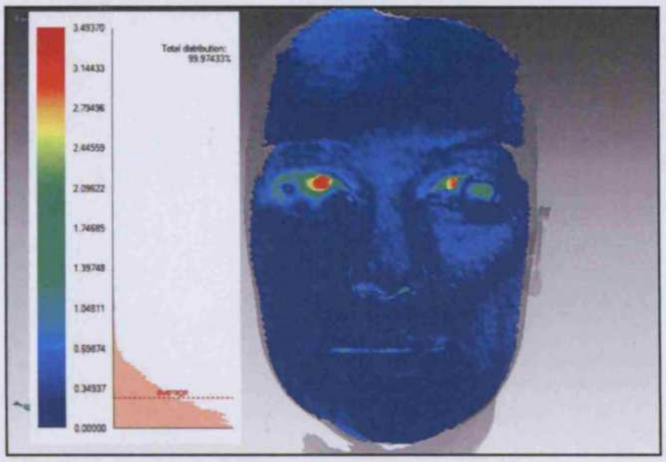


Fig 5.2 This figure shows a front-on scan and paired scanned technique superimposed on one another. There is no difference in the general facial morphology as shown by the uniform blue colour throughout the majority of the face. Small coloured portions exist around the eyes but these are due to the mesh production during the computer methods portion.

5.1.3 FEASIBILITY CAPTURING SOFT TISSUES IN CHILDREN

The methods of this study have been described previously and the findings are summarized in Tables 5.3 and 5.4 and have been reported (Kau et al. 2004b).

5.1.3 (a) Errors associated with merging left and right scans according to sex within subject groups

The mean ± SD shell deviations for the 30 adult females and males were 0.24 ± 0.08mm and 0.27 ± 0.10mm respectively. The difference in errors of these two groups was 0.03mm. The un-paired *t*-test revealed no statistically significance differences in shell to shell errors between genders in the adult group ($p > 0.05$). The mean ± SD shell deviations for the 30 male and female children were 0.31 ± 0.10 mm and 0.30 ± 0.08 mm respectively. The difference in mean errors for these two groups was 0.01 mm. Paired *t*-test revealed no statistically significant differences in shell to shell errors in these two groups ($p>0.05$).

5.1.3 (b) Mean shell deviations of left and right scans for the adults and children

The mean ± 1 SD shell deviations for the total sample of adult and children groups were 0.25 ± 0.09 mm and 0.30 ± 0.09mm respectively. The difference in merging errors associated in left and right scans for these two groups was less than 0.05 mm. Once again, un-paired *t*-test revealed that there was no significance between these two groups of subjects ($p > 0.05$).

Table 5.3 Average Mean ± 1 SD of the left and right laser scans of the adult and children groups.

Subjects		Number	Mean (mm)	SD (mm)	Min (mm)	Max (mm)
Adults	Males	15	0.27	0.10	0.16	0.49
	Females	15	0.24	0.08	0.16	0.45
	Total	30	0.25	0.09	0.16	0.49
Children	Males	15	0.31	0.11	0.20	0.53
	Females	15	0.30	0.08	0.18	0.45
	Total	30	0.30	0.09	0.18	0.53

Table 5.4 Mean differences of the shell deviations of the males and females within each group and the total sample as a whole.

Subjects		Number in each group	Mean Differences (mm)	SD (mm)	P value
Males	Adult and Children	15	0.04	0.19	0.42
Females	Adult and Children	15	0.06	0.10	0.44
Total	Adult and Children	30	0.05	0.15	0.18

5.1.4 REPRODUCIBILITY OF SOFT TISSUES CAPTURE IN CHILDREN

The results of the reproducibility studies are as follows. Forty randomly selected individuals (21 males, 19 females, mean age of 11 years 3 months) were recruited to participate in a validation exercise (Kau et al. 2005b).

5.4 (b) Reliability of whole face as T1, T2 and T3

The mean shell differences between the faces at T1, T2 and T3 are shown in Table 5.5. The results showed that the mean difference of the merged composite face for T1 and T2 was 0.31 ± 0.08 mm and T1 and T3 was 0.40 ± 0.11 mm. Paired *t*-tests were carried out on the mean shell differences (P = 0.91) and found to be not statistically significant.

5.4 (c) Level of tolerance

The level of tolerance was used as a basis of measuring the minimum clinically acceptable limit for reproducing facial pose. The results indicated that the amount of overlap between 2 faces, expressed in percentages for the tolerance levels of 0.50mm, 0.85mm and 1.00 mm, were 72.26%, 90.16% and 93.53% respectively (Table 5.6). In general, if the clinical difference was seen in less than 90% of the face, this was deemed to be reliable and reproducible. The superimposed faces at T1, T2 and T3 showed that on average 90% of the created composite facial scans correlated to one another with an error less than or equal to 0.85mm. This was considered to be a clinically acceptable level of reproducibility.

Table 5.5 Mean shell deviations of composite facial images at T1 and T2, T1 and T3

Subjects (n=40)	Mean shell deviations (mm)	SD (mm)	Max (mm)	Min (mm)
T1 and T2	0.31	0.08	0.51	0.02
T1 and T3	0.41	0.082	0.76	0.21

Table 5.6 Tolerance level between shells at 0.5mm, 0.85mm and 1.00mm expressed as a percentage.

Subjects	**1.00 mm**	**0.85 mm**	**0.5 mm**
(n=40)	(%)	(%)	(%)
Mean	93.53	90.16	75.26
SD	4.00	5.08	9.65
Max	99.67	99.30	92.96
Min	85.40	79.45	50.71

5.1.5 SUMMARY OF VALIDATION FINDINGS

The validation studies performed on the laser scanning system proved that system was accurate and reliable in capturing facial morphology. These results serve as the foundation for future studies for the capture of facial morphology in young children and also as a measurement tool for three-dimensional cranio-facial imaging. The following conclusions could be made from the validation:

(1) The error in measuring linear distances was less than 1%.

(2) The error of the system in aligning left and right scans of inanimate objects is 0.13 ± 0.18 mm.

(3) The error in measuring linear lengths on a phantom head was 0.56 ± 0.25mm.

(4) The system could be used in adults and children and the associated errors did not prejudice against either types of groups.

(5) There was little or no distortion of the final facial images as a result of combining left and right scans. The advantage of using a two scan technique meant that a greater surface area of the face could be captured in one sitting.

(6) The mean errors associated in capturing facial posture were 0.31 ± 0.08 mm for scans taken within 3 minutes and 0.40 ± 0.11mm over 3 days.

(7) The overall reliability associated with facial posture was 0.85mm.

(8) Three-dimensional imaging could be reliably undertaken on young children and adults.

5.2.1 RESULTS OF THE LONGITUIDNAL GROWTH DATA

The results of the longitudinal cohort study are presented in this section.

5.2.2 DEMOGRAPHIC EVALUATION

5.2.2 (a) Sample Size

A total of 95 subjects from two large comprehensive schools gave written consent to participate in this study. The sample was further separated into male and female groups with normal or high BMIs and a recorded history of whether orthodontic treatment had been undertaken (Table 5.7). During the course of the study, a number of subjects were not available either because they had left the school or were not physically present in the school (due to a variety of reasons) on the days of the screenings.

Table 5.7 Results of recruitment. Subjects distribution placed into the various sub-groupings based on gender, weight and treatment type (NT – No treatment and T – Treatment).

MALES				FEMALES			
Normal BMI		High BMI		Normal BMI		High BMI	
NT	T	NT	T	NT	T	NT	T
37	12	4	0	27	12	3	0
TOTAL = 95							

The final sample available for the three-dimensional imaging study evaluation was 86 subjects. Nine out of 95 subjects were not included, as they did not meet the requirement of three or more physical attendances during the study period. This represented a drop out rate of 9.5% of the overall study group. The numbers of subjects who were present at the scanning sessions were recorded according to time intervals as follows: T1 (Base line), T2 (2^{nd} investigative session)...T*x* (*x* investigative session). Eight hundred and sixty left and right facial scans were obtained. These sample numbers are represented in Table 5.8. A further 4240 computer models were generated, pre-processed and transformed into usable images for analysis.

Table 5.8 Subject numbers arranged by sample groups, time intervals, subjects lost to the study and final sample size.

Subjects	Sample (Start)	T1	T2	T3	T4	T5	Lost to Study	Sample (Final)
MNT	37	36	32	33	32	31	4	33
FNT	27	24	25	26	24	25	1	26
MT	12	10	10	10	10	9	2	10
FT	12	12	11	11	12	12	0	12
MHBMI	4	4	4	4	4	4	0	4
FHBMI	3	2	2	1	1	1	2	1
Total	**95**	**90**	**84**	**85**	**83**	**82**	**9**	**86**

5.2.2 (b) Age

The data used for this study forms part of an on-going longitudinal growth study. The study period started on the 10th of May 2003 and consists of data acquired up to the 20th of April 2005. The mean age of the subjects at the start and completion of the trial were 12.1 years old and 14.1 years old respectively. (Table 5.9)

5.2.2 (c) Appliance Indicators

Twenty-five of the 86 subjects (26% of the cohort) received some form of orthodontic treatment during the course of the study. All children in the treatment groups received fixed multi-band orthodontic appliance treatment. Eight of the female subjects and 6 male subjects had teeth removed for orthodontic reasons. The appliances were placed at various time intervals within the study. The information as to when these appliances were placed exactly were not available as it was not part of the original study design. However, due to the possible influence that this form of treatment might have on the lower thirds of the face, these subjects were evaluated separately.

Table 5.9 The children represented as means, standard deviations, minimum and maximum ages at the various time intervals

Sample (n=86)	Mean	Std. Deviation	Minimum	Maximum
Age at T1	12.14	0.31	11.41	12.78
Age at T2	12.71	0.31	11.98	13.35
Age at T3	13.13	0.31	12.40	13.77
Age at T4	13.67	0.31	12.95	14.32
Age at T5	14.07	0.31	13.33	14.70

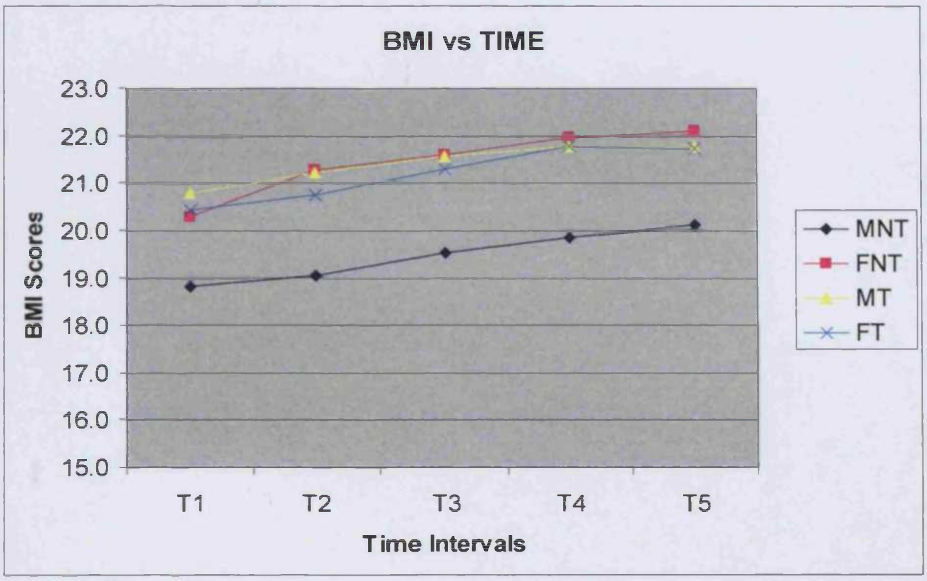
5.2.2 (d) BMI

Five subjects fell into the High BMI grouping (BMI scores 25 and above). The numbers in this subject groups were considered too small for clinical comparisons and meaningful data evaluation. In addition, none of the subjects in the high BMI groups received any form of orthodontic treatment. As a result, it was decided that these subjects were to be excluded from analysis.

The BMI scores of the subjects in the other sub-groups with normal BMI scores fell within the ranges of the 50th and 75th percentiles of the BMI charts for recognized averages. The fluctuations in BMI scores during the course of the study for these sub-groups are displayed in Figure 5.3.

Interestingly, the BMI scores for the MNT group were consistently lower. This score was approximately two BMI scores lower than all other groups but the rate of increase was similar to the other study groups over the period. The differences in mean weight between the FNT (females) and MNT (males) were 4.4 Kilograms and 4.0 Kilograms at T1 and T2 respectively, with the females being heavier at both time intervals.

Fig 5.3 BMI recordings of the groups MNT (Males who received no treatment), FNT (Females who received no treatment), MT (Males who received treatment) and finally FT (females who received treatment)



5.2.3 FACIAL DIFFERENCES IN GROUPS STUDIED

Average facial shells were used to the morphological differences between the groups. The differences in full facial morphologies were studied for the following groups at T1 and T5.

1) MNT (Males) versus FNT (Females) at T1
2) MNT (Males) versus MT (Males) at T1
3) FNT (Females) versus FT (Females) at T1
4) MNT (Males) versus HBMI (Males) at T1
5) MNT (Males) versus MT (Males) at T5
6) MNT (Males) versus FNT (Females) at T5
7) FNT (Females) versus FT (Females) at T5

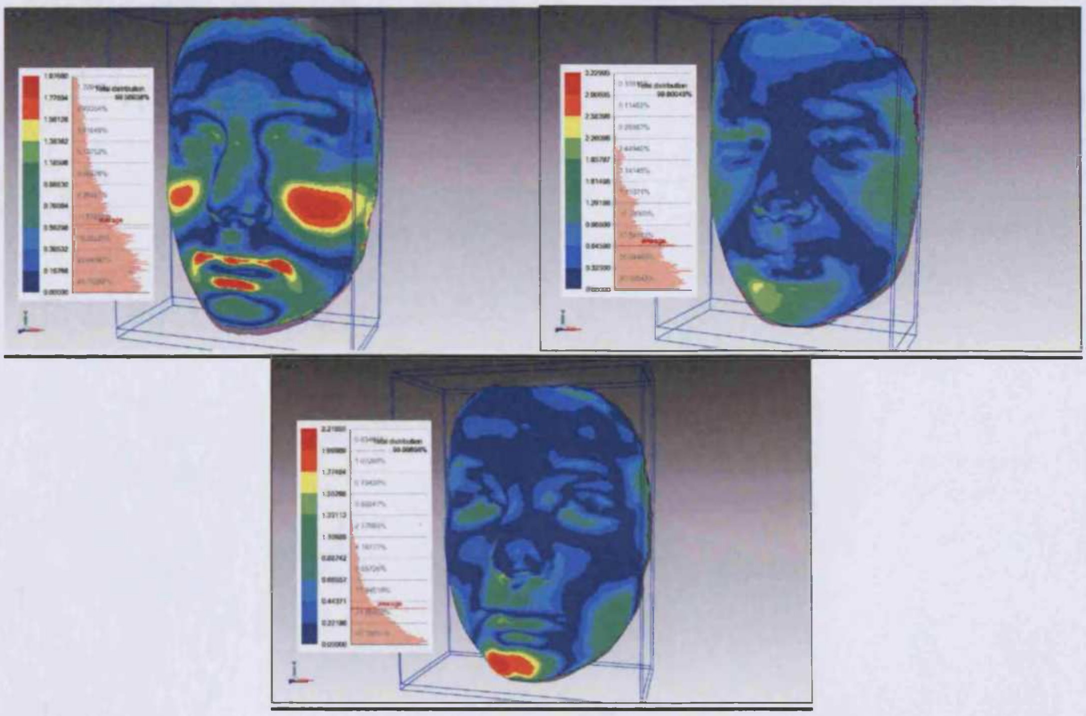


Fig 5.5 The figures should be read in a clockwise fashion starting from the top left. **a)** differences in the faces at T5, average males (MNT) versus Female (FNT). The mean error between the two facial shells was 0.65 ± 0.58mm and the composite errors had a range of 1.98mm. **b)** males treatment (MT) versus males no treatment (MNT) at T5. The mean error between the faces was 0.65 ± 0.49mm and the composite range of errors was 3.23mm. **c)** females no treatment (FNT) versus females treatment (FT) at T5. The mean error was 0.35mm ± 0.36mm and the composite range of errors was about 2.21mm.

5.2.3 (b) Surface differences between groupings observed and presented

The surface changes between the groups MNT and FNT were observed and presented as colour distributions in Fig 5.4 (a) and 5.5 (a). The surface changes were localised to the followings areas: the nasal bridge, length of the nose, zygomatic regions and lower thirds of the face. The distribution of surface changes was similar at T1 and T5.

There were large surface differences between the two groupings for average faces MNT and MT (Fig 5.4b and 5.4b). These surface differences were seen at the nose, zygomatic regions, lateral extremities and lower facial thirds. The magnitude of the surface changes was larger than the surface changes seen between MNT and FNT. One analysis was carried out for the male HBI and MNT groups. The results showed a large variation between facial shells. This indicated that a large variation existed between average facial shells of subjects with normal and high BMI's. Finally, the surface changes seen in the last two groups FNT and FT were the smallest, as indicated by the mean shell deviation scores and colour maps. The greatest shell deviations were seen at the tips of the nose and lower jaw areas. However, whilst a good proportion of the faces was similar at T1 there was a greater distribution of surface change at T5.

5.2.3(c) Surface shapes and volumes

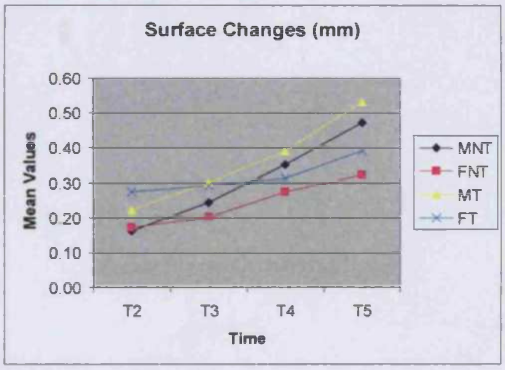
The diversity of the surface changes meant that it was more accurate to treat each sub-group of average faces as separate entities. As a result, surface shape and volumes were not established for these groups.

5.2.4 FACIAL CHANGES OVER TIME

The facial changes over time were compared using average facial shells evaluated over five time frames from T5 to T1 (Baseline). The average faces were brought into close alignment by superimposing corresponding points on the inner and outer canthi of the eyes and the corners of the mouth as previously described. Finally, these averages faces were superimposed using the iterative closest point algorithm or best fit method for analysis (Kau et al. 2006a). The four main groups identified earlier: a) MNT, b) FNT, c) MT and d) FT were analysed. A tolerance of 0.425mm was used as it represented the mean of the reproducibility error previously obtained (0.85mm is the reproducibility error for faces of an individual subject) from validation investigations and also took into account mathematical and clinical errors when average faces rather than individual faces were used (Kau et al. 2005b). Each time frame within the evaluated subgroup was superimposed onto the baseline time frame (T1). The deviation between the shells were obtained and illustrated in Fig 5.7.

5.2.4(a) Linear Measurements and histogram plots

The mean shell deviation values on the coloured histogram maps increased over time for all 4 groups (Fig 5.6). There were distinct changes in the faces in each sub-group over time. These changes are best described pictorially and illustrated in Figure 5.7. There was a corresponding percentage decrease between matching surfaces of shells of incremental time intervals within the same subject groups with time. The results showed that as the subjects became older, more surface changes and deviations were seen on the face from baseline.



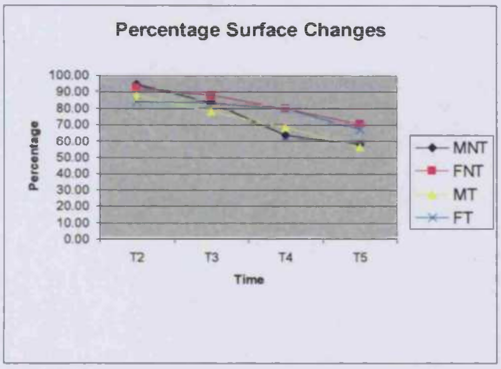


Fig 5.6 a) and **b)** Mean shell deviation between the two shells depicting surface changes over time. Percentages correspond to a value of 0.425mm or less between time frame intervals.

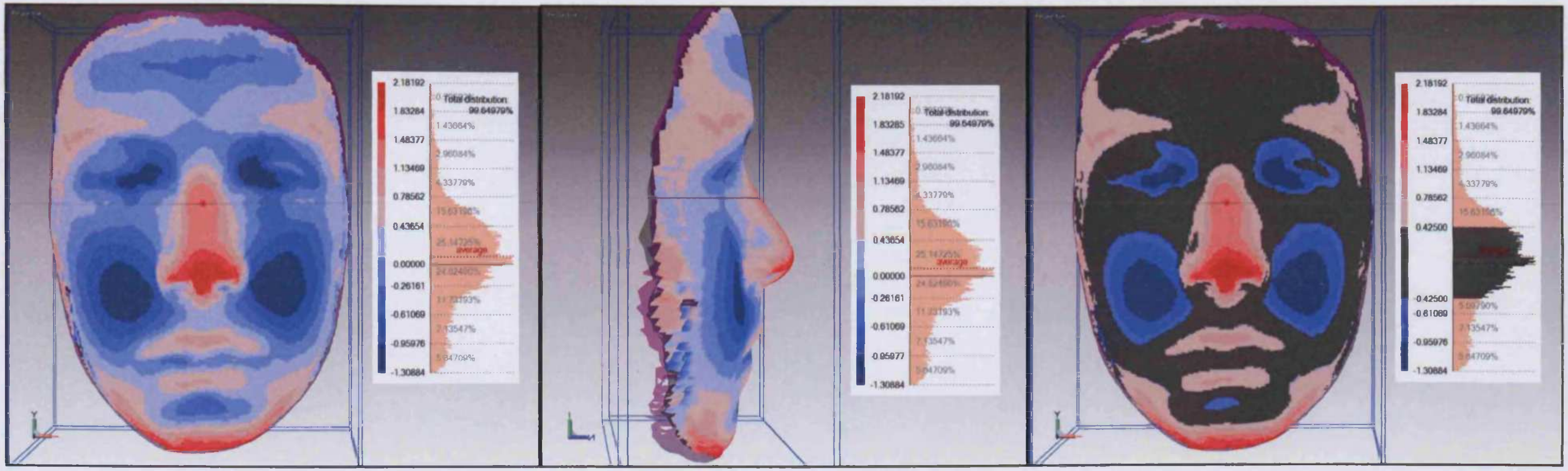


Figure 5.7: These images from left to right represent the average face of the male group with no treatment at T5 over T1. **a)** and **b)** Frontal and profile views showing surface changes as a color map and histogram plot. The changes range from +2.18mm and -1.31mm. There was a greater proportion of the face exhibiting positive rather than negative changes. **c)** The black areas of the face indicated areas of "little or no change" consistent to a tolerance value of 0.425mm. This was applied to take into account clinical reproducibility and mathematical errors. Positive changes were seen in the brow areas, nose and facial heights, whilst negative changes were seen at the cheeks.

5.2.4(b) General Description of Surface changes seen on average faces

This section shows the general trends seen for the surface changes and will be described in a manner that incorporates the upper and lower face.

Surface changes were seen at the brow areas and these thin wafer projections were observed pointing towards the mid-line of the face. These areas increased in size and thickness as the time intervals increased. This occurred mainly in the vertical *(y-axis)* direction and was most marked in the MNT group.

The nose exhibited the most change with time and its greatest change occurred at the tips of the nose. The patterns and shapes observed were uniformly triangular in nature. There was a widening of the alar base and general deposition along the nasal bridge. In general, the isolated surface area changes suggested that there was a gradual increase in the nasal surface volume and that these surfaces widened to a triangular shape in all three planes of space. The changes occurred in an asymmetrical manner on the left portion of the nose at first but eventually occupied a more central portion corresponding to the middle of the face.

There was also a flattening of the cheek areas with time and this could be best seen as an increasing elliptical pattern in the cheek areas.

There were translations of the upper lip in T2 but this increased to a more downward translation of the upper and lower lips by T5. There was also a corresponding translation of the lips in the downward direction. There was a general increase in the facial heights of most of the average shells. There was also an increase in the vertical height of the lower face with the mandible occupying a more inferior position relative to the cranial base.

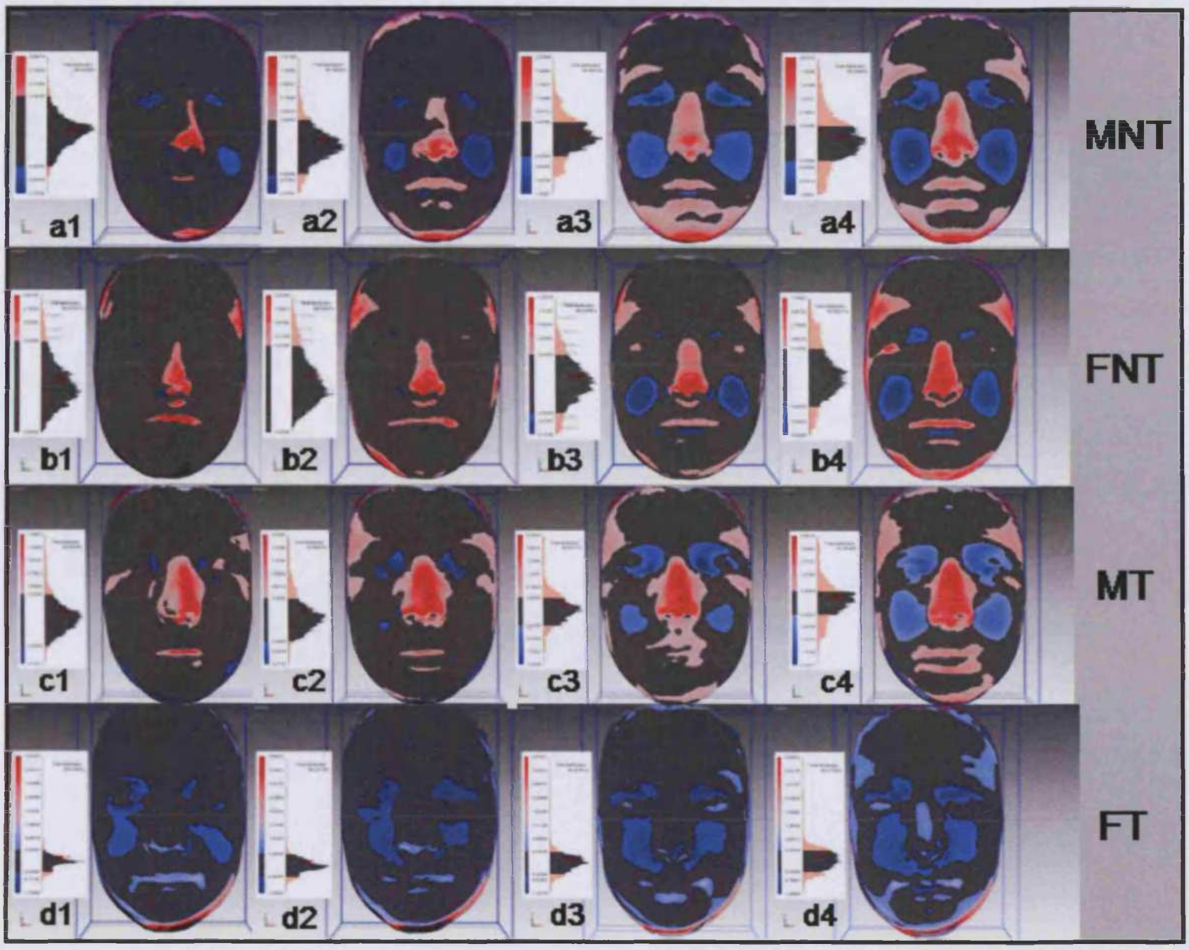


Fig 5.8 Figure showing the changes in surface shape taken over 6 monthly intervals. a1-a4) Facial changes to the male (no treatment) average faces. Positive surface changes are seen in red and are seen progressively on the brows, nose, lips and mandible. Negative changes shown in blue were seen on the cheeks. b1-b4) Facial changes to the female (no treatment) average faces. Positive surface changes are seen in red and are seen progressively on the brows, nose, lips and mandible. The magnitudes of change are smaller to the MNT group. Negative changes shown in blue were seen on the cheeks. c1-c4) Facial changes to the male (treatment) average faces. Positive surface changes are seen in red and are seen progressively on the brows, nose, lips and mandible. Negative changes shown in blue were seen on the cheeks. These changes are similar to the MNT group. d1-d4) Facial changes to the female (treatment) average faces. Surface changes are seen in predominantly on the cheeks and lips.

