8-2003

An Empirical Examination of Frontal Sinus Outline Variability Using Elliptic Fourier Analysis: Implications for Identification, Standardization, and Legal Admissibility

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Recommended Citation

Christensen, Angi M., "An Empirical Examination of Frontal Sinus Outline Variability Using Elliptic Fourier Analysis: Implications for Identification, Standardization, and Legal Admissibility. " PhD diss., University of Tennessee, 2003.
https://trace.tennessee.edu/utk_graddiss/1981

To the Graduate Council:

I am submitting herewith a dissertation written by Angi M. Christensen entitled "An Empirical Examination of Frontal Sinus Outline Variability Using Elliptic Fourier Analysis: Implications for Identification, Standardization, and Legal Admissibility." I have examined the final electronic copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Anthropology.

Lyle W. Konigsberg, Major Professor

We have read this dissertation and recommend its acceptance:

Kenneth A. Rule, Richard L. Jantz, Murray K. Marks

Accepted for the Council:
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Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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A Dissertation
Presented for the
Doctor of Philosophy
Degree
The University of Tennessee, Knoxville

Angi M. Christensen
August 2003

Acknowledgements

The quality of this research was significantly enhanced by the copious and kindly contributions of numerous individuals. I would first like to thank the members of my doctoral committee, Dr. Richard Jantz, Dr. Kenneth Rule, Dr. Murray Marks, and Dr. Hermann Prossinger (a courtesy member) for their direction, supervision, and support. I would especially like to thank Dr. Lyle Konigsberg, the chair of the committee, without whose resourcefulness, assistance, and dedication this research could not have taken place. I would also like to thank Dennis Slice who was a great help in developing the protocol for the study. Adam Sylvester provided assistance throughout the course of the study, particularly with data collection, analysis, and emotional support. Cathy Graves spent innumerable hours assisting with data collection. Matt Adamson contributed his legal knowledge and reviewed parts of the manuscript. My parents, Chet and Kahni Christensen, have supported me in every endeavor of my existence, and I thank them for their support throughout my graduate career and this project. Lastly, I would like to thank the William M. Bass Endowment for providing financial assistance for the project.

Abstract

The comparison of frontal sinus radiographs for positive identification has become an increasingly applied and accepted technique among forensic anthropologists, radiologists, and pathologists. However, the current method of outline comparison by visual assessment fails to meet evidence admissibility guidelines as set forth in the 1993 case of *Daubert v. Merrell-Dow Pharmaceuticals, Inc*. Specifically, no empirical testing of the uniqueness of frontal sinus outlines has ever been performed, there has been no evaluation of the probability of misidentification using the technique, there are no standards controlling the technique's operation, and there are no subjective standards for confirming or rejecting a putative identification. Despite the fact that identifications based upon frontal sinus radiograph comparisons have been routinely accepted by scientists, medical examiners and law enforcement officers, these shortcomings could pose serious problems if forensic scientists were ever called upon to testify regarding such an identification in trial.

This study investigated frontal sinus outline variability using Elliptic Fourier Analysis (EFA), a geometric morphometric approach that fits a closed curve to an ordered set of data points, generating a set of coefficients that can be treated as shape descriptors used as variables in discriminatory or other multivariate analyses, or used to reproduce the outline. By modeling 2-dimensional representations of frontal sinuses (as seen in posterior-anterior cranial radiographs) as closed contours by digitizing their outer borders, differences in their shapes were assessed quantitatively by comparing the Euclidean distances between the EFA-generated outlines. The probability of misidentification was assessed using likelihood ratios and posterior probabilities based on the EFA coefficients.

Results showed that there is a quantifiable and significant difference between the shapes of different individuals' frontal sinus outlines as represented by Euclidean distances, since distances between outlines of different individuals were shown to be significantly larger than those between replicates (simulated antemortem and postmortem) of the same individual. Likelihood ratios using EFA coefficients showed that the probability of a frontal sinus match given the correct identification versus the probability of a match from the population at large was very high, and therefore the probability of misidentification was very low.

This study concluded that for individuals with sufficiently remarkable frontal sinus outlines, using EFA coefficients of digitized frontal sinus outlines to estimate the probability of a correct identification, and thereby confirm or reject a presumptive identification, is a reliable technique. Given these results, EFA comparison of frontal sinus outlines is recommended when it may be necessary to provide quantitative substantiation for a forensic identification based on these structures.

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Introduction

The use of frontal sinus radiographs in confirming the identity of human remains of an unknown individual has a relatively long history in forensics dating back to1925 (Culbert and Law, 1927). Traditionally, such identifications have been made by comparison of antemortem and postmortem radiographic records by a qualified expert (usually, a forensic anthropologist, pathologist, or radiologist) who makes a visual assessment as to the agreement (or lack thereof), making a largely subjective judgment as to whether the two radiographs are of the same individual. In the past, such assessments have received approval, and resulting opinions have been readily accepted in courts of law.

However, it is exceedingly rare that an expert's opinion goes unchallenged by other experts and/or opposing council. Moreover, recent rulings concerning admissibility of scientific evidence in court require more than credibility, persuasion, and manifest experience of the scientific expert. Methods used in positive identification need not only be considered valid and reliable, but they must be standardized and repeatable by other experts. Dwight (1878), clearly acknowledging the place of forensic anthropology within the legal system, noted that: "…it is for the jury, not the expert, to decide on the identity of a skeleton; it is for the expert to show whether the identity is possible or probable." However, without a standardized means for comparison, how do we show (quantitatively) whether an identification is possible or probable? The lack of an answer is a major shortcoming of current practices of identification by the visual comparison of antemortem and postmortem radiographs of frontal sinuses of the putatively same individual.

Furthermore, despite the fact that many believe that the shapes of frontal sinus outlines are unique to each individual, no empirical studies have ever rigorously tested this hypothesis. Several studies use linear measurements (such as height and width) and descriptive variables (such as the presence of asymmetry and number of septa) to examine differences in frontal sinuses between groups or to construct categories for comparison, but such studies are insufficient and inconclusive as to the reliability of comparing individual frontal sinuses for positive identification. The lack of such testing consequently results in a lack of statistical estimates of reliability and therefore no knowledge of the probability of misidentification. The value of comparing antemortem and postmortem radiographs in forensic contexts is fully and widely appreciated, but more extensive research into the uniqueness of each individual's frontal sinus outline and the statistical reliability of diagnostic features used in positive identification is necessary.

The study presented here was undertaken in response to these observed shortcomings and its purpose was three-fold:

1. To emphasize the need for objectivity and a standardized methodology for identification using frontal sinus outlines, especially in light of recent rulings in admissibility law;

2. To empirically assess frontal sinus outline variability using Elliptic Fourier Analysis (EFA);

3. To investigate the reliability of the EFA method for identification, and estimate the probability of misidentification (at least in a forensic context).

Chapters 1-4 describe and review several prerequisites needed to understand the research presented in the subsequent chapters. Since this investigation deals with a method of positive identification, Chapter 1 discusses the concept of personal identification and why this task is important in our society, and reviews the history of forensic applications using radiology, including (and in particular) applications to cases of personal identification, thus providing an essential background as to how and why radiology has come to be so important to forensic investigations concerning identification. Chapter 2 is devoted to the frontal sinuses as an anatomical structure; it is imperative to have a comprehensive understanding of the growth, development, purpose, function and sources of variation of any structure used in personal identification. Chapter 3 reviews the use of frontal sinuses in positive identification (including previous investigations into its variation) and case studies in which the technique has been used. Chapter 4 summarizes the history and importance of the laws pertaining to the admissibility of scientific evidence, which is essential to understanding the purpose and implications of the following investigation.

Chapter 5 describes the materials and methods used to undertake the study, and chapter 6 presents the results. Chapter 7 consists of a discussion of the preceding study including its significance, possible sources of error, and limitations.

Chapter 1: Personal Identification

The Importance of Identification

Establishing positive identification of an unknown individual is important in our society for both legal and humanitarian reasons. Legally, issues of inheritance and succession to property, collection of insurance policies and pensions, administration of wills, lawsuits involving negligent parties, prosecution of homicide, detection of fraudulent deaths, accident reconstruction, remarriage, issuance of a death certificate and other matters concerning property and business interactions all depend on the ability to establish a positive identification (Phrabhakaran et al., 1999; Sopher, 1972; Wentworth and Wilder, 1932). Morally, confirming identification is usually critical in the closure and resolution of surviving relatives and friends as well as being the subject of matters of international concern such as investigations in conflict regions including Kosovo, Argentina, Bosnia and Rwanda.

Wentworth and Wilder (1932) noted that it “would seem to be possible under all circumstances [to positively identify an individual] only by making use of some mark or peculiarity permanently and unalterably fixed upon the body itself.” The suggestion of some kind of artificial permanent mark or tattoo to ensure unequivocal identification has often been proposed, but we have come to discover that such markings are not necessary since we can take advantage of our individual unique features. Recent progress has allowed us to further explore and document differences among individuals, increasing the potential avenues for positive identification.

So important is the issue of identification in today's society that all possible avenues should be explored in order to accurately identify deceased individuals. Accordingly, forensic experts in identification methods should utilize all available evidence in an attempt to assess identification as accurately as possible. Sometimes, this is a straightforward process, particularly when remains are fresh and visual clues are readily available. Other times, however, it is necessary to use less conventional methods of identification based on individual peculiarities or variations in anatomy.

Identification Systems

It is important to remember that although certain features of individuals are commonly referred to as "identification symbols", they are more aptly called "*re*identification symbols". Any valid system of identification is based on two already established and previously known facts—the identity of that individual, and a record of her or her own particular uniqueness. Identification by "reidentification symbols" is a method for verifying that the individual concerned is the same as the one previously concerned.

The task of reidentification is usually the responsibility of the forensic pathologist, coroner, or law enforcement officer. The identification method used in forensic contexts is dictated by the postmortem condition of the body as well as the availability of antemortem information about the deceased for comparison. The reliability of individual methods varies, but a corroboration of several less reliable methods can increase the probability of a correct identification (Sopher, 1972). Although the present study focuses on identification using frontal sinus radiographs, the reader should be aware of and minimally familiar with the numerous other identification methods in use, particularly since methods are frequently compared and contrasted in attempts to identify their respective strengths and weaknesses.

Visual examination is the most frequent mode of personal identification (Sopher, 1972). It usually involves recent deaths with well-preserved bodies whose facial and other physical features or markings are not distorted by decomposition or injury and can be readily identified by relatives or friends. Less frequently, friends or relatives may be asked to identify personal effects found in context with the deceased. Fingerprint comparison, based on the premise that no two individuals have identical ridge patterns on their fingers, provides the most widely used means of quantifiable identification (Sopher, 1972) and is supported by studies that suggest that the probability of two individuals having identical fingerprints is extremely remote (Pankanti et al., 2001). The use of deoxyribonucleic acid (DNA) in identification is an increasing trend. Scientists have realized since the 1950s that an individual's DNA (located in the cellular nuclei of all living organisms) encodes information about the individual's inherited characteristics, and moreover, that this code is unique to each individual. DNA analysis allows identification by reference to the inheritable traits contained in any human nucleic cell.

Identification by comparison of antemortem and postmortem dental records is a well-documented, accepted, and widely used procedure (Farrell, 1979; Sopher, 1972), and is considered one of the most effective means of identification of unknown bodies (Sainio et al., 1990). Its reliability rests in the fact that there are innumerable combinations of restorations, prosthetics, dentition gaps, and carious lesions that an individual may possess. While these are usually compared using radiographs, even hand-written notes have been shown to be applicable to the dental identification process

(Adams, 2002). Identification by comparison of various aspects of the skeleton (including morphological peculiarities, unusual allometric relations, epigenetic traits, healed fractures, and evidence of previous medical care) has become increasingly popular with forensic anthropologists, pathologists and radiologists. As this method is intimately linked to the investigation of frontal sinus outline variability, it will be reviewed in greater detail below.

Skeletal Identification

One problem in identification is that of establishing the identity of bodies that are skeletal, decomposed, dismembered, or badly burned. Visual recognition in these cases is obviously out of the question, and fingerprint evidence is often unobtainable. Teeth may also become scattered and lost so that dental comparisons may not be possible even if most of the skull has been recovered. In these cases, identification must rely on the bones alone, and forensic anthropology is of great necessity here (Dwight, 1878). An anthropological (skeletal) analysis is often the method of choice for estimating the ancestral (and perhaps ethnic) affinity, sex, age and stature of the individual. This assessment, though useful in narrowing the pool of potential candidates in the search for identity, is not (yet) a positive identification.

A positive identification is generally made on the basis of agreement between the skeleton and facts known about a putative deceased person who has been selected for comparison on the basis of being missing and possibly dead (Kerley, 1977). Any distinguishing features or traits such as prosthetics, fractures, and congenital or traumatic deformities or abnormalities may be particularly convincing evidence and can often provide the basis for a highly probable identification (Dwight, 1878). Generally, the greater the number of skeletal peculiarities that match peculiarities of a sought-for individual and the more unusual the peculiarity, the greater the probability that the identification is correct (Dutra, 1944).

In addition to comparing aspects of the skeleton, photographic superimposition can sometimes be applied in a skeletal identity investigation (Kerley, 1977). This method involves superimposing a photograph of a suspected victim over a radiograph of a skull. While this technique can be used to positively exclude the possibility that the skull of the remains would have fitted with the contours of the face of the deceased, it cannot be taken as absolute identification (Kerley, 1977).

Increasingly frequent is the direct (visual) comparison of antemortem and postmortem radiographs for the purpose of confirming a presumptive identification by matching specific unique visual findings or features on the antemortem and postmortem radiographs of that person (Brogdon, 1998). The history and development of this method of identification is closely related and particularly pertinent to the investigation of the techniques presented in this study.

History and Basic Radiological Concepts

On Friday afternoon, 8 November, 1895, Wilhelm Conrad Röntgen, working in his Würzburg physics laboratory, made a serendipitous and monumental discovery: "If the discharge of a fairly large Rühmkorff induction coil is allowed to pass through a Hittorf vacuum tube … and if one covers the tube with a fairly close-fitting mantle of thin black cardboard, one observes in the completely darkened room that a paper screen with barium platinocyanide placed near the apparatus glows brightly or becomes fluorescent with each discharge, regardless of whether the coated surface or the other side is turned toward the discharge tube. The fluorescence is still visible at a distance of two meters from the apparatus. It is easy to prove that the cause of the fluorescence emanates from the discharge apparatus and not from any other point of the conducting circuit" (Röntgen, 1895; English translation in Pais, 1986)

In this same publication, Röntgen reports that materials containing atoms with a high atomic number Z, notably lead, attenuated these rays, which he called "*X-Strahlen*" (from which derives the English name "x-rays"; in German they are called "*Röntgenstrahlen*" in his honor), much more readily than atoms with few protons in the nucleus, such as hydrogen and many other atoms in soft tissues. Indeed, one of the first medical photographs (the first roetgenogram or radiograph) is of his wife's hand, made on December 22, 1895. As usual, she was wearing her wedding ring, and its image showed up clearly on the photograph; this is how Röntgen found out about the scattering of x-rays by high-Z atoms. Subsequent studies by Röntgen and others have shown that the intensity distribution of x-ray wavelengths depends on (1) the supply voltage between anode and cathode, (2) the material of the anode, and (3) the current between cathode and anode.

Modern x-ray equipment used in medicine takes advantage of our knowledge of the various mechanisms *generating* x-rays in the anode material: (1) bremstrahlung and (2) K- or L-shell capture; as well as our knowledge of *attenuation* mechanisms: (1) Compton scattering, (2) pair production, (3) nuclear reaction, (4) photon scattering, and (5) photoelectric effect (Dössel, 2000). By suitably adjusting the parameters controlling these mechanisms, medical radiologists can produce very clear and diagnostically revealing images of either bony material or soft tissue.

What is imaged on an x-ray film is conventionally called a radiograph in the medical profession, not an x-ray as it is called in common parlance, and will be referred to as a radiograph in this study. Conventional radiographs are produced in the following manner: The attenuated beam that has passed through the body part(s) being investigated illuminates a gelatin film containing silver bromide crystals in an emulsion. A bromide ion in such a crystal hit by an x-ray photon is oxidized into elementary bromine, releasing an electron (Br^- + x-ray photon ? $Br + e^-$) that diffuses within the crystal. This electron subsequently reduces an Ag^+-ion to a Silver atom ($Ag^+ + e^-$? Ag). During the 'development process' of the emulsion (usually by hydochinone or some chemically similar reducing agent) practically all Ag^+-ions in the crystal containing the 'seed' Ag atom are reduced to elementary Silver, while the process called "fixing" removes the non-excited Silver bromide crystals. In other words, in a radiograph, dark regions are where x-ray beams illuminated the film, white ones are where the beam was absent. Very few x-rays reach the part of the film directly under bones because of the large amounts of calcium they contain which attenuates many of the x-ray beams. Substances that attenuate x-ray beams considerably (such as bone minerals) are referred to as *radiopaque*, while less attenuating material (such as soft tissues) are called *radiolucent*.

The examination of radiographs has become commonplace in medicine and has many prognostic and diagnostic applications. The x-ray wavelengths used in medical diagnoses vary, and x-ray technologists are trained to select and use wavelengths according to the attenuation properties and thickness of the parts they are filming. This is done by varying the operating voltage (usually several kilovolts (kV)) of the machine; the higher the voltage, the harder or more penetrating the x-ray beams are. The time of exposure can also be altered, and the dosage of radiation can be adjusted by varying the current driving the tube (usually in the miliampere range).

Both making and examining radiographs requires some knowledge of the relative radiodensities of various substances; keeping thickness as well as other technical parameters constant, the radiographic appearance of substances will vary as a function of their attenuation numbers. In practice, the radiologist adjusts the technical parameters to accentuate those differences as defined by what is being examined. This is an important aspect to keep in mind, since x-ray examinations of the body often involve beam penetrations through various tissues of differing attenuations, and what is actually rendered on the film can be called a "composite shadowgram." The shadowgram represents the integral of the attenuations along the beam line from source to film (Novelline, 1999; Prossinger and Bookstein, 2003; Spoor et al., 2001).

Forensic Radiology

Radiographic investigation of human remains began soon after the discovery of x-rays as investigators came to realize that x-rays provided a non-destructive means of examining human remains. The method was actually first applied to ancient rather than forensic specimens. By the end of the 19th Century, Culin and Lester made radiographs of a Peruvian mummy from Pachacamac (Rowe, 1953). In 1898, Culin published a radiograph of a spear thrower from Colorado and soon thereafter, a large number of Peruvian and Egyptian mummy bundles were examined using x-rays (Petrie, 1898; Rowe, 1953). Other early applications of radiology in anthropology included the study of bone pathologies (Hooton, 1930) and growth (Greulich and Pyle, 1959). Being far less laborious than dissection or serial section, radiography also permitted the examination of much larger samples, allowing more quantitative approaches (Spoor et al., 2001). Early radiographic investigations, however, typically considered only general anthropological and pathological findings with little or no emphasis on skeletal variability (Brothwell et al., 1968).

Radiology, however, soon found applications in many medicolegal and forensic anthropological investigations including:

- age estimation (Greulich and Pyle, 1959; Murphy and Gantner, 1982),
- sex estimation (Krogman and Iscan, 1986; McCormick et al., 1985; Morgan and Harris, 1953; Murphy and Gantner, 1982),
- ancestry estimation (Stewart, 1979),
- stature estimation (Murphy and Gantner, 1982),
- determining whether or not remains were human (Messmer, 1986; Murphy and Gantner, 1982),
- locating and recovering bullets and other foreign bodies and determining the direction, angle and location of wounds (Eckert and Garland, 1984; Fatteh and Mann, 1969; Schmidt and Kallieris, 1982),
- detecting air-embolisms (Camps, 1969; Schmidt and Kallieris 1982),
- detecting and aging fractures and other trauma (Camps, 1969; Eckert and Garland, 1984; Fatteh and Mann, 1969; Schmidt and Kallieris, 1982),
- diagnosing tuberculosis (Schmidt and Kallieris, 1982),
- examining hyoid or cartilage fractures in hanging or strangulation victims (Camps, 1969; Fatteh and Mann, 1969),

- examining past medical history (Murphy and Gantner, 1982),
- illustrating dental morphologies and anomalies (Eckert and Garland, 1984; Krogman and Iscan, 1986),
- separating skeletal remains from wood charcoal and other charred material (Krogman and Iscan, 1986; Morgan and Harris, 1953),
- diagnosing premortem skeletal health (Krogman and Iscan, 1986),
- studying the relationship between bone and soft tissue as a check of and development of methods for facial reconstruction (Rowe, 1953),
- detecting metallic poisons such as arsenic, lead and mercury in suspected poisoning cases (Fatteh and Mann, 1969; Schmidt and Kallieris, 1982), and
- examining burned, skeletonized or decomposed individuals for the purpose of identification (see below).

As a result, the value of radiography has become well established in the criminal and medicolegal work of police officers, medical examiners and attorneys (Cornwell, 1956).

Positive identification following a presumptive identification by comparing antemortem and postmortem radiographs has become an increasingly applied technique in medicolegal investigations. The earliest suggestion of the use of radiology in the identification of unknown human bodies was by Schuller (1921) who called attention to the potential use of frontal sinus variability in this context. The technique is based on the notion that osteological features as seen in radiographs may be sufficiently individual as to aid in the confirmation of identity based on the variability of these features. Often, such positive identifications are based on several features or details of agreement, but an identification can even be based on a single bony feature if it is deemed to be distinctly unique (Brogdon, 1998; Messmer, 1986). Comparative radiography for the purpose of identification has become a well-established technique in forensic anthropology and it has been said that it compares favorably well with fingerprint and dental identifications (Murphy et al., 1980).

In cases where a visual or fingerprint identification is not possible, radiographic identification has come to predominate since the teeth and skeleton will usually survive longer than other identifying characteristics and is hence almost always available for examination (Murphy et al., 1980). It has even been noted that it is virtually impossible to destroy a body by fire so completely that no element remains accessible for examination and comparison (Bass, 1984). For this reason, radiographic identification is routinely used following mass disasters and in the identification of burned, mutilated, decomposed, fragmented, skeletonized and otherwise unrecognizable human remains. Especially in these latter cases, radiography is sometimes the only means by which an individual’s identity can be established (Cornwell, 1956), particularly in the absence of teeth and/or dental records (Atkins and Potsaid, 1978; Jensen, 1991; Marlin et al., 1991). Moreover, given that radiographs have become a common diagnostic tool for various other medical investigations thus increasing the availability of antemortem records for comparison, the potential for applying the technique is improving. Indeed, radiographic comparison is a common procedure in the identification of unknown remains in most forensic facilities throughout the world (DiMaio and DiMaio, 1989).

Some suggest that “abnormal” features such as anomalous or unusual development, healed fractures, deformities, degenerations, pathologies, abnormal calcifications, tumors, trauma, and prosthetic devices are most important for identification purposes (Brogdon, 1998; Murphy et al., 1980). Such assertions are based on the idea that abnormalities and post-surgical features produce traits that are very likely to be unique to that individual. Moreover, in the event of some abnormality, the chance that the individual will have an antemortem radiograph available for comparison is high. This technique has been applied in various published case studies including identification using:

- a foot deformity (Sudimack et al., 2002),
- bone spurs present on the legs and feet (Owsley and Mann, 1989),
- post-surgical cranial defects (Hogge et al., 1995),
- surgical fusion of foot bones (Sivaloganathan and Butt, 1988),
- prosthetic devices (Penalver et al., 1997),
- pelvis deformities (Angual and Derczy, 1998),
- iliac crest peculiarities (Brogdon, 1998),
- bony spicules on the innominate and flattened regions of the obturator foramen (Rouge et al., 1993),
- congenital acetabular dysplasia (Varga and Takacs, 1991),
- wrist fractures (Atkins and Potsaid, 1978),
- a patellar defect (Riddick et al., 1983), and
- fusion of the sacroiliac joint (Murphy and Gantner, 1982).

However, many recognize that the richness of normal anatomical detail revealed in radiographs is equally, if not more, important since the widespread occurrence of nonpathological anatomical features available for comparison in most radiographs may obviate the need to use pathological or abnormal features (Joblanski and Shum, 1989). This technique makes many parts of the skeleton usable for identification, and while those that tend to be more variable may be more reliable, nearly every bone in the body could be (or has been) used for identification (Hogge et al., 1993).

Comparison of normal anatomical variation may significantly increase the potential number of corresponding features for identification (Joblanski and Shum, 1989). Radiographic examinations of the details of bone structure often reveal individual characteristics that can be compared (like fingerprints) to establish identity (Kade et al., 1967). Identity can be established in these cases by comparison of minute details of external cortical contours and bone surfaces (Kerley, 1977) and metric analysis (Sassouni, 1959; Thorne and Thyberg, 1953), as well as the internal architecture of the bones such as their trabecular pattern (Joblanski and Shum, 1989; Kahana et al., 1998; Kahana and Hiss, 1994; Mann, 1998) and vascular grooves (Brogdon, 1998).

Numerous reported cases and studies illustrate the use of radiography (often in conjunction with other evidence) to establish individuality using nonpathological variation of various aspects of the skeleton including:

- parts of the skull (Culbert and Law, 1927; Fatteh and Mann, 1969; Joblanski and Shum, 1989; Murphy et al., 1980; Rhine and Sperry, 1991; Sassouni, 1959; Singleton, 1951; Thorne and Thyberg, 1953),
- the chest (Martel et al., 1977; Murphy et al., 1980; Singleton, 1951),

- the sternum (Rouge et al., 1993),
- the abdomen (Angyal and Derczy, 1998; Joblanski and Shum, 1989; Murphy et al., 1980),
- costal cartilage (Marek, 1983),
- the spine (Brogdon, 1998; Fatteh and Mann, 1969; Jensen, 1991; Kahana et al., 2002; Kahana et al., 1997; Murphy et al., 1980; Owsley et al., 1993; Singleton, 1951; Stevens, 1966; Valenzuela, 1997),
- the clavicle (Adams and Maves, 2002; Marek, 1983; Sanders et al., 1972),
- the scapula (Ubelaker, 1990),
- the hand and wrist (Greulich, 1960; Koot, 2003),
- the pelvis (Singleton, 1951),
- the femur (Dutra, 1944), and
- the ankle and foot (Kade et al., 1967; Singleton, 1951).

The lumbosacral region has been cited as being especially useful since it tends to survive the longest, especially in fires (Cornwell, 1956).

An important caveat to observe, however, is that the anatomy of adult bone is not stable, but continually remodeled and restructured in response to changes in function (Currey, 1984). The stability of the bone is related to the stability of the loading regimes to which it is subjected as well as advanced age, which is associated with a loss of cortical bone. One study (Sauer et al., 1988), however, demonstrated that aspects of the postcranial axial skeleton generally chosen to compare for identification are quite stable, and the ability to make a positive identification from postcranial axial material may not diminish, even after two-and-a-half decades.

Prior to comparison for the purpose of identification, an investigator must be equipped with an appreciation for how, why and where a structure may vary, and what constitutes “normal” and “non-normal” variation. Such an appreciation can only be gained through a comprehensive understanding of the anatomical structure of interest including a working knowledge of how the structure develops, its sources of variation, and the purpose and function of the structure. To this end, before addressing the use of frontal sinuses in positive identification, the following chapter presents a synopsis of the frontal sinuses as an anatomical structure in order to increase appreciation for the adult form and its variability.

Chapter 2: The Frontal Sinuses

Ontogeny

The frontal sinuses are formed by invagination of the epithelium covering the walls of the nasal cavity. Around the fourth or fifth fetal month, this invaginated pouch is directed upward and medially resulting in the emergence of ethmoidal and frontal cells (cavities). There appears to be some variation in which cells, exactly, give rise to the frontal sinuses. They are usually considered a derivative of the recessus frontalis, one or more of the cellulae ethmoidales anterior, or both (Schaeffer, 1916a). However, others maintain that they may also develop by the expansion of the cellulae infundibulares, the recessus conchalis, or the infundibulum ethmoidale (Davis, 1918). The relative rate of advancement of the cells appears to determine which of them will eventually become the frontal sinus (Davis, 1918) and its extent (Prossinger and Bookstein, 2003).

Toward the end of the fifth fetal month, a marked differentiation of this pouch takes place with the invagination of the vesicles into the frontal bone. These cavities, later involved in the emergence of the frontal sinuses, are lined with a mucous membrane and surrounded by a thin layer of compact bone. The development of the frontal sinuses then proceeds by two simultaneous processes: the progressive advancement of the sinus mucosa and the concomitant resorption of the adjacent bone. Frontal sinus expansion proceeds very slowly in this manner until birth. Very little is known about the processes of pneumatization at the cellular and tissue level, and even less is known about how pneumatization is controlled (Witmer, 1999).

At birth, the frontal sinuses are very small and essentially indistinguishable from the ethmoid air cells. During the first year after birth, the frontal sinus complex is still ethmoidal in topography (Samuel and Lloyd, 1978), but by the second year, pneumatization has reached the frontal bone (Figure 2.1). The frontal sinuses become more conspicuous in size by the second or third year when their apex often extends above nasion. Further expansion into the vertical portion of the frontal bone begins around the fifth year, with most children over the age of six demonstrating vertical projection radiographically (Brown et al., 1984; Dolan, 1982a; Donald et al., 1994; Libersa and Faber, 1958; Maresh, 1940; Prossinger and Bookstein, 2003; Szilvassy, 1973). The main enlargement of the sinuses occurs during puberty with a small additional increase in height several years after this growth spurt in some individuals (Brown et al., 1984; Prossinger and Bookstein, 2003). This spurt in enlargement is completed slightly earlier in girls than in boys (around 10 and 14 years, respectively), and frontal sinus growth is generally completed by the twentieth year (Prossinger and Bookstein, 2003).

"Normal" Anatomy

In adults, the frontal sinus usually appears as two irregularly shaped and asymmetric cavities extending backward and laterally for a variable distance between the tables of the frontal bone, often separated from each other by a thin bony septum that is usually deflected to one side of the median plane (Gray, 1901) (Figure 2.2). One frontal sinus lobe on each side of the cranium is the prevailing anatomical arrangement, but supernumerary or absent frontal sinuses have been observed (Szilvassy, 1973). The most common outline of the frontal sinus resembles a triangle with the base inferior and the apex superior. It is not uncommon for frontal sinuses to extend into the orbital margin

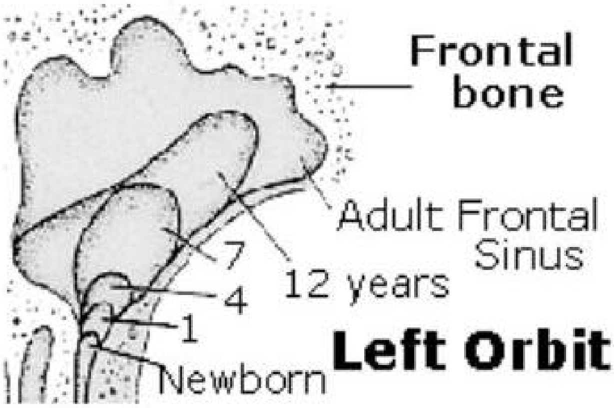
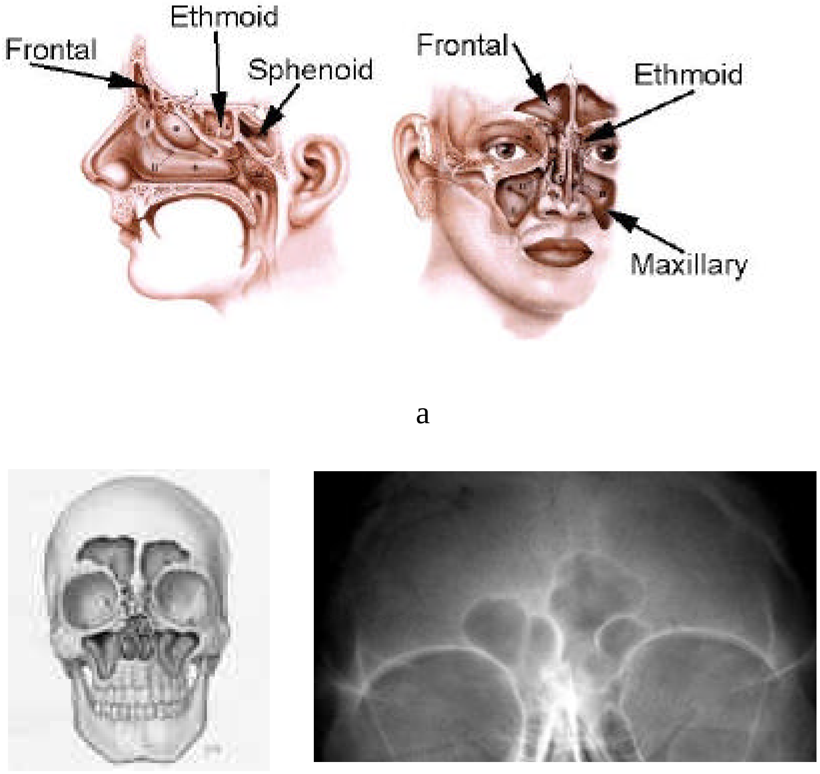


Figure 2.1: Development of the Frontal Sinuses.

(From Baylor College of Medicine, 1996)



a

b

c

Figure 2.2: “Normal” Adult Frontal Sinuses.

The frontal sinuses in (a) frontal and lateral view of a living individual (Kids ENT Home Page, 2000), (b) cut-away skull (University of Calgary Medical Clinic, 2000), and (c) radiograph (The University of Tennessee Forensic Anthropology Center, 2003).

of the frontal bone (sometimes called “supraorbital sinuses”), and in some cases, this is the only region where they are present, with no projection into the vertical portion (Cryer, 1907; Schaeffer, 1916b; Shapiro and Janzen, 1960).

Along the roof and the anterior wall there may be numerous bony ridges (called lamellae). In an anterior-posterior radiograph, these ridges, which are incomplete partitions of varying lengths, appear as projections extending downward into the sinus, producing recesses and giving the sinuses their irregular “scallop-like” outlines (see Figure 2.2c). Membranes and septa arise from these ridges, hanging into the sinus. They may partly or completely divide the sinus, with partial division more common than complete division (Samuel and Lloyd, 1978; Shapiro and Janzen, 1960). At least one complete bony septum is usually present internally, separating the sinus cavity, and as a rule it is very thin (< 0.5 mm) (Turner, 1902). The septum is usually situated along the medial plane, but deviation is very common. In most cases, the inferior and anterior portion of the septum is medially oriented, with displacement occurring superiorly and posteriorly.

There are three primary boundaries of the frontal sinuses: the anterior (forehead), posterior (cranial cavity), and inferior (orbital plate) (Hajek, 1926), forming the three bony walls of the sinus, which are best visible in a lateral view of the sinus cavity (see Figure 2.2a). The anterior wall is formed by the convex outer table of the frontal bone and may include the superciliary ridges and glabella. The anterior wall is generally the thickest of the borders but may vary considerably in thickness (from < 1 mm to 8 mm) (Turner, 1902). The posterior wall is formed by the inner table of the vertical portion of the frontal bone and is thus slightly convex forward. It, too, varies in thickness, but tends to be much thinner (usually < 0.5 mm) and with a more constant thickness (Turner, 1902). The posterior aspect of this wall is in contact with the frontal lobes of the brain and thus may be characterized by meningeal markings. The inferior wall of the frontal sinus is the orbital plate (the upper and inner roof of the orbits) and the ethmoidal labrynth, and is the thinnest of the three frontal sinus walls (Turner, 1902).

The sinus cavity is filled with air and fluids and lined by a thin muco-periosteal membrane that is continuous with the lining of the nasal chamber (Turner, 1902). This membrane is covered by a layer of ciliated epithelium and contains a number of mucous glands (Caffey, 1993). There appears to be some variation in the manner of connectivity between the frontal sinus and the nasal cavity in accordance with the embryology of the sinus. In most cases, the pneumatic space extends downward and inward communicating with the frontal recess either by a true naso-frontal duct, or by an ostium frontale directly in the caudal portion of the frontal sinus (Schaeffer, 1915; Turner, 1902). Fronto-nasal ducts vary greatly in diameter, length and direction (Samuel and Lloyd, 1978) ranging from 2.6–5.1 mm in diameter and averaging 6.2 mm in length (Lang, 1989).

While Schuller (1921) noted that the form, size and position of the frontal sinuses do not change throughout adult life, slight changes are possible and have been noted. Changes in the appearance of frontal sinuses during life are attributable primarily to bone thinning with old age and trauma. The following list indicates six key mechanisms by which frontal sinus size and/or morphology may change during life (Buckland-Wright, 1970; Dolan, 1982b; Schuller, 1943):

1. With age, the walls of the frontal sinus may become thin causing the sinuses to appear larger.

2. Aging corresponds to shrinkage of the frontal lobes of the brain causing sinus enlargement as a compensatory process.
3. Post menopausal women may experience symmetrical hyperostosis on the inner surface of the forehead causing a reduction in sinus size.
4. Changes to the appearance of frontal sinuses may be induced by chronic inflammatory processes such as sinusitis, tuberculosis and syphilis, which can lead to either a thinning or thickening of the bone and subsequently causing an increase or reduction in sinus volume.
5. Tumors, injury, trauma and obstruction of the fronto-nasal duct may cause changes in sinus volume.
6. Other disease processes including mucoceles, osteomas, fibrous dysplasia, benign tumors and malignant neoplasms may alter the radiological appearance of the frontal sinuses.