5.2.5 DETAILED DESCRIPTION OF SURFACE CHANGES ON THE AVERAGE FACES

The average faces were analysed in detail over the two year study period for all 4 groups (MNT, FNT, MT and FT). The superimposition was carried out on the T1 baseline face unique to that study group. For the ease of discussion, 6 monthly changes were labelled as comparison periods (i.e. T2vsT1, T3vsT1...etc). Each analysis was made from the glabella down to the mandibular region.

5.2.5 (a) Males (n=33, No Treatment)

There were no apparent changes to the central portion of the forehead region. There was a general thickening of the lateral glabella region. This ranged from 0.01mm to 0.91mm. The nose showed the greatest and most prominent change with time and all these changes were positive. There was a general forward and downward thrust of the nose and the linear measurements taken the nasal tip ranged from 0.90mm to 2.08mm at T2vsT1 and T5vsT1 (Fig 5.8a1-a4, Fig 5.9b). There were visible and negative changes in the cheek areas. This change became evident only on the left side of the face at T2vsT1 before becoming more symmetrical on both sides of the face at T4vsT1 and T5vsT1. The negative change was as a range from -0.52mm to -1.25mm at its deepest points. These differences were similar on both sides of the face. There was a forward and downward translation of the lips away from the forehead. This change mirrored the growth of the nose. These changes ranged from 0.52mm to 1.25mm for the upper lips and 0.30mm and 1.03mm for the lower lips. There was an elongation of the face leading to the downward projection of the soft tissue chin. This ranged from 0.45mm and 2.08mm. The amount of forward projection of the chin was approximately 2mm. A full illustration may be viewed on the electronic file in the CD enclosed (Fig 5.9).

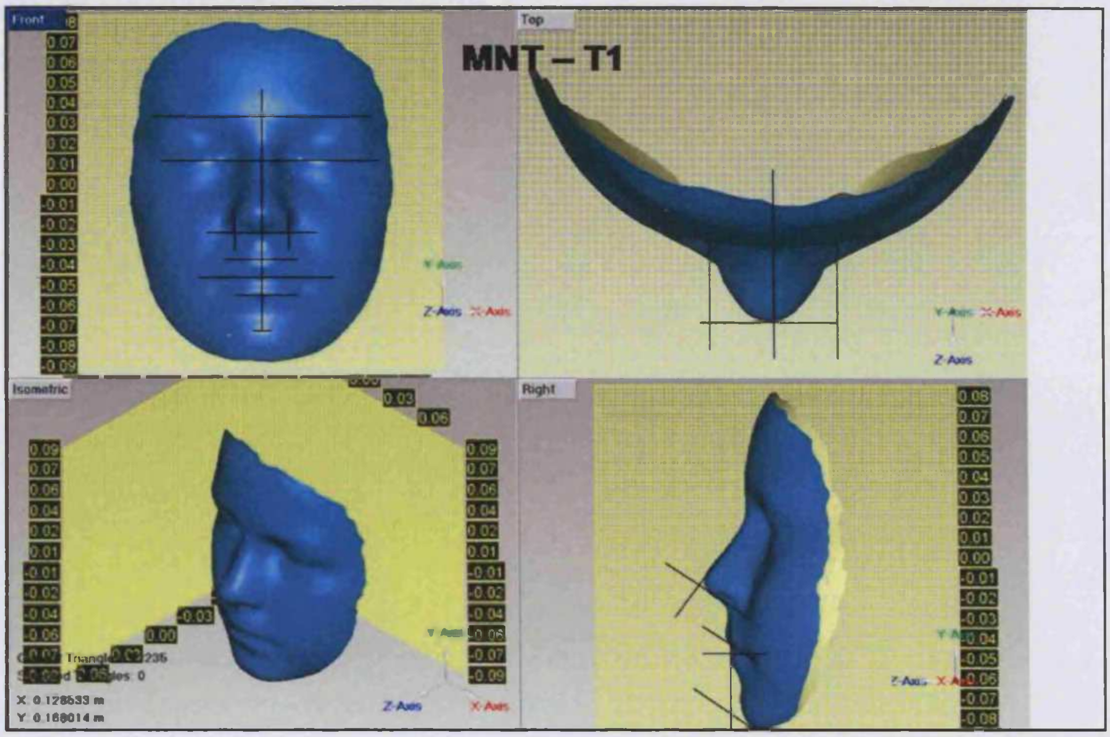


Fig 5.9a) Different views of the average face for the subject group MNT at T1

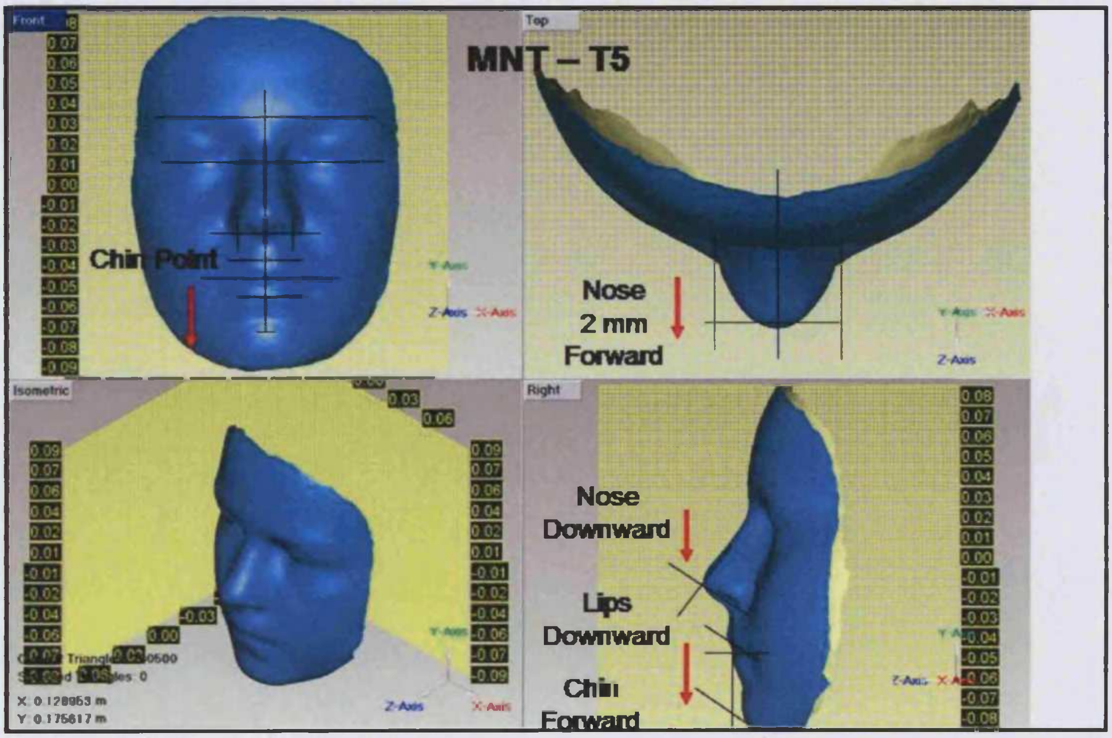


Fig 5.9b) Different projected views showing the changing morphology of the average face for the subject group MNT at T5.

5.2.5(b) Females (n=26, No Treatment)

There were no apparent changes to the central portion of the forehead region. There was a general thickening of the lateral glabella region. This ranged from 0.58mm to 0.84mm.

The nose showed the greatest and most prominent change with time. These changes were positive. There was a general forward and downward movement of the nose and the linear measurements taken at the nasal tip ranged from 0.73mm to 1.90mm at T3vsT1 and T5vsT1 (Fig 5.8 b1-b4 and Fig 5.10b).

There were visible and negative changes in the cheek areas. This change became evident only on both sides of the face at T4vsT1 and T5vsT1. The negative change was as a range from no change mm to -0.83mm at its deepest points. These differences were similar on both sides of the face.

There was a forward and downward translation of the lips away from the forehead. This change mirrored the growth of the nose. These changes ranged from 0.52mm to 0.79mm for the upper lips and no changes and 0.60mm for the lower lips. There was an elongation of the face leading to the downward projection of the soft tissue chin. This ranged from no changes and 1.12mm. The amounts of forward projection of the chin were minimal (Fig 5.10b). A full illustration of the changes in facial morphology can be viewed on the file in the enclosed CD.

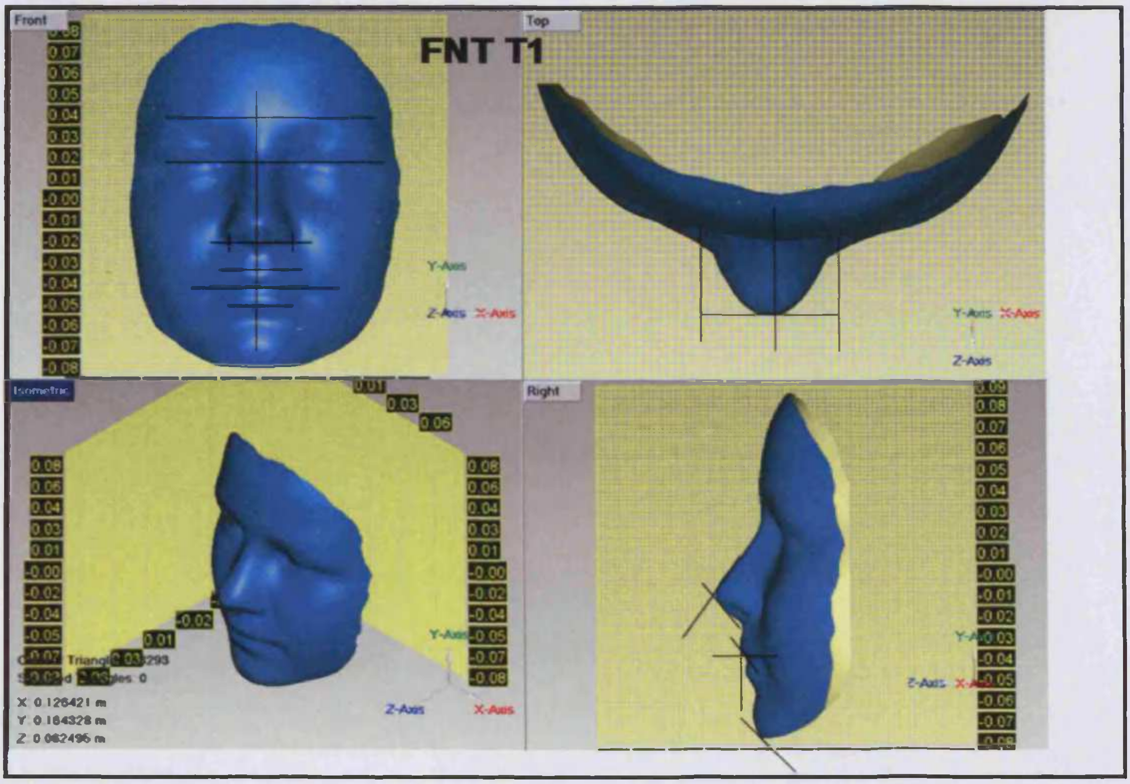


Fig 5.10a) Different views of the average face for the subject group FNT at T1

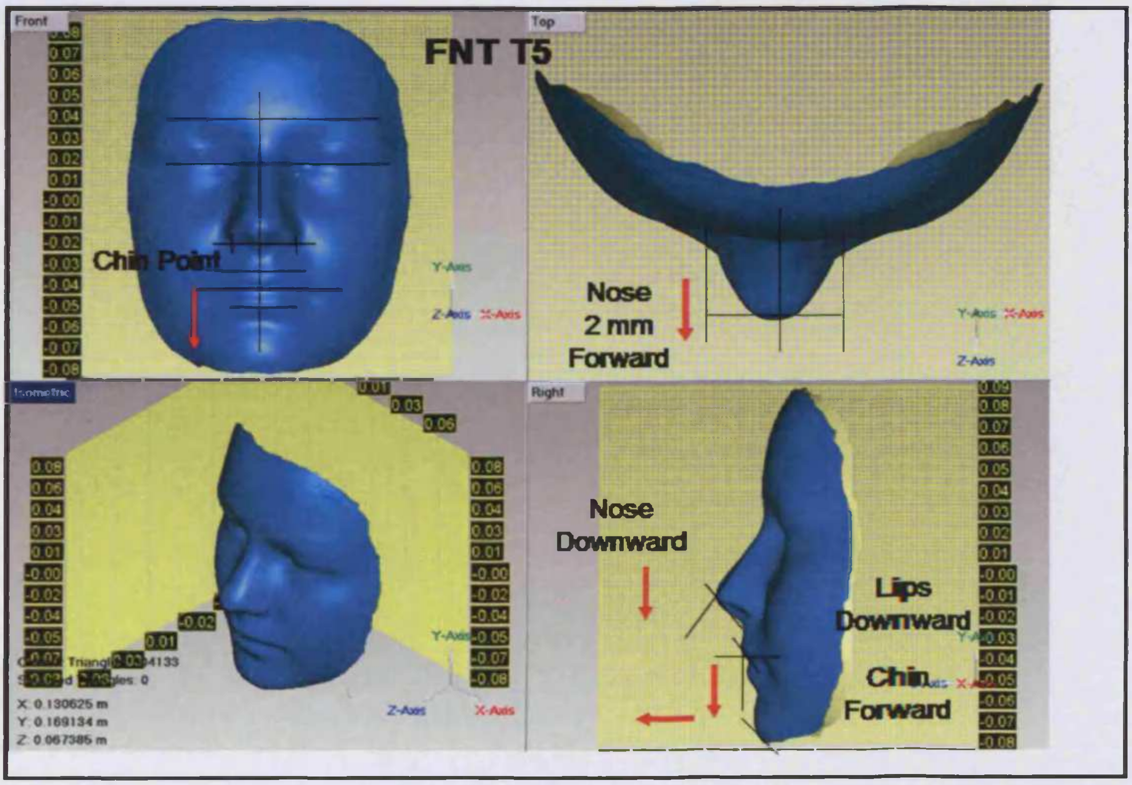


Fig 5.10b) Different projected views showing the changing morphology of the average face for the subject group FNT at T5.

5.2.5(c) Males (n=12, Treatment)

There were no apparent changes to the central portion of the forehead region. There was a general thickening of glabella region. These changes began on the left side of the face first from T2vsT1 before relatively symmetrical on both sides. The changes ranged from 0.49mm to 1.12mm (Fig 5.8 c1-c4).

The nose showed the greatest and most prominent change with time. These changes were positive. There was a general anterior and downward thrust of the nose and the linear measurements taken the nasal tip ranged from 1.14mm to 2.30mm at T2vsT1 and T5vsT1 (Fig 5.11b). There were visible and negative changes in the cheek areas. This change became evident only on the left side of the face at T2vsT1 before becoming more symmetrical on both sides of the face at T4vsT1 and T5vsT1. The negative change was as a range from -0.52mm to -1.34mm at its deepest points. These differences were similar on both sides of the face.

There was a forward and downward translation of the lips away from the forehead. This change mirrored the growth of the nose. These changes ranged from 1.11mm to 1.60mm for the upper lips and no changes and 1.53 for the lower lips. There was an elongation of the face leading to the downward projection of the soft tissue chin. This ranged from no change to 1.60mm. The amounts of forward projection of the chin were minimal (Fig 5.11b). A full illustration is given in the CD enclosed.

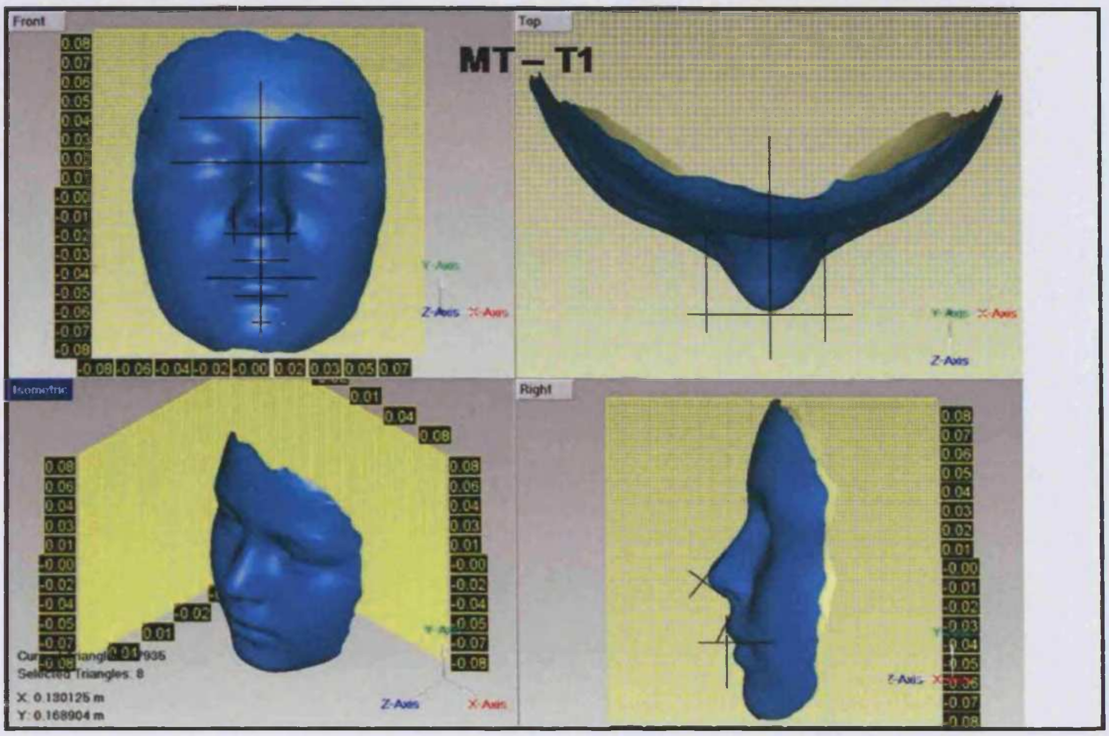


Fig 5.11 a) Different views of the average face for the subject group MT at T1

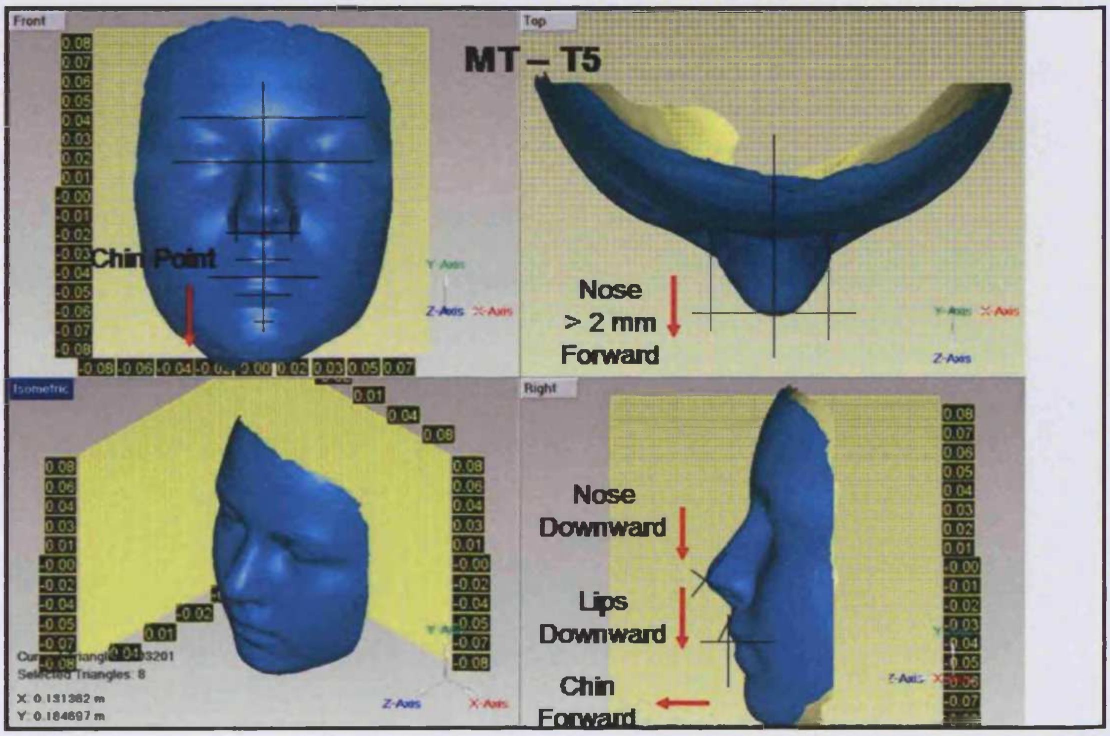


Fig 5.11b) Different projected views showing the changing morphology of the average face for the subject group MT at T5.

5.2.5 (d) Females (n=12, Treatment)

There were no apparent changes to the central portion of the forehead region. There was only a general thickening of lateral glabella regions in the last time intervals T4vsT1 and T5vsT1. This ranged from 0.62mm to 0.60mm at these time intervals (Fig 5.8 d1-d4).

The nose showed little change with time and there was no characteristic forward and downward thrust as seen in the other three groups. There were some changes confined to the bridge area of the nose and there changes were positive. These changes ranged from negligible changes to 0.54mm (Fig 5.12b).

There were visible and negative changes in the cheek areas. This change became evident only on the left side of the face at T2vsT1 before becoming more symmetrical on both sides of the face at T4vsT1 and T5vsT1. The negative change was as a range from -0.59mm to -1.31mm at its deepest points. These differences were similar on both sides of the face.

There was backward and inward translation of the lips. These changes ranged from 0.79mm to -0.50mm for the upper lips and 0.40 and -0.50 for the lower lips. There was an elongation of the face leading to the downward projection of the soft tissue chin. This ranged from 0.45mm and 1.2mm. The amounts of forward projection of the chin were minimal (Fig 5.12b). A full illustration is given on the CD enclosed.

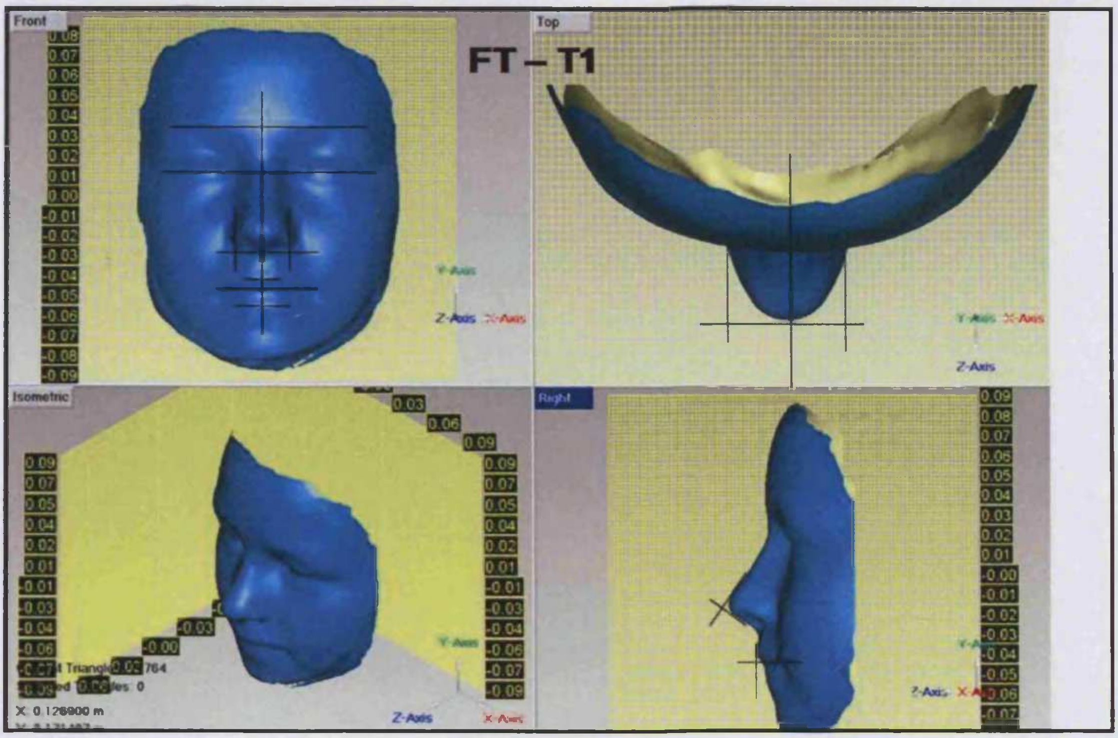


Fig 5.12a) Different views of the average face for the subject group FT at T1

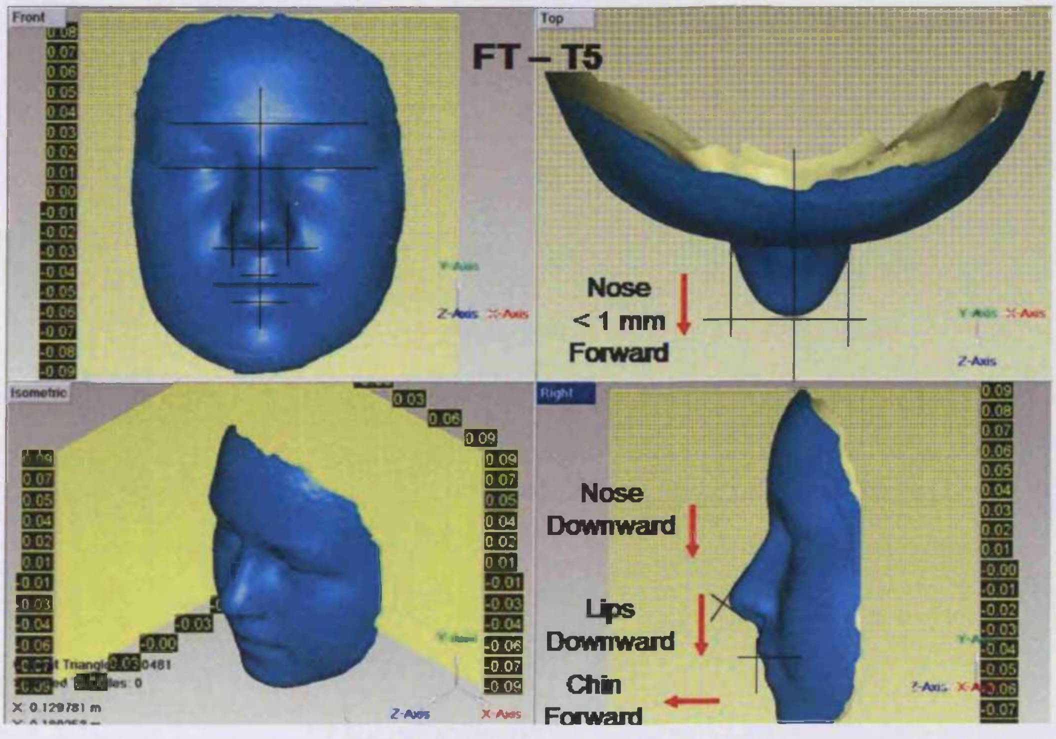


Fig 5.12b) Different projected views showing the changing morphology of the average face for the subject group MNT at T5.