Variations

Wide variations in frontal sinus anatomy seem to be the rule. The medial and orbital portions of adult frontal sinuses are relatively uniform, but the upper and lateral portions are quite irregular in appearance. Researchers have reported on variation in frontal sinus volume, cross-sectional area, outline geometry, and shape related to:

- sex (Buckland-Wright, 1970; Hanson and Owsley, 1980; Harris et al., 1987b; Schuller, 1943),
- climate (Koertvelyessy, 1971; Kondrat, 1995),
- extent of the supraorbital ridges (Hajek, 1926; Samuel and Lloyd, 1978),

- presence of a metopic suture (Hodgson, 1957; Montiero et al., 1957; Samuel, 1952; Samuel and Lloyd, 1978; Schuller, 1943; Torgersen, 1950; Van Alyea, 1951),
- acromegaly or cretinism (Schuller, 1943; Shapiro and Janzen, 1960),
- cranial indices (Gulisano et al., 1987; Strek, 1992; Turner and Porter, 1922), and
- ancestry (Brothwell et al., 1968; Ikeda, 1980; Turner, 1902).

Several suggestions have been put forth as being major contributors to the final adult shape of frontal sinuses and thus being responsible for the wide variation including:

- cranio-facial configuration (Koppe and Nagai, 1999; Shapiro and Schorr, 1980),
- endocrine factors (Buckland-Wright, 1970),
- hormonal factors (Samuel and Lloyd, 1978; Schuller, 1943; Shapiro and Schorr, 1980),
- biomechanical factors (Koppe and Nagai, 1999),
- genetics (Koppe and Nagai, 1999; Maresh, 1940; Samuel and Lloyd, 1978; Walander, 1965; Wolfowitz, 1974,),
- irregular or varying degrees of resorption of the diploe (Hajek, 1926; Shapiro and Janzen, 1960),
- thickness of the frontal bone (Shapiro and Schorr, 1980),
- environmental factors (Koppe and Nagai, 1999),
- ambient air pressure and breathing (Maresh, 1940; Walander, 1965),

- trauma (Maresh, 1940),
- infection (Carmody, 1929; Walander, 1965), and
- congenital abnormalities (Montiero et al., 1957).

Others suggest that their development is random (Asherson, 1965).

Extreme variation is seen in the size (often measured as volume, cross-sectional area, or dimensions) of frontal sinuses. Sinuses may be absent or too small to be detected, or on the other extreme, may extend well into the frontal region or beyond. Studies show varying findings, but indicate that average adult frontal sinus size is about 28 mm high, 27 mm wide, and 17 mm deep (Donald et al., 1994). Smaller or less developed sinuses generally consist of a single centrally concave recess and are usually located along the inner upper margin of the orbit (Hajek, 1926). In rare cases, the frontal sinuses may be considerably large, hyperpneumatizing into other bones of the skull including the lesser wings of the sphenoid, the temporal bone, the nasal bone, the crista galli of the ethmoid, and the ascending process of the maxilla (Cryer, 1907; Dolan, 1982a; Hajek, 1926; Shaeffer, 1916b). Some studies have commented on the increase in size of frontal sinuses in those with well-marked supraorbital ridges (Hajek, 1926; Samuel and Lloyd, 1978), and increased pneumatization has been noted to be characteristic of individuals with acromegaly (Shapiro and Janzen, 1960).

Since the left and right frontal sinus lobes develop independently, it is not surprising that they display a high degree of asymmetry in dimensions, as first noted by Zuckerkandl (1895). Asymmetry is generally attributed to a more rapid development on one side at the expense of the other (Turner, 1902). Directional asymmetry has received some attention in the literature, but the results are inconclusive. While some report that right sinus lobes tend to be larger than their left counterparts (Hajek, 1936; Lang, 1989; Schuller 1943), others have reported the opposite (Harris et al., 1987b; Marciniak and Nizankowski, 1957). Others (including Strek et al., 1992) have found no significant differences between the sizes of the left and right frontal sinus lobes. Perhaps these findings are population specific.

Sex differences in frontal sinus dimensions and morphology have been widely noted, with sinuses generally reported to be larger in males than in females (Buckland-Wright, 1970; Hajek, 1926; Harris et al., 1987b); one exception is Canadian Eskimo populations (Yoshino et al., 1987). While some studies indicate that females display more numerous scallops (loculations) along the upper border (Krogman and Iscan, 1986; Schuller, 1943), others indicate that increased loculations are more frequent in males (Harris et al., 1987b). Hanson and Owsley (1980), however, indicate no significant sex differences.

Inter-group variability has been noted for many features of the frontal sinuses, though an early study attempting to determine racial and/or ethnic characteristics showed negative results (Mayer, 1935). There have, however, been reports on general trends in certain populations. For example, frontal sinuses are reported to be frequently absent in Australian Aborigines (Turner, 1902), while modern African Negros often have well-developed sinuses (Brothwell et al., 1968). Turner and Porter (1922) reported greater frontal sinus development in “mixed European races” than in “pure races.” Several studies suggest an environmental or climatic factor contributing to the configuration or size of the frontal sinuses. Koertvelyessy (1972) suggested that cold and/or cold-dry adapted populations are characterized by smaller sinuses and reported that Alaskan

Eskimos have relatively small sinus surface areas with a high frequency of bilateral absence. West Hudson Bay Eskimos are reported to have sinus surface areas smaller than Alaskans (Hanson and Owsley, 1980). Kondrat (1995) found a strong positive correlation between annual seasonal temperature fluctuation and frontal sinus dimensions.

Two sinus cavities separated by a bony septum (most often located near the mid-sagittal plane) is the usual configuration, but variations have been reported on the number of sinus cavities present. A small percentage of individuals have been noted to have an unpartitioned central sinus (Quatrehomme et al., 1996). The presence of three or more sinus lobes is considered by some to be quite rare (Phrabhakaran et al., 1999), but others suggest that duplicate and triplicate (Schaeffer, 1916b) or even four and five sinus cavities (Cryer, 1907) are quite common. One author (Lang, 1989) suggests that supernumerary sinuses are more common on the left side than the right.

Occasionally, there is a complete absence or agenesis of one or both of the frontal sinus lobes. The first observation of the absence of a (maxillary) sinus was by Morgagni in 1723 (Blanton and Biggs, 1969). Studies report varying findings, but indicate that complete agenesis of the frontal sinus occurs in 5-15% of adults and the percentage may vary in different geographic groups (Harris et al., 1987b).

The reason for the absence of the frontal sinus has been debated, some having suggested that the congenital absence or underdevelopment of the frontal sinuses is associated with metopism (Hodgson, 1957; Montiero et al., 1957; Samuel, 1952; Samuel and Lloyd, 1978; Schuller, 1943; Torgersen, 1950; Van Alyea, 1951). The justification for this assumption is based on the fact that frontal sinus development occurs together with the development of the frontal bone, perhaps with a feedback regulating mechanism. If the frontal bones do not fuse, the metopic suture persists and pneumatization of the frontal sinuses may be retarded or suppressed, or they may fail to develop altogether (Samuel and Lloyd, 1978; Van Alyea, 1951).

One report supports this view by indicating a higher frontal sinus agenesis rate in metopic skulls (24%) versus non-metopic skulls (5%) and that when sinuses are present in metopic skulls, they tend to be reduced (Torgersen, 1950). In contrast, however, another study reported that among metopic individuals, bilateral absence of frontal sinuses only occurred in 8% of a sample, indicating no strong association between metopism and frontal sinus agenesis (Marciniak and Nazankowski, 1959).

Estimates of the frequency of unilateral agenesis also vary, but suggest that failure of development of one of the frontal sinuses occurs in 1-15% of adults (Donald et al., 1994). Some indicate that unilateral agenesis is more common than bilateral agenesis, and that the absence of both sinus lobes is considerably more rare (Samuel and Lloyd, 1978). Sex and geographic trends may exist for unilateral and bilateral absence, with one report suggesting greater agenesis in women than in men (36.8% and 47.1% for “white” and “yellow” races, respectively, in women, versus 19.6% and 39.7% in men), and greater agenesis rates in Eskimo and Indian populations (31.7%) than in European populations (16.9%) (Strek et al., 1992).

Several authors question the reported frequency of agenesis, ascribing it to a shortcoming of the employed methodology, namely, the inadequate examination of the horizontal portion of the frontal bone (Schaeffer, 1916b; Shapiro and Janzen, 1960). Not infrequently, the frontal sinus extent is limited to within the orbital plate of the frontal bone, and not invading the vertical part (or hugging very closely to the ethmoid labyrinth). Thus, such cases, not being visible radiographically, are falsely reported as frontal sinus absence. Reports of agenesis based solely on radiographic images invariably present higher estimates than those based on cadaveric dissections that include examination of the orbital portion.

Purpose and Function

While Weinert (1925) indicates that there is no evidence of frontal sinus pneumatization in the phylogenetic scale below the mammalian level, O'Malley (1924) suggests that it is present in some reptiles. Witmer (1999) suggests that the difference may be that while mammals possess ("proper") pneumatized paranasal sinuses, other clades of vertebrates exhibit air-filled epithelial diverticula of the nasal cavity. Paranasal sinuses appear to have evolved independently at least twice in Mammalia and Archosauria, with only the maxillary sinus being a nearly ubiquitous feature (Witmer, 1999). Frontal sinuses have appeared independently in a number of eutherian clades, but the homologies are far from clear (Witmer, 1999).

The reason for the presence of the paranasal sinuses in higher animals (including humans) has been a matter of some debate since their presence was first noted in the early 1st Century AD (Blanton and Biggs, 1969). Several theories for their anatomical and physiological significance have been proposed, and while some are considered more plausible than others, no single theory has been universally accepted as the reason for their existence (Blanton and Biggs, 1969). Indeed, one wonders why the possibility of more than one proposed mechanism has not been adequately and thoroughly discussed in the literature.

Proposed theories include enhancing resonance amplification to the voice, warming and humidifying inhaled air, increasing the olfactory membrane area, absorbing shock applied to the head in order to protect sensory organs, secretion of mucus to maintain adequate moisture levels in the nasal chambers, thermal insulation of the nervous centers (or maintaining adequate internal cranial temperature), aiding facial growth and architecture, decreasing bone mass in the skull, and existence as an evolutionary remnant (Blanton and Biggs, 1969; Bookstein et al., 1999; Prossinger and Bookstein, 2003; Prossinger et al., 2000; Ravosa et al., 2000).

O'Malley (1924) contends, based on a comparative anatomical study, that the primary function of the frontal sinuses is to give necessary bulk and strength to the facial skeleton without adding too much weight. He notes that frontal sinuses may serve other functions as well including completing saturation of inhaled air, widening the skull base to carry the more numerous permanent teeth, and acting as resonating chambers which would enhance the modulation of tones in nuanced speech (O'Malley, 1924). He suggests that the bulging forward of the cranial roof and downward inclination of the face bring the sinuses in front of the sound producing mechanism in the larynx, maximizing the result (O'Malley, 1924).

Shapiro and Schorr (1980) suggest that the presence of frontal sinuses has to do with the size and shape of the face, i.e., its form. Cranial enlargement due to increased brain growth tends to be associated with reduction in facial size. Whenever the neurocranium changes its form, they contend, the orbits might need to re-orientate because the optical axes of the eyes determine their orientation. They suggest that when there is a marked cranio-facial incongruence due to a small cranium and a large face, sinuses help create a spatial gap, and that the orientation of the orbits is important (Shapiro and Shorr, 1980). In support of this, they note that animals such as large dogs have a large distance between the neurocranium and the orbits; thus, the orbits must be placed significantly anterior to the anterior part of the cranium. Consequently, the frontal sinuses in dogs are quite large. In humans, where the orbits lie directly below the anterior frontal lobes (and are thus not anterior to the neurocranium), sinuses are comparably smaller.

Because only very few theories are currently considered sufficiently rigorous, the frontal sinuses in *H. sapiens* remains a bit of an anatomical curiosity. A more comprehensive understanding of the significance of paranasal sinuses, including the frontal sinuses, will likely require additional studies in comparative anatomy, further investigation into the bases of human variation, and perhaps controlled laboratory investigations (Hylander et al., 1991).

Radiology of the Skull and Sinuses

The majority of the diversity in frontal sinus morphology can be ascribed to its dimensions, outline shape and situation, all of which can be detected in radiographs of frontal sinuses (see Figure 2.2c). Sinuses are typically examined radiographically for two reasons: one, diagnosing and examining pathological conditions affecting the paranasal sinuses, and two, use in forensic applications.

The earliest report of the use of radiographs in determining the presence or extent of paranasal sinuses was by Scheier in 1896 (Maresh, 1940). Since its first application, the radiograph has become a valuable tool in the diagnosis of sinus disease and in the determination and delineation of anatomic conformations.

There are several standard positions used to assess the paranasal sinuses by standard radiographs (Samuel and Lloyd, 1978):

a) occipito-mental

b) submento-vertical

c) lateral

d) 39° oblique

e) occipito-frontal

These different positions are generally used to best inspect a particular sinus cavity or portion of a sinus. The occipito-mental view (especially when the mouth is open) provides a good view of the spheniodal sinus and while useful for examination of the periphery of the frontal sinus, usually obscures orbital surfaces (Dolan, 1982a). The submento-vertical view is also primarily used to expose the sphenoidal sinus. The lateral position is the best for viewing the fluid levels in the antrum and for diagnosing sphenoidal sinus diseases, and also provides a good view of the nasopharynx and soft palate. The occipito-frontal position is named for the first person to extensively investigate and report on studying the paranasal sinuses using radiography (Caldwell, 1918). Through position experimentation, he was also able to develop projections that allowed frontal sinus anatomy to be defined adequately and clearly, and led to the Caldwell projection, which is traditionally thought to be the best for examining frontal sinuses, and now serves as a standard in modern sinus surveys (Dolan, 1982a). To obtain this view, the radiographic baseline is tilted 15-20° upwards from a line through nasion that is parallel to the Frankfort horizontal, with the sagittal plane vertical (Figure 2.3). Advantages of this position include: (1) the frontal sinus is almost in direct contact with

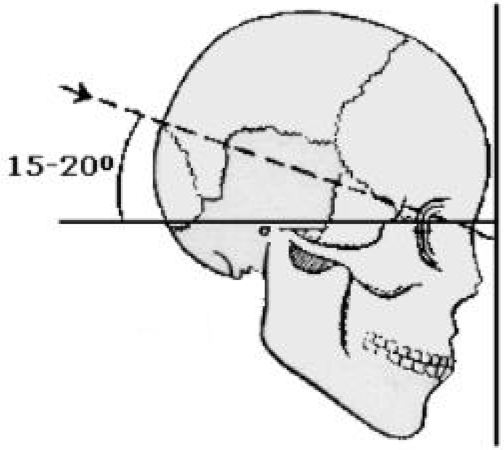


Figure 2.3: Positioning the Skull for a Caldwell View of the Frontal Sinuses.

(From Baylor College of Medicine, 1996)

the film, (2) distortion is limited, (3) geometric blur is minimal, and (4) the outlines are clearly shown.

Frontal sinuses are not visible radiographically until they have extended into the base of the vertical plate of the frontal bone (2 to 6 years) and don't reach the level of the orbital roots until around 6 to 8 years (Caffey, 1993). Even if visible, however, the radiographic appearance of frontal sinuses in children is cloudy and not well defined as the sinuses are developing closer to the posterior than the anterior frontal bone (Samuel and Lloyd, 1978).

There exist several other methods of radiographic examination of the sinuses, though they are not as frequently used. Tomography uses tomographic units capable of pluridirectional or circular movement to take film sequences in three planes (coronal, lateral and axial). Sometimes a contrast media method is used, where a radio-opaque medium is introduced into the paranasal sinuses. Ultrasound examination is possible though rarely used because of its limited diagnostic usefulness. While sometimes useful in the diagnoses of diseased maxillary sinuses in children, the air content of the sinuses generally limits the penetration of the ultrasound ray. Computerized axial tomography *(CAT)* scans are becoming a more frequently used method for examining the sinuses. Using this method, the head is scanned by a collimated fan of x-ray beams. An image of one "slice" of tissue is made by rotating this fan about the individual's skull. A large number of different but coplanar beam attenuations is recorded, allowing a reconstruction of the attenuated regions (Hounsfeld, 1973; Spoor et al., 2001; Zonnefeld, 1987). An image of the tissue slice in then reconstructed as a series of attenuation values.

It has oftentimes been suggested that the frontal sinus morphology of no two individuals is alike—that the configuration of the frontal sinus is as unique to an individual as his or her fingerprints. This idea was first put forth by Schuller (1921) and has been supported by numerous researchers since (see the following chapter for specific studies and references). The significance of such observations was immediately recognized and was first used in identification in 1925 (Culbert and Law, 1927). Before x-ray diagnostic methods, observation Szilvassy of frontal sinuses were limited to those made on cadavers by anatomists, but now it has become possible to observe the anatomy of the frontal sinuses of living individuals as well. The irregular shape of frontal sinus outlines as observed in radiographs has been fairly extensively studied (though never quantitatively), and accordingly developed as a method of identifying individuals following Schuller's 1921 suggestion, with some regarding the accuracy of this technique to be 100% (Sassouni, 1959). This notion is further supported by reports that even monozygotic twins differ in their frontal sinus morphology (Asherson, 1965; Schuller, 1921). Previous studies of frontal sinus uniqueness and the history of identification using frontal sinuses merit review, to be undertaken in the following chapter.

Chapter 3: The Frontal Sinuses in Positive Identification

Previous Studies on Uniqueness

In order to be considered a viable means of confirming identity, we must know whether observed details of the morphology of frontal sinus outlines are unique to each individual. Many researchers' claims of the individualized nature of frontal sinus morphology stem from observations of numerous, even thousands, of radiographs and failing to find two that were identical (Asherson, 1965; Cryer, 1907; Culbert and Law, 1927; Poole [from Mayer 1935]; Schuller, 1921). While these observations are noteworthy in that they provide some subjective support for claims of uniqueness, they fall short of actually being able to quantify the chances that two different people would have identical or very similar frontal sinus patterns since they did not quantitatively assess outline shape.

Some studies have made attempts at more quantitative assessments of uniqueness, but many of these involved very small sample sizes (Harris et al., 1987a (N=32); Ubelaker, 1984 (N=35)). Others have used larger samples, but addressed somewhat different questions such as applying standard measurements and the affect of experience level on the ability to make a correct match (Gulisano et al., 1987; Kullman et al., 1990; Ribeiro, 2000). Most investigations of frontal sinus variability have focused on inter-group variation and often describe differences in terms of linear dimensions of the frontal sinus from the radiograph including maximum height and lateral extension or an index based on these measurements, surface areas, or asymmetry of left versus right sinus lobes

(Brothwell et al., 1968; Buckland-Wright, 1970; Gulisano et al., 1987; Hanson and Owsley, 1980; Harris et al., 1987a; Koertvelyessy, 1972; Strek, 1992).

Studies by Yoshino et al. (1987) and Reichs and Dorion (1992) quantify sinus attributes by a code system and suggest that the possible combinations of codes is extremely large, but this method does not address sinus morphology per se, only general characteristics. Moreover, as Reichs and Dorion (1992) point out, their analysis does not permit assessment of what proportion of the population exhibits a particular configuration since certain characteristics may co-vary and not all traits occur simultaneously. While revealing quantifiable differences in frontal sinus characteristics as observed in radiographs and suggesting that the probability of misidentification would be small, such studies haven't estimated the probability of misidentification using the technique. More rigorous estimating attempts have been carried out for other identification systems such as fingerprints (Pankanti et al., 2001), with the consequence that the methodology has become more accepted.

Systems of Classification, Description and Comparison

Many investigators have recognized that frontal sinuses provide various parameters for classifications and methods for comparing, with the result that classification systems of frontal sinuses and methods of their anthropomorphic description have become important in the study of frontal sinuses. Such classification systems can be used for studies of variation, recording and storing information about frontal sinuses, and making the knowledge available for identification cases. Most proposed systems are based on a number of basic characteristic features of the frontal sinuses including: the presence or absence of one or both lobes, size (codified by height, breadth, or cross-sectional area), symmetry/asymmetry, and position/number of septa (Marek et al., 1983; Reichs and Dorion, 1992; Ribeiro, 2000; Schuller, 1943; Yoshino et al., 1987). Even though they may be useful for their intended investigation, none have received widespread acceptance. Many classification systems have not been standardized, and there is a suspected lack of reproducibility.

The typical method of comparison in an identification case generally follows these steps: (1) A suitable antemortem radiograph of the putative victim is obtained from an appropriate source. This is usually done following a presumptive identification based on other evidence and involves canvassing medical facilities for possibly available records. (2) A radiograph is taken of the forensic skull at a similar orientation and magnification as the antemortem specimen. Orientation similarity is important because it is desirable to assess the features from the same perspective, as many osteological features appear different from different angles. Standardized methods have been suggested for obtaining reproducible, identical angulation (Harris et al., 1987a), but this can usually be accomplished through repeated trial. Similar magnification is also considered necessary, and laws of radiological optics explain the differences seen due to differing distances: X-rays diverge, so magnification of an x-rayed image results as a function of the distance from the film. If using two radiographs with differing magnification is unavoidable, the magnification coefficient can be determined by dividing the dimensions of a given linear structure in the image by the dimensions of the same structure in the object. (3) The two frontal sinuses (in the cases studied here, ante- and postmortem) are compared either by direct visual inspection of side-by-side radiographs, or by tracing one of the outlines onto orthodontic paper and superimposing it onto the other radiograph to compare the height, width and pattern of edge loculations. It is recommended that viewboxes are used for the comparison and that overhead lights are extinguished (Messmer, 1986). A number of common features (or negative features) of comparison should be sought. There is currently no standard or minimum number of required points of concordance, but one to four unique concordant features and no discrepancies has been suggested as enough evidence for a positive identification (Fischman, 1985).

The problem with this comparison method is that it involves a simple visual comparison with the consequence that the final identification decision is subjective and based solely on the knowledge, experience or ability of the examiner. In addition to insufficient data necessary to estimate the probability of two individuals possessing indistinguishable frontal sinus morphologies, the technique of visually comparing frontal sinus outlines is also characterized by a distinct lack of standardized methods when being used to confirm identity. Nonetheless, visual comparison seems to remain the method of choice.

Frontal Sinus Outlines vs. Fingerprints

The technique of identification by frontal sinus radiographs is often compared and contrasted with fingerprint analysis which is widely recognized to be a well-established system of identification. Due to the importance of positive identification, it is to be expected that frontal sinus outline comparison acquires a degree of reputation for rigor as does fingerprint identification. Asherson (1965) proposes four criteria for the feature that a system of identification should be based upon: 1) it is present on every individual; 2) it is unique to each individual; 3) it is permanent, fixed, and unalterable by deformity, displacement or replacement; and 4) it is classifiable. Table 3.1 summarizes to what extent fingerprints and frontal sinuses meet Asherson's criteria, as well as other advantages and disadvantages that have been pointed out by researchers for each method.

Commonly cited advantages of using frontal sinuses rather than fingerprints for identification are that frontal sinuses cannot be altered by human ingenuity (i.e. they cannot be changed with criminal intent as with fingerprints by, for example, acid treatment, skin grafting or the use of gloves), frontal sinus radiographs have prognostic and diagnostic as well as identification use, and skeletal elements including the frontal sinus region of the skull are more often recovered than hands in cases of accidents, burning, decomposition, dismemberment, etc. Advantages of fingerprints include being cheaper to secure and store, more individuals have their prints on record, prints can be left unintentionally and lifted if not available on record, and fingerprints are present on all individuals and do not change with time (although no known study has investigated the configuration of the frontal sinuses over time with identification purposes in mind (Kullman et al., 1990)). Both records are simple to secure and can be taken non-intrusively, the data can be stored and retained in a precise and cost effective manner (Ribeiro, 2000), and both methods are less expensive than DNA testing.

Applications/Case Studies

Suggested applications of frontal sinus identification are broad and include having radiographs on file for those in nationalized industries or those who are at risk of dying in their careers such as soldiers, flight crewmembers, police officers and firefighters. Radiographs may be taken prior to cremation to prevent the wrong body from being

Table 3.1: Characteristics of Identification by Fingerprints and Frontal Sinuses

Characteristic or Criterion	**Fingerprints**	**Frontal Sinuses**
Present on every individual	Yes, present on every individual	No, only present on about 95% of individuals
Unique to each individual	Yes, unique to each individual	Not yet empirically established
Permanent and fixed	Yes, permanent and fixed	Changes with age, trauma, infection, etc.
Unalterable by human ingenuity	No, may be altered	Yes, unalterable
Recordable	Recordable by ink impression	Recordable by radiograph
Recovery from deceased	Not often recovered	Often recovered
Cost	Inexpensive to record and store	Relatively expensive to record and store
Availability for comparison	Widely available	Not widely available
Liftable	Can be lifted/left unintentionally	Cannot be left unintentionally or lifted
Easy to obtain	Simple and nondestructive to secure	Simple and nondestructive to secure
Safe to obtain	Yes	Minimal exposure to x-rays
Other applications	None	Prognostic/diagnostic
Applicable to all	Yes	Not present in subadults
Time to make ID	Less time than frontal sinuses	More time than fingerprints
Classified and centrally stored and retrievable	Yes, located at FBI	No

cremated. Other individuals of specific identification interest may include inmates and mental patients, twins, and those involved in immigration services. The following summary of significant forensic case reports in the literature makes it clear that frontal sinus radiographs are a valid aid to identification and that this value has been recognized in many scientific fields including anthropology, radiology, and odontology.

Culbert and Law (1927) documented the first identification obtained through the use of radiographs of the skull. It was the first of its kind to be accepted in American court, setting a precedent for the method of radiographic comparison for establishing identity. Frontal sinus radiographs (along with other radiographically established details) were compared in the positive identification of an American who was discovered in a river in India and whose body had been disfigured by decomposition, precluding identification by other means.

When the authenticity of postmortem radiographs and photographs taken during the autopsy of President John F. Kennedy at the U.S. Naval Hospital on November 22 1963 was questioned by conspiracy theorists, two anthropology consultants were asked by the House Select Committee on Assassinations in 1979 to examine the materials and, if scientifically possible, determine whether or not they were those of the late President. Based on comparisons of frontal skull views, they found that “the outlines of the frontal sinuses of the autopsy X-rays were virtually superimposable on those shown in the clinical X-rays” (Kerley and Snow, 1979).

While these two cases are prominent by virtue of their historical significance, there has been a recent surge of publications in the forensic and radiological literature describing numerous cases in which identification was established based on frontal sinus comparison (Anguyal and Derczy, 1998; Atkins and Potsaid, 1978; Camps, 1969; Cheevers and Ascencio, 1977; Haglund and Fligner, 1993; Joblanski and Shum,1989; Kirk et al., 2002; Marek et al., 1983; Marlin et al.,1991; Murphy and Gantner, 1982; Owsley, 1993; Phrabhakaran et al.,1999; Quatrehomme et al.,1995; 1996; Reichs, 1993; Reichs and Dorion, 1992; Stewart, 1979; Ubelaker, 1984; Yoshino et al., 1987). Numerous unpublished comparisons undoubtedly exist, although there does not appear to be a reliable statistic on how frequently frontal sinus radiographs are uses as the basis for positive identification.

While many recognize the necessity and usefulness of frontal sinus radiograph comparisons in confirming identity, previous methods of comparison and studies of uniqueness are not rigorous enough for meeting the criteria established in recent trends in admissibility law. Forensic experts including anthropologists, radiologists and pathologists are now expected to meet stricter standards when substantiating their claims that two radiographs belong to the same individual. As forensic scientists, our pursuits differ from those of purely academic (research-driven) physical anthropologists; in addition to performing scientific research and acquiring knowledge as an end unto itself, we must also consider the applications of our findings to legal matters. In the case of identification by frontal sinus morphology, it is necessary to consider the legal applications and ramifications of comparison methodologies. The following chapter reviews the history and current standards of scientific evidence admissibility law that must be considered, as well as the impact these standards (should) have on testimony and research in forensic anthropology.

Chapter 4: The Admissibility of Scientific Evidence

History of Scientific Evidence Admissibility

Expert witness testimony is one case in which physical anthropologists' knowledge of techniques and methodology are needed in the legal system. Although forensic anthropology is a relatively young discipline (its beginning is traditionally considered to be the creation of the Physical Anthropology section of the American Academy of Forensic Sciences in 1972 (Iscan, 1988)), testifying as an expert witness has become an important and increasingly accepted role of the forensic anthropologist. As scientific techniques in many disciplines have become more varied and sophisticated, the use of scientific evidence in the criminal justice system has become an increasing trend.

In the American system of law, scientific evidence is generally thought of as somewhat novel even though the use of scientific evidence in trial dates back nearly 500 years (Eckert and Wright, 1997). The first record of presenting a scientific case in a court of law was when surgeon Ambrose Pare, considered the father of French legal medicine (Thomas, 1974), in the mid 1500s scientifically described firearm wounds, deduced the location of a bullet given the victim's position when hit, and located bullets by palpation (Hunter et al., 1996). Pare was responsible for beginning what is now the science of ballistics (Bono, 1981). His conclusions were enthusiastically accepted by both the scientific and legal communities, and scientific opinion thereafter began to appear more frequently in the judicial system.

As late as the middle of the 19th century, however, there was still an abundance of controversy and ensuing legal challenges during court trials due to the lack of sophistication and rigor in various scientific disciplines, rendering investigations largely subjective (Eckert, 1997a, b). Forensic medicine, however, would soon thereafter begin a rapid increase in sophistication followed closely by other forensic sciences. With the further development of laboratory instrumentation and techniques, the importance of forensic toxicology and serology rose at the beginning of the 20th century. Soon to follow were fields such as criminology, odontology and anthropology (Eckert, 1997b).

Today, most American forensic scientists are organized into the American Academy of Forensic Sciences, founded in 1948 by Dr. R.H. Gradwohl as “a professional society dedicated to the application of science to the law.. [and] committed to the promotion of education and the evaluation of accuracy, precision and specificity in the forensic sciences” (American Academy of Forensic Sciences, 2003). There are currently over 5,000 members from the United States, Canada, and fifty other countries worldwide representing a wide range of forensic specialists including physicians, attorneys, dentists, toxicologists, physical anthropologists, document examiners, psychiatrists, engineers, criminologists, educators, and others who practice, study and perform research in the forensic sciences. However, the types of expert witnesses appearing in trial are vast, with one consulting company advertising 7,600 categories of experts in areas ranging from those mentioned above to specialties as obscure as pit bulls and yarn (Cwik, 1999).

Concurrent with the increase in expert testimony in the courts, debate in the legal community arose regarding standards for the admissibility of such evidence (Cwik, 1999). These standards have evolved significantly in the last century largely due to several Supreme Court rulings and Congressional Acts.

The first important ruling regarding the admissibility of scientific evidence was issued in *Frye v. United States* (1923). In this case, Frye wished to provide the results of an earlier "lie detector" test as support of his plea of "not guilty" to a murder charge. "Systolic blood pressure deception testing" was, at the time, a new technique, leaving the Court unsure as to how to assess its validity. The Court decided to give an opinion on the standard for the admissibility of scientific expert witness testimony. The critical words of the Court's opinion state:

> "Just when a scientific principle or discovery crosses the line between the experimental and demonstrable stages is difficult to define. Somewhere in this twilight zone the evidential forces of the principle must be recognized, and while courts will go a long way in admitting expert testimony deduced from a well-recognized scientific principle or discovery, the thing from which the deduction is made must be sufficiently established to have gained general acceptance in the particular field in which it belongs." (*Frye v. United States,* 1923).

No authority was cited, however, and the Court concluded that the technique in question had not yet gained the required standing and scientific recognition among authorities in the fields of physiology and psychology to be considered admissible under this new guideline (McCormick, 1972).

Historically, general acceptance in a particular field has been shown by scientific publications and evidence of practical use and testimony by scientists on their peers' position regarding their competence about the evidence in question. The "*Frye* Rule", as this general acceptance test came to be known, became the dominant standard for determining admissibility of scientific evidence in the majority of courts. This dominance was facilitated in large part by the fact that the rule was easy to apply and required little scientific sophistication on the part of the judges.

Several rationales were offered in support of the using the "*Frye* Rule" as a means of excluding evidence including: it guarantees a minimum number of knowledgeable experts, promotes uniformity of decisions, eliminates the need for time-consuming hearings on admissibility, and assures a method by which those best qualified to assess the validity of scientific evidence would effectively determine its admissibility (Beggs, 1995).

Over time and with advancements in science, many courts and legal commentators began to modify or ignore the *Frye* standard. One of the key concerns was that new scientific evidence, though sound, often failed the *Frye* test. McCormick, a key legal commentator on evidence, indicated:

> "'General scientific acceptance' is a proper condition for taking judicial notice of scientific facts, but not a criterion for the admissibility of scientific evidence. Any relevant conclusions which are supported by a qualified expert witness should be received unless there are other reasons for exclusion" (McCormick, 1972).

In 1975, Congress enacted the *Federal Rules of Evidence* (1975), which was the first modern and uniform set of evidentiary rules for the trial of civil and criminal cases in federal courts. *Rule 702* specifically addressed expert witness testimony, stating that:

> "If scientific, technical or other specialized knowledge will assist the trier of fact to understand the evidence or to determine a fact in issue, a witness qualified as an expert by knowledge, skill, experience, training or education may testify thereto in the form of an opinion or otherwise" (*Fed. R. Evid. 702*, 1975).

The adoption of the *Federal Rules of Evidence* did not remove the confusion in the courts concerning the admissibility of scientific evidence. The text of the *Federal Rules* did not include the *Frye* standard, and the legislative history made no mention of *Frye* or its general acceptance standard. This led to a mixed use of *Frye*, the *Federal*

Rules of Evidence or some hybrid of the two. When called upon to apply *Rule 702,* a majority of federal courts continued to utilize *Frye,* being reluctant to accept the overruling of a precedent of *Frye*'s stature and often incorporating general acceptance into the relevance determination of *Rule 702* (Beggs, 1995).

The confusion over the admissibility of scientific evidence continued until the United States Supreme Court decided *Daubert v. Merrell-Dow Pharmaceuticals, Inc* (1993). The case involved birth defects allegedly caused by a mother's use of Bendictin, an anti-nausea drug, during her pregnancy.

Merrell-Dow moved for summary judgment, submitting an affidavit of Dr. Lamm, a physician and epidemiologist who was considered a respected authority on health risks from exposure to chemical substances. After reviewing numerous published studies, he concluded that Bendictin was not a risk factor for human birth defects, whereupon Merrell-Dow contended that Daubert could not produce any scientific evidence to show otherwise.

In response, Daubert presented affidavits from eight experts who claimed to have found a link between the drug and birth defects based on test tube and live animal studies suggesting causation, analyses of pharmacological similarities between Bendictin and other substances known to cause birth defects, and reanalyses of published studies concerning Bendictin. The trial court granted Merrell-Dow's motion for summary judgment, finding that Daubert's experts relied on evidence that was not sufficiently established to have general acceptance in the field. The Court of Appeals affirmed the trial court's decision based upon the *Frye* standard. The case was appealed to the United

States Supreme Court who granted review to resolve the "sharp divisions regarding the proper standard for admission of expert testimony" (*Daubert v. Merell-Dow*, 1993).

The Supreme Court first had to address the question of whether the general acceptance test of *Frye* survived the enactment of the *Federal Rules of Evidence*. The Court ultimately concluded that the *Federal Rules of Evidence* superceded *Frye* and should thus govern admissibility, indicating that a "rigid and absolute general acceptance test" should not be the standard in order that a reasonable minority opinion may be admitted into evidence, usually in the form of new and emerging research based on reliable, well-designed studies (*Daubert v. Merrell-Dow*, 1993).

In addition to acknowledging that the *Federal Rules of Evidence* superceded *Frye*, the Court interpreted the language of *Rule 702* to set forth standards for the admissibility of scientific evidence: *reliability* (which requires "scientific knowledge" be grounded in the methods and procedures of science and more than subjective belief or speculation), and *relevance* (which requires that the information facilitate the fact-finder in reaching a conclusion in the case, i.e. that there is a valid scientific connection to the pertinent inquiry). Furthermore, the Court identified some of the factors relevant to determining whether the evidence is scientific. These factors are often referred to as the "*Daubert* guidelines" (Table 4.1).