In general, the three groups MNT, FNT and MT had similar patterns of change. There was an increase in the mean differences with time. There was a gradual deposition of the brow areas that were triangular in nature with the apex pointing towards the middle of the forehead. The nose tended to exhibit asymmetrical growth which finally assumed a triangular pattern described earlier. The cheeks in all three groups had elliptical patterns that flattened with time and increased in surface area. There was also a gradual translation of the lips along the vertical axis of the face and an increase in the general face height.

The exception to these data sets was the female group that underwent treatment. This group had early pronounced flattening of the cheeks and an early increase in face height. There was, interestingly enough, less changes to the nose than the other groups.

5.2.6 SURFACE AREA AND VOLUME CHANGES

Volume changes were also obtained after the relevant areas of change were isolated from the average faces. The methods of acquiring these volumes have been described previously in the materials and methods section. The surfaces corresponding to 0.425mm were eliminated leaving the surface volumes to be evaluated. These facial volumes were calculated and sub-divided into regions of the face for analysis. These were classified as follows: the left and right brows, left and right cheeks, lips, mandible and nose. Volumes were calculated using the methods described early in Chapter 3; the accuracy of which has been independently verified and found to have an accuracy within 1.5% (Kau et al. 2007). The volumes are presented in tabular form for individual regions.

Figure 5.13 shows the average changes in the face between T5 and T1. The surface changes in the brow are triangular in nature with the base at the lateral extremities of the face and gradual deposition towards the mid line of the face.

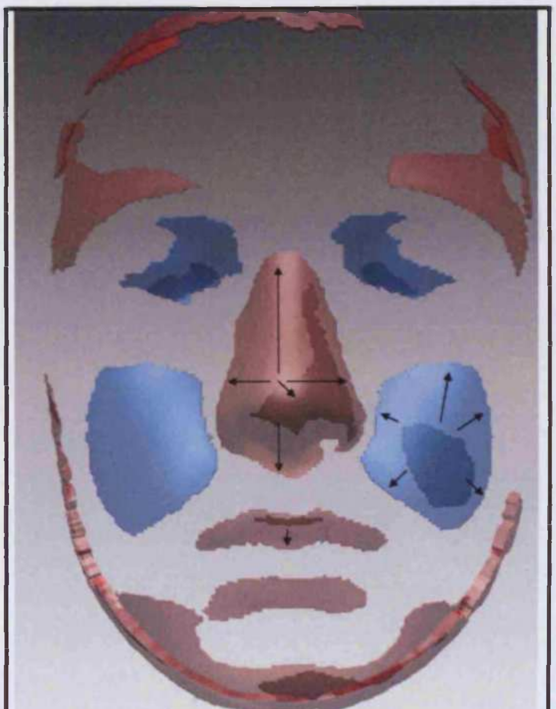


Fig 5.13 Diagrammatic Volumetric changes

Surface shape changes followed a similar pattern in the groups MNT, FNT and MT. These surface changes were seen developing in the earlier stages in the nose, followed by changes in the cheeks, changes in the brow and increases in the vertical dimension. Interestingly the facial patterns on FT group showed little changes to the nose region and large changes to the cheek regions (Fig 5.14).

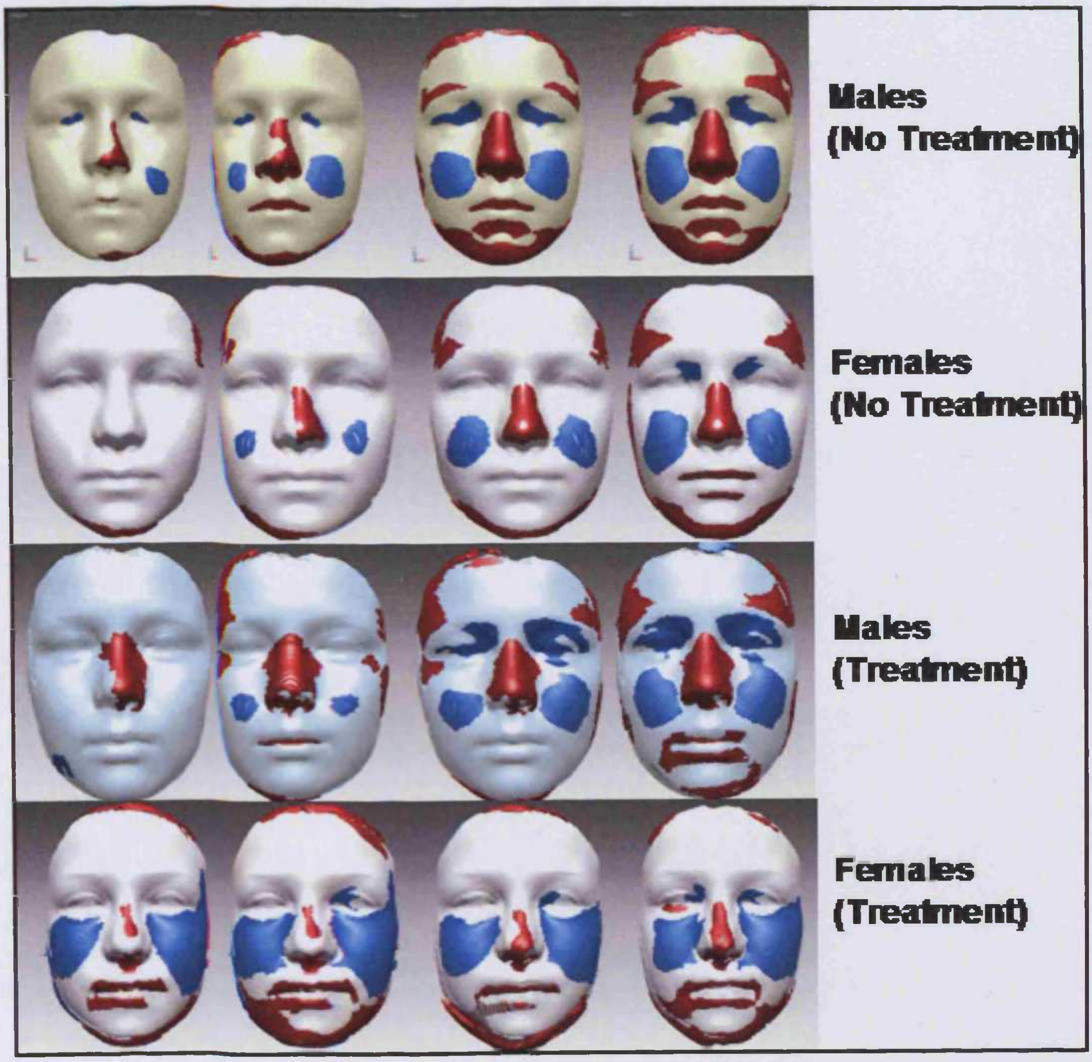


Fig 5.14 Shape changes for the 4 different groups over time

The measurements showed an increase in volume as the time line increased. These results are shown in Table 5.10.

Table 5.10 Volume measurements in mm^3 according to the various regions.

Subject	Region	T2vsT1	T3vsT1	T4vsT1	T5vsT1
Females (NT)	Brow (L)	289.67	224.52	413,21	491.26
	Brow (R)	145.18	450.72	394.67	460.00
	Cheek (L)	1.00	1.00	416.66	465.54
	Cheek (R)	1.00	1.00	298.54	428.82
	Lips	70.15	72.68	96.90	167.32
	Mandible	1.00	1.00	143.05	647.98
	Nose	78.71	74.20	415.11	454.87
Females (T)	Brow (L)	1.00	1.00	1.00	466.38
	Brow (R)	1.00	1.00	1.00	557.83
	Cheek (L)	237.29	155.73	317.66	414.47
	Cheek (R)	378.70	270.93	461.88	651.92
	Lips	296.69	86.41	104.19	91.49
	Mandible	379.15	1.00	1.00	2031.98
	Nose	91.95	141.02	145.00	147.92
Males (NT)	Brow (L)	1.00	1.00	199.93	766.73
	Brow (R)	1.00	274.13	225.36	710.43
	Cheek (L)	132.42	356.37	698.86	907.83
	Cheek (R)	1.00	132.93	633.62	1017.29
	Lips	11.31	177.36	451.46	541.35
	Mandible	125.07	1728.48	2288.51	4832.98
	Nose	279.70	710.57	1470.61	2220.94
Males (T)	Brow (L)	220.87	471.59	715.60	760.70
	Brow (R)	1.00	338.55	992.15	756.68
	Cheek (L)	1.00	1.00	358.76	1071.69
	Cheek (R)	1.00	113.78	385.12	954.15
	Lips	92.40	66.21	140.90	584.76
	Mandible	1.00	892.88	1401.60	3478.42
	Nose	1630.10	2378.43	3000.18	3340.98

The volumes seen in the male groups (MNT and MT) were generally larger than the female groups (FNT and FT) (Fig 5.15).

The volumes seen in the brow areas of the males were 1.54 times (710/460) to 1.66 times (67/460) the size of the female groups in the brow regions. The changes in the cheek areas were in general 2.19 (907/414) times and 2.59 times greater in males than females. The largest differences seen were in the nose. The males generally had larger changes to the nasal volumes and this ranged from 4.88 times to 7.34 times.

The changes in the lips were less reliable as these structures did not necessary change in size but were the results of a down and forward translation. However, the percentage changes were consistent to the changes seen in the brows and cheeks.

The changes in the mandibular region produced large volumetric changes. However, these readings needed to be interpreted with caution as the volumes were often not fully closed.

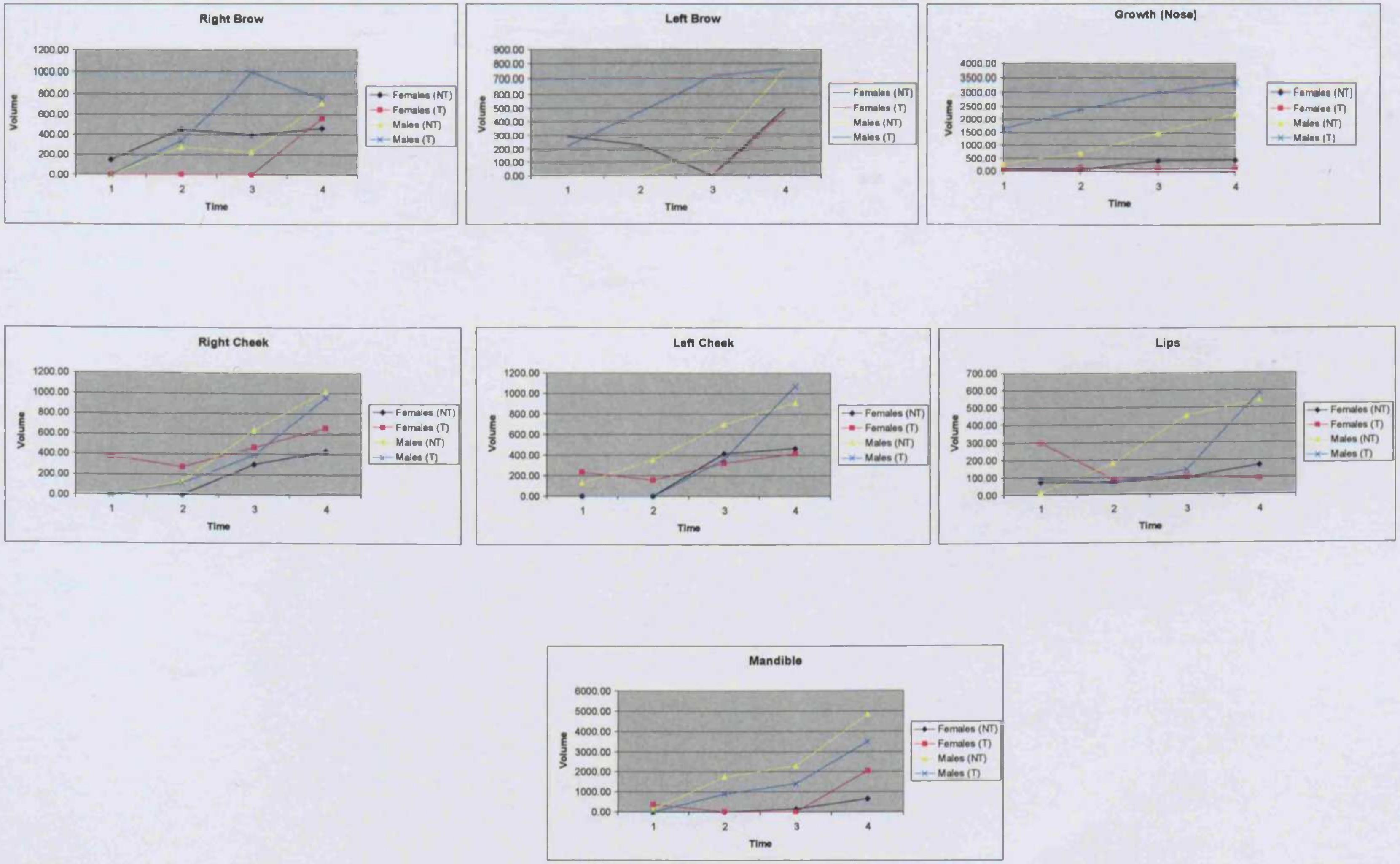


Figure 5.15 Graphical representation of the changes in volumes of the 4 groups of averages as the longitudinal study progressed.

5.3 FACIAL SURFACE CHANGES AND AGE

Facial surface changes and the ages of each individual subject were further analysed according to the five recorded time intervals and the results studies in the following manner: 1) Shell to shell surface differences, 2) Facial changes and age.

5.3.1 Shell to shell surface differences

The faces of each subject were analysed at each time interval against the subject's original baseline face at T1. The shell-to-shell differences for each subject represented a sum total of the absolute difference of the match for the two facial shells. The mean value and the range of differences were recorded on a histogram. These scores are represented in Tables 5.11 and 5.12 as the percentage and mm readings of the means, standard deviations (SD), minimum and maximum values. As these shell differences were measured for individual subjects rather than the average faces, the reproducibility error of 0.85mm was applied at each comparison to reflect the findings of the validation findings in studies in Chapter 5 (Kau et al. 2005b).

The results showed that, in general, there was a decrease in percentage (%) match of the faces as the study progressed with time. This was mirrored by an increase in the absolute mean face to face deviations over time. This meant that as the age of the subjects increased, there was a corresponding decrease in the matching of two faces together. The overall magnitude of change between shells, measured in mm, also increased in line with the percentage decrease in shell-to-shell match.

Males generally had larger shell-to-shell differences ranging from 0.53mm to 0.84mm for males (no treatment) and from 0.66mm to 0.90mm for males (treatment). Females had a shell-to-shell difference ranging from 0.47mm to 0.69mm for females (no treatment) and 0.54mm to 0.65mm females (treatment).

Table 5.11 Recordings of shell-to-shell deviations over the comparison periods using T1 as a baseline. The percentage scores indicate the surface areas of the shells matching one another within a value of 0.85mm.

	T2 vs T1 (%)				T3 vs T1 (%)				T4 vs T1 (%)				T5 vs T1 (%)			
	Mean	**Sd**	**Min**	**Max**	**Mean**	**Sd**	**Min**	**Max**	**Mean**	**Sd**	**Min**	**Max**	**Mean**	**Sd**	**Min**	**Max**
Males (NT)	81.41	7.76	65.41	96.50	75.42	8.61	56.12	89.92	69.09	11.32	45.02	91.03	63.63	12.08	39.89	89.62
Females (NT)	84.80	8.51	66.70	99.77	80.49	10.38	58.99	95.65	74.17	9.32	60.97	95.36	70.25	9.75	54.24	87.70
Males (T)	74.47	11.44	57.04	88.80	70.06	11.35	46.74	86.07	64.43	7.99	54.94	79.91	57.78	10.70	40.95	79.91
Females (T)	80.21	8.46	63.29	92.93	76.42	7.70	62.40	86.63	76.98	7.16	64.88	89.78	72.36	8.61	60.72	87.22

Table 5.12 Recordings of shell-to-shell deviations over the comparison periods using T1 as a baseline. The means, standard deviations (sd), minimum and maximum values are recorded in millimeters.

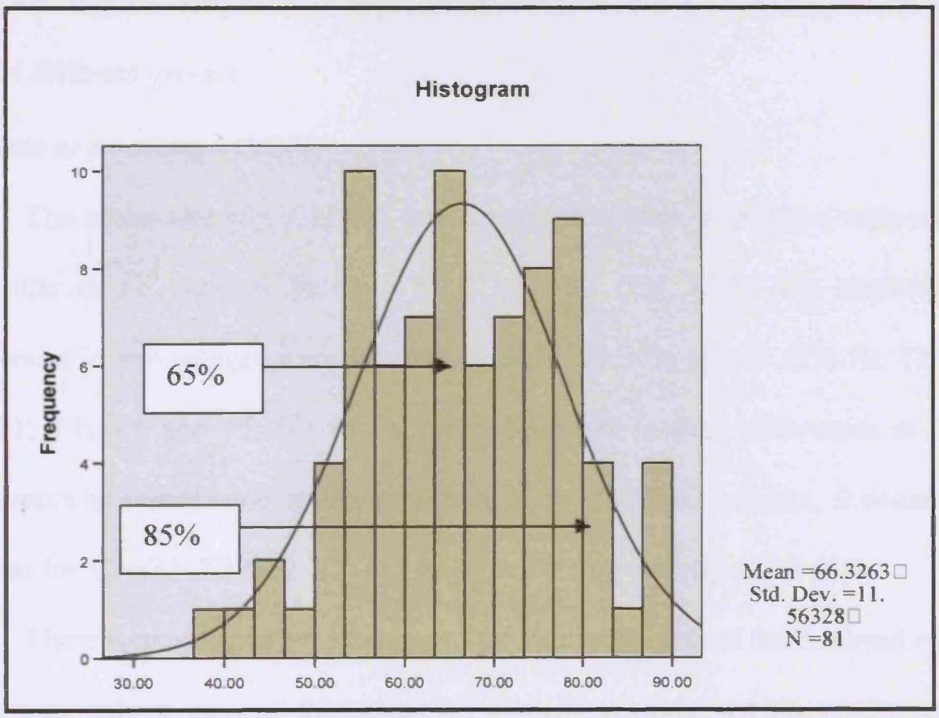
	T2 vs T1 (mm)				T3 vs T1 (mm)				T4 vs T1 (mm)				T5 vs T1 (mm)			
	Mean	**Sd**	**Min**	**Max**	**Mean**	**Sd**	**Min**	**Max**	**Mean**	**Sd**	**Min**	**Max**	**Mean**	**Sd**	**Min**	**Max**
Males (NT)	0.53	0.11	0.28	0.73	0.64	0.14	0.45	1.02	0.73	0.20	1.19	0.43	0.84	0.22	0.39	1.50
Females(NT)	0.47	0.15	0.07	0.84	0.55	0.16	0.34	1.00	0.63	0.16	0.34	0.98	0.69	0.15	0.42	0.99
Males (T)	0.66	0.21	0.43	1.08	0.72	0.22	0.46	1.23	0.79	0.16	0.54	1.04	0.90	0.20	0.54	1.18
Females (T)	0.54	0.14	0.36	0.80	0.59	0.11	0.45	0.81	0.60	0.11	0.41	0.81	0.65	0.14	0.43	0.85

The rates of change between the mean absolute difference between shells at T5 and T1 was larger for males. These were 0.31mm for the males (no treatment) and 0.24mm for males (treatment) groups.

5.3.2 Facial Changes and Age

The results in section 5.3.1 were further analyzed and a histo-plot made of the mean shell to shell scores. These are represented in Figure 5.16.

Figure 5.16 Distribution of mean shell to shell deviation scores on a histogram plot. The values 65% and 85% correspond to clear breaks in the normal distribution pattern.



From the plot, it was possible to group the shell to shell deviation scores in the following manner:

(i) Little or No changes ≥ 85%

(ii) Moderate Change 65% - 85%

(iii) Significant Change ≤ 65

The scores for little to no changes between composite faces was based on the previous validation findings that 90% of the maps should be well aligned before a reproducible facial morphology was acceptable (Kau et al. 2005b). A 5% leeway was incorporated and hence the value of N ≥ 85%. The moderate change grouping was to take into account changes that would incorporate a change in shell-to-shell difference of 1/3 of the face. Significant change was deemed to have happened to less than 65% composite faces match one another.

5.3.2 (a) Subject Examples

It is not possible within this thesis to analyze each change in the face for each individual subject. Therefore an appreciation of the results will be made for example in the 4 different groups.

- ***Little or no change (MNT)***

The composite face CL0036 was chosen at random to depict a male subject with little or no changes between all 4 intervals (Fig 5.17). The shell-to-shell differences in percentages were 88.10%, 86.72%, 91.30% and 89.62% for T2vsT1, T3vsT1, T4vsT1 and T5vsT1 respectively. The shell-to-shell differences in linear measurements represented as mean scores were 0.47mm, 0.48mm, 0.44mm and 0.39mm for T2vsT1, T3vsT1, T4vsT1 and T5vsT1 respectively.

There were no apparent changes to the central portion of the forehead region. There was only a general thickening of glabella regions just above the central portions of the eyes in the last time intervals T4vsT1 and T5vsT1. This ranged from 0.60mm to 0.62mm at the most prominent points at the two intervals. It seemed that the eyes moved anteriorly as the face changed with time. This area was confined to the eyeballs rather than inner and outer canthi of the eyes. The ranges of measurements were -2.93mm and -4.50mm. The nose showed the most changes with time and that general straightening of the nasal bridge and elongation of the nose in an anterior and downward direction. These changes ranged from 1.17mm to 2.0mm at the most prominent areas. There were visible negative changes in the cheek areas and the changes ranged from -1.08 mm to –2.50mm at its deepest points. There were some initial changes to the lips at the start but this was negligible at the end of the study period. The changes ranged from 1.17mm to little change for the upper lips. There were no apparent changes in the lower lip area. There was negligible soft tissue chin projection and elongation of the face.

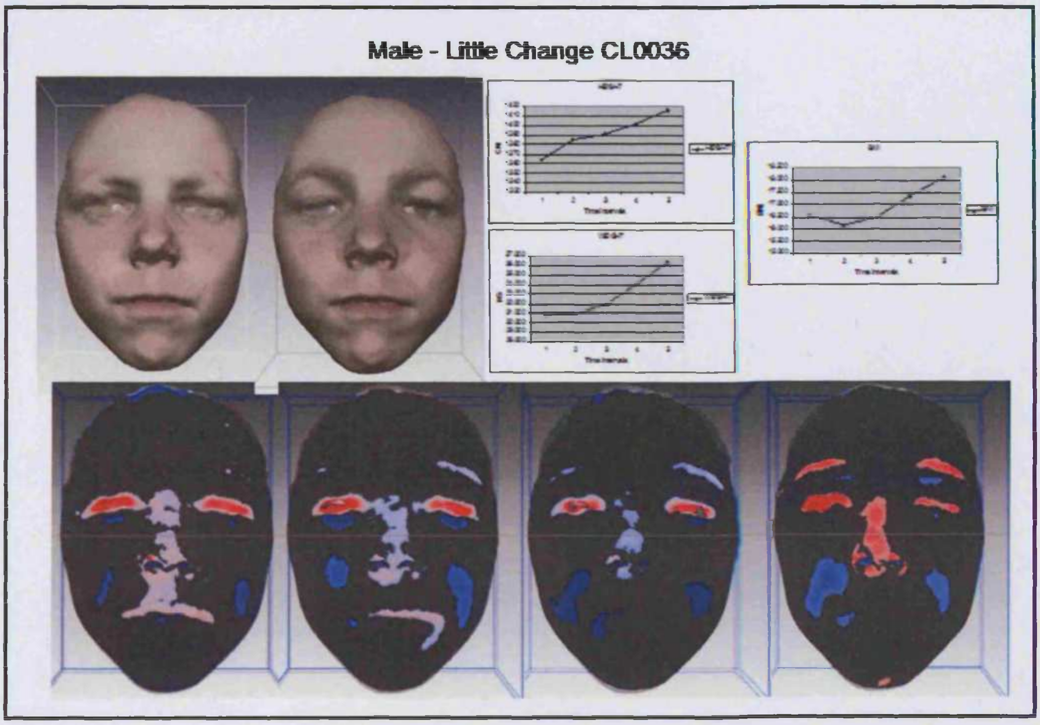


Fig 5.17 Male Subject CL0036 showing little or no change. Final Composite Face Comparisons. Body Parameters and soft tissue surface changes at T2vsT1, T3vsT1, T4vsT1 and T5vsT1.

- ***Moderate Changes (FNT)***

The composite face CN023 was chosen at random to depict a female subject with reasonable surface changes between all 4 shell-to-shell comparisons. (Fig 5.18). The shell-to-shell differences in percentages were 84.87%, 76.55%, 75.48% and

70.50% for T2vsT1, T3vsT1, T4vsT1 and T5vsT1 respectively. The shell-to-shell differences in linear measurements represented as mean scores were 0.41mm, 0.61mm, 0.60mm and 0.70mm for T2vsT1, T3vsT1, T4vsT1 and T5vsT1 respectively.

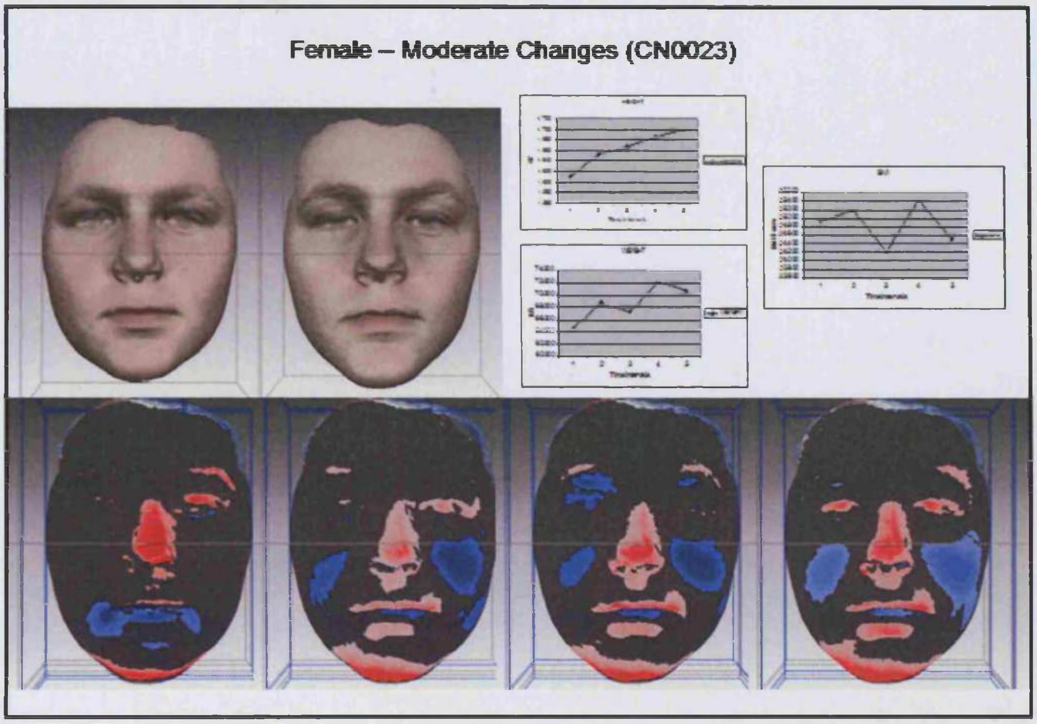


Fig 5.18 Female Subject CN0023 showing moderate change. Final Composite Faces Comparisons. Body Parameters and soft tissue surface changes at T2vsT1, T3vsT1, T4vsT1 and T5vsT1.

There were no apparent surface changes to the forehead region and eyes in this subject over the study period. The nose showed considerable changes with time. There was a general straightening of the nasal bridge and elongation of the nose in an anterior and downward direction. These changes ranged from 2.91mm to 3.53mm at the most prominent areas. There were visible and negative changes in the cheek areas across the time range and the changes ranged from negligible changes to -2.33mm at its deepest points. There were some initial changes to the lips at the start but this was negligible at the end of the study period. The changes were a direct result of the translation of the lips in a downward direction in correspondence with the nose. The changes ranged from 1.36 mm to 2.06mm of change for the upper lips. The lower lip changes ranged from negligible readings to 2.06mm. There was a small area of elongation of the vertical dimension of the face. This range was from 1.98mm to 3.53mm.

- ***Significant Changes (MNT)***

The composite face CN046 was chosen at random to depict a male subject with great changes between all shell-to shell comparisons against the baseline. (Fig 5.19) The shell-to-shell differences in percentages were 96.50%, 71.97%, 61.44% and 59.69% for T2vsT1, T3vsT1, T4vsT1 and T5vsT1 respectively. The shell-to-shell differences in linear measurements represented as mean scores were 0.28mm, 0.86mm, 0.94mm and 1.00mm for T2vsT1, T3vsT1, T4vsT1 and T5vsT1 respectively. The changes at T2vsT1 were not clinically significant.

There was little change to the majority of the central portion of the forehead region with the exception of T4vsT1. The eyes deepened as the face changed with time. This ranged from -0.30mm to -1.36mm. The nose showed changes with time and there was a general straightening of the nasal bridge and elongation of the nose in an anterior and downward direction. There was also a general broadening of the nose in a triangular fashion. These changes had a maximum difference of 2.35mm. There were considerable visible negative changes in the cheek areas. These values ranged from -1.42 mm to -2.58mm at its deepest points. The lip changes seem to follow the translation of the lips in a downward direction in correspondence with the nose. There was a greater translation of the upper and the changes ranged from 0.1mm to 1.95mm of change for the upper lips. The lower lip changes were approximately 0.90mm. There was a projection of the chin in an interior direction resulting in considerable elongation of the vertical dimension of the face. This was approximately 5.05mm.

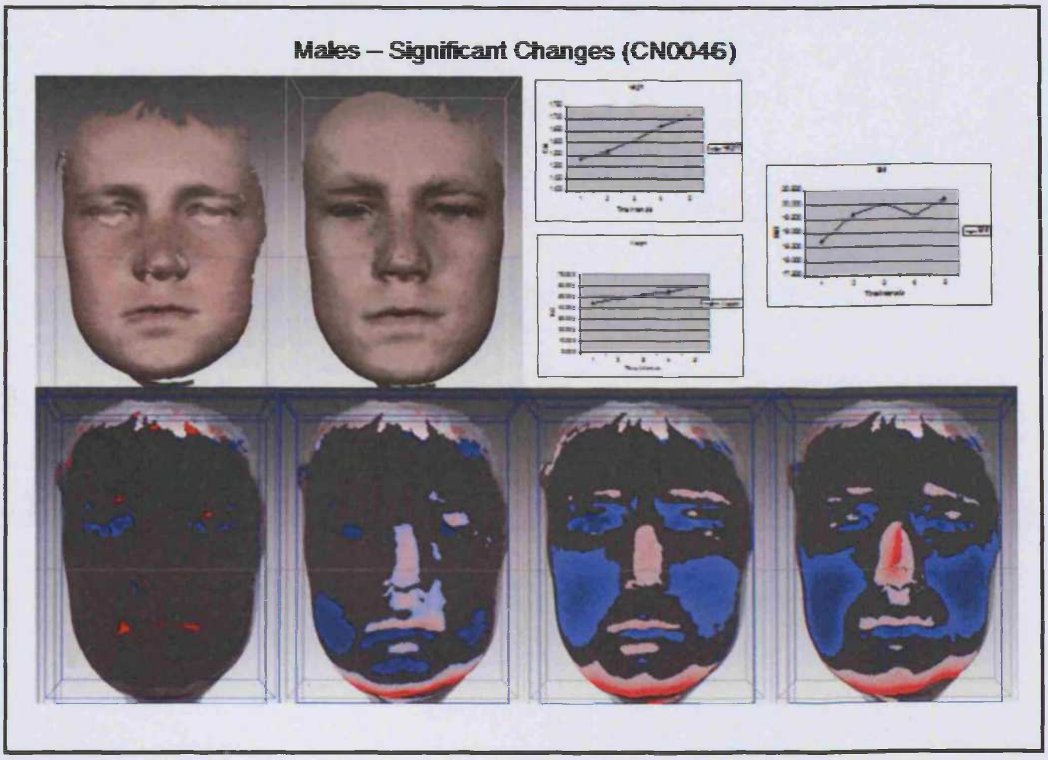


Fig 5.19 Male Subject CN0046 showing significant changes. Final Composite Face Comparisons. Body Parameters and soft tissue surface changes at T2vsT1, T3vsT1, T4vsT1 and T5vsT1.

- *Female Example (Treatment)*

The composite face CN019 was chosen at random to depict a female subject who had undergone orthodontic. Her appliances were placed in the mouth during the time of the first recall and the appliance treatment was completed before the last scan was taken (Fig 5.20). The shell-to-shell differences in percentages were 63.29%, 62.40%, 76.87% and 71.10% for T2vsT1, T3vsT1, T4vsT1 and T5vsT1 respectively. The shell-to-shell differences in linear measurements represented as mean scores were 0.79mm, 0.81mm, 0.67mm and 0.72mm for T2vsT1, T3vsT1, T4vsT1 and T5vsT1 respectively.

There was little change to the majority of the central portion of the forehead region. There were changes to the lateral portions in the time frame T5vsT1 and these were confined to the lateral portions above the orbits. The nose showed the most consistent changes with time and this was seen as a straightening of the nasal bridge and elongation of the nose in an anterior and downward direction. These changes had a maximum difference of 2.36mm. There were some changes in the cheek areas. These values ranged from -1.80 mm to -1.10mm at its deepest points. There were some interesting lip changes. There was large displacement of the lips within the two time frames corresponding roughly to the time when a removable and fixed appliance was placed. This displacement of the lips decreased as the patient became more adapted to the appliances and as the angulations of the incisor teeth changed. There was a small forward and downward translation of the lower lip and this was approximately 3.35mm. There was a considerable elongation of the vertical dimension of the face. This was approximately 4.75mm at its most prominent points.

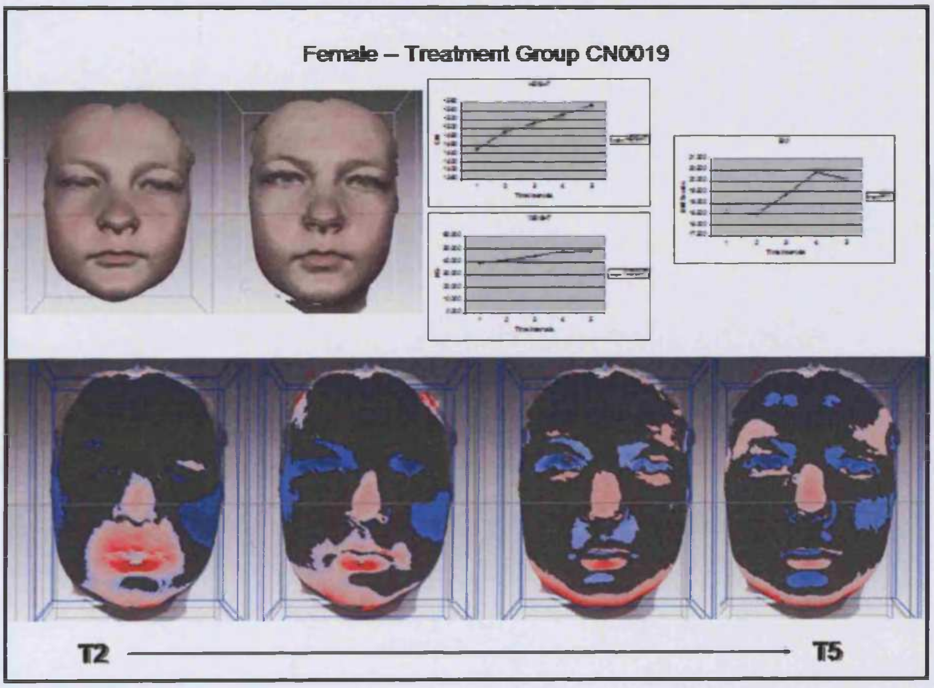


Fig 5.20 Female subject CN0019. Final composite facial comparisons, body parameters and soft tissue surface changes at T2vsT1, T3vsT1, T4vsT1 and T5vsT1.

5.3.2 (b) Summary and analysis of the normal BMI subjects

The results showed that as age increased, there was a corresponding increase in the surface differences of the individual's composite faces. To analyze the data further, the subjects were grouped by surface differences: little, moderate and significant changes. A tabular representation of the number of subjects grouped by gender and treatment and non-treatment groups are attached (Table 5.13). The number of subjects exhibiting the surface changes at the time intervals is displayed as well.

The subject numbers for each gender group was compared to determine if there were inter-pair differences between independent proportions (Newcombe 1998). For example, the numbers of males (MNT) and females (FNT) were compared at a particular time interval to determine if that particular inter-pair relation was significant. Only subjects in the non-treatment group were tested as the subject numbers in the other groups were too small to make meaningful comparisons.

The results of the statistical analysis showed that was a significant difference during the last time frame, T5vsT1, between males and females. The value of 0.28 obtained with a 95% confidence between 0.02 and 0.48, suggested that males exhibited a significantly greater amount of change and the magnitudes were larger (Kau and Richmond 2007b) (Table 5.14).

Table 5.13 Subjects ranked according to gender and treatment type undergoing differences rates of surface changes

Subjects	Changes	C1	C2	C3	C4
Males (NT) n=33	Little	16	8	4	1
	Moderate	17	21	19	14
	Significant	0	4	10	18
Females (NT) n = 26	Little	17	12	5	2
	Moderate	9	12	14	17
	Significant	0	2	7	7
Males (T) n=10	Little	3	1	0	0
	Moderate	5	7	5	2
	Significant	2	2	5	8
Females (T) n=12	Little	4	3	2	1
	Moderate	7	8	10	11
	Significant	1	1	0	0

Table 5.14 Statistical Analysis between male (NT) and females (NT) for surface changes. (L)-Little Changes, (M)-Moderate Changes and (S)-Significant Changes.

Comparison	Statistical Value	95% confidence	Significance
T2vsT1M(L)*T2vsT1F(L)	-0.17	-0.39 – 0.08	NS
T2vsT1M(M)*T2vsT1F(M)	0.17	-0.08 – 0.39	NS
T2vsT1M(S)*T2vsT1F(S)	NA	NA	NA
T3vsT1M(L)*T3vsT1F(L)	-0.22	-0.43 – 0.02	NS
T3vsT1M(M)*T3vsT1F(M)	-0.17	-0.08 – 0.40	NS
T3vsT1M(S)*T3vsT1F(S)	-0.04	-0.14 – 0.21	NS
T4vsT1M(L)*T4vsT1F(L)	-0.07	-0.27 – 0.12	NS
T4vsT1M(M)*T4vsT1F(M)	-0.04	-0.20 – 0.28	NS
T4vsT1M(S)*T4vsT1F(S)	-0.03	-0.20 -0.25	NS
T5vsT1M(L)*T5vsT1F(L)	-0.05	-0.21 – 0.09	NS
T5vsT1M(M)*T5vsT1F(M)	-0.23	-0.45 – 0.03	NS
T5vsT1M(S)*T5vsT1F(S)	0.28	0.02 – 0.48	S

5.3.3 DISTRIBUTION OF LEFT TO RIGHT SURFACE CHANGES

In this section, the distribution of left and right surface changes is presented. The face was also sub-divided into left and right halves to determine if there were differences in the surface changes with time. Two lines were incorporated manually and projected onto the face; one horizontally passing through the inner and outer cantus of the eyes, and one vertical line perpendicularly intersecting the horizontal line through soft tissue nasion. The surface change on the left and right sides was analyzed. If a surface change representing more than half the visual surface area was present, an asymmetric type pattern was deemed to have occurred.

5.3.3 (c) Summary of Results

The numbers of subjects exhibiting these types of surface changes are represented in Table 5.15. From the results there seems to be a presence of asymmetric difference in surface changes in 35% of the cohort of normal BMI children. This presence was present more in the right side (60%) of the face than the left side (40%).

Table 5.15 Distribution of right and left sided changes of facial surfaces.

Subjects (n=81)	Right Surface Changes	Left Surface Changes	Total	Percentage
MNT	6	5	11	13.58
FNT	9	3	12	14.81
MT	1	2	3	3.70
NT	1	1	2	2.47
Total	17	11	28	34.56

5.3.3 (b) Case examples

Two case examples are reported as an illustration to the results.

- *Female (FASY)*

The composite face CN034 was chosen at random to depict a female subject with asymmetric changes on the facial surfaces between progressive shell-to shell comparisons of all four time intervals (Fig 5.21).

The shell-to-shell differences in percentages were 85.85%, 84.29%, 79.44% and 74.40% for T2vsT1, T3vsT1, T4vsT1 and T5vsT1 respectively. The shell-to-shell differences in linear measurements represented as mean scores were 0.58mm, 0.73mm, 0.79mm and 0.76mm for T2vsT1, T3vsT1, T4vsT1 and T5vsT1 respectively. There was little change to the majority of the central portion of the forehead region with the exception of T4vsT1. There were some changes apparent more on the left side of the forehead region. These were small surfaces and ranged from 0.86mm to 2.44mm

The nose showed little surface changes with time. There were considerable visible negative changes in the cheek areas in time T4vsT1 and T5vsT1. These values ranged from – 0.42mm to -1.43mm at its deepest points. There was translation of the upper lips and the changes were in the period T5vsT1 and this ranged from negligible changes at T2vsT1 to 1.44mm of change for the upper lips. The lower lip changes were approximately 1.12mm. There was a small projection of the chin point downward resulting in an elongation of the vertical dimension of the face. In addition, there were asymmetric changes in the mandibular areas with the left side of the jaws exhibiting more changes than the right.

- *Male (MASY)*

The composite face CN002 was chosen at random to depict a female subject with asymmetric changes on the facial surfaces between progressive shell-to shell comparisons of all four time intervals (Fig 5.22).

The shell-to-shell differences in percentages were 81.78%, 73.80%, 50.70% and 45.79% for T2vsT1, T3vsT1, T4vsT1 and T5vsT1 respectively. The shell-to-shell differences in linear measurements represented as mean scores were 0.52mm, 0.67mm, 1.06mm and 1.10mm for T2vsT1, T3vsT1, T4vsT1 and T5vsT1 respectively. There was little change to the majority of the central portion of the forehead region in time T2vsT1 and T3vsT1. However, there were surface changes in the entire area above the orbital regions. These incorporated soft tissue nasion and the superior portions of the nose. These changes ranged from 1.02mm to 1.93mm. The nose showed large changes with time. There was a triangular pattern of growth seen in the frontal scans and these ranged between 1.31mm and 3.70mm. There were considerable visible negative changes in the cheek areas in time T4vsT1 and T5vsT1. These values ranged from – 0.01mm to -1.76mm at its deepest points. There was translation of the upper lips and the changes were in the period T5vsT1 and this ranged from 2.19mm to 2.85 for the upper lips. The lower lip changes were approximately 3.78mm. There was a small projection of the chin point inferiorly resulting in an elongation of the vertical dimension of the face. This was approximately 3.24mm to 5.17mm in the vertical direction. In addition, there were asymmetric changes in the mandibular areas with the left side of the jaws exhibiting more changes than the right and these changes seem to "shuffle" with time.

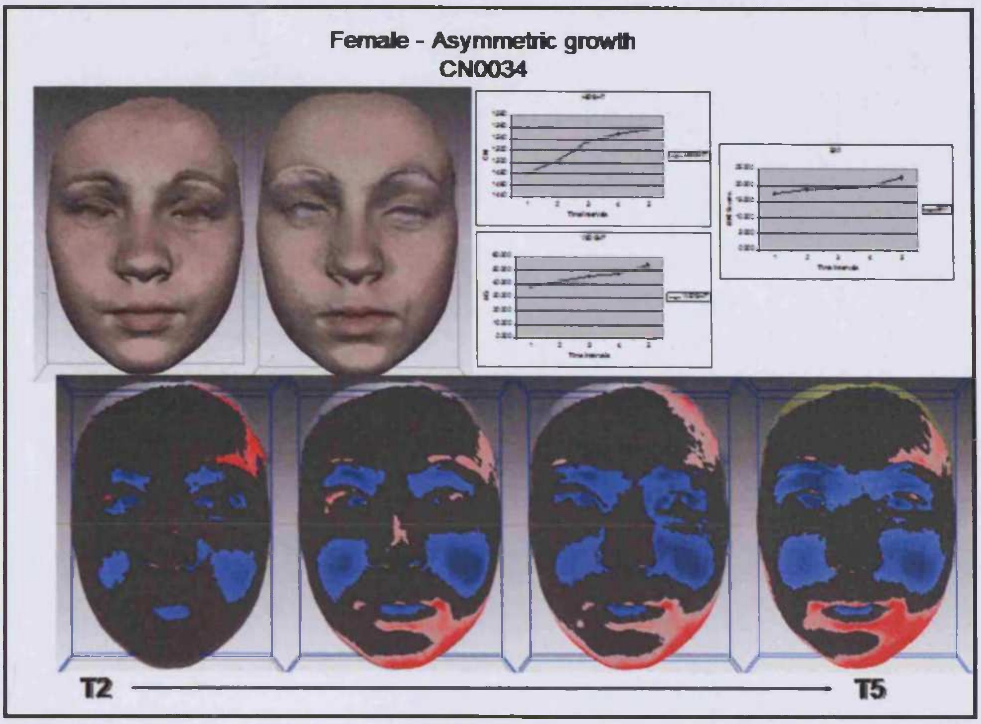


Fig 5.21 Figure showing the asymmetric pattern of growth in the mandible especially on the left side.

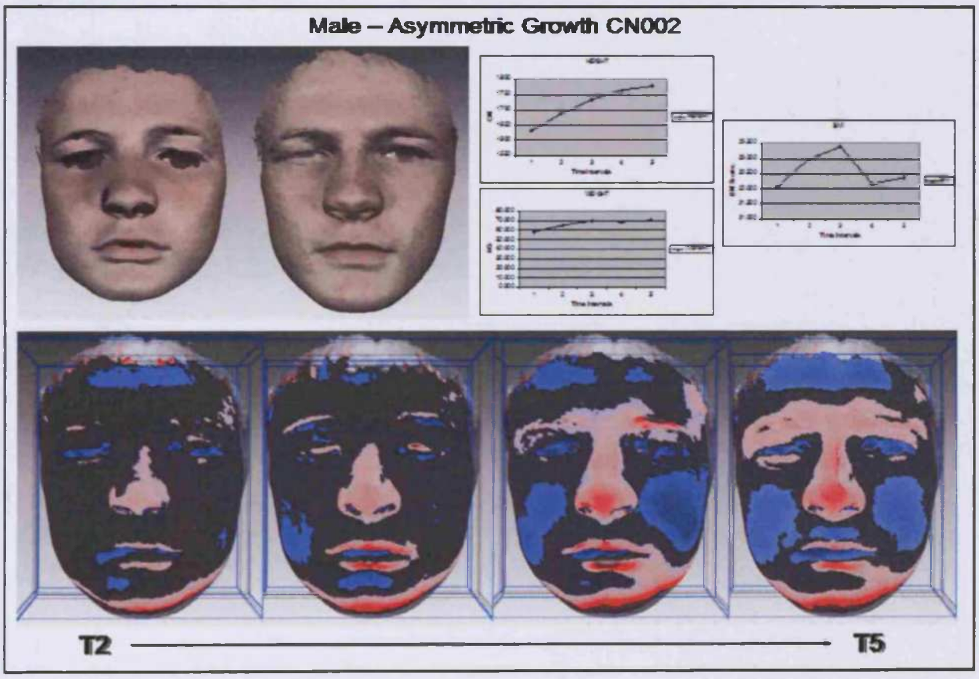


Fig 5.22 Figure showing the asymmetric pattern of growth in the nose and mandible especially on the left side.

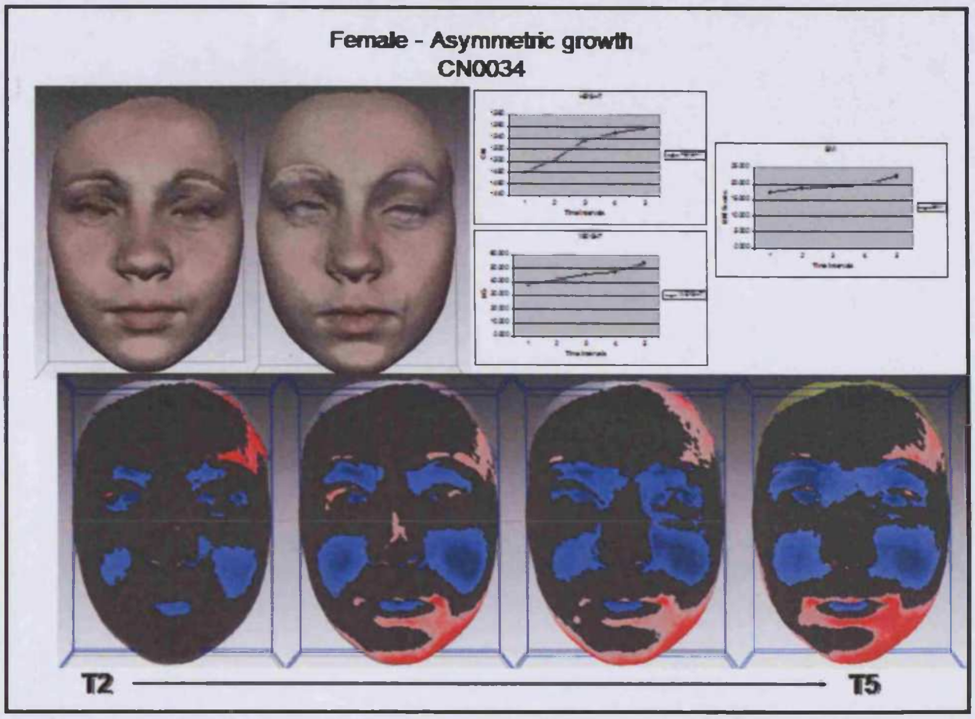


Fig 5.21 Figure showing the asymmetric pattern of growth in the mandible especially on the left side.