The first of these guidelines pertains to whether the content of the testimony can be (and has been) empirically tested using the scientific method. This guideline was based upon the persuasions of two philosophers of science who have indicated that the scientific status of a theory rests in its falsifiability, or refutability, or testability (Popper, 1989), and that statements constituting a scientific explanation must be capable of

Table 4.1: The *Daubert* Guidelines for Determining Whether Evidence is Scientific and Therefore Admissible Under *Federal Rule 702*

The Daubert Guidelines
1. The content of the testimony can be (and has been) tested using the scientific method
2. The technique has been subject to peer review, preferably in the form of publication in peer reviewed literature
3. Consider known or potential error rates and applicable professional standards
4. Consider general acceptance within the relevant scientific community

empirical test (Hempel, 1966). Second, the technique should be subject to peer review, preferably in the form of publication in peer-reviewed literature. Although publication is not required for admissibility and in some instances may not ensure reliability, the review process increases the likelihood that the scientific community will detect any error or fundamental flaw that exists in the technique or its application.

Third, for particular techniques, the court should consider known or potential error rates for the technique as well as any professional standard(s) that may be applicable. These error rates are generally derived during the process of scientific testing and can help to clarify the accuracy of the technique to the trier(s) of fact.

Lastly, the Court may also consider general acceptance by identifying the relevant scientific community and assessing the degree of acceptance within that community. The Court summarized that "general acceptance" is not a necessary precondition to the admissibility of scientific expert evidence under the *Federal Rules of Evidence*, and that pertinent evidence based on scientifically valid principles better suits the demands of *Rule 702*.

Another landmark decision on admissibility was the 1999 case of *Kumho Tire Co., Ltd. v. Carmichael* (1999). In *Kumho Tire,* the Court held that the *Daubert* interpretation of *Rule 702* applies with equal force to proposed tests based on technical or otherwise specialized knowledge.

In 2000, another significant event occurred when the *Federal Rules of Evidence*, including *Federal Rule 702,* were amended, effective December 1, 2000 to read:

> "If scientific, technical or other specialized knowledge will assist the trier of fact to understand the evidence or to determine a fact in issue, a witness qualified as an expert by knowledge, skill, experience, training or

> education may testify thereto in the form of an opinion or otherwise, if (1) the testimony is based upon sufficient facts or data, (2) the test is the product of reliable principles and methods, and (3) the witness has applied the principles and methods reliably to the facts of the case." *(Federal Rules of Evidence*, 2000*)*

This amendment considers *Daubert* guidelines and interpretations and better clarifies the issues of reliability and relevance.

The Impact of Daubert

The *Daubert* guidelines have had some remarkable consequences on expert witness testimony, and in fact, some have even called the *Daubert* ruling a "revolution" and "perhaps the most significant change in scientific evidence law in years" (Baute, 2000). Since the *Daubert* decision, scholars have commented extensively on the increased use of expert scientific evidence in courts, particularly in the fields of mass tort litigation, criminal law, and federal civil rights litigation (Beggs, 1995). Some have viewed the courts' past unwillingness to grapple with the basics of the scientific method as a principle failing of the legal system's approach to scientific evidence, and see the *Daubert* guidelines as progress by calling on judges to apply scientific standards to evaluate evidence (Faigman, 1994).

The *Daubert* opinion emphasized that the court should be flexible in conducting its inquiry and should focus on the principles and methodology that underlie the evidence and not the conclusions they generate. For this reason, a separate proceeding, called a *Daubert* hearing, is often held within or before the trial in which the expert has been asked to testify. It generally focuses on the methods themselves and not the result, and can help to shed light on substandard procedures and protocols ahead of time. Unlike the *Frye* test, by evaluating a technique on its own merits independent of how long the technique has been in use or how large a following it has, *Daubert* helps clear the way for admitting novel, yet sound, scientific evidence.

Needless to say, the *Daubert* ruling has also caused some confusion and debate. The dissenting opinion in *Daubert* warns of the pitfalls inevitably created when the Supreme Court offers general observations in its opinions, and questions the definitions of “scientific knowledge”, “the scientific method”, “scientific validity”, and “peer review” (*Daubert v. Merell-Dow*, 1993, Opinion of Chief Justice Rehnquist and Justice Stevens). The suggested “gatekeeping” role also places trial judges in a challenging position, forcing them to determine whether a technique, of which they presumably have little or no knowledge, is scientifically valid. The competence of federal judges to decide whether a scientific theory can and has been tested has been seriously questioned, and it has been previously cautioned that the courts cannot be considered arbiters of scientific validity, but are an institution established for the resolution of disputes (Herman, 1990). Moreover, unlike scientific inquiry, legal fact-finding is generally not subject to revision as additional data becomes available, but rather must settle issues based on currently available data and information within the constraints of a dispute resolution system (Beggs, 1995). Others have commented on the inherent difficulty of evaluating a process or technique independent of external considerations (Majmudar, 1993).

Furthermore, while many forensic disciplines are organized by associations or societies which have certification boards for identifying individuals who they recognize as being qualified as an expert, the credentials of those appearing on the stand vary widely as there are currently no minimum standards set by the court for determining who is qualified to testify (Frankel, 1989). Cross-examination, however, should theoretically weed out the unqualified. Rules have been proposed for the regulation of expert testimony, but none have received widespread acceptance (Travis, 1974).

Another issue to bear in mind is the difference between the admissibility of a particular piece of evidence and its weight (Matt T. Adamson, personal communication). Just because scientific evidence is admissible, does not mean that the fact-finder (the judge or the jury) must believe it or give it any weight. For example, while a particular piece of evidence may be admissible under *Daubert*, an opposing expert could convince the fact-finder(s) that such evidence is only accurate 60% of the time, and that his own methods are more accurate. It is then up to the fact-finder(s) to decide which testimony deserves more weight. The decision is ostensibly based on the research and techniques used to back up the testimony, but may also be influenced by such things as appearance and presentation. Thus, the research itself is initially important in getting past the gatekeeper (i.e. the judge) on admissibility, but it is also important that the expert convince the fact-finders(s) of its believability (Matt T. Adamson, personal communication).

Since *Daubert* is a statutory rather than a constitutional case, it is not necessarily binding on the states and is not used in all state courts. *Daubert* applies only to federal trials, and since admissibility standards vary from state to state in lower courts, they are free to continue to follow the *Frye* Rule or other state tests (Gianelli, 1993). The trend is for states to adopt the *Federal Rules of Evidence* and apply *Daubert* standards, though some have chosen to reject doing so. Table 4.2 indicates which states currently apply which standard.

Table 4.2: Scientific Evidence Admissibility Standards by State.

(From Lustre, 2003)

States applying *Daubert* or similar test	**States which continue to apply *Frye***	**States which have not rejected *Frye* but which apply *Daubert* factors**	**States that have developed their own test**
Alaska	Arizona	Alabama	Georgia
Arkansas	California	Hawaii	Utah
Colorado	District of Columbia	Massachusetts	Virginia
Connecticut	Florida	Nevada	Wisconsin
Delaware	Illinois	New Hampshire	
Idaho	Kansas	New Jersey	
Indiana	Maryland		
Iowa	Michigan		
Kentucky	Minnesota		
Louisiana	Mississippi		
Maine	Missouri		
Montana	Nebraska		
Nebraska	New York		
New Mexico	North Dakota		
North Carolina	Pennsylvania		
Ohio	Washington		
Oklahoma			
Oregon			
Rhode Island			
South Carolina			
South Dakota			
Tennessee			
Texas			
Vermont			
West Virginia			
Wyoming			

Although a number of states continue to follow the *Frye* standard or some other state test (Mahle, 1999), given that *Daubert* is the current standard for federal courts as well as the most scientifically stringent standard to date, it provides an appropriate guideline for conducting research and preparing testimony. The *Frye* Rule, however, should be borne in mind since many states do continue to apply this standard and forensic scientists are considerably more likely to testify in state court (Matt T. Adamson, personal communication).

Implications for Forensic Anthropology and Frontal Sinuses

Given the novelty of the field of forensic anthropology coupled with the rate of scientific progress in general, many techniques testified to by forensic anthropologists may be considered new and emerging information. Anthropologists must therefore be particularly cautious that their investigations result in methods and techniques that will be admissible under the *Daubert* guidelines. This is not to say that anthropological research has been or is lacking in scientific rigor, but forensic anthropological techniques have not often met the *Daubert* test, so it is as of yet unclear how many of them will or would be received in court if and when they are put to this challenge. It should thus be a specific aim of anthropological studies to meet *Daubert* standards when the potential exists for the resulting technique to be considered in court.

In the case of identification by frontal sinus morphology, many have proffered (or at least supported) the notion that it is unique to each individual, and it has been used in numerous cases to confirm identity. In 1977, the American Board of Forensic Anthropology (ABFA) was formed in response to the "need to identify forensic scientists qualified to provide essential professional services for the nation's judicial and executive branches of government." In the ABFA's definition of forensic anthropology, the board indicates that forensic anthropologists apply standard scientific techniques developed in physical anthropology to identify human remains and to assist in the detection of crime (ABFA, 1996). It is not clear, however, that "standard scientific techniques" have been applied to the question of frontal sinus uniqueness or their reliability in establishing positive identification. Previous observations have tried, it seems, but none approached the empirical issue rigorously enough to provide the kind of testing and reliability estimates requested by the *Daubert* guidelines.

The lack of reliability estimates is an important point because the courts have a history of strongly emphasizing this issue, and indeterminate or essentially unknown error rates have often contributed to decisions to exclude evidence, as have non-compliance with standards in assessing the reliability of a technique and the use of flawed statistics (Beggs, 1995). While many courts have concluded that fingerprint testing is sufficiently scientific and reliable to be admitted under *Rule 702,* the case of *United States v. Plaza* (2002) seriously questioned the admissibility of fingerprint analysis. When examined in light of the *Daubert* guidelines, the Supreme Court concluded the following: With regard to scientific testing, it seems that fingerprint identification techniques have only been subject to adversarial courtroom testing, and have not been tested in a manner that could properly be characterized as scientific. There are no objective standards, with the final identification decision being subjective and based on the knowledge, experience or ability of the examiner. In addition, there seems to be a lack of peer review. The Court, moreover, felt that since fingerprint examiners learn their craft on the job without concomitant scientific training, fingerprint examiners do not constitute a "scientific community."

Studies investigating error rates have been conducted to test the likelihood of two people having the same fingerprint (Pankanti et al., 2001), but there are currently no standards controlling the technique's operation, no subjective determination standards, and no mandatory qualification standards for individuals to become fingerprint examiners. Examinations are generally accepted as reliable by fingerprint examiners, but as the Court noted, fingerprint examiners (though well-respected) do not constitute a scientific community. The Court thus found it difficult to find fingerprint identification consistent with the *Daubert* guidelines and thus was faced with the possibility of disallowing fingerprint evidence. The Court decided, however, that excluding the government from presenting fingerprint testing in this case would be unwarranted and heavy handed. In the end, the ruling indicated that presentation of how the fingerprints were obtained as well as differences and similarities between fingerprints would be allowed, but that evaluations as to the "opinion" that the fingerprint is of a particular person (or not) would not be allowed (*United States v. Plaza*, 2002).

This has very important implications for the potential of frontal sinus identifications to be upheld against the rigor of the *Daubert* guidelines (Table 4.3). With regard to the four *Daubert* guidelines, the technique of identification by frontal sinus morphology fulfills two of the criteria at best. There are certainly a large number of publications relating to the possible uniqueness of each individual's frontal sinus morphology and substantial literature on case studies marking situations where the technique has been used to establish a positive identification. However, no standard

Table 4.3: Fingerprints and Frontal Sinus Outlines in Positive Identification—

How Well Do They Satisfy the *Daubert* Guidelines?

Guideline	**Fingerprints**	**Satisfies *Daubert?***	**Frontal Sinuses**	**Satisfies *Daubert?***
Scientific testing	?Only subject to adversarial courtroom testing- no proper scientific testing	No	?No empirical tests have been performed	No
Error rates and standards	?Test of the probability of two people having the same fingerprints indicate that it is small	Yes	?Previous observations *suggest* that the probability of two people having identical frontal sinuses is small	No
	?No standard controlling the technique's operation	No	?No standard controlling the technique's operation	No
	?No objective determination standards	No	?No objective determination standards	No
	?No qualification standards for individuals to become fingerprint examiners	No	?ABFA certifies qualified forensic anthropologists	Yes
General acceptance	?Generally accepted as reliable, but not by a scientific community	No	?Generally accepted as reliable within relevant scientific community	Yes
Peer review and publication	?Many publications, but not in (scientifically) peer-reviewed literature	No?	?Extensive publication in peer-reviewed literature	Yes

methodology has ever been accepted. There appears to be general acceptance within the fields of forensic anthropology and radiology that the technique is sufficiently reliable.

However, while the technique is *capable* of being empirically tested, no such tests have ever been performed or perhaps even devised. As mentioned earlier, the reliability of comparing postmortem and antemortem radiographs of frontal sinuses should be well-founded since sinuses show differences even in monozygotic twins, but to reiterate, statistical estimates of reliability have never been established. Anthropologists appear to be fond of phrases like “unique to each person” and “like a fingerprint”, while no empirical studies that establish this claim as a fact have ever been performed. Moreover, (and partially as a consequence of the lack of empirical testing), there seems to be a complete lack of attempts to estimate potential error rates for the identification technique.

Anyone offering a novel theoretical basis or methodology that has not been subject to meticulous adversarial or empirical testing should be prepared to present convincing evidence that the methodology has a basis in good science as required by *Daubert*. The following chapters describe a study undertaken with the aim of providing this basis by empirically testing the variability of frontal sinus outlines and estimating the potential rate of error when using frontal sinus outlines in identification.

Chapter 5: Materials and Methods

Geometric Morphometrics

The field of morphometrics is concerned with methods for the description and statistical analysis of shape variation within and among samples of organisms and any of their structures, and is used when one needs to describe and compare shapes of organisms or of particular structures (Rohlf and Marcus, 1993). Historically, as biological inquiry became more quantitative, a plethora of methods were borrowed from modern statistics, some of which (such as significance testing) have become mandatory in published analyses of biological data (Richtsmeier et al., 2002). Using morphometric methodologies, observations designed to capture the essence of biological shapes can be analyzed simultaneously by using multivariate statistics. Recently, the focus has been steered from multivariate space back to the geometry of biological shape. This movement and the methods developed subsequently comprise what is now referred to as geometric morphometrics, the fusion of geometry and biology (Bookstein, 1982).

This approach is characterized by using coordinate data to capture the geometry of the structure being studied. The geometric relation among the points is then used to fit an appropriate function to them, and the estimates of the parameters of the fitted function can then be used as variables in standard univariate and multivariate statistical analyses (Rohlf and Marcus, 1993). This approach has flourished because of investigators' desires to analyze biological shapes in ways that preserve the geometric integrity of shape and avoid collapsing the form into a series of linear or angular measures that do not include information pertaining to geometric relationships of the whole (Richtsmeier et al., 2002).

Complementing the emphasis in recent years on landmark-based morphometric methods, there have been important advances in other methods for the analysis of outline data (Rohlf, 1996). Fitting curves to outlines is a method of interest when there are few (if any) homologous landmarks on a structure or when the outlined shape itself is of interest rather than its relationship to various landmarks (Rohlf, 1990). Sometimes there are either not enough landmarks (or not enough biologically homologous ones) to adequately capture the variation in the biological structure of interest (Rohlf, 1996). In cases such as frontal sinus outline projections, the shape can be captured by the coordinates of a sequence of points along its outline. Since this study is concerned with variation in frontal sinus shape and size in two dimensions, and since it is recognized that frontal sinuses lack obvious biologically homologous landmarks, a geometric morphometric analysis of coordinates of points along its outline is the most suitable approach for the question at issue.

Closed contours (data consisting of points along a closed outline) are commonly used in morphometrics. While several different techniques for analyzing closed contour data could be employed, some type of Fourier analysis is usually used, and is considered one of the best-known methods for characterizing the variation in the shapes of outlines (Sampson et al., 1996). Fourier analysis has been applied to biological problems such as comparison of wing shape in different taxa of mosquitoes (Rohlf and Archie, 1984) and distinguishing between populations of mussels (Ferson et al., 1985), and is considered to have potential applications in taxonomic and phylogenetic inference (Rohlf and Marcus, 1993).

Geometric morphometrics have found wide application in anthropology including evolutionary and paleoanthropology (Bacon, 2000; Havarti et al, 2002; Zollikofer, 2002), primatology and comparative primate anatomy (Lockwood et al., 2002; Lynch et al, 1996), bioarchaeology (McKeown, 1999), and modern human growth and variation (Hennessy and Stringer, 2002; Mitterocker et al., 2001; Ross et al., 1999). However, a limited number of studies have applied Fourier analyses to problems in anthropology (Christensen and Slice, 2002; Ferrario et al., 1996; Friess and Baylac, 2001; Tanaka et al., 2000). The current study will examine frontal sinus outlines using Fourier analysis by representing each frontal sinus as a closed contour. Bookstein et al. (1982) note that there are limitations to the amount of biological information one can give to the coefficients of Fourier functions, suggesting that such data sets are sensitive only to differences in shape and not to differences in interpretation of homology between radii at different points along an outline. However, as Rohlf and Archie (1984) note, if the goal is to measure shape per se (which, in this investigation, it is), then this could actually be considered an advantage. While there may be some limitations to EFA in certain investigations, given that this study is intended to examine shape per se, it seems a well-suited approach.

Sample

Frontal sinus radiographs used for this study were obtained from four sources. First, radiographs of skulls of two skeletal collections kept at the University of Tennessee Department of Anthropology were taken specifically for this study. The William M. Bass Donated Skeletal Collection consists of partial and complete skeletal remains of individuals who have donated their remains to that program, 257 of which were suitable for this study (by virtue of having present, complete, and undamaged frontal regions). The University of Tennessee Forensic Skeletal Collection consists of skeletons of human and non-human remains from forensic cases, 105 of which were appropriate for this study.

The other two sources were two sets of previously taken radiographs: 61 historic plains Arikara crania, and 161 radiographs from the University of Tennessee Student Health Center (the latter taken for clinical purposes). All specimens were known to be of adult status, but no other information (age, sex, ancestry, etc.) was recorded (except for the fact that Arikara were of known ancestry). Inquiry into Human Subjects Review revealed that since no identifying information was to be examined or recorded, the study did not constitute a research project which would fall under the purview of the Institutional Review Board (IRB).