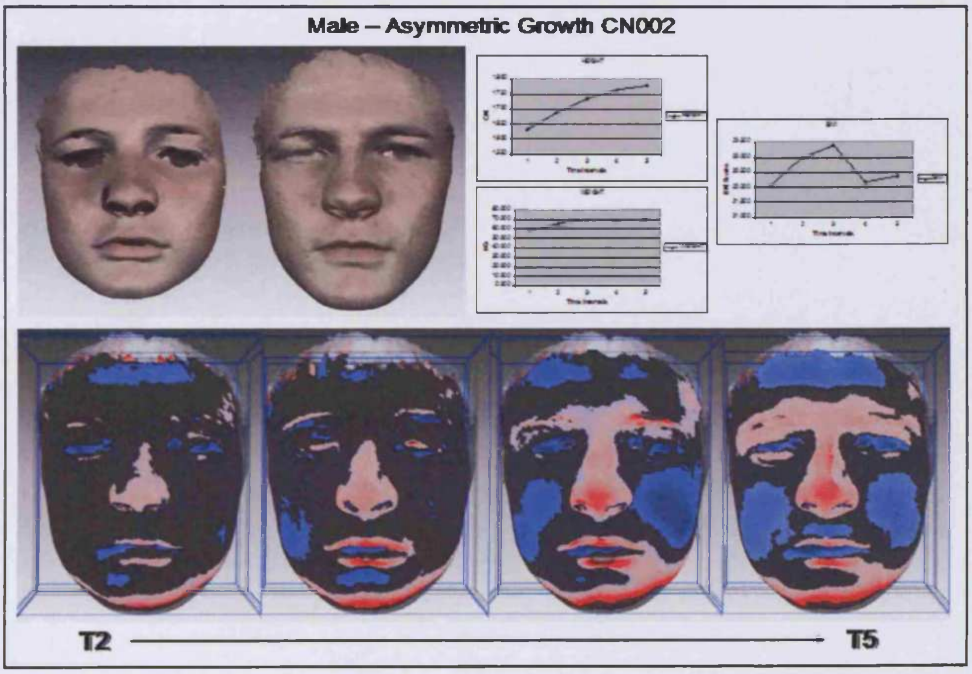


Fig 5.22 Figure showing the asymmetric pattern of growth in the nose and mandible especially on the left side.

CHAPTER 6

DISCUSSION

6.1 INTRODUCTION

The availability of low-cost, portable three-dimensional scanners has made the evaluation of soft tissue change due to growth or treatment possible (Kau and Richmond 2007a; Kusnoto and Evans 2002).

This study represents the first longitudinal growth studies using a three-dimensional laser imaging scanner. The subjects in the study were evaluated in a qualitative and quantitative manner. Careful attention was made to ensure standardization of image capture, in an attempt to determine the changes in facial shells over time to represent soft and hard tissue changes resulting from growth. This section will discuss the results and make inferences and evaluations based on current knowledge in the literature.

6.2 VALIDATION STUDIES

The use of three-dimensional laser imaging scanners on children is generally considered less ideal in the study of facial morphology (Ayoub et al. 2003). However, the validation studies have shown that the reliability of laser scanning in children and adults are of an acceptable level.

Interestingly, the validation studies showed that in general, males had higher mean shell deviation scores than females. The male subjects tended to be easily distracted when asked to remain perfectly still for the scanning process. Further analysis revealed a small difference in the facial maps of adults and children. The tolerance levels for the adults were more uniform than the children. This may be attributed to the fact that adults maintained a stable facial posture (Fig 6.1). The children scanned also seemed to be prone to minor muscular responses in the eyelid region and areas near the lips and chin. These errors were however, small, patchy and did not exceed 1.2mm (Fig 6.2).

Finally, the scanning time to capture facial morphology may be considered as being too long. This study has shown a high level of compliance both for a group of adults and children. It has been reported that the image capture of three-dimensional soft tissue morphology is complex (Mah and Enciso 2003) and should not be based solely on the speed of a scanning system alone, but on the ability to capture reliable soft tissue morphology over a range of time frames. Many facial expressions can occur within a couple of seconds, and it is important that the best and most consistent representation of facial morphology is captured each time a subject is scanned. Therefore, the reliability and quality of a laser-scanned image is dependent not only on the accuracy and speed of the capture system, but on an ideal and relaxed subject free from distractions. The system as described enables the accurate facial morphology to be captured.

6.3 REPRODUCIBILITY OF FACIAL POSTURE

There are very few studies that report the reliability of facial soft tissues. Only one study to date has attempted this but the small sample consisted of adults and the images were averaged before measuring between time frames (Nute and Moss 2000). This potentially amalgamates all errors during the averaging process (for example, cancellation of positive and negative errors) and may not give a true picture of reliability.

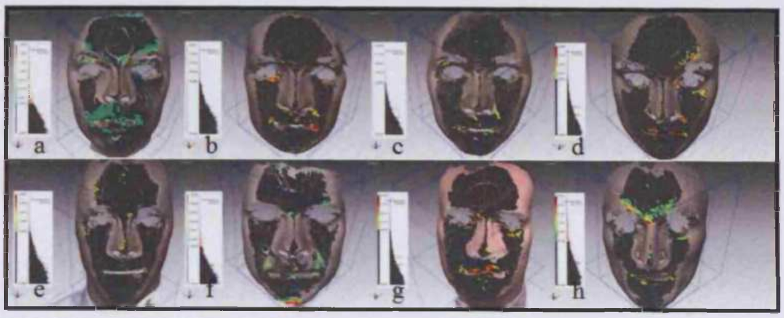


Fig 6.1 Adult facial maps set at a tolerance level of 0.5mm. Black < 0.5, Green <0.75mm and Red< 1.1mm. (a-d) Tolerance maps of female subjects. (e-h) Tolerance maps of male subjects.

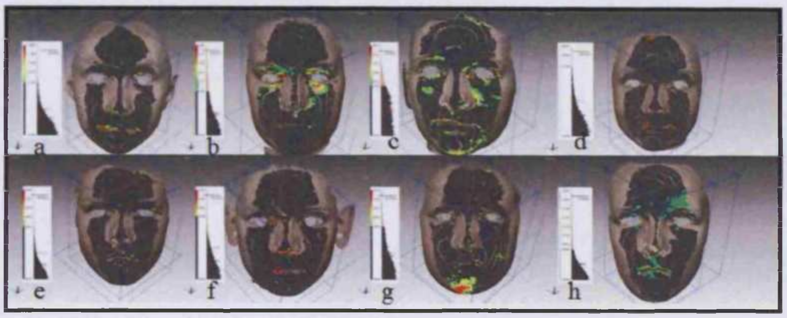


Fig 6.2 Facial maps of children set at a tolerance level of 0.75mm. Black areas <0.75mm, Green areas <0.90mm and Red areas <1.20mm. (a-d) facial maps of female subjects. (e-h) Facial maps of male subjects. In general, the levels of error are very small, patchy and non-uniform. This level of error is highly acceptable and non-significant.

This investigation within the validation studies, attempted to give an accurate reflection of the reproducibility of measuring soft tissues over a short period of time during which growth changes were unlikely. It did, however, rely on a strict protocol for capturing facial soft tissue morphology. When comparing the mean scores associated with the facial differences over two time periods (T1 and T2, T1 and T3), the results were similar. This implies that the subjects had the ability to adopt the same facial posture over time. Further analysis using colour histograms associated with the facial maps showed that a high level of soft tissue reproducibility could be achieved in the chosen cohort of subjects as seen by the dark area indicating no change within reproducibility limits (Fig 6.3). The greatest errors generated were in zones L, M and N in the lower jaw area (Fig 6.4). This finding was not unexpected as the lower jaw is freely movable. This error however does not, with the exception of one subject, affect more than 2 adjacent zones and never exceeds a mean error of 1.35mm. All other error zones are patchy, non systematic and are not detrimental to the overall reproducibility of facial morphology.

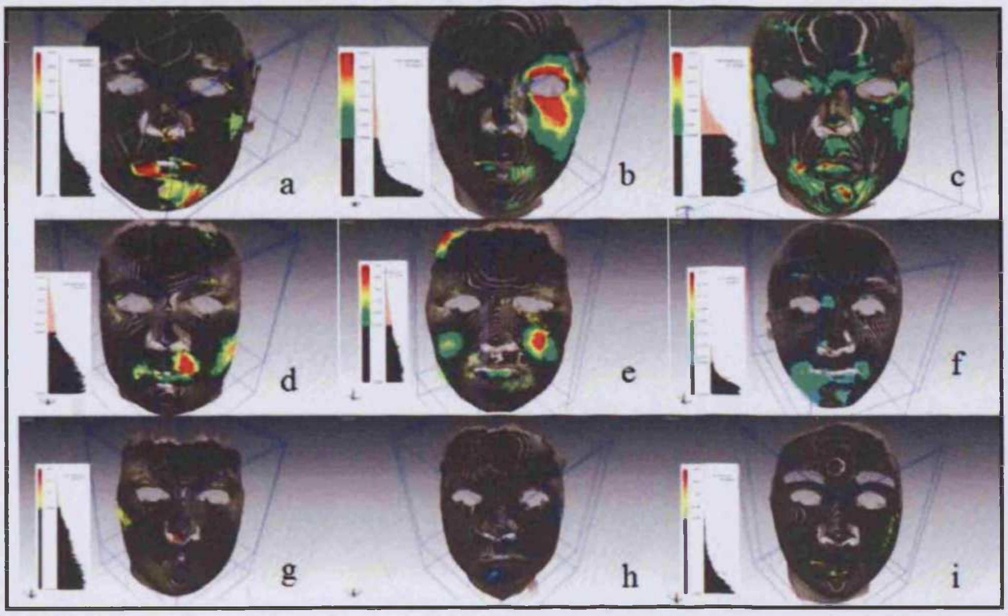


Fig 6.3 These figures illustrate the shell deviation maps when merged composite faces are aligned on top of one another with a tolerance level set at 0.85mm (black). Coloured areas indicate that the errors are higher than 0.85mm. Red scores range from 1.5-1.8mm and green scores from 0.9mm to 1.5mm. Fig 6(a) scores (1) in zone M, Fig 6(b) scores (1) each in zone F and G, Fig 6c (the worst facial map) scores (1) in each zone D, E, F, K and N, Fig 6(d) scores (1) in zone J, K, Fig 6(e) scores (1) in zone D and F, Fig 6(f) scores (1) in zone L, Fig 6 (g), (h) and (i) do not accrue scores.

At the tolerance level of 0.85mm, the errors recorded in the zones did not exceed more than 8 readings per zone and the number of zones with more than 5 readings was small. This accounted for only 5 out 15 zones (Fig 6.4). Furthermore, the shell errors were often small and non-uniform. Presentations of the range of facial maps corresponding to a tolerance of 0.85mm are shown in Fig 6.3. The reproducibility value of 0.85mm was applied to all comparisons of surface changes between faces in the longitudinal cohort study and represented an accurate means to assess facial growth.

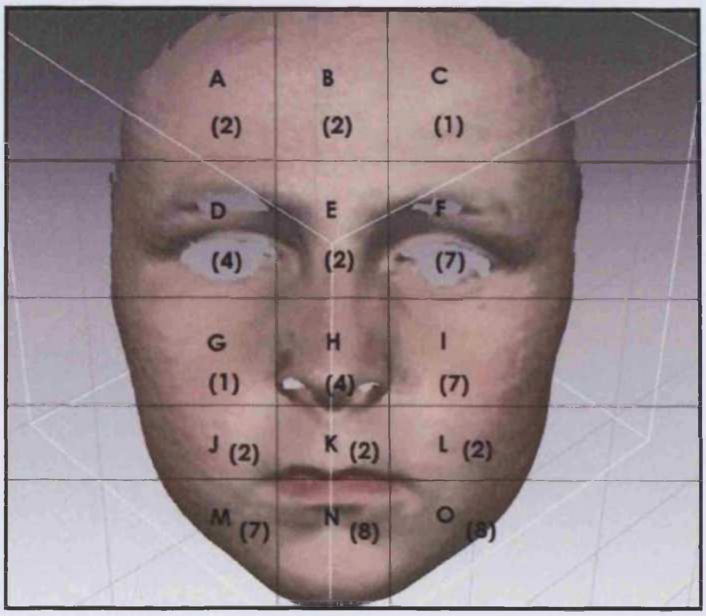


Fig 6.4 Facial map showing 15 zones and number of errors in each zone for 40 subjects used in the validity studies.

6.4 LONGITUDINAL GROWTH STUDY

As previously mentioned, the results of this study form part of an on-going longitudinal investigation of soft tissue changes in a cohort of Welsh children now known as the Cardiff longitudinal study of facial morphology. Longitudinal studies have the advantages of providing real indications of changes that occur in individual subjects. The investigation provided three-dimensional scans over five time intervals 6 months apart. The disadvantage of a longitudinal study design lies in the enormous effort required to collect the data and retain the subjects.

This study was set up to assess the feasibility of quantifying facial change in a cohort of children aged 12-14. The sample size consisted initially of 95 subjects and

86 remained at the end of the investigation. Nine subjects left the school due to a variety of reasons. Nevertheless, it was possible to determine facial change in males and females greater than 0.85mm. Other challenges within the study cohort included the difficulty in monitoring the orthodontic treatment undertaken. The number of subjects who had not received orthodontic treatment was reduced to 64 (75%) at the end of the study period.

6.5 SUPER-IMPOSITION METHODS

Many superimposition methods have been used by orthodontists to assess facial change as a result of growth and orthodontic treatment. The main approach is to superimpose stable structures of the face at two time points and to evaluate changes around those stable structures. However there are no truly stable points in a growing child. Some researchers have found that the anterior cranial base is relative stability after 8 years of age (Stamrud 1959) but its absolute stability is questionable. In later years, techniques have been simplified to incorporate super-imposition points (e.g. Sella and Nasion) to provide clinicians with a quick and easy way of evaluating change. However, depending on the point of superimposition (either S or N) different changes are observed (Ghafari et al. 1998). Probably the gold standard for a stable point is to create them (e.g. Implants) but these come with ethical issues and may be displaced if placed in regions that undergo remodelling and deposition (Björk 1968).

The variability of soft tissue superimpositions of the face is even more contentious than hard tissues due to changes in these surfaces. However attempts have been made successfully in the past to study soft tissue changes. Nute and co-authors (2000) used 5 points (the inner and outer corners of the eyes and nasal tip) to create a plane from which 5 other points were mathematically constructed to line faces for analysis. Hajeer and co-workers identified anthropometric landmarks to line faces before using a Procrustes best-fit method for analyzing soft tissue changes (Hajeer et al. 2002b; Hajeer et al. 2004a). Guest and co-workers (Guest et al. 2001) evaluated four different methods of superimposing faces on two surgical patients. They found that all the methods employed produced some error when calculating the final surface changes. However, the "closest point" algorithm and Correspondence by Sensitivity to Movement (CSM) algorithm produced the most promising and realistic results as these methods made no assumptions to the direction of the displacement between surfaces.

In this study, the superimposition method known as the "best fit" or "iterative closest point" algorithm was used. This method is mathematically derived and essentially matches closely related triangular vertices of two similar surface shells and approximates them to one another. The resultant errors in distances corresponding to two surfaces are averaged and the shells are fitted together. This method is used in the automotive and aeronautical industries to detect defects and quality control to an ideal template mould of different service parts and has been showed to be a reliable tool.

To evaluate the reliability of the method, the sets of facial scans of 5 individuals were randomly selected. The method of superimposition showed points of stability matching to areas previously known to be stable. For example, the outer canthi of the eyes did not change and a line running over the eyelids stayed essentially unchanged when seen on the lateral view (Fig 6.5). – CD version included.

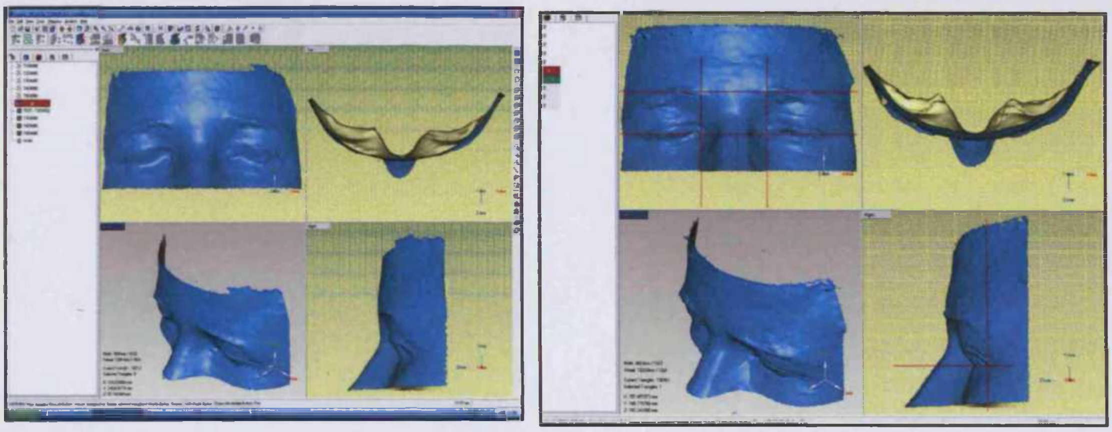


Fig 6.5 Superimposition techniques using the best fit or ICP algorithm showing regions of stability and change (note the high stability and reproducibility of the outer canthi of the eyes).

6.6 METHODS OF ANALYSIS OF CHANGING DATA

Several studies have used landmark identification for assessing three-dimensional growth (Farkas and Posnick 1992; Hennessy and Moss 2001) to identify changes in shape and landmarks. Growth, however, is more complex as facial anatomical landmarks do not exist in the same sense as projected landmarks.

Coombes (1991) reported one of the first articles utilizing mathematical modelling to quantify facial changes. The author used measurements of facial changes on 2 subjects and described surface types based on an extension from an earlier concept described. These included a total of eight surface types - peak, flat, minimal, ridge, pit, saddle, valley and saddle valley (Besl and McKay 1992).

Furthermore, changes in patch sizes and movements on the face - changes in the areas, centres of gravity, orientation of lengths of the principle axis and secondary axis were - compared (Coombes et al. 1991). Some other mathematical methods used facial polygons to determine the changing facial features according to the shadowing of facial features in light and facial expression (Okada 2001).

Mathematical models are a clever way to say describe three-dimensional information but they do not describe volumetric changes and the general shape of the face.

Another method of facial analysis utilised colour facial mapping. These were used in the laser based studies and often had large measurement intervals (1-2mm) and were carried out predominately on facial averages (Ismail et al. 2002a; McCance et al. 1992b).

Early volume measurements were inaccurate as they required a skilled operator to manually outline the volumetric change and extract the data. Later versions were semi-automated but still required human manipulation and the errors were in the region of 3-5% of the volumes measured (Hajeer et al. 2005; Yip et al. 2004).

Three-dimensional assessment of growth requires quantification in terms of topography, surface area and volume. This study has shown that colour mapping with associated histogram evaluations could be used as an efficient tool. Furthermore, the automatic quantification of surface and volume changes has enhanced the visualization of facial changes over time.

6.7 THE USE OF AVERAGE FACES

Three-dimensional average faces have been described previously in the literature and serves as an excellent basis to understand complex three-dimensional data sets (Kau et al. 2006c). Hutton and co-workers built dense surface models from 421 facial scans of subjects aged 1-80 years old (Hutton et al. 2001). In his study, the faces were aligned, based arbitrarily on 10 surface landmarks before a hybrid combination of iterative closest point and active shape fitting algorithms were applied. The final dense surface model was used to assist in the diagnosis of

Noonan's Syndrome (Hammond et al. 2004). Average faces have also been described by Moss et al. His group used average faces to compare treatment changes amongst extraction versus non-extraction (Ismail and Moss 2002a) cohorts and also cross-sectional growth changes amongst children (Nute and Moss 2000). However, the process of averaging faces was not mentioned.

6.8 FACIAL DIFFERENCES IN GROUPS STUDIED

The average faces for males and females enables determination of morphological differences. Morphological differences were seen in the zygomatic regions, nose and lips. The prominence of the glabella, nasal bridges and lower face height tended to be greater in males. Females tended to show greater prominence in the cheeks and lips (Fig 6.6).

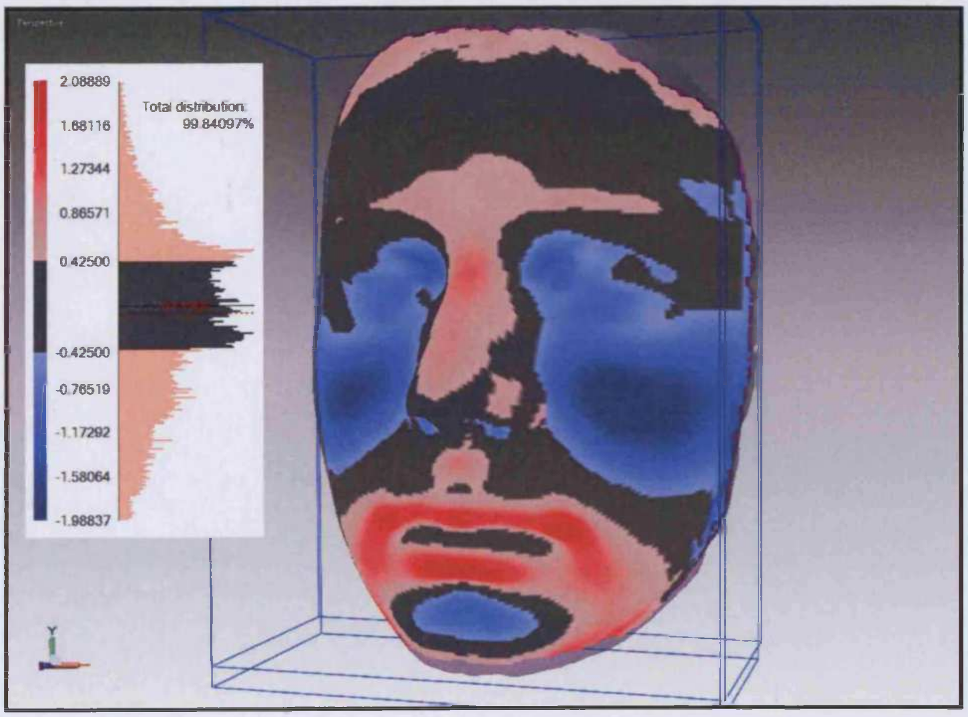


Fig 6.6 Facial averages of males and females superimposed on one another. Areas in blue show negative changes whilst areas in red show positive changes.

6.9 ANALYZING FACIAL GROWTH

Not many studies have been reported in the literature on soft tissues changes in the face. The majority have been undertaken on photographic and cephalometric soft tissue profiles. The results from this study in part supports some of the previous reported soft tissue studies.

Genecov and co-workers (1990) looked at the soft tissue changes of 64 cases (32 Class I and 32 Class II cases). Three time frames were selected (T1- 7 years and 6 months, T2 – 12 years and 5 months, T3 – 17y years and 2 months). Anterior posterior changes were present in the early years (7-12 years) with females exhibiting more anterior posterior nasal changes. During the middle years the males showed a much greater change of 4-5mm compared with 2mm for females. In addition, the vertical dimensions were larger for males than females at age 17 years by almost 7mm.

6.10 SURFACE CHANGES AND CLINICAL IMPLICATIONS

Most of the available data on the changing soft tissue profile has been obtained from cephalometric data with additional material from a small number of three-dimensional studies. Research into soft tissue imaging must take into account a valid and reliable set up to capture facial posture and the premise that changes to the soft tissue should be correlated to the underlying hard tissues (Riolo et al. 1987).

Correlating soft tissue profiles to body parameters like BMI, can be questionable. Probably the only reference correlating BMI to soft tissue profile was carried out by Riolo and co-workers on a pre-selected sample of the Michigan growth. He used data collected from the ages of 6-16 years (Riolo and TenHave 1986) and found that the BMI had a significant effect on the relationship between growth changes in the hard and soft tissue profiles in children with higher BMIs. This group of children also had thicker soft tissue profile measurements and greater horizontal profile measurements. However, no conclusive differences were found in other sample groups. As a result of these findings, children with a high BMI (n=7) were excluded from this study due to the variability to the possible findings.

6.10.1 Surface Changes and age

In this sample of normal children who received no history of orthodontic treatment, it was found that the magnitude of soft tissue changes, measured as absolute values between individual and average facials shells, was larger in males when compared to females. This was consistently the case in all the time frames measured. Previous studies have shown that the magnitudes of change are larger in boys than in girls (Bishara 2000; Vig and Fields 2000). For example, male subjects exhibit larger changes in facial dimensions and also at a later stage than their female counterparts. This was certainly the case in this sample group. In addition, the number of subjects falling into the "significant changes" category was significantly more in males and females. Interestingly, this change was also seen at around the age of 14 years for males, indicating the possibility that these changes could be related to the timing of puberty for males (Proffit 2000a).

In the average faces, there was a general downward and forward growth of the nose in relation to soft tissue nasion. The lips also translated in a downward direction as the nose grew and there was a general increase in the vertical dimension. The brows become more prominent and there was a flattening of the cheeks on both sides of the face. If the soft tissue nose is taken into account, then the profile of the face also increases in convexity with time.

The results seem to suggest that clinicians have to be careful when treatment plans are prescribed and administered (Kau and Richmond 2007b). Clinicians must therefore be weary not to be over zealous in extraction treatment or borderline camouflage treatments (retraction of the upper lips in mild Class II cases), as these may inevitably worsen the profile. The timing of such treatments should also be taken into consideration, as males seem to have later facial changes. Furthermore, these changes are relatively large in magnitude.

6.11 SURFACE AREAS AND VOLUMES

Surface areas and volume changes were successfully illustrated and quantified in this study of facial changes in time. This represents a unique addition to the literature as no previous studies have been carried out. This study was able to illustrate the surface changes by means of visual video sequences. Furthermore, a unique way of presenting volumes was also illustrated.

Studies in the literature have reported on the three-dimensional volume changes to a varying degree of accuracy. O'Grady (1999) was one of the first to show that volumes could be calculated. His study on a plaster model and silicone implants reported a 16.2% error in volume from the originals. Yip and co-workers used a model involving 20 human subjects to simulate facial swelling for image acquisition and measurement in order to assess the accuracy and reproducibility of the a light structured three-dimensional range finder. A systematic error of 1.25% and reproducibility of 3.27% was determined for the imaging system. Finally, Hajeer and co-workers used 30 facial silicones explants and added these to various regions of the face. They found that a 2.82% error existed in volume calculations.

Volumes are becoming more important in quantifying surface changes. It gives an added dimension and adds to the diagnostic database in treatment planning.

6.12 ORTHODONTIC VERSUS NO ORTHODONTIC TREATMENT

The extraction and non-extraction debates of Angle (1900) and Case (1896) are well known. These debates led to a change in the extraction philosophies of Tweed (1944) and Begg (1954) and have had a profound influence on the way orthodontics has been practised and taught clinically (Begg 1954; Tweed 1944).