Radiograph Methodology

Cranial radiographs were taken by me expressly for this study of the two collections kept at the University of Tennessee Department of Anthropology—the UT Donated and UT Forensic specimens. They were taken at the University of Tennessee Student Health Center with the assistance of an x-ray technician using a HoLogic HFQ Series 100kHz High Frequency machine. Although the x-ray technician had previous experience taking radiographs of skeletal remains, the settings used for the present study were developed on a trial-and-error basis, and for most specimens the parameters were:

KVP (peak kilovoltage): 48 kV_{peak}
CM (distance from tube to film): 40 cm
MA (current in the x-ray tube): 75 mA

SEC (exposure time): 65 ms

For denser (i.e. more opaque) skulls, the KVP was increased to 50kV$_{peak}$.

A standardized methodology was used to orient the skulls in the following manner: The image beams traversed the skull posterior to anterior with the frontal bone nearest the film to allow minimal distortion and maximum clarity of the frontal sinus outline. The skull was placed face down on a foam/cloth doughnut with the midsagittal plane perpendicular to the x-ray plate using the median palatine suture as a guide (Figure 5.1a). Next, the skull was oriented with the cassette perpendicular to a straight line running through nasion and the superior border of the external auditory meatus, an orientation within the range considered a “Caldwell view” (Figure 5.1b). The central axis of the x-ray beam was centered on a point between the external occipital protuberance and lambda.

This subset of the total sample, i.e. those radiographs taken specifically for this study, allowed repeated access to the same crania without fear of unhealthy side-effects such as repeated exposure to x-rays. Consequently, duplicate radiographs could be taken, simulating ante- and post-mortem conditions. Each duplicate was taken using the same methodology but at a different time so that the skull would have to be re-aligned and duplicates would not simply be copies. It was considered necessary to allow for the introduction of an error that would resemble the forensic context where the precise orientation of the antemortem film would not be able to be replicated.

Obtaining and Digitizing Outlines

While the upper and lateral limits of the frontal sinus are easily defined and readily discernable, the lower limit is significantly more difficult to locate on

a b

Figure 5.1: Orientation of Skulls for Radiographs.

Orientation (a) along the median palatine suture, and (b) along a straight line through the upper margin of the external auditory meatus and nasion.

radiographs. Many researchers have recognized this problem, and as a consequence, several methods of arbitrarily delimiting the lower margin have been proposed. Schueller (1943) suggested a line drawn at the level of the planum sphenoidale, which theoretically indicates the maximum downward extension of the frontal sinus, but this feature is not easy to find on many radiographs. Another suggested method involves drawing a horizontal line at nasion (Brothwell et al., 1968), but this too has been considered problematic. One widely accepted method, first proposed by Libersa and Faber (1958), involves a “baseline” drawn tangential to the upper margin of the orbits (Figure 5.2). This method was based on Terracol and Guerrier’s (1958) statement that paranasal sinuses are only to be considered frontal when they extend above this line. Whether one considers this statement to be valid or not, it does provide a simple, standardized way of identifying a lower border.

This baseline method was the one selected for the current study because (1) it is easy to apply and replicate, and (2) it has been recognized by several previous researchers as an accepted methodology (Brothwell et al., 1968; Buckland-Wright, 1970; Hanson and Owsley, 1980; Ikeda, 1980; Koertvelyessy, 1972; Libersa and Faber, 1958; Ribeiro, 2000; Strek et al., 1992).

To obtain frontal sinus outlines for comparison, each radiograph was superimposed with Mead “ACADEME” tracing paper, and the frontal sinus outline was traced in pencil onto the paper over a light table. Since the selected method of analysis necessitates closed contours, only the outermost border of each frontal sinus was traced and did not include partial or complete septations. At the time that the radiographs were traced, a method for delineating the lower border had not yet been decided upon, so the

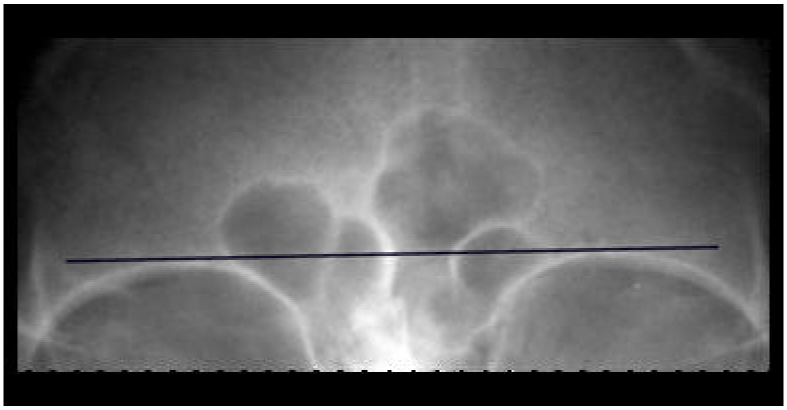


Figure 5.2: “Baseline” Delineating Lower Margin of Frontal Sinus.

upper borders of the orbits were also traced onto the tracing paper for possible later use. After the use of the above described "baseline" was chosen, the line was drawn in over the traced outlines and the orbital borders erased, resulting in a set of outlines representing the upper and lateral outermost borders or the frontal sinuses with a straight line at the base (Figure 5.3).

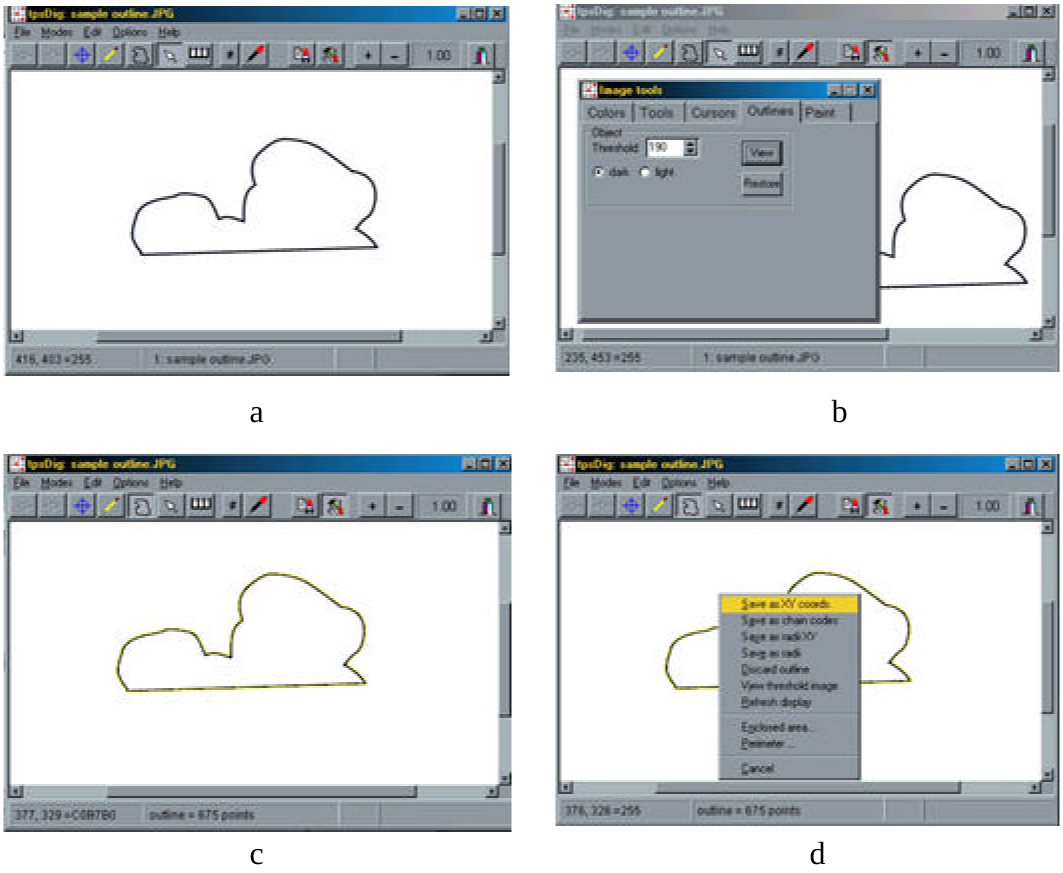
A total of 946 radiographs were examined for the study (584 individuals, 362 of which had duplicates). Some of the radiographs could not be outlined, however, either because there was no frontal sinus visible at all or because the sinus present was so small that it did not project above the baseline. The resulting sample consisted of 503 individuals, 305 of whom had "ante" and "postmortem" duplicates (Table 5.1).

The traced outlines were then scanned using a UMAX Astra 2400s scanner. Images were saved in *.JPG format as black and white images with 600 dpi resolution. Next, the outlines were digitized (i.e. x,y-coordinates were obtained) using the software package tpsDig (Rohlf, 1997). Individual images were imported into tpsDig, which results in the image being displayed in the main window (Figure 5.4a). Outlines of structures using tpsDig can be computed automatically whenever they are separated from the rest of the image; this can be achieved by choosing an appropriate brightness threshold (Rohlf, 1997). The default value is 128, but a different threshold can be specified using the toolbox option (Figure 5.4b). Since the imported images were pencil tracings on tracing paper, the contrast was not the same from image to image or sometimes even within the image. This required that the threshold be adjusted for each image by trial-and-error. In each image, a threshold that best separated the outline from the paper and other "noise" was selected. These values ranged from 175 to 210.

Figure 5.3: Sample Outline Including Baseline.

Table 5.1: Sample of Radiographs Used

Sample	**Total number of radiographs examined**	**Number not used due to absent or too small sinuses**	**Total number of radiographs used in this study**
UT Donated	257 (x2)	27 (x2)	230 (x2)
UT Forensic	105 (x2)	28 (x2)	75 (x2)
UT Arikara	61	10	51
UT Student	161	15	146
Total	584	80	503 (305 of which have "ante" and "post-mortem" duplicates)



Threshold 190

416, 403 =255 1: sample outline.JPG

235, 453 =255 1: sample outline.JPG

377, 329 =C0B7B0 outline = 675 points

376, 328 =255 outline = 675 points

a

b

c

d

Figure 5.4: Digitizing Outlines with tpsDig.

(a) An outline image imported into tpsDig; (b) the threshold tool used to choose an appropriate value; (c) the outline" tool used to register the x and y-coordinates of the outline; and (d) the outline coordinates saved.

In several instances (due to the variable shades of the pencil), parts of the outline were not sufficiently dark to be picked up without including other background noise from the paper or erased portions of the outline. If breaks were present in the outline (i.e. if it did not appear as a fully closed curve in the image), tpsDig would outline both the outer and inner portion of the structure leading to a misrepresentation of the shape of interest. In these cases, the image was imported into Arcsoft PhotoImpression (1998), a 32-bit photo-editing program for Windows, where they were edited by erasing and/or drawing, so that the images that could be properly outlined in tpsDig.

The coordinate data was saved in *.tps files (Figure 5.4d). All of the data were saved into two files; one that contained all the coordinate data for single copies of each frontal sinus outline examined (hereafter referred to as “singles”), and a second that contained all the coordinate data for duplicate outlines of individuals with two frontal sinus outlines to examine (“duplicates”).

Elliptic Fourier Analysis

The method of Elliptic Fourier Analysis (Kuhl and Giardina, 1982) is a very general procedure that can fit a closed curve to an ordered set of data points with any desired degree of precision. It uses an orthogonal decomposition of a curve into a sum of harmonically related ellipses. The algorithm does not require the points to be equally spaced, and the ellipses can be combined to approximate practically any closed plane curve arbitrarily well given enough harmonics (Ferson et al., 1985).

Elliptic Fourier Analysis (EFA) is based on separate Fourier decomposition of the first differences of the x and y-coordinates (?x_i and ?y_i) as parametric functions of the cumulative chordal distance, t, of the points around the outline where t is scaled to go from 0 to $2p$ (Rohlf, 1990). The *x*- and *y*-coordinates of points along the length, *t*, of an outline can be represented as a sum of *k* harmonics using sine and cosine terms:

$$x(t) = A_0 + \sum_{k=1}^{n} \left(A_k \cos kt_k + B_k \sin kt_{k\text{-}1} \right)$$

$$y(t) = C_0 + \sum_{k=1}^{n} \left(C_k \cos kt_k + D_k \sin kt_{k-1} \right)$$

Elliptic Fourier Analysis generates four coefficients (A_k, B_k, C_k, D_k) that are treated as a set of shape descriptors used for variables in discriminatory or other multivariate analyses (Bookstein et al., 1982). The coefficients of the k^{th} harmonic of the outline's *x*-projection are:

$$A_k = \frac{T}{2p^2p^2} \sum_{k=1}^{p} \frac{\Delta x_i}{\Delta t_i} \left[\cos \frac{2pkt_i}{T} - \cos \frac{2pkt_{i-1}}{T} \right]$$

$$B_k = \frac{T}{2p^2p^2} \sum_{k-1}^{p} \frac{\Delta x_i}{\Delta t_i} \left[\sin \frac{2pkt_i}{T} - \sin \frac{2pkt_{i-1}}{T} \right]$$

where:

p = the number of steps around the outline

? $x_i = x_i - x_{i\text{-}1}$

? t_i = the chordal distance of the step between points *i-1* and *i*

t_i = the cumulative length of such steps up to step *i*

$T = t_p$ = the total length of the outline contour

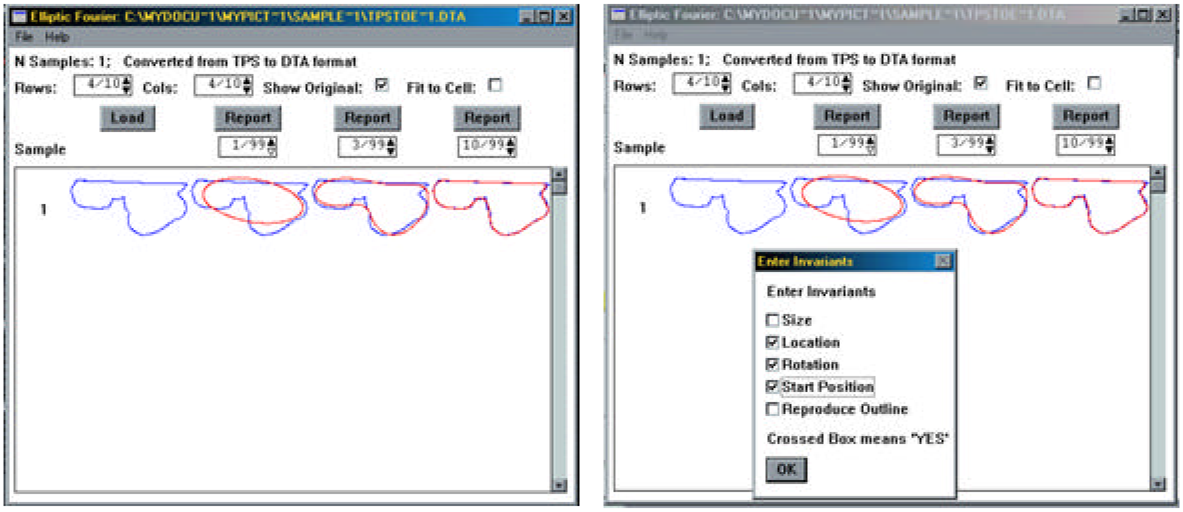
The coefficients for the *y*-coordinates, C_k and D_k are found in the same way using the incremental changes in the *y*-direction. Here, elliptic Fourier coefficients were generated using the software package EFAWin.

Computing Fourier Coefficients

EFAWin (Isaev, 1995) is a program that computes elliptic Fourier coefficients for an outline described by a set of *x*- and *y*-coordinates. The input file contains these *x*- and *y*-coordinates for the outline(s) along with an optional file label and the number of points around the outline. These coordinates, obtained in tpsDig, were converted to an EFAWin-compatible format using tpstoefa (Page, 1998), a program that converts a directory of *.tps files with outlines into a single file for EFAWin.

The outlines are loaded, together with their Fourier outlines, as shown in the example outline of Figure 5.5a. (Note that outlines appear inverted in the figure because the coordinates (0,0) in tpsDig are in the lower right-hand corner; this does not affect the result of EFA because it is invariant to orientation.) The number of harmonics to be computed can be adjusted here, and is constrained to be less than or equal to the number of points divided by 2 (Nyquist Theorem). Increasing the number of harmonics provides an increasingly better approximation of the original outline. Figure 5.5 shows a sample outline of a frontal sinus and improvements in its characterization with increasing the number of harmonics from 1 (producing the best-fitting ellipse), through 3, to 10 harmonics. In this study, 20 was selected as an appropriate number of harmonics to analyze the frontal sinus outlines because it was found that even the most complex outlines could be represented sufficiently well.

After clicking the report button, EFAWin lists the available options (Figure 5.5b). These include invariance to size, location, rotation and starting point of the digitized outline, as well as the option for a reproduced outline. Size standardization can be



N Samples: 1; Converted from TPS to DTA format

Rows: 4/10 Cols: 4/10 Show Original: ☑ Fit to Cell: ☐

Sample 1/99 3/99 10/99

Enter Invariants

☐ Size

☑ Location

☑ Rotation

☑ Start Position

☐ Reproduce Outline

Crossed Box means "YES"

Figure 5.5: Obtaining EFA Coefficients with EFAWin.

(a) Imported outline data and Fourier outlines, and (b) saving the coefficients invariant to location, rotation and start position.

achieved by estimating the area of the enclosed region (measured as the area of the ellipse defined by the first harmonic), and then dividing by its square root. In this study, however, size was not selected as an invariant since it was considered optimal to retain size as a factor for consideration when looking at the differences between frontal sinus outlines. Invariance to location is accomplished by estimating the *x*- and *y*-coordinates of the centroid of the enclosed region and then subtracting these from the input *x*- and *y*-coordinates. Invariance to rotation and starting point are achieved by procedures that are somewhat arbitrary. The outline is rotated so that the major axis of the ellipse defined by the first harmonic is parallel to the *x*-axis. Invariance to start position is achieved by restarting the outline at a point at the major vortex of the ellipse on the positive *x*-axis. These two operations have the problem that they make the alignment of the outlines dependent on their shape.

The output is a file that contains a set of four elliptic Fourier coefficients and (optionally) an estimated outline for each harmonic (Figure 5.6). Here, coefficients were calculated for each of the files of coordinate data (“singles” and “duplicates”) using 20 harmonics.

Computing Distances and Likelihood Ratios

The resulting EFA coefficients were then used in two ways. First, they were used to regenerate the outlines by determining the *x*- and *y*-coordinates around the centroid. Euclidean (data space) distances between pairs of outlines were then calculated by summing the distances between corresponding *x*- and *y*- coordinates for every second degree around the outline from 0 to 360 (180 points total). For “duplicates”, this yields 305 total comparisons (each individual compared to its own duplicate), and for “singles”,

```
Input file:  C:\MYDOCU~1\MYPICT~1\SAMPLE~1\TPSTOE~1.DTA
Label: Converted from TPS to DTA format

N points = 675, N harmonics = 10
Invariant to location
  Centroid of outline = 382.77,271.066
Invariant to rotation
  Rotation angle (radians) = 0.163495
Invariant to start angle
  Start angle (radians) = 1.33617

Elliptic Fourier coefficients:

Zeroth harmonic:
A0=1.82452, C0=1.51298

Coefficients for harmonics:
              A                B                  C                  D
  1      112.473167     -3.21394896e-06    4.11202166e-07    -48.1969948
  2     -2.80686545      17.6074181         0.72632217       -17.3480072
  3      9.00702        -6.05565834       -11.5538206        -11.2342672
  4     -4.15845299      0.30120638         2.67414689         7.89381552
  5      0.0526259504   -3.00395513         3.22234154        -2.64744735
  6      0.221028835    -0.218118504        0.668859839        0.161757961
  7      2.17653227     -1.95158231        -0.370202005        0.836782455
  8      1.88338804     -1.71468508         0.890924871       -0.603945851
  9      0.935728848    -0.498330325       -1.59179389         0.0319974422
 10      1.62672162      0.12535736         0.343770295       -0.0943612307
```

Figure 5.6: EFAWin Output with EFA Coefficients.

126,253 comparisons result (each individual compared to every other individual), though a random sample of 1000 was selected from this latter group for analysis. Distances were calculated using R (2003), and summary statistics for the distances were calculated in SAS (2001).

What is really needed to estimate reliability, however, is a quantified assessment of individual uniqueness and the probability of misidentification using this method for an individual case. Assertions of uniqueness should be given as the probability of a match given the correct identification versus the probability of a match from the population at large. To make this assessment, the EFA coefficients were used to calculate likelihood ratios and posterior probabilities.

A likelihood ratio is the probability of the evidence supposing a hypothesis is true, divided by the probability of the evidence supposing it is false (Robertson and Vignaux, 1995). Here, the hypothesis is "these two frontal sinus outlines belong to the same individual", and the odds ratio or likelihood ratio is represented as the probability of the frontal sinuses matching given the correct identification over the probability of a match from the population at large:

$$\frac{P(x_2 \mid x_1)}{P(x_2 \mid m)}$$

To calculate this, one first needs a parametric form for the above. Multivariate normal would be ideal, but it doesn't work here, because the coefficients are Laplace, not normally, distributed. The likelihood ratio is represented as:

$$\frac{b_s}{b_d} \exp \frac{\left(-\left|x_1 - x_2\right| / b_s\right)}{\left(-\left|x_1 - m\right| / b_d\right)}$$

where:

x_1 = the EFA coefficients from duplicate 1 (simulated antemortem)

x_2 = the EFA coefficients from duplicate 2 (simulated postmortem)

b_s = the variation among “singles”

b_d = the variation within “duplicates”

Likelihood ratios were calculated in R (2003), and summary statistics for the rations were calculated in Microsoft Excel (1999). A likelihood ratio greater than 1 indicates evidence in favor of the hypothesis, while a ratio less than one is evidence against it, with exactly 1 being neutral. Any evidence with a likelihood ratio greater than 1 is relevant from an evidentiary perspective, and the further from 1 the ratio is, the greater the probative value of the evidence (Robertson and Vignaux, 1995).

The posterior probability represents the probability that the identification is correct assuming that the identification (prior to the osteological evidence) is as likely to be correct as incorrect (this assumption is discussed further later), and is calculated by dividing the likelihood ratio by the likelihood ratio plus one. This operation was performed in Microsoft Excel (1999).

Assessing the Effect of Orientation

Many consider it essential in a forensic context that the second (postmortem) radiograph is taken at precisely the same angle as the first (antemortem) film (Asherson, 1965; Culbert and Law, 1927), which is usually done on a trial-and-error basis. It may be argued, however, that the practice of taking multiple postmortem radiographs until they best resemble the antemortem radiographs may be problematic from an evidentiary perspective. For example, opposing council may question the expert regarding how many attempts were necessary before the two radiographs “matched” precisely enough. In order to test the error contribution of slightly different orientation when making a comparison, 3 skulls were radiographed an additional 8 times. The specimens were selected to represent one “small” frontal sinus (specimen 1), one “medium” frontal sinus (specimen 2), and one “large” frontal sinus (specimen 3).   Each specimen was radiographed at angles differing from the original (standard) orientation in the following ways:

5° and 10° laterally;

5°, 10°, and 15° superiorly; and

5°, 10°, and 15° inferiorly.

These radiographs were then evaluated in the same manner as was previously described. Tracings were made by hand onto tracing paper, with only 22 outlines resulting; two were unobtainable, because for the “small” frontal sinus, angling the skull down caused the entire frontal sinus outline to fall below the baseline. The tracings were then converted to digital images, digitized and saved as *.tps files, and converted using tpstoefa. EFA coefficients were calculated using EFAWin and saved as angles.txt. Likelihood ratios comparing off-angle replicates and normals (standards) of the same individual were then calculated from the EFA coefficients as described above.

Chapter 6: Results

Euclidean Distances Between Outlines

Summary statistics for the Euclidean distances between “duplicates” (same individuals compared to themselves) and “singles” (individuals compared to all other individuals not including themselves) for 20 harmonics are shown in Tables 6.1 and 6.2, respectively, and histograms representing the occurrences of distances in the samples are shown in Figures 6.1 and 6.2 (a N=1000 random subset of the singles data was used here instead of all 126,253 comparisons due to the extremely large number of comparisons and resulting time required to perform the calculations). The average distance between different individuals (978.26) is significantly higher than the average distance between duplicate outlines of the same individual (88.91), and a test of means showed that they were different at a highly significant level despite significantly different variances (Table 6.3) indicating a significant shape difference in the outlines of frontal sinuses of different individuals. One can see from examining the percentiles in Tables 6.1 and 6.2 that there is some overlap in the distances between the groups (in other words, some of the singles compared show smaller Euclidean distances between them than between some duplicates, and some duplicates show larger distances between them than between some singles). However, a plot of the cumulative density function shows this overlap to be minimal (Figure 6.3).

Typicalities are another way of assessing similarity between the duplicate outlines as compared to other outlines. Here, the typicalities represent the similarity of each

Table 6.1: Summary of Distances Between Duplicates

Statistic	***Value***
N	305
Mean	88.91
Standard Deviation	39.06
Skewness	1.24
Variance	1525.79
Percentiles	
100% Max	262.36
99%	213.99
95%	168.89
90%	135.29
75% Q3	105.72
50% Median	82.14
25% Q1	62.76
10%	45.93
5%	39.32
1%	30.73
0% Min	21.19

Table 6.2: Summary of Distances Between Singles

Statistic	***Value***
N	1000
Mean	978.26
Standard Deviation	520.92
Skewness	0.83
Variance	271359.72
Percentiles	
100% Max	2894.41
99%	2550.05
95%	1964.43
90%	1719.98
75% Q3	1294.80
50% Median	892.76
25% Q1	582.50
10%	382.60
5%	298.57
1%	199.06
0% Min	118.14

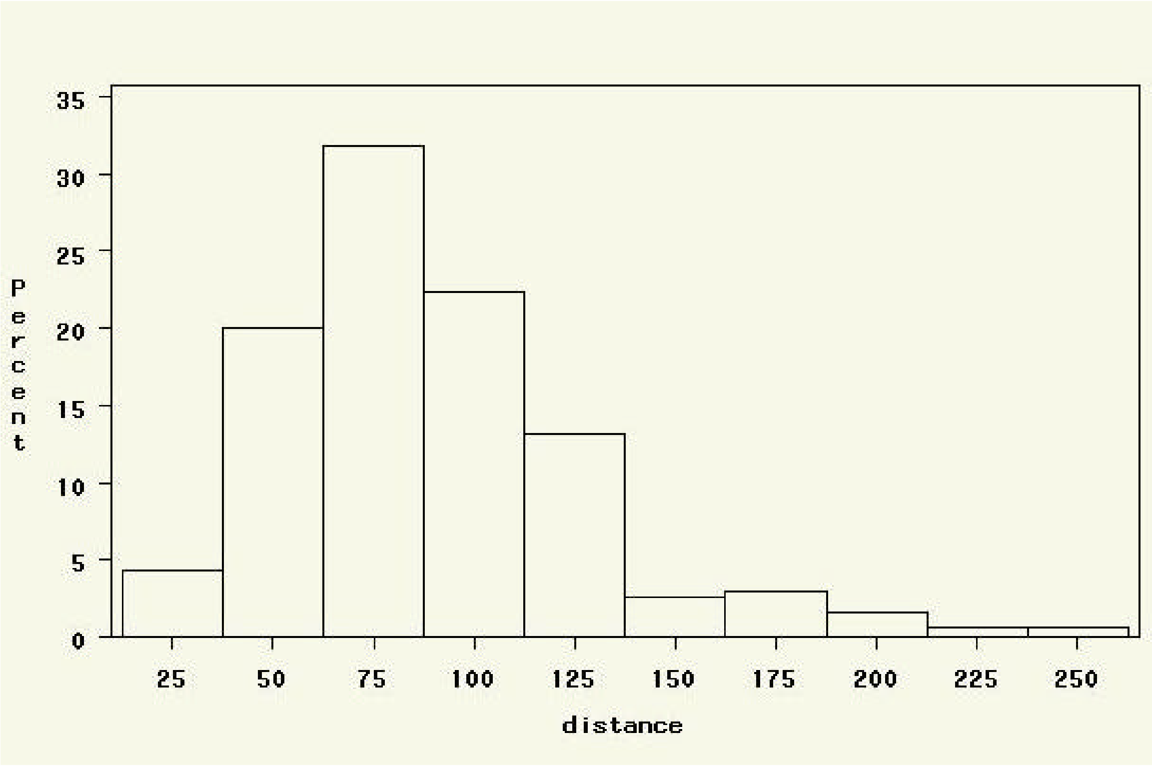


Figure 6.1: Distances Between Duplicates.

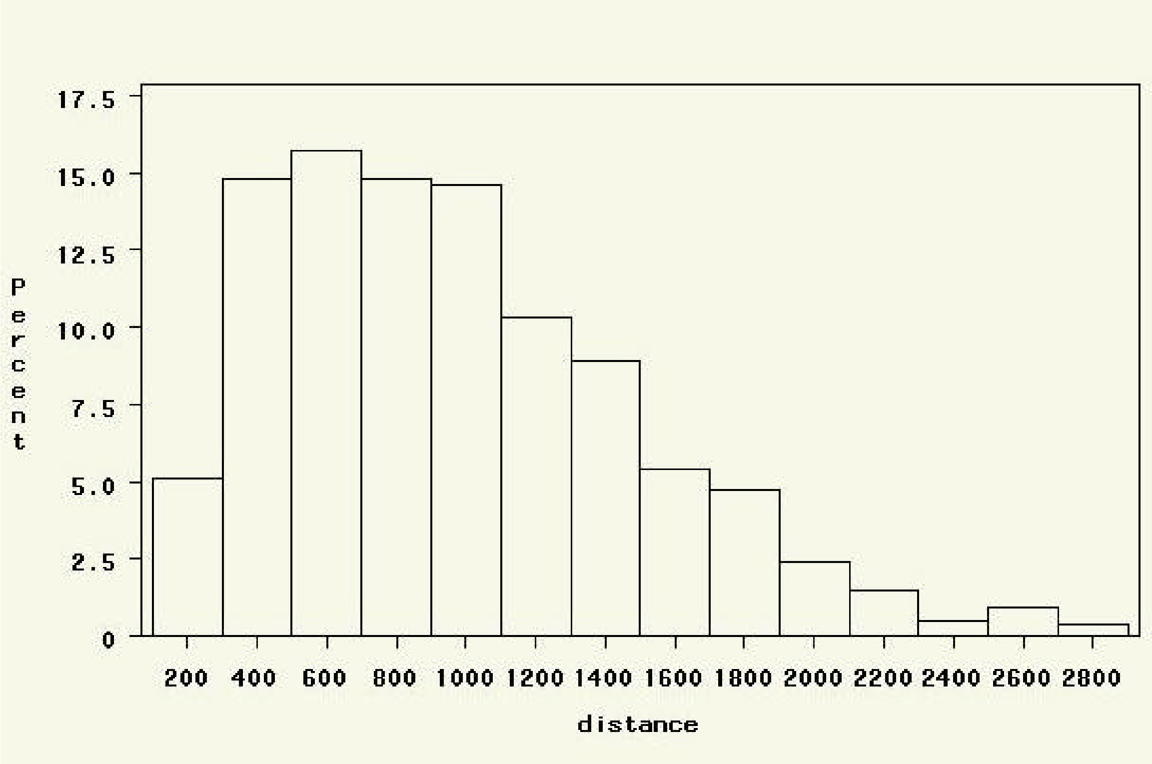


Figure 6.2: Distances Between Singles.

Table 6.3: Test of Means

Statistic	*Test Value*	*P-value*
Levene’s test for equality of variances	123.92 (F-value)	<0.0001
T-test for equality of means using unequal variances	53.50 (T-value)	<0.0001

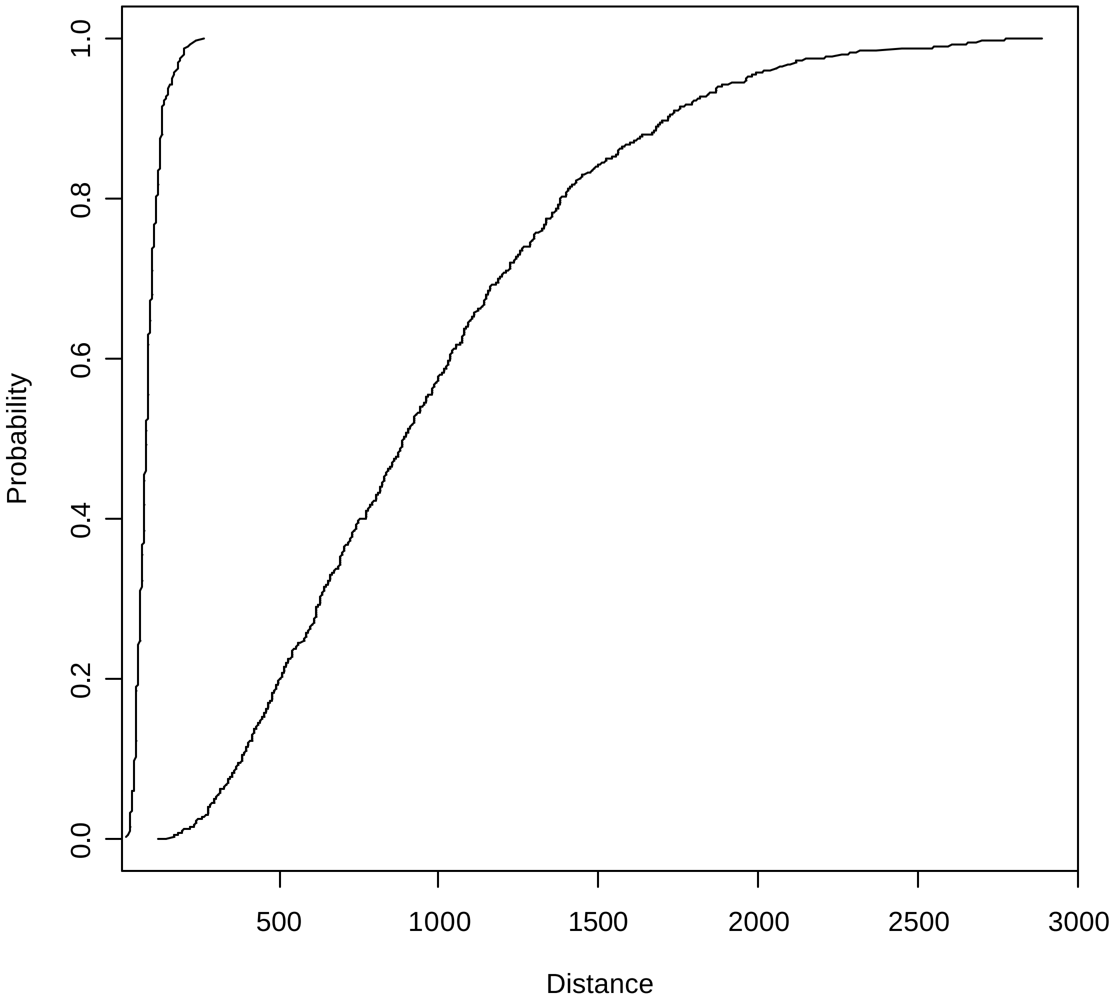


Figure 6.3: Cumulative Density Plot of Distances Between Duplicates and Singles. Cumulative densities of Euclidean distances between duplicates (left), and between singles (right).

individual when compared to its own duplicate versus when compared to other individual outlines. The typicality for each case is calculated by summing the occurrences in the singles comparisons of a distance greater than or equal to the distance between the duplicate of that individual case. The typicalities of each case are illustrated in Figure 6.4, which shows that most typicalities are very close to if not equal to 1. In other words, for an individual case, the probability of finding a non-duplicate with a Euclidean distance less than or equal to that case's duplicate is very small.

Figures 6.5 through 6.8 show examples of the extreme distance comparisons—the smallest and largest distances between duplicates of the same individual, and the smallest and largest distances between pairs of different individuals. Figure 6.5 shows that for 3 of the 4 different individuals showing similar outlines (i.e. small Euclidean distances), this was due primarily to the fact that these outlines were very small and unremarkable to begin with. As Figure 6.6 shows, the smallest distances between duplicate outlines of the same individuals were again due to the outlines being quite small, usually a single concave recess. The smaller the outlines are to begin with, the better the chance that they will have small distances between them, and this is somewhat intuitive. What it suggests for forensic comparisons, however, is that it may not be advisable to use this method for comparing very small, unremarkable frontal sinuses.