In recent times, the treatment philosophies have moved from an extraction to non-extraction approach based on facial aesthetics rather than the dental occlusion. Most studies to date have used retrospective two-dimensional data from lateral cephalograms for analysis (Paquette et al. 1992; Young and Smith 1993).

Ismail and Moss (2002) carried out a three-dimensional laser scanned study on 24 patients with similar occlusions . They found that the average face of the non-extraction patients was of generally greater in dimension compared to the extraction average, both at the start and the end of treatment. During the fixed appliance treatment, the vermilion of the upper lip became more protrusive to a similar extent in both groups in relation to the reference plane. The lower lip vermilion and the philtrum showed no change for either group over the treatment time. The labio-mental fold area showed a slightly greater forward movement in the extraction group with treatment. Three-dimensional optical surface scanning allows data from the whole of the face to be assessed, as opposed to the lateral profile view used in the majority of the studies to date. The effects of the two types of treatment on the facial soft tissues were very similar, indicating that orthodontic treatment involving the extraction of teeth does not have a detrimental effect on the face.

The findings in our study indicated that large differences existed between the MNT and MT groups evaluated over time. As a result it was not possible to make comparisons between the two groups. The separate evaluations of these two groups however, show little difference in the trends of surface changes (i.e. the brows, cheeks, lips, nose and mandible grew in similar increments). It could be inferred that the subjects in this group did not differ in great detail as they grew.

Interestingly, the FNT and FT were better matched as indicated by a closer match of the average faces (Fig 6.7). The final T5 result showed more changes to the upper lip and lower regions (0.5mm – 2.12mm). This may be attributed to the number of subjects under going an extraction form of treatment. However, the results should be treated with caution as the samples were not matched exactly to malocclusion and the details of treatment undertaken were not known.

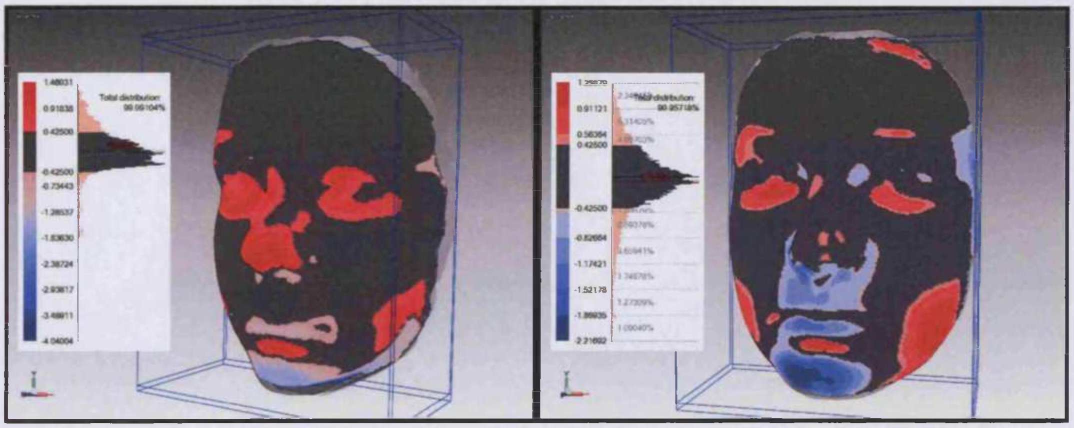


Fig 6.7a) Little differences between two shells FT and FNT at T1. b) Visible changes to upper lip and lower mandible at T5.

6.13 FACIAL ASYMMETRY

The assessment of facial asymmetry can only be carried out on from the frontal view. The posterior anterior, frontal photographs and traditional anthropometry are such examples. Whilst many growth studies have evaluated profile changes in anterior posterior and vertical dimensions, the transverse dimension has been largely ignored.

The results show that up to 35% of the subjects studied exhibited some form of asymmetry during the growth period examined. Some asymmetric growth patterns may lead to pathological problems in the future whilst others may account for the "normal asymmetry" described by some authors (Proffit 2000b).

These findings have shown that three-dimensional serves as a useful tool for the better understanding of transverse diagnosis and problem solving in the transverse dimension.

CHAPTER 7

CONCLUSIONS

The following conclusions could be drawn from this study of facial morphology:

1. The three-dimensional laser capture technique described is both valid and reliable.
2. The study has shown that the use of three-dimensional imaging is a feasible method in the analyzing and perceiving of changes to the face over time.
3. Males and females show differing facial morphology.
4. The magnitudes of surface changes are larger in males than in females.
5. There is a significant difference in the timing of the surface changes in males than in females, with males exhibiting later changes.
6. There is forward growth particularly occurring in the nose, brows, lips and vertical dimensions of the face.
7. There seems to be a deepening of the eyes and flattening of the cheeks.
8. Clinicians should be aware of three-dimensional surface changes that result from growth and treatment.
9. Growth was shown to be variable in this age group of 11-14 year olds. Some children have illustrated significant growth changes whilst others very little, and this may depend on the period of capture related to their growing period.
10. There was a difference between the facial morphology of females who received and did not receive orthodontic treatment. These differences were seen particularly in the upper and lower lip regions.
11. However, there was very little difference in individuals who received and did not receive orthodontic treatment.
12. Asymmetric growth patterns were seen occurring in 35% of the cohort studied with right sided differences being more than left sided differences.

CHAPTER 8

REFLECTION AND FUTURE WORK

This thesis forms the first known longitudinal study using a three-dimensional scanner. The ease of use and its portability means that this device can be taken directly to the subjects (i.e. school setting) rather than the subjects travelling to a specialised facility.

The results have shown that three-dimensional scanning is both valid and reliable. As a result of the initial investigative work, a number of software macros and analysis procedures have been developed to create a better understanding of facial morphology. There was a unique way of representing facial changes and the exact nature by which the face changes with time were better illustrated in the third dimension. This data may be used in the future to monitor and predict facial change during growth, identify differences from normal plan treatment and surgery for those patients presenting with craniofacial anomalies (Appendix 5) and allow facial modelling for missing persons over time.

In recent years, three-dimensional technologies (hard and soft-ware) have improved. Newer systems are lighter and more portable and possess a quicker image acquisition. The surface mesh qualities have also improved.

During the course of this study, land-marking was avoided as points in three-dimensional co-ordinate of space did not fully represent the changes that occurred. As a result tools were developed to depict surface and volume changes and used to evaluate changes on the average faces. As result, a clearer understanding of facial changes was achieved. However, these tools are still prototypes and are being refined to compute surface and growth changes on individual samples, and were not available during this study. These will be carried out at a later date and for future analysis.

It is hoped that this study will serve as a basis for the recruitment and analysis of larger cohorts of subjects and patients. In combination with CBCT, magnetic resonance imaging and ultra sound imaging, surface imaging will provide a better understanding of the three-dimensional relationships of the hard and soft tissues.

Three-dimensional imaging is becoming readily available and the methods and techniques used in this thesis form the basis of routine assessment that can be applied to other areas of craniofacial research.

CHAPTER 9

REFERENCES

Ackerman, J. L., Proffit, W. R. and Sarver, D. M. (1999).
The emerging soft tissue paradigm in orthodontic diagnosis and treatment planning.
Clinical Orthodontic Research **2**: 49-52.

Adams, C. P. (1971).
A study of individual dental and facial growth from five to fifteen years.
Tandlaegebladet 75(12): 1235-46.

Aldridge, K., Boyadjiev, S. A., Capone, G. T., DeLeon, V. B. and Richtsmeier, J. T. (2005).
Precision and error of three-dimensional phenotypic measures acquired from 3dMD photogrammetric images.
American Journal of Medical Genetics **138**(3): 247-53.

Andrews, L. F. (1972).
The six keys to normal occlusion.
American Journal of Orthodontics **62**(3): 296-309.

Angle, E. H. (1900).
Treatment of malocclusion of the teeth and fractures of the maxillae.
Philadelphia, SS White Mfg Co.

Angle, E. H. (1907).
Treatment of malocclusion of teeth.
Philadelphia, SS White Dental Manufacturing Company

Arnett, G. W. and Bergman, R. T. (1993).
Facial keys to Orthodontic Diagnosis and Treatment Planning. Part 1.
American Journal of Orthodontics and Dento-facial Orthopedics **103**: 299-312.

Aung, S. C., Ngim, R. C. and Lee, S. T. (1995).
Evaluation of the laser scanner as a surface measuring tool and its accuracy compared with direct facial anthropometric measurements.
British Journal of Plastic Surgery **48**(8): 551-8.

Ayoub, A., Garrahy, A., Hood, C., White, J., Bock, M., Siebert, J. P., Spencer, R. and Ray, A. (2003).
Validation of a vision-based, three-dimensional facial imaging system.
Cleft Palate Cranio-facial Journal **40**(5): 523-9.

Ayoub, A. F. and Stirrups, D. R. (1993).
The practicability of finite-element analysis for assessing changes in human craniofacial morphology from cephalographs.
Archives of Oral Biology **38**(8): 679-83.

Ayoub, A. F., Wray, D., Moos, K. F., Siebert, P., Jin, J., Niblett, T. B., Urquhart, C. and Mowforth, R. (1996).
Three-dimensional modeling for modern diagnosis and planning in maxillofacial surgery.
International Journal of Adult Orthodontics and Orthognathic Surgery **11**(3): 225-33.

Ayoub, A. F., Wray, D., Moos, K. F., Jin, J., Niblett, T. B., Urquhart, C., Mowforth, P. and Siebert, P. (1997).
A three-dimensional imaging system for archiving dental study casts: a preliminary report.
International Journal of Adult Orthodontics and Orthognathic Surgery **12**(1): 79-84.

Ayoub, A. F., Siebert, P., Moos, K. F., Wray, D., Urquhart, C. and Niblett, T. B. (1998).
A vision-based three-dimensional capture system for maxillofacial assessment and surgical planning.
British Journal of Oral Maxillo-facial Surgery **36**(5): 353-7.

Barnett, A. and Whitaker, L. A. (1986).
Facial form analysis of the lower and middle face.
Plastic and Reconstructive Surgery **78**(2): 158-65.

Baumrind, S. and Frantz, R. C. (1971a).
The reliability of head film measurements. 2. Conventional angular and linear measures.
American Journal of Orthodontics **60**(5): 505-17.

Baumrind, S. and Frantz, R. C. (1971b).
The reliability of head film measurements. 1. Landmark identification.
American Journal of Orthodontics **60**(2): 111-27.

Begg, P. R. (1954).
Stone Age man's dentition.
American Journal of Orthodontics **40**(3): 298-312.

Behrents, R. G. (1984).
A treatise on the continuum of growth in the aging craniofacial skeleton.
PhD Thesis. Ann Arbor. University of Michigan. Center for Human Growth and Development.

Berghagen, M. (1951).
Photogrammetric principles applied to intra-oral radiodontia. A method for diagnosis and therapy in odontology.
Stockholm

Berkowitz, S. and Cuzzi, J. (1977).
Biosterometric analysis of surgically corrected abnormal faces.
American Journal of Orthodontics **72**(6): 526-538.

Besl, P. J. and McKay, N. D. (1992).
A method for registration of 3-D shapes.
IEEE Transactions on Pattern Analysis and Machine Intelligence **14**(2): 239-256.

Bhatia, S. N. and Leighton, B. C. (1993).
A manual of facial growth: A computer Analysis of longitudinal cephalomteric data.
Oxford, Oxford Medical Publications

Bishara, S. E. (2000).
Facial and dental changes in adolescents and their clinical implications.
Angle Orthodontist **70**(6): 471-83.

Bjork, A. (1968).
The use of metallic implants in the study of facial growth in children: method and application.
American Journal of Physical Anthropology **29**(2): 243-54.

Bjork, A. (1969).
Prediction of mandibular growth rotation.
American Journal of Orthodontics: 39-53.

Bjork, A. (1991).
Facial growth rotation--reflections on definition and cause.
Proceedings of the Finnish Dental Society **87**(1): 51-8.

Bjork, A., V Skieller and T Linde-Hansen (1963).
Variations in the growth pattern of the human mandible: Longitudinal Radiographic Study by the implant method.
Journal of Dental Research. **42**(1): 400-411.

Bjork, A., V Skieller and T Linde-Hansen (1984).
Prediction of mandibular growth rotation evaluated from a longitudinal implant sample.
American Journal of Orthodontics **86**(5): 359-385.

Bjorn, H., Lundqvist, C. and Hjelmstrom, P. (1953).
A photogrammetric method of measuring the volume of facial swellings.
Journal of Dental Research **33**(3): 295-308.

Blais, F. (2004).
Review of 20 years of range sensor development.
Journal of Electronic Imaging **13**(1): 231-240.

Boersma, H. (1966).
Enkele aspecten van het gelaatspatroon bij 9-jarige kinderen.
PhD Thesis. Groningen. University of Groningen.

Bourne, C. O., Kerr, W. J. and Ayoub, A. F. (2001).
Development of a three-dimensional imaging system for analysis of facial change.
Clinical Orthodontic Research **4**(2): 105-111.

Broadbent, B. H., Sr. (1931).
A new x-ray technique and its application to orthodontia.
Angle Orthodontist **1**(April): 45-66.

Broadbent, B. H. S., Broadbent, B. H. J. and Golden, W. H. (1975).
Bolton Standards of Dentofacial Developmental Growth.
St Loius, CV Mosby

Burke, P. H. and Beard, F. H. (1967).
Stereophotogrammetry of the face. A preliminary investigation into the accuracy of a simplified system evolved for contour mapping by photography.
American Journal of Orthodontics **53**(10): 769-82.

Burke, P. H. and Beard, L. F. (1979).
Growth of soft tissues of the face in adolescence.
British Dental Journal **146**(8): 239-46.

Burke, P. H. (1980).
Serial growth changes in the lips.
British Journal of Orthodontics 7(1): 17-30.

Burke, P. H. (1983).
Serial stereophotogrammetric measurements of the soft tissues of the face. A case of a girl with mild facial asymmetry from 3 weeks to 10 years of age.
British Dental Journal **155**(11): 373-9.

Burke, P. H. (1984).
Four-dimensional facial change.
British Journal of Orthodontics **11**(4): 170-84.

Burke, P. H. and Hughes-Lawson, C. A. (1988a).
The adolescent growth spurt in the soft tissues of the face.
Annals of Human Biology **15**(4): 253-62.

Burke, P. H. and Hughes-Lawson, C. A. (1988b).
The growth and development of the soft tissues of the human face.
Journal of Anatomy **158**: 115-20.

Burke, P. H. and Hughes-Lawson, C. A. (1989).
Stereophotogrammetric study of growth and development of the nose.
American Journal Orthodontics and Dento-facial Orthopedics **96**(2): 144-51.

Bush, K. and Antonyshyn, O. (1996).
Three-dimensional facial anthropometry using a laser surface scanner: validation of the technique.
Plastic and Reconstructive Surgery **98**(2): 226-35.

Channel 4 Dispatches (1999)
Tooth Trouble. Dispatches. London.

Caruso, A. J., Stanhope, S. J. and McGuire, D. A. (1989).
New technique for acquiring three-dimensional orofacial nonspeech movements.
Dysphagia **4**(2): 127-32.

Case, C. S. (1896)
The aesthetic correction of facial contours in the practice of dental orthopedia. Catching's compendium of practical dentistry. B. H. Catching (Eds). Atlanta, Franklin Printing and Publishing Co: 165-172.

Case, C. S. (1964).
The questions of extractions in orthodontics.
American Journal of Orthodontics **50**: 658-691.

Chaconas, S. J., Engel, G. A., Gianelly, A. A., Gorman, J. C., Grummons, D. C., Lemchen, M. S. and Nanda, R. S. (1990a).
The DigiGraph work station. Part 1. Basic concepts.
Journal of Clinical Orthodontics **24**(6): 360-7.

Chaconas, S. J., Jacobson, R. L. and Lemchen, M. S. (1990b).
DigiGraph work station. 3. Accuracy of cephalometric analyses.
Journal of Clinical Orthodontics **24**(8): 467-71.

Chiu, C. S. and Clark, R. K. (1991).
Reproducibility of natural head position.
Journal of Dentistry **19**(2): 130-1.

Cole, T. J., Bellizzi, M. C., Flegal, K. M. and Dietz, W. H. (2000).
Establishing a standard definition for child overweight and obesity worldwide: international survey.
British Medical Journal **320**(7244): 1240-3.

Coombes, A. M., Moss, J. P., Linney, A. D., Richards, R. and James, D. R. (1991).
A mathematical method for the comparison of three-dimensional changes in the facial surface.
European Journal of Orthodontics **13**(2): 95-110.

Da Silveira, A. C., Daw, J. L., Jr., Kusnoto, B., Evans, C. and Cohen, M. (2003).
Craniofacial applications of three-dimensional laser surface scanning.
Journal of Cranio-facial Surgery **14**(4): 449-56.

Deng, Z., Neumann, U., Lewis, J. P., Kim, T. Y., Bulut, M. and Narayanan, S. (2006).
Expressive facial animation synthesis by learning speech co-articulation and expression spaces.
IEEE Transactions on Visualisation and Computer Graphics (TVCG) **12**(6): 1523-1534.

Dibiase, A. T. and Sandler, P. J. (2001).
Does orthodontics damage faces?
Dental Update **28**(2): 98-102.

Donald, E. H. and Hans, M. G. (1996).
Essentials of facial growth.
Philadelphia, W.B. Saunders Company.*0-7216-6106-8*

Duffy, S., Noar, J. H., Evans, R. D. and Sanders, R. (2000).
Three-dimensional analysis of the child cleft face.
Cleft Palate Cranio-facial Journal **37**(2): 137-44.

Eian, J. and Poppele, R. (2002).
A single camera method for three-dimensional video imaging.
Journal of Neuroscience Methods **120**: 65-83.

Ekstrom, C. (1982).
Facial growth rate and its relation to somatic maturation in healthy children.
Swedish Dental Journal. Supplement **11**: 1-99.

Enciso, R., Memon, A., Fidaleo, D. A., Neumann, U. and Mah, J. (2003).
The virtual craniofacial patient: 3D jaw modeling and animation.
Studies in Health Technology and Informatics **94**: 65-71.

Enlow, D. H. (1966).
A morphogenetic analysis of facial growth.
American Journal of Orthodontics **52**(4): 283-99.

Enlow, D. H., Williams, K. and Williams, P. (1969).
An instrument for the analysis of facial growth.
Angle Orthodontist **39**(4): 316-9.

Enlow, D. H. (1979).
Facial growth and development.
International Journal of Oral Myology **5**(4): 7-10.

Faculty of General Dental Practioners(UK) (1998)
Selection Criteria for Dental Radiography,. London, Faculty of General Dental Practioners, UK Royal College of Surgeons, England.

Farkas, L. (1994).
Anthropometry of the head and face.
New York, Raven Press

Farkas, L. G., Posnick, J. C., Hreczko, T. M. and Pron, G. E. (1992).
Growth patterns of the orbital region: a morphometric study.
Cleft Palate Cranio-facial Journal **29**: 215-18.

Farkas, L. G. and Posnick, J. C. (1992).
Growth and development of regional units in the head and face based on anthropometric measurements.
Cleft Palate Cranio-facial Journal **29**(4): 301-2.

Ferrario, V. F., Sforza, C., Miani, A. and Tartaglia, G. (1993).
Craniofacial morphometry by photographic evaluations.
American Journal of Orthodontics and Dento-facial Orthopedics **103**(4): 327-37.

Ferrario, V. F., Sforza, C., Poggio, C. E. and Serrao, G. (1996).
Facial three-dimensional morphometry.
American Journal of Orthodontics and Dento-facial Orthopedics **109**(1): 86-93.

Ferrario, V. F., Sforza, C., Poggio, C. E., Colombo, A. and Tartaglia, G. (1997a).
The relationship between facial 3-D morphometry and the perception of attractiveness in children.
International Journal of Adult Orthodontics and Orthognathic Surgery **12**(2): 145-52.

Ferrario, V. F., Sforza, C., Miani, A., Jr. and Pizzini, G. (1997b).
A size-standardized analysis of soft tissue facial profile during growth.
American Journal of Orthodontics and Dento-facial Orthopedics **112**(1): 28-33.

Ferrario, V. F., Sforza, C., Poggio, C. E. and Schmitz, J. H. (1998a).
Craniofacial growth: a three-dimensional soft-tissue study from 6 years to adulthood.
Journal of Cranio-facial Genetics Developmental Biology **18**(3): 138-49.

Ferrario, V. F., Sforza, C., Poggio, C. E. and Schmitz, J. H. (1998b).
Facial volume changes during normal human growth and development.
Anatomy Records **250**(4): 480-7.

Ferrario, V. F., Sforza, C., Schmitz, J. H. and Santoro, F. (1999a).
Three-dimensional facial morphometric assessment of soft tissue changes after orthognathic surgery.
Oral Surgery Oral Medicine Oral Pathology Oral Radiology and Endodontics **88**(5): 549-56.

Ferrario, V. F., Sforza, C., Serrao, G., Colombo, A. and Ciusa, V. (1999b).
Soft tissue facial growth and development as assessed by the three-dimensional computerized mesh diagram analysis.
American Journal of Orthodontics and Dento-facial Orthopedics **116**(2): 215-28.

Ferrario, V. F., Sforza, C., Schmitz, J. H., Ciusa, V. and Colombo, A. (2000).
Normal growth and development of the lips: a 3-dimensional study from 6 years to adulthood using a geometric model.
Journal of Anatomy **196** (**Pt 3**): 415-23.

Ferrario, V. F., Sforza, C., Serrao, G. and Schmitz, J. H. (2002).
Three-dimensional assessment of the reliability of a postural face-bow transfer.
Journal of Prosthetic Dentistry **8**7(2): 210-5.

Ferrario, V. F., Sforza, C., Serrao, G., Ciusa, V. and Dellavia, C. (2003).
Growth and aging of facial soft tissues: A computerized three-dimensional mesh diagram analysis.
Clinical Anatomy **16**(5): 420-33.

Genecov, J. S., Sinclair, P. M. and Dechow, P. C. (1990).
Development of the nose and soft tissue profile.
Angle Orthodontist **60**(3): 191-8.

Ghafari, J., Baumrind, S. and Efstratiadis, S. S. (1998).
Misinterpreting growth and treatment outcome from serial cephalographs.
Clinical Orthodontic Research **1**(2): 102-6.

Girod, S., Keeve, E. and Girod, B. (1995).
Advances in interactive craniofacial surgery planning by 3D simulation and visualization.
International Journal of Oral Maxillo-facial Surgery **24**(1 Pt 2): 120-5.

Gray, C. F., Staff, R. T., Redpath, T. W., Needham, G. and Renny, N. M. (2000).
Assessment of maxillary sinus volume for the sinus lift operation by three-dimensional magnetic resonance imaging.
Dento-maxillofacial Radiology **29**(3): 154-8.

Grevers, G., Assal, J., Vogl, T. and Wilimzig, C. (1991).
Three-dimensional magnetic resonance imaging in skull base lesions.
American Journal of Otolaryngology **12**(3): 139-45.

Gross, M. M., Trotman, C. A. and Moffatt, K. S. (1996b).
A comparison of three-dimensional and two-dimensional analyses of facial motion.
Angle Orthodontist **66**(3): 189-194.

Guest, E., Berry, E. and Morris, D. (2001).
Novel methods for quantifying soft tissue changes after orthognathic surgery.
International Journal of Oral Maxillo-facial Surgery **30**(6): 484-9.

Hajeer, M. Y., Ayoub, A. F., Millett, D. T., Bock, M. and Siebert, J. P. (2002).
Three-dimensional imaging in orthognathic surgery: the clinical application of a new method.
International Journal of Adult Orthodontics and Orthognathic Surgery **17**(4): 318-30.

Hajeer, M. Y., Ayoub, A. F. and Millett, D. T. (2004a).
Three-dimensional assessment of facial soft-tissue asymmetry before and after orthognathic surgery.
British Journal of Oral Maxillo-facial Surgery **42**(5): 396-404.

Hajeer, M. Y., Millett, D. T., Ayoub, A. F. and Siebert, J. P. (2004b).
Applications of 3D imaging in orthodontics: part II.
Journal of Orthodontics **31**(2): 154-62.

Hajeer, M. Y., Millett, D. T., Ayoub, A. F. and Siebert, J. P. (2004c).
Applications of 3D imaging in orthodontics: part I.
Journal of Orthodontics **31**(1): 62-70.

Hajeer, M. Y., Mao, Z., Millett, D. T., Ayoub, A. F. and Siebert, J. P. (2005).
A new three-dimensional method of assessing facial volumetric changes after orthognathic surgery.
Cleft Palate Cranio-facial Journal **42**(2): 113-120.

Hamada, Y., Kondoh, T., Nakaoka, K. and Seto, K. (2000).
Magnetic resonance imaging findings and clinical symptoms in the temporomandibular joint in patients with mandibular continuity defects.
Journal of Oral Maxillo-facial Surgery **58**(5): 487-93; discussion 493-4.

Hammond, P., Hutton, T. J., Allanson, J. E., Campbell, L. E., Hennekam, R. C., Holden, S., Patton, M. A., Shaw, A., Temple, I. K., Trotter, M., Murphy, K. C. and Winter, R. M. (2004).
3D analysis of facial morphology.
American Journal of Medical Genetics A **126**(4): 339-48.

Harrison, J. A., Nixon, M. A., Fright, W. R. and Snape, L. (2004).
Use of hand held laser scanning in the assessment of facial swelling: a preliminary study.
British Journal of Oral Maxillo-facial Surgery **42**(1): 8-17.

Hennessy, R. J. and Moss, J. P. (2001).
Facial growth: separating shape from size.
European Journal of Orthodontics **23**(3): 275-85.

Hill, D. L., Berg, D. C., Raso, V. J., Lou, E., Durdle, N. G., Mahood, J. K. and Moreau, M. J. (2002).
Evaluation of a laser scanner for surface topography.
Studies in Health Technology and Informatics **88**: 90-4.

Hood, C. A., Bock, M., Hosey, M. T., Bowman, A. and Ayoub, A. F. (2003).
Facial asymmetry - 3D assessment of infants with cleft lip and palate.
International Journal of Pediatric Dentistry **13**: 404-410.

Hutton, T. J., Buxton, B. F. and Hammond, P. (2001).
Dense surface point distribution models of the human face
IEEE Workshop on mathematical methods in biomedical image analysis, Kauai, Hawaii.

Isaacson, K. G. and Thom, A. R., Eds. (2001).
Guidelines for the use of radiographs in clinical orthodontics. London, British Orthodontic Society.

Ismail, S. F. and Moss, J. P. (2002a).
The three-dimensional effects of orthodontic treatment on the facial soft tissues--a preliminary study.
British Dental Journal **192**(2): 104-8.

Ismail, S. F., Moss, J. P. and Hennessy, R. (2002b).
Three-dimensional assessment of the effects of extraction and nonextraction orthodontic treatment on the face.
American Journal of Orthodontics and Dento-facial Orthopedics **121**(3): 244-56.

Israel, H. (1978)
The fundamentals of cranial and facial growth.
Human Growth. F. Falkner and J. M. Tanner (Eds). New York, Plenum Press. **2:** 357-380.

Ji, Y., Zhang, F., Schwartz, J., Stile, F. and Lineaweaver, W. C. (2002).
Assessment of facial tissue expansion with three-dimensional digitizer scanning.
Journal of Craniofacial Surgery **13**(5): 687-692.

Kau, C. H., Zhurov, A. I., Knox, J. and Richmond, S. (2004a).
The validity and reliability of a portable 3-dimensional laser scanner for field studies
7th European Craniofacial Congress, Bologna, Italy, Monduzzi Editore - International Proceedings Division.

Kau, C. H., Zhurov, A. L, Scheer, R., Bouwman, S. and Richmond, S. (2004b).
The feasibility of measuring three-dimensional facial morphology in children.
Orthodontics and Craniofacial Research 7(4): 198-204.

Kau, C. H., Hartles, F. R., Knox, J., Zhurov, A. I. and Richmond, S. (2005a)
Natural head posture for measuring three-dimensional soft tissue morphology
Computer methods in biomechanics & biomedical engineering - 5. J. Middleton, M. G. Shrive and M. L. Jones (Eds). Cardiff, FIRST Numerics Ltd.

Kau, C. H., Richmond, S., Zhurov, A. I., Chestnutt, L, Hartles, F. R., Knox, J. and Playle, R. (2005b).
Reliability of measuring facial morphology using a 3-dimensional laser scanning system.
American Journal of Orthodontics and Dento-facial Orthopedics **128**(4): 424-430.

Kau, C. H., Zhurov, A. I., Bibb, R., Hunter, M. L. and Richmond, S. (2005c).
The investigation of the changing facial appearance of identical twins employing a three-dimensional laser imaging system.
Orthodontics Craniofacial Research **8**(2): 85-90.

Kau, C. H., Richmond, S., Palomo, J. M. and Hans, M. G. (2005d).
Three-dimensional cone beam computerized tomography in orthodontics.
Journal of Orthodontics **32**(4): 282-93.

Kau, C. H., Zhurov, A. I., Richmond, S., Bibb, R., Sugar, A. S., Knox, J. and Hartles, F. (2006a).
The 3-dimensional construction of the average 11-year old child face- a clinical evaluation and application.
Journal of Oral Maxillo-facial Surgery **64**(7): 1086-1092.

Kau, C. H., Richmond, S., Savio, C. and Mallorie, C. (2006b).
Measuring adult facial morphology in Three Dimensions.
Angle Orthodontist **76**(5): 771-6.

Kau, C. H., Zhurov, A., Richmond, S., Cronin, A., Savio, C. and Mallorie, C. (2006c).
Facial templates: a new perspective in three dimensions.
Orthodontics and Craniofacial Research 9(1): 10-7.

Kau, C. H., Cronin, A., Durning, P., Zhurov, A., Sandham, A. and Richmond, S. (2006d).
A new method for the 3D measurement of postoperative swelling following orthognathic surgery.
Orthodontics and Craniofacial Research 9(1): 31-7.

Kau, C. H., Richmond, S. and Zhurov, A. I. (2006e)
Application of 3-dimensional soft tissue imaging in orthodontics
Digital radiography and three-dimensional imaging. J. A. McNamara, Jr. and S. Kapila (Eds). Ann Arbor, Center for Human Growth and Development. **43:** 159-179.

Kau, C. H. and Richmond, S. (2007a)
Evaluation of facial growth: a 3D soft tissue prespective
Early orthodontic treatment: Is the benefit worth the burden? J. A. McNamara, Jr. (Eds). Ann Arbor, Michigan, Needham Press. **44:** 305-344.

Kau, C. H. and Richmond, S. (2007b).
A three-dimensional analysis of surface changes to the facial morphology in a longitudinal study of 12-year old normal untreated children.
American Journal of Orthodontic Dento-facial Orthopedics **Accepted**: In Press.

Kau, C. H., Llyod, C., Richmond, S. and Zhurov, A. I. (2007).
A 3-dimensional analysis of facial swelling and it's application to surgery.
Angle Orthodontist **In Press.**

Khambay, B., Nebel, J. C., Bowman, J., Walker, F., Hadley, D. M. and Ayoub, A. (2002a).
3D stereophotogrammetric image superimposition onto 3D CT scan images: the future of orthognathic surgery. A pilot study.
International Journal of Adult Orthodontics and Orthognathic Surgery **17**(4): 331-41.

Khambay, B., Nebel, J. C., Bowman, J., Walker, F., Hadley, D. M. and Ayoub, A. (2002b).
3D stereophotogrammetric image superimposition onto 3D CT scan images: the future of orthognathic surgery. A pilot study.
International Journal of Adult Orthodontics Orthognathic Surgery **17**(4): 331-41.

Kohn, L. A., Cheverud, J. M., Bhatia, G., Commean, P., Smith, K. and Vannier, M. W. (1995).
Anthropometric optical surface imaging system repeatability, precision, and validation.
Annals of Plastic Surgery **34**(4): 362-71.

Kowalski, C. J. and Prahl-Andersen, B. (1979)
General considerations in the design of studies of growth and development
A mixed-longitudinal study of growth and development. B. Prahl-Andersen, C. J. Kowalski and P. Heydendael (Eds). New York, Academic Press.

Kusnoto, B. and Evans, C. A. (2002).
Reliability of a 3D surface laser scanner for orthodontic applications.
American Journal of Orthodontics and Dento-facial Orthopedics **122**(4): 342-8.

Lee, J. Y., Han, Q. and Trotman, C. A. (2004).
Three-dimensional facial imaging: accuracy and considerations for clinical applications in orthodontics.
Angle Orthodontist **74**(5): 587-93.

Lewis, A. B. and Roche, A. F. (1988).
Late growth changes in the craniofacial skeleton.
Angle Orthodontist **58**(2): 127-35.

Lux, C. J., Conradt, C., Burden, D. and Komposch, G. (2004).
Three-dimensional analysis of maxillary and mandibular growth increments.
Cleft Palate Cranio-facial Journal **41**(3): 304-14.

Mah, J. and Bumann, A. (2001).
Technology to create the three-dimensional patient record.
Seminars in Orthodontics 7(4): 251-257.

Mah, J. and Sachdeva, R. (2001).
Computer-assisted orthodontic treatment: the SureSmile process.
Am J Orthod Dentofacial Orthop **120**(1): 85-7.

Mah, J. (2002).
3D imaging in private practice.
American Journal of Orthodontics and Dento-facial Orthopedics **121**(6): 14A.

Mah, J. and Ritto, A. K. (2002).
Imaging in othodontics: present and future.
Journal of Clinical Orthodontics **36**(11): 619-25.

Mah, J. and Enciso, R. (2003)
The virtual craniofacial patient. J. A. McNamara (Eds). Michigan, Center for human growth and development, Craniofacial Growth Series. **40**.

Mah, J., Enciso, R. and Jorgensen, M. (2003a).
Management of impacted cuspids using 3-D volumetric imaging.
Journal of the Californian Dental Association **31**(11): 835-41.

Mah, J. and Hatcher, D. (2003).
Current status and future needs in craniofacial imaging.
Orthod Craniofac Res **6 Suppl 1**: 10-6; discussion 179-82.

Mah, J. and Hatcher, D. (2004).
Three-dimensional craniofacial imaging.
American Journal of Orthodontics and Dento-facial Orthopedics **126**(3): 308-9.

Mah, J. K., Danforth, R. A., Bumann, A. and Hatcher, D. (2003b).
Radiation absorbed in maxillofacial imaging with a new dental computed tomography device.
Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiology and Endodontics **96**(4): 508-13.

Mamandras, A. H. (1988).
Linear changes of the maxillary and mandibular lips.
American Journal of Orthodontics **94**(5): 363-452.

Manera, J. F. and Subtelny, M. D. (1961).
A cephalometric study of the growth of the nose.
American Journal of Orthodontics **47**: 703-705.

Marmulla, R., Hassfeld, S., Luth, T. and Muhling, J. (2003).
Laser-scan-based navigation in cranio-maxillofacial surgery.
Journal of Cranio-maxillofacial Surgery **31**(5): 267-77.

McCance, A. M., Moss, J. P., Wright, W. R., Linney, A. D. and James, D. R. (1992a).
A three-dimensional soft tissue analysis of 16 skeletal class III patients following bimaxillary surgery.
British Journal of Oral Maxillo-facial Surgery **30**(4): 221-32.

McCance, A. M., Moss, J. P. and James, D. R. (1992b).
Stability of surgical correction of patients with Skeletal III and Skeletal II anterior open bite, with increased maxillary mandibular planes angle.
European Journal of Orthodontics **14**(3): 198-206.

McCance, A. M., Moss, J. P., Fright, W. R., Linney, A. D., James, D. R., Coghlan, K. and Mars, M. (1997a).
Three-dimensional analysis techniques--Part 4: Three-dimensional analysis of bone and soft tissue to bone ratio of movements in 24 cleft palate patients following Le Fort I osteotomy: a preliminary report.
Cleft Palate Cranio-facial Journal **34**(1): 58-62.

McCance, A. M., Moss, J. P., Fright, W. R. and Linney, A. D. (1997b).
Three-dimensional analysis techniques--Part 3: Color-coded system for three-dimensional measurement of bone and ratio of soft tissue to bone: the analysis.
Cleft Palate Cranio-facial Journal **34**(1): 52-7.

McCance, A. M., Moss, J. P., Fright, W. R., Linney, A. D. and James, D. R. (1997c).
Three-dimensional analysis techniques--Part 2: Laser scanning: a quantitative three-dimensional soft-tissue analysis using a color-coding system.
Cleft Palate Cranio-facial Journal **34**(1): 46-51.

McCance, A. M., Moss, J. P., Fright, W. R., Linney, A. D. and James, D. R. (1997d).
Three-dimensional analysis techniques--Part 1: Three-dimensional soft-tissue analysis of 24 adult cleft palate patients following Le Fort I maxillary advancement: a preliminary report.
Cleft Palate Cranio-facial Journal **34**(1): 36-45.

McDonagh, S., Moss, J. P., Goodwin, P. and Lee, R. T. (2001).
A prospective optical surface scanning and cephalometric assessment of the effect of functional appliances on the soft tissues.
European Journal of Orthodontics **23**(2): 115-26.

Meintjes, E. M., Douglas, T. S., Martinez, F., Vaughan, C. L., Adams, L. P., Stekhoven, A. and Viljoen, D. (2002).
A stereo-photogrammetric method to measure the facial dysmorphology of children in the diagnosis of fetal alcohol syndrome.
Medical Engineering & Physics **24**(10): 683-9.

Meredith, H. V., Knott, V. B. and Hixon, E. H. (1958).
Relation of the nasal and subnasal components of facial height in childhood.
American Journal of Orthodontics(April): 285-294.

Mew, J. (2000).
C4 Dispatches.
Dental Update **27**(6): 307.

Minolta (2001).
Polygon Editing Tool.
Osaka, Minolta Co Ltd

Morris, D. O., Illing, H. M. and Lee, R. T. (1998).
A prospective evaluation of Bass, Bionator and Twin Block appliances. Part II--The soft tissues.
European Journal of Orthodontics **20**(6): 663-84.

Moss, J. P. (1989).
Northcroft revisited.
British Journal of Orthodontics **16**(3): 155-67.

Moss, J. P. and Linney, A. D. (1990).
The prediction of facial aesthetics.
New York State Dental Journal **56**(6): 44-6.

Moss, J. P., Ismail, S. F. and Hennessy, R. J. (2003).
Three-dimensional assessment of treatment outcomes on the face.
Orthodontics and Cranio-facial Research **6 Suppl 1**: 126-31; discussion 179-82.

Motoyoshi, M., Namura, S. and Arai, H. Y. (1992).
A three-dimensional measuring system for the human face using three-directional photography.
American Journal of Orthodontics and Dento-facial Orthopedics **101**(5): 431-40.

Nagao, M., Sohmura, T., Kinuta, S., Kojima, T., Wakabayashi, K., Nakamura, T. and Takahashi, J. (2001).
Integration of 3-D shapes of dentition and facial morphology using a high-speed laser scanner.
International Journal of Prosthodontics **14**(6): 497-503.

Nanda, R. S., Meng, H., Kapila, S. and Goorhuis, J. (1990).
Growth changes in the soft tissue facial profile.
Angle Orthodontist **60**(3): 177-90.

Nanda, R. S. and Ghosh, J. (1995).
Facial soft tissue harmony and growth in orthodontic treatment.
Seminars in Orthodontics **1**(2): 67-81.

Newcombe, R. G. (1998).
Interval estimation for the difference between independent proportions: comparison of eleven methods.
Statistics in Medicine **17**(8): 873-90.

Nguyen, C. (1999).
3D image construction of the craniofacial complex.
Masters Thesis. Philadelphia. Temple University. Orthodontics.

Nkenke, E., Benz, M., Maier, T., Wiltfang, J., Holbach, L. M., Kramer, M., Hausler, G. and Neukam, F. W. (2003a).
Relative en- and exophthalmometry in zygomatic fractures comparing optical non-contact, non-ionizing 3D imaging to the Hertel instrument and computed tomography.
Journal of Cranio-maxillofacial Surgery **31**(6): 362-8.

Nkenke, E., Langer, A., Laboureux, X., Benz, M., Maier, T., Kramer, M., Hausler, G., Kessler, P., Wiltfang, J. and Neukam, F. W. (2003b).
Validation of in vivo assessment of facial soft-tissue volume changes and clinical application in midfacial distraction: a technical report.
Plastic and Reconstructive Surgery **112**(2): 367-80.

Nooreyazdan, M., Trotman, C. A. and Faraway, J. J. (2004).
Modeling facial movement: II. A dynamic analysis of differences caused by orthognathic surgery.
Journal of Oral Maxillo-facial Surgery **62**(11): 1380-6.

Nute, S. J. and Moss, J. P. (2000).
Three-dimensional facial growth studied by optical surface scanning.
Journal of Orthodontics **27**(1): 31-8.

O'Grady, K. F. and Antonyshyn, O. M. (1999).
Facial asymmetry: three-dimensional analysis using laser surface scanning.
Plastic and Reconstructive Surgery **104**(4): 928-37.

Ohta, N., Okada, M., Sakuma, K. and Ide, Y. (1982).
A cross-sectional study of facial growth with the Moire camera.
Bulletin of Tokyo Dental College **23**(1): 25-35.

Okada, E. (2001).
Three-dimensional facial simulations and measurements: changes of facial contour and units associated with facial expression.
Journal of Cranio-facial Surgery **12**(2): 167-74.

Palomo, J. M., Hunt, D. W., Jr., Hans, M. G. and Broadbent, B. H., Jr. (2005).
A longitudinal 3-dimensional size and shape comparison of untreated Class I and Class II subjects.
American Journal of Orthodontics and Dento-facial Orthopedics **127**(5): 584-91.

Papadopoulos, M. A., Christou, P. K., Athanasiou, A. E., Boettcher, P., Zeilhofer, H. F., Sader, R. and Papadopulos, N. A. (2002).
Three-dimensional craniofacial reconstruction imaging.
Oral Surgery Oral Medicine Oral Pathology Oral Radiology and Endodontics **93**(4): 382-93.

Paquette, D. E., Beattie, J. R. and Johnson, L. E. (1992).
A long term comparision of non-extraction and premolarextraction edgewise therapy in border-line Class II cases.
American Journal of Orthodontics and Dento-facial Orthopedics **102**: 1-14.

Persson, M. and Thilander, B. (1985)
Craniofacial development and growth
Introduction to orthodontics. B. Thilander and O. Ronning (Eds). Stockholm, Tandlakarforlaget.

Proffit, W. R. (2000a)
Later stages of development
Contemporary Orthodontics. W. R. Proffit and H. W. Fields (Eds). St Louis, Mosby.

Proffit, W. R. (2000b).
Contemporary orthodontics.
St Louis, Mosby

Rabey, G. (1968).
Morphanalysis.
London, Hatch, Pinner and Co Ltd

Ranly, D. (1988).
A synopsis of craniofacial growth.
Singapore, Prentice-Hall International Editions

Ranly, D. M. (2000).
Craniofacial growth.
Dental Clinics of North America **44**(3): 457-70, v.

Ras, F., Habets, L. L., van Ginkel, F. C. and Prahl-Andersen, B. (1994a).
Three-dimensional evaluation of facial asymmetry in cleft lip and palate.
Cleft Palate Cranio-facial Journal **31**(2): 116-21.

Ras, F., Habets, L. L., van Ginkel, F. C. and Prahl-Andersen, B. (1994b).
Facial left-right dominance in cleft lip and palate: three-dimension evaluation.
Cleft Palate Cranio-facial Journal **31**(6): 461-5.

Ras, F., Habets, L. L., van Ginkel, F. C. and Prahl-Andersen, B. (1995a).
Method for quantifying facial asymmetry in three dimensions using stereophotogrammetry.
Angle Orthodontist **65**(3): 233-9.

Ras, F., Habets, L. L., van Ginkel, F. C. and Prahl-Andersen, B. (1995b).
Longitudinal study on three-dimensional changes of facial asymmetry in children between 4 to 12 years of age with unilateral cleft lip and palate.
Cleft Palate Cranio-facial Journal **32**(6): 463-8.

Ras, F., Habets, L. L., van Ginkel, F. C. and Prahl-Andersen, B. (1996).
Quantification of facial morphology using stereophotogrammetry--demonstration of a new concept.
Journal of Dentistry **24**(5): 369-74.

Richmond, S. (1984).
The feasibility of categorising orthodontic treatment difficulty: the use of three dimensional plotting.
MScD Dissertation Thesis. Cardiff. University of Wales.

Richmond, S., Andrews, M. and Roberts, C. T. (1993).
The provision of orthodontic care in the general dental services of England and Wales: extraction patterns, treatment duration, appliance types and standards.
British Journal of Orthodontics **20**(4): 345-50.

Riolo, M. L., Moyers, R. E., McNamara, J. A. and Hunter, W. S. (1979).
An atlas of craniofacial growth (Vol 2).
Michigan, Needham Press

Riolo, M. L. and TenHave, T. R. (1986)
The effects of different appliance therapy on the facial soft tissue profile
Science and clinical judgment in orthodontics. P. S. Vig and K. A. Ribbens (Eds). Ann Arbor, Center for Human Growth and Development. **Monograph 19.**

Riolo, M. L., Moyers, R. E., TenHave, T. R. and Mayers, C. A. (1987)
Facial soft tissue changes during adolescence
Craniofacial growth during adolescence. D. S. Carlson and K. A. Ribbens (Eds). Ann Arbor, Center for Human Growth and Development. **Monograph 20.**

Robertson, N. (1976).
Contour Photography.
British Journal of Orthodontics **3**: 105-109g.

Robertson, N. R. and Volp, C. R. (1981).
Telecentric photogrammetry: its development, testing, and application.
American Journal of Orthodontics **80**(6): 623-37.

Sadar, R., Zeilhofer, H. F., Horch, H. H., Krol, Z., Hoffman, K. H., Michaelis, M. and Gabel, H. (1997).
Diagnostic possibilities of 3-dimensional imaging of ultrasound image data in mouth-, jaws- and facial surgery.
Biomedical Technology **42**: 211-2.

Sarver, D. M. (1998).
Esthethic Orthodontics and Orthognathic Surgery.
St Louis, Mosby

Sassouni, V. (1957).
Palatoprint, physioprint and roentgenographic cephalometry as new methods in human identification.
Journal of Forensic Sciences **2**: 428-442.

Sforza, C., Dellavia, C., Vizzotto, L. and Ferrario, V. F. (2004).
Variations in facial soft tissues of italian individuals with ectodermal dysplasia.
Cleft Palate Cranio-facial Journal **41**(3): 262-7.

Smith, S. L. and Buschang, P. H. (2001).
Midsagittal facial tissue thicknesses of children and adolescents from the Montreal growth study.
Journal of Forensic Sciences **46**(6): 1294-302.

Smith, S. L. and Buschang, P. H. (2002).
Midsagittal facial soft-tissue growth of French Canadian adolescents.
American Journal of Human Biology **14**(4): 457-67.

Soh, M. (1983).
A study on morphological changes in the palate associated with orthodontic treatment--the application of Moire topography--1. Adult females with upper protrusions.
Journal of the Nihon University School of Dentistry **25**(3): 171-82.

Soncul, M. and Bamber, M. A. (1999).
The optical surface scan as an alternative to the cephalograph for soft tissue analysis for orthognathic surgery.
International Journal of Adult Orthodontics and Orthognathic Surgery **14**(4): 277-83.

Soncul, M. and Bamber, M. A. (2000).
The reproducibility of the head position for a laser scan using a novel morphometric analysis for orthognathic surgery.
International Journal of Oral Maxillo-facial Surgery **29**(2): 86-90.

Stamrud, L. (1959).
External and internal cranial base: a cross-sectional study of growth and association in form.
Acta Odontologica Scandanvica **17**: 239-266.

Subtelny, J. D. (1959).
A longitudinal study of soft tissue facial structures and their profile characteristics defined in relation to underlying skeletal structures.
American Journal of Orthodontics **45**(7): 481-507.

Subtelny, J. D. (1961).
The soft tissue profile, growth and treatment changes.
Angle Orthodontist **31**(2): 105-122.

Sukovic, P. (2003).
Cone beam computed tomography in craniofacial imaging.
Orthodontics and Cranio-facial Research **6 Suppl 1**: 31-6; discussion 179-82.

Takacs, B., Pieper, S., Cebral, J., Kiss, B., Benedek, B. and Szijarto, G. (2004).
Facial modeling for plastic surgery using magnetic resonance imagery
SPIE Electronic Imaging, The Engineering Reality of Virtual Reality 2004 (EI06), San Jose, CA, USA.

Takasaki, H. (1970).
Moire Topography.
Applied Optics **9**: 1457-72.

Tanner, J. M. and Weiner, J. S. (1949).
The reliability of the photogrammetric method of anthropometry.
American Journal of Physical Anthropology 7(2): 145-186.

Tanner, J. M. (1962).
Growth at adolescence.
Oxford, Blackwell Scientific Publications

Trotman, C. A., Gross, M. M. and Moffatt, K. (1996).
Reliability of a three-dimensional method for measuring facial animation: a case report.
Angle Orthodontist **66**(3): 195-8.

Trotman, C. A. and Faraway, J. J. (2004).
Modeling facial movement: I. A dynamic analysis of differences based on skeletal characteristics.
Journal of Oral Maxillo-facial Surgery **62**(11): 1372-9.

Tsang, K. H. and Cooke, M. S. (1999).
Comparison of cephalometric analysis using a non-radiographic sonic digitizer (DigiGraph Workstation) with conventional radiography.
European Journal of Orthodontics **21**(1): 1-13.

Tuncay, O. C. (2001).
Three-dimensional imaging and motion animation.
Seminars in Orthodontics 7(4): 244-250.

Tweed, C. H. (1944).
Indications for the extraction of teeth in orthodontic procedures.
American Journal of Orthodontics **30**(2): 405-27.

Tyrrell, A. J., Evison, M. P., Chamberlain, A. T. and Green, M. A. (1997).
Forensic three-dimensional facial reconstruction: historical review and contemporary developments.
Journal of Forensic Sciences **42**(4): 653-61.

Ursi, W. J., Trotman, C. A., McNamara, J. A., Jr. and Behrents, R. G. (1993).
Sexual dimorphism in normal craniofacial growth.
Angle Orthodontist **63**(1): 47-56.

Vanezi, P., Vanezis, M., McCombe, G. and Niblett, T. (2000).
Facial reconstruction using 3-D computer graphics.
Forensic Science International **108**(2): 81-95.

Vig, K. W. and Fields, H. W. (2000).
Facial growth and management of orthodontic problems.
Pediatric Clinics of North America **47**(5): 1085-123.

Volp, C. R. (1979).
A photogrammetric technique of recording the human face.
Masters Thesis. University of Salford.

Weeden, J. C., Trotman, C. A. and Faraway, J. J. (2001).
Three dimensional analysis of facial movement in normal adults: influence of sex and facial shape.
Angle Orthodontist 71(2): 132-40.

Weinberg, S. M., Scott, N. M., Neiswanger, K., Brandon, C. A. and Marazita, M. L. (2004).
Digital three-dimensional photogrammetry: evaluation of anthropometric precision and accuracy using a Genex 3D camera system.
Cleft Palate Cranio-facial Journal **41**(5): 507-18.

Weinberg, S. M. and Kolar, J. C. (2005).
Three-dimensional surface imaging: limitations and considerations from the anthropometric perspective.
Journal of cranio-facial Surgery **16**(5): 847-51.

WHO (1997)
Obesity: preventing and managing the global epidemic. Geneva, World Health Organisation.

Xia, J., Ip, H. H., Samman, N., Wang, D., Kot, C. S., Yeung, R. W. and Tideman, H. (2000a).
Computer-assisted three-dimensional surgical planning and simulation: 3D virtual osteotomy.
International Journal of Oral Maxillo-facial Surgery **29**(1): 11-7.

Xia, J., Samman, N., Yeung, R. W., Shen, S. G., Wang, D., Ip, H. H. and Tideman, H. (2000b).
Three-dimensional virtual reality surgical planning and simulation workbench for orthognathic surgery.
International Journal of Adult Orthodontics and Orthognathic Surgery **15**(4): 265-82.

Xia, J., Samman, N., Yeung, R. W., Wang, D., Shen, S. G., Ip, H. H. and Tideman, H. (2000c).
Computer-assisted three-dimensional surgical planing and simulation. 3D soft tissue planning and prediction.
International Journal of Oral Maxillo-facial Surgery **29**(4): 250-8.

Xia, J., Wang, D., Samman, N., Yeung, R. W. and Tideman, H. (2000d).
Computer-assisted three-dimensional surgical planning and simulation: 3D color facial model generation.
International Journal of Oral Maxillo-facial Surgery **29**(1): 2-10.

Yamada, T., Sugahara, T., Mori, Y., Minami, K. and Sakuda, M. (1999).
Development of a 3-D measurement and evaluation system for facial forms with a liquid crystal range finder.
Comput Methods Programs Biomed **58**(2): 159-73.

Yamada, T., Mori, Y., Katsuhiro, M., Katsuaki, M. and Tsukamoto, Y. (2002).
Three-dimensional analysis of facial morphology in normal japanese children as control data for cleft surgery.
Cleft Palate Cranio-facial Journal **39**(5): 517-526.

Yip, E., Smith, A. and Yoshino, M. (2004).
Volumetric evaluation of facial swelling utilizing a 3-D range camera.
International Journal of Oral Maxillo-facial Surgery **33**(2): 179-182.

Young, T. M. and Smith, R. J. (1993).
Effects of orthodontics on facial profile: a comparison of changes during non-extraction and four premolar extraction treatment.
American Journal of Orthodontics and Dento-facial Orthopedics **103**: 452-458.

Zhurov, A. I., Kau, C. H. and Richmond, S. (2005)
Computer Methods for measuring 3D facial morphology
Computer methods in biomechanics & biomedical engineering - 5. J. Middleton, M. G. Shrive and M. L. Jones (Eds). Cardiff, FIRST Numerics.

APPENDICES

Appendix 1: Ethical Approval

AWDURDOD IECHYD
BRO TAF
HEALTH AUTHORITY

21 October 2002 JJS/JJL

Professor S Richmond,
Dept. of Dental Health & Biological Sciences,
Dental School,
University of Wales College of Medicine,
Heath Park,
Cardiff.

Dear Professor Richmond,

02/4574 - A critical analysis of the effect of orthodontic treatment on facial development

Thank you for your letter of the 17th October 2002, regarding the above application for ethical approval.

The Chairman of the Bro Taf Local Research Ethics Committee (Panel D), Dr D E B Powell, has confirmed that your response is satisfactory.

Dr Powell has therefore taken 'Chairman's Action' to grant full ethical approval to this application.

Yours sincerely,

Mrs Jagjit Sidhu
Deputy Executive Officer
Local Research Ethics Committee

☎: 029 20402446/20402309
JSidhu@bro-taf-ha.wales.nhs.uk

HEADQUARTERS:
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17 Churchill Way, Cardiff, CF10 2TW
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Ffordd Churchill, Caerdydd, CF10 2TW

Temple of Peace and Health
Cathays Park, Cardiff, CF10 3NW
Teml Heddwch ac Iechyd:
Parc Cathays, Caerdydd, CF10 3NW

NHS CYMRU WALES

Tel: 029 20 402402 Fax/Ffacs: 029 20 402403 WHTN: 1809

Theory of Operation

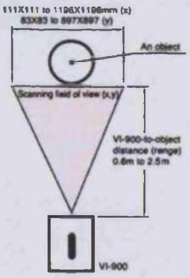
<Basic Principle>

The VI-900 uses LASER triangulation. The object is scanned by a plane of laser light coming from the VI-900's source aperture. The plane of light is swept across the field of view by a mirror, rotated by a precise galvanometer. This LASER light is reflected from the surface of the scanned object. Each scan line is observed by a single frame, captured by the CCD camera. The contour of the surface is derived from the shape of the image of each reflected scan line. The entire area is captured in 2.5 seconds (0.3 seconds in FAST mode), and the surface shape is converted to a lattice of over 300,000 vertices (connected points). VI-900 gives you more than a point cloud; a polygonal-mesh is created with all connectivity information retained, thereby eliminating geometric ambiguities and improving detail capture. A brilliant (24-bit) color image is captured at the same time by the same CCD. Unlike other scanners, the VI-900 has no parallax error, its "spot - on"!

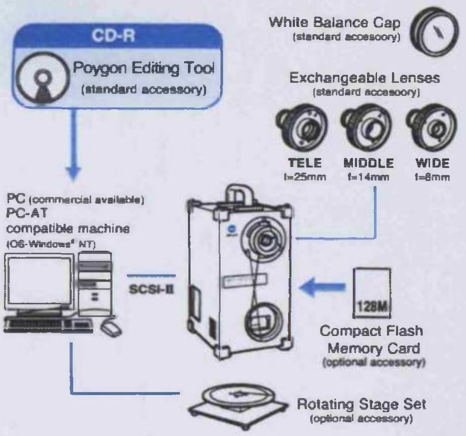
<High Accuracy Measurement>

A high-accuracy scanner and a high-accuracy Calibration facility unit to be used for calculation of 3-D data have been developed for the VI-900.

The 3-D reference chart traceable to the national standards has also been established to utilize the technology and algorithm that enable higher accuracy measurement.



System Block Diagram



■ Optional accessories

- Rottating Stage Set
- Compact Flash Memory Card
- PC Card Adapter
- Tripod
- Pan head

Specifications

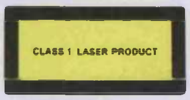
Type	Non-contact 3D digitizer VI-900
Measuring method	Triangulation light block method
AF	Image surface AF (contrast method), active AF
Light-Receiving Lens (Exchangeable)	TELE: Focal distance f=25mm MIDDLE: Focal distance f=14mm WIDE: Focal distance f=8mm
Image Input Range	0.6 to 2.5m (2m for WIDE)
Measurement Input Range	0.6 to 1.2m
Laser Output	"Eye safe", Class 1 (FDA), Class 2 (IEC), Maximum 30mW 690nm
Laser Scan Method	Galvano mirror
Input Time	0.3 sec (FAST mode), 2.5 sec (FINE mode), 0.5 sec (COLOR)
Transfer Time to Host Computer	Approx. 1 sec (FAST mode), 1.5 sec (FINE mode)
Ambient Lighting Condition	Office Environment, 500 lx or less
Imaging Element	3-D data:1/3-inch frame transfer CCD (340,000 pixels) Color data:3-D data is shared (color separation by rotary filter).
Number of Output Pixels	3-D data : 640 x 480 (for FINE mode), 320 x 240 (for FAST mode) Color data : 640 x 480
Output Format	3-D data : Minolta format, & (STL, DXF, OBJ, ASCII points, VRML) (Converted to 3-D data by the Polygon Editing Software/ standard accessory) Color data: RGB 24-bit raster scan data
Recording Medium	Compact Flash memory card (128MB)
Data File Size	Total 3-D and color data capacity: 1.6MB per data (for FAST mode), 3.6MB per data (for FINE mode)
Viewfinder	5.7-inch LCD (320 x 240 pixels)
Output Interface	SCSI II (DMA synchronous transfer)
Power	Commercial AC power 100 to 240V (50 to 60Hz), rated current 0.6A (when 100Vac is input)
Dimensions (WxHxD)	213 x 413 x 271 mm (8-3/8 x 16-1/4 x 10-11/16 in.)
Weight	Approx.11kg
Operating environment	temperature: 10 to 40°C (50 to 104°F) ; relative humidity 65% or less with no condensation, Pollution degree: 2, Installation category: II
Storage temperature range	-10 to 50°C (14 to 122°F) ; relative humidity 85% or less (at 35°C/95°F) with no condensation

- Specifications are subject to change without notice.
- Product names in this brochure are trademarks of their respective companies.

SAFETY PRECAUTIONS

Read all safety and operating instructions

- before operating the VI-900.
  Use only a power source of the specified rating.
  Improper connection may cause a fire or electric shock.
- Do not stare into the laser beam.
  (MAX. 30mW 690nm / CLASS 1 (FDA), CLASS 2 (IEC) LASER PRODUCT)



Minolta Co.,Ltd.
Radiometric Instruments Operations 3-13, 2-Chome, Azuchi-Machi,Chuo-Ku, Osaka 541-8556, Japan
EMail : vividinfo@minolta.co.jp
Web : www.minolta-rio.com/vivid/

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Appendix 3

MINOLTA

The essentials of imaging

www.minolta.co.jp

CERTIFICATE

DESCRIPTION OF GOODS

NON CONTACT 3D DIGITIZER

MODEL NAME : VIVID900 / VIVID900T / VIVID910

We hereby certify that the above models are classified Class I and comply with the requirements of 21 CFR 1040.10 and 1040.11 (FDA Regulation).

"CLASS I" levels of laser radiation are not considered to be hazardous.

Takao Sakai
Manager
Quality Assurance Department
Instrument Systems Company

18 December 2002

MINOLTA Co.,Ltd. Toyokawa Administrative Center
1-8, Kanayanishi-machi, Toyokawa-shi, Aichi 442-8558, Japan
Tel: +81-533-89-3569 Fax: +81-533-89-3576

Appendix 4

STUDY TO ASSESS FACIAL GROWTH
CARDINAL NEWMAN SCHOOL

Section A: Biostatistics

(1) Child's Name :________________________

(2) Form :________________________

(3) Sex :________________________

(4) Date of Birth :________________________

(5) Height :________________________

(6) Weight :________________________

Section B: Questionnaire

(1) Have you had your teeth removed for orthodontic reasons? Yes No

(2) Have you ever worn a brace? Yes No

(3) If you have worn a brace, when was it fitted? ________

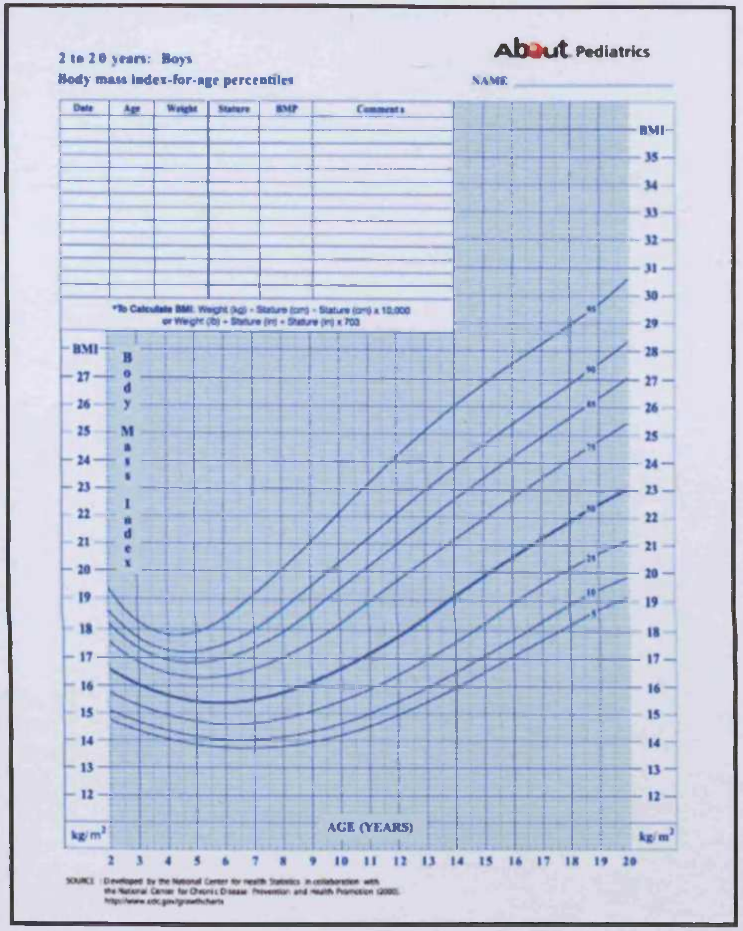
(4) What type of brace did you wear?
- a) Upper removable brace only
- b) Upper fixed brace only
- c) Lower removable brace only
- d) Lower fixed brace only
- e) Head-Gear
- f) Upper and lower removable appliances (Functional)
- g) Upper and lower fixed braces
- h) Don't know

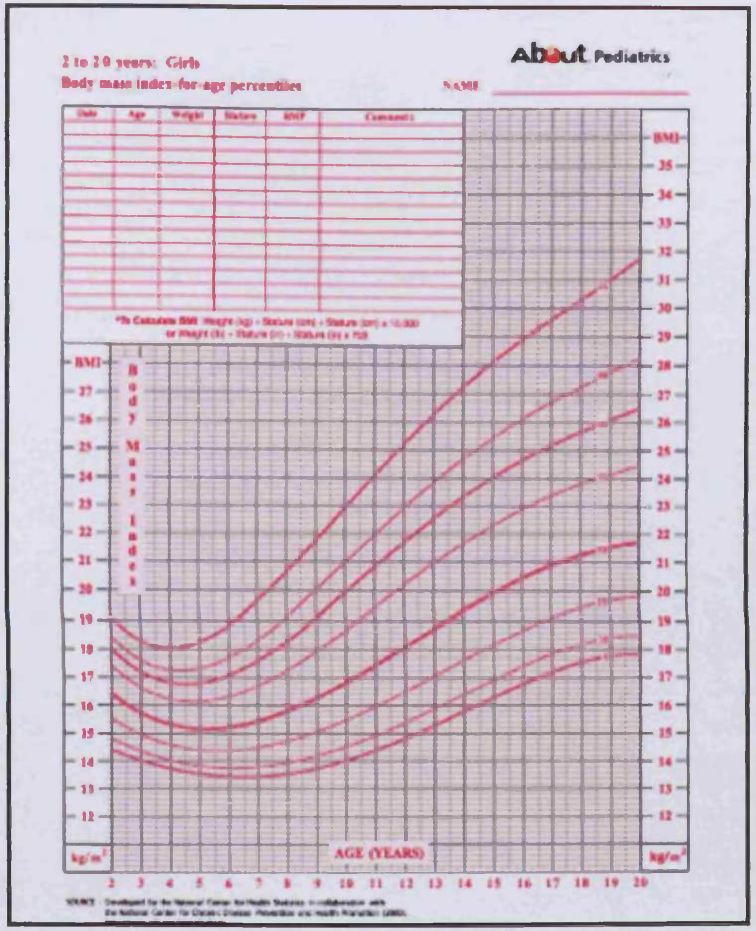
(5) Who were the dentists / orthodontists who fitted your braces?

Name:________________________

Address:________________________

Appendix 5


2 to 20 years: Boys
Body mass index-for-age percentiles
About Pediatrics
NAME
Date
Age
Weight
Stature
BMI*
Comments
*To Calculate BMI: Weight (kg) ÷ Stature (cm) ÷ Stature (cm) x 10,000
or Weight (lb) ÷ Stature (in) ÷ Stature (in) x 703
BMI
Body Mass Index
AGE (YEARS)
kg/m²
SOURCE: Developed by the National Center for Health Statistics in collaboration with
the National Center for Chronic Disease Prevention and Health Promotion (2000).
http://www.cdc.gov/growthcharts


2 to 20 years: Girls
Body mass index-for-age percentiles
About Pediatrics
NAME
BMI
Body Mass Index
AGE (YEARS)
kg/m²

Appendix 6

BBC NEWS

Helping teenagers face the world

Scores of children are taking part in a study using state-of-the-art technology to find out how their faces grow.

The aim of the research, by doctors in Cardiff, is to plan better treatment for people with conditions like missing teeth or cleft lip and palate.

A laser scanning system has been used to make three-dimensional (3-D) images of the children's faces.

The team has also taken pictures of children with a range of conditions which affect their facial appearances.

Dr Chung How Kau from the University of Wales College of Medicine said about 100 children at two secondary schools in Pontypridd, south Wales, had already taken part, and the team would return to take more 3-D pictures of them over the next year.

It was something like an animation in a computer game or a film - I felt a bit like a character in Toy Story
Megan, aged 11

"They're really amazed that we can move their heads all the way around - they've never looked from the top view down at their heads, or up their noses before - it's really interesting for them," he said of the children's reaction.

"It's interesting from the point of view of lay people, but it's also good for science because we can see much more now, and we can understand things better," he added.

Braces

Dr Kau said the benefits of the £60,000 laser scanning system included the fact that it was portable, and avoided invasive technology like X-ray.

"The purpose of the study is, using new technology, to evaluate how the face grows with time," Dr Kau said.

He explained that it would help doctors plan surgery or other treatment for people with facial anomalies.

"We don't know, how, say moving the skeleton forward by one centimetre will affect the soft tissue. The soft tissue, the outer shell, is the more important part of the facial appearance, so by using this technology we can understand what will happen, in 3-D."

He said it could, for example, better predict how braces on a young person's teeth would affect their appearances, and there had been an interesting early discovery about the way faces develop.

"We are starting to see that growth doesn't just occur bilaterally on both sides (of the face)...growth happens on one side first, and then the other side catches up.

That might mean that we might need to change our health care intervention... we need to find a way to use that information," Dr Kau said.

One of the children who has taken part in the study is 11-year-old Megan. She and her eight-year-old sister have a genetic condition called ectodermal dysplasia which has left them with teeth missing.

"It was a bit strange to see yourself on the screen," she said after being photographed.

"It was something like an animation in a computer game or a film - I felt a bit like a character in Toy Story.

"I'm hoping it'll help Dr Kau with his research so that he'll know more about how to make me and my sister look like other people," she added.

Story from BBC NEWS:
http://news.bbc.co.uk/go/pr/fr/-/2/hi/uk_news/wales/south_east/3881581.stm

Published: 2004/07/15 12:26:07 GMT

PEER REVIEWED

LECTURES AND PUBLICATIONS

(A) LECTURES

International Invitations

1. Three-dimensional Cone Beam Technology, North East Society of Orthodontists, American Orthodontic Association, 13th September 2008, Rhode Island, UNITED STATES OF AMERICA
2. Three-dimensional imaging in dentistry, Course in Prague (Carolina Servis), 16th June 2007, Prague, CZECHOSLOVAKIA
3. Mapping the face and its underlying structures for use in epidemiological surveys and clinical trials, British Orthodontic Society Conference, 23-26 September 2007, Harrogate, UNITED KINGDOM
4. Surface Acquisitions Systems, New Horizons in Diagnosis and Treatment Planning of Cranio-MaxilloFacial Deformity,10-11 November 2006, Burges, BELGIUM
5. Three-dimensional imaging in orthodontics, The 5th Congress of the Baltic Orthodontic Association, 18-20 May 2006, Tallin, ESTONIA
6. Three-dimensional soft tissue imaging in clinical orthodontics, 106th American Association of Orthodontists Annual Session, 5 -9 May 2006, Las Vegas, UNITED STATES OF AMERICA
7. Orthodontic technology in skeletal problems, Hungarian Orthodontic Congress, 7-12 April 2006, Gyula, HUNGARY
8. Surface Acquisition systems in Orthodontics, The Dental Branch, University of Texas Health Science Center, 1 March 2006, Houston, UNITED STATES OF AMERICA
9. Three-dimensional imaging in Orthodontics, Enrichment Seminar, The School of Dental Medicine, The University of Pittsburgh, 28 February 2006, Pittsburgh, UNITED STATES OF AMERICA
10. Facial Growth – A new perspective in three-dimensional, 32nd Annual International Conference on Craniofacial Research (Moyers Pre-symposium), The University of Michigan, 24 February 2006, Ann Arbor, UNITED STATES OF AMERICA
11. Three-dimensional imaging in Orthodontics, Clinical Seminar, School of Dentistry, The University of Indianapolis, 20 February 2006, Indiana, UNITED STATES OF AMERICA
12. Three-dimensional Soft tissue imaging and its clinical application in orthodontics, 31st Annual International Conference on Craniofacial Research (Moyers Pre-Symposium), The University of Michigan, 25-26 February 2005, Ann Arbor, UNITES STATES OF AMERICA
13. The application of three-dimensional Technology in soft tissue imaging in Orthodontics, Continuing Professional Education, Department of Orthodontics, The School of Dentistry, The Ohio State University, 30 November 2004, Columbus Ohio, THE UNITED STATES OF AMERICA
14. The application of three-dimensional imaging in orthodontic diagnosis, Continuing Professional Education, Faculty of Dentistry, National University of Singapore, 10 March 2004, REPUBLIC OF SINGAPORE

Local Invitations

1. Soft tissue applications for the orthodontist, South Wales Orthodontic Group Meeting, 30 June 2006, Cardiff, UNITED KINGDOM
2. Invited Press Interview, Helping Teenagers Face the World, BBC News Online and BBC Good Morning Wales, Wales Today; 15,17 July, 30 November 2004
3. Three-dimensional imaging of cleft patients, Network Development Day, Frenchay Hospital, 12 November 2004Bristol, UNITED KINGDOM
4. Modern three-dimensional imaging in Orthodontics, 30th MScD Reunion, Cardiff and Vale Country Club, 14-15 October 2004, Cardiff, UNITED KINGDOM

Oral Presentations

1. Three-dimensional evaluation of facial growth, 6th International Orthodontic Congress, 11-15 September 2005, Paris, FRANCE
2. A three-dimensional analysis of facial growth in a cohort of children, 81st Congress of the European Orthodontic Society, 3-7 June 2005, Amsterdam, THE NETHERLANDS
3. The construction of the three-dimensional average face – A clinical evaluation and application, 2nd International conference for Advanced International Technology in Head and Neck Reconstruction, 10-13 March 2005, Banff, CANADA
4. Natural Head posture in the measurement of facial morphology. 80th European Orthodontic Society Congress, 4-10 June 2004, Aarhus, DENMARK
5. Three-dimensional laser scanning as a method of studying craniofacial growth, Senior Colgate Prize at the BSDR Annual Scientific Meeting, 6-8 April 2004, Birmingham, UNITED KINGDOM
6. Measuring three-dimensional soft tissue morphology in natural head posture, 6th International Symposium on computer methods in biomechanics and biomedical engineering, 25-28 February 2004, Madrid, SPAIN
7. Reliability of measuring three-dimensional soft tissue images in children, 6th International Symposium on computer methods in biomechanics and biomedical engineering, 25-28 February 2004, Madrid, SPAIN
8. Validity and reliability of a portable three-dimensional optical scanning device for field studies, 7th European Craniofacial Congress, 20-23 November 2003, Bologna, ITALY

(B) PUBLICATIONS

1. An analysis of facial growth – three-dimensional perspective. Craniofacial Growth Series. Centre for Human Growth and Development, The University of Michigan, Ann Arbor, Needham Press. Vol 44, 2007.
2. Three-dimensional construction of the 11 year average face – A clinical evaluation and application. *Kau CH, Zhurov A, Richmond S, Knox J, Sugar S, Bibb R, Hartles F* (Journal of Oral Maxillo-facial Surgery 2006, 64(7): 1086-1092)

3. Facial Templates – A new perspective in three dimensions. *Kau CH, Richmond S, Zhurov AI, Savio C and Mallorie C* (Orthodontics and Craniofacial Research, 2006, 9(1), 10-7)
4. Three-dimensional soft tissue imaging and its clinical application in orthodontics. *Kau CH*, Zhurov AI and Richmond S (Digital Radiography and Three-dimensional imaging: Craniofacial Growth Series. Centre for Human Growth and Development, The University of Michigan, Ann Arbor, Needham Press, 2006, Vol 43, 157-179)
5. Three-Dimensional Cone Beam Computerised Tomography. *Kau CH, Palomo JM, Richmond S and M G Hans* (Journal of Orthodontics 2005, 32 (4) 281-292)
6. Reliability of measuring facial morphology using a three-dimensional laser scanning system. *Kau CH, Zhurov AI, Knox J, Chestnutt I, Playle R, Hartles FR and Richmond S* (American Journal of Orthodontics and Dentofacial Orthopedics, 2005, 128(3):424-430)
7. The investigation of the changing facial appearance of identical twins employing a three-dimensional laser device. *Kau CH, Zhurov AI, Bibb R, Hunter ML, Richmond S* (Orthodontics and Craniofacial Research, 8(2): 85-90)
8. Naturliche Kopfhaltung fur die messung der dreidimensionalen weichgewebmorphologie. *Kau CH (*KN Kieferorthopadie Nachrichten 2005, April Pg 3-7, ISSN: 1612-2577)
9. Feasibility of measuring three-dimensional morphology in children. *Kau CH, Zhurov AI, Bouwman S, Scheer R and Richmonds S* (Orthodontics and Craniofacial Research, 2004, 7(4) 198-204)
10. Natural head posture for measuring three-dimensional facial morphology. *Kau CH, Zhurov AI, Harltes FR, Knox J and Richmond S* (Computer methods in biomechanics and biomedical engineering – 5, Editors Middleton J, Shrive NG and Jones ML, 2006, ISBN: 0-9549670-0-3)
11. Measuring facial morphology in young subjects. *Kau CH, Zhurov AI, Harltes FR, Knox J and Richmond S* (Computer methods in biomechanics and biomedical engineering – 5, Editors Middleton J, Shrive NG and Jones ML, 2006, ISBN: 0-9549670-0-3)
12. Computer Methods in three-dimensional modelling of human facial images. *Zhurov AI, Kau CH and Richmond S* (Computer methods in biomechanics and biomedical engineering – 5, Editors Middleton J, Shrive NG and Jones ML, 2006, ISBN: 0-9549670-0-3)

In Press

1. A textbook of three-dimensional imaging for orthodontics and maxillofacial surgery, *Kau CH and Richmond* S (Eds). Blackwell Books 2009
2. A three-dimensional analysis of surface changes to the facial morphology in a longitudinal study of 12 year normal untreated children. *Kau CH and Richmond S.* American Journal of Orthodontics and Dento-facial Orthopedics, 2008.

About the author.....

Chung How completed his dental training at the Faculty of Dentistry at the National University of Singapore. In 1999, following a period of general practice, he moved to Cardiff, Wales in the United Kingdom to complete his orthodontic speciality and academic training as a visiting specialist registrar and orthodontic postgraduate at the Cardiff Vale and Morriston Hospital NHS Trusts. He was appointed as a clinical lecturer and specialist in orthodontics at the School of Dentistry, Cardiff University in November 2002 and held this position until June 2006. He was subsequently appointed as a locum Consultant Orthodontist at Gloucestershire Royal Hospital until his present appointment. He keeps a link with Europe as a visiting Clinical Senior Lecturer in Orthodontics at Cardiff University.

He is an active researcher with a keen interest in three-dimensional research. He is an invited speaker on this topic and has shared his work on an international stage that includes North America, Western and Central Europe, the Baltic States, Hungary and the Far East. He actively contributes and publishes in the orthodontic literature and currently has 1book, 4 book chapters, more than 35 peer reviewed publications and 35 conference papers, that have been published or are in preparation. His other research interests include multi-centre randomized control trials in orthodontics and the clinical management of hypodontia. He is also the winner of two of the British Orthodontic Society's prestigious prizes – the Chapman (2002) and Houston Prizes (2006).

He completed an AMBA accredited Business Program programme and was awarded a Masters in Business Administration from the Leeds University Business School in 2003.

He is an Associate Professor in Orthodontics at the Dental Branch University of Texas, Health Science Center at Houston and Director of the 3-dimensional facial imaging laboratory. His lab possesses US$250,000 worth of 3-dimensional imaging equipment and has 3 support staff and 2 adjunct faculty.

He also participates in the Faculty Practice in at the Dental Branch, University of Texas Health Science Center. He is fully registered as a specialist and dentist in the United Kingdom and Singapore and holds a faculty license in orthodontics in the United States..