Large distances between different individuals was quite expected, and clearly illustrated in Figure 6.7. Duplicates showing large distances are relatively large and complex outlines to begin with, and again, this seems intuitively predictable. In looking at the outlines in Figure 6.8, however, it becomes clear that a visual assessment of these

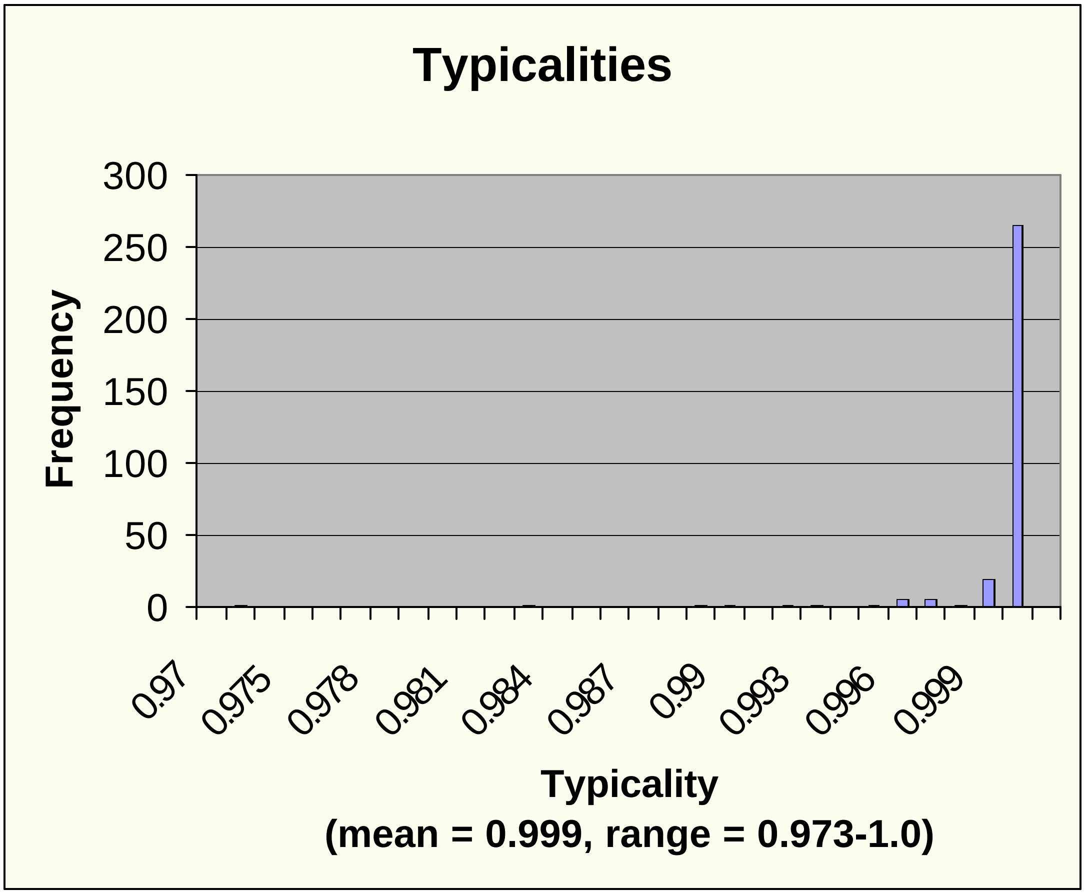


Figure 6.4: Typicalities of Duplicate Outlines

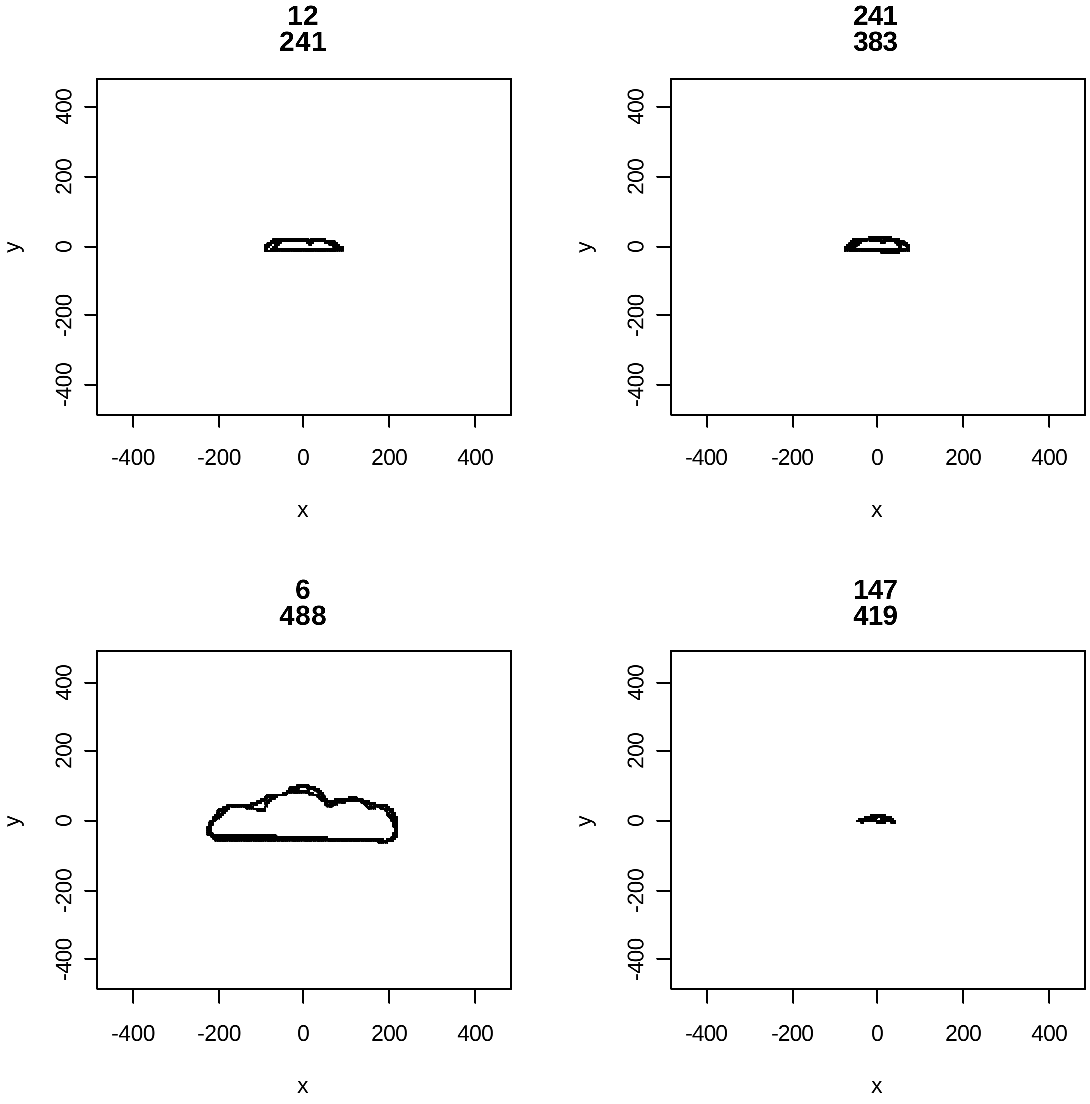


Figure 6.5: Smallest Distances Between Different Individuals

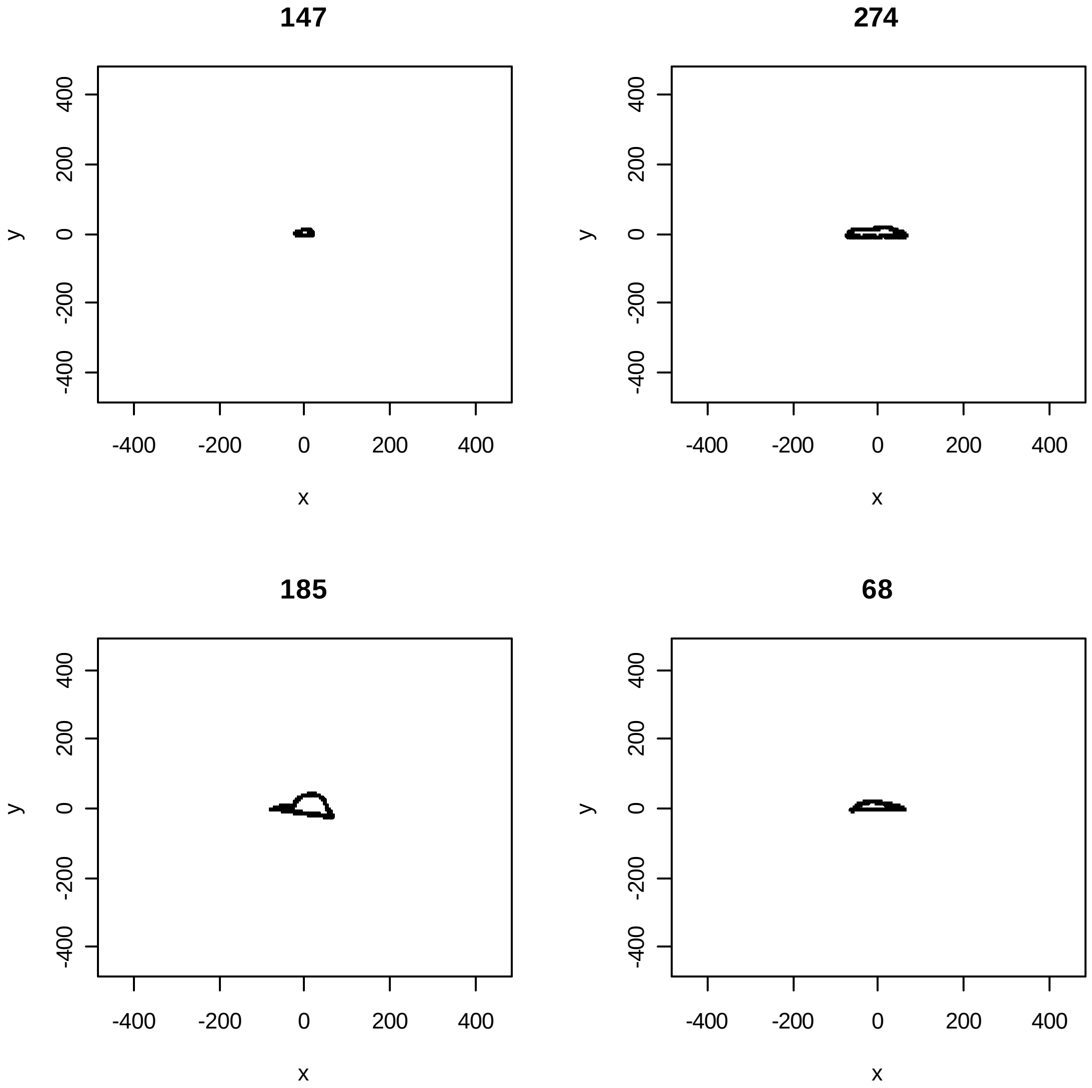


Figure 6.6: Smallest Distances Between Duplicate Individuals

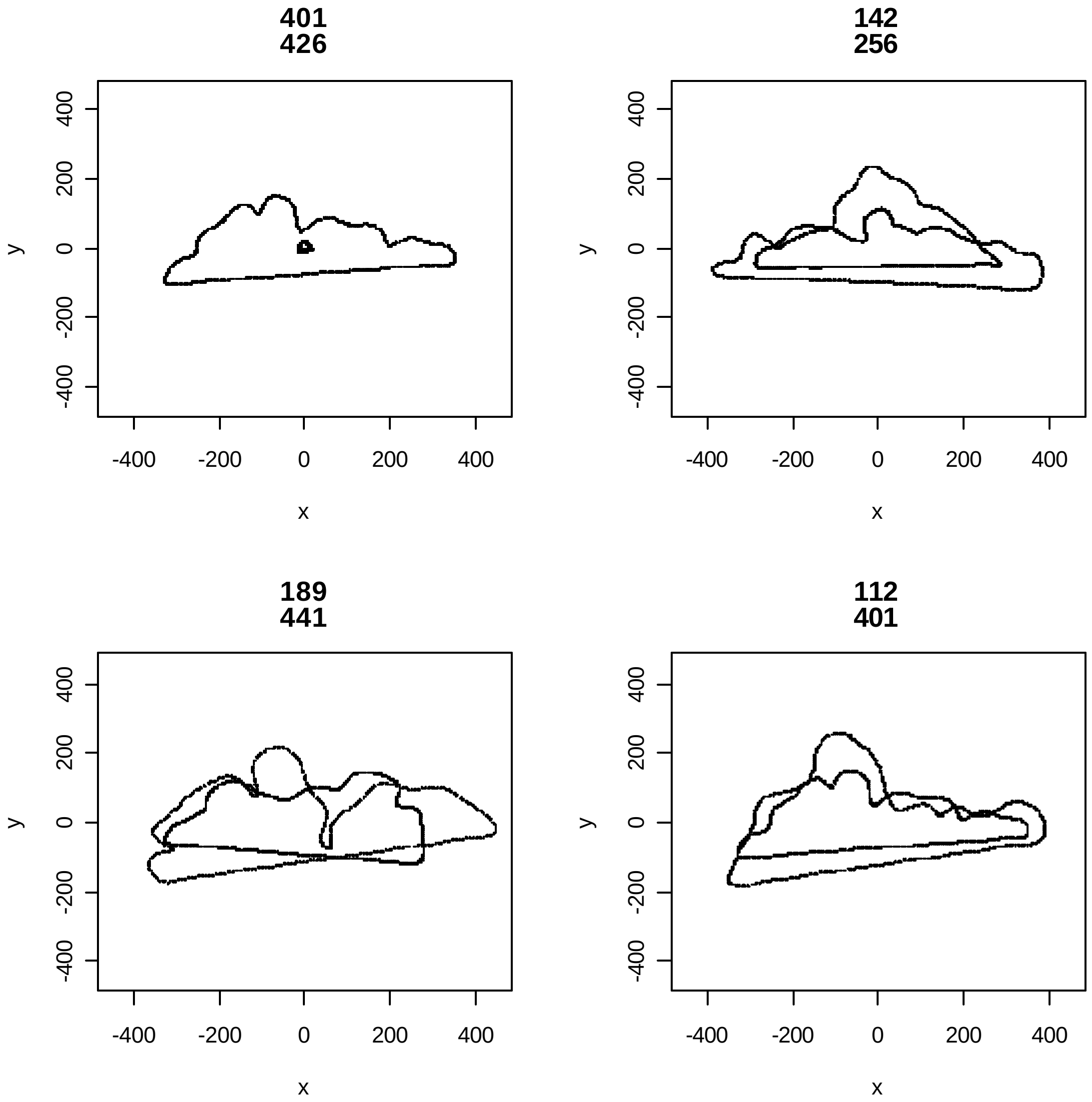


Figure 6.7: Largest Distances Between Different Individuals

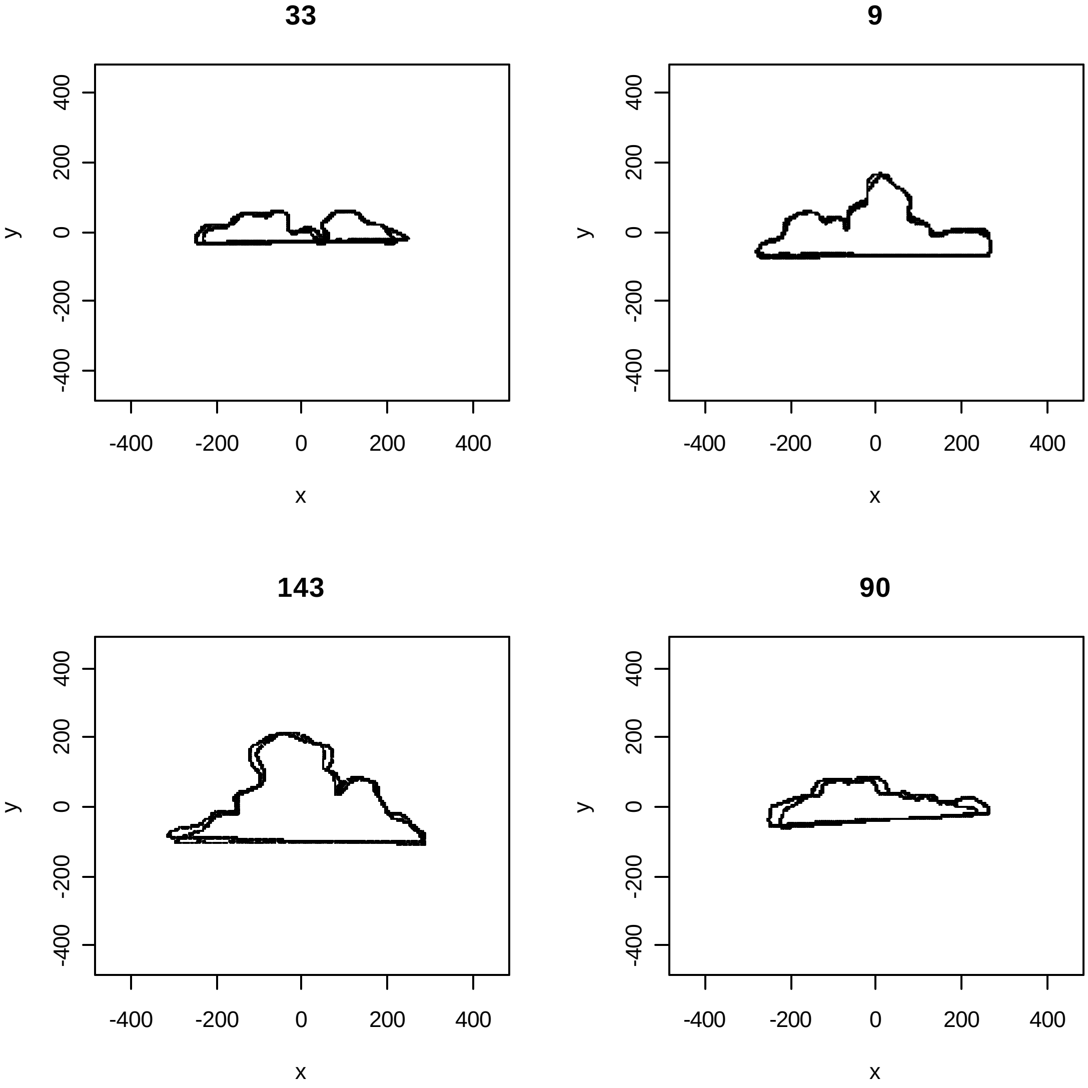


Figure 6.8: Largest Distances Between Duplicate Individuals

outlines would probably lead to the conclusion that they were from the same individual, despite the fact that an EFA assessment may suggest otherwise.

Likelihood Ratios from EFA Coefficients

The EFA coefficients themselves do not follow a normal distribution, but a Laplace, or double-exponential distribution (Evans et al., 1993), with the distribution function:

$$\frac{1}{2}\exp\left[-\left(\frac{a-x}{b}\right)\right], \quad x < a \qquad 1-\frac{1}{2}\exp\left[-\left(\frac{a-x}{b}\right)\right], \quad \mathrm{x} \geq \mathrm{a}$$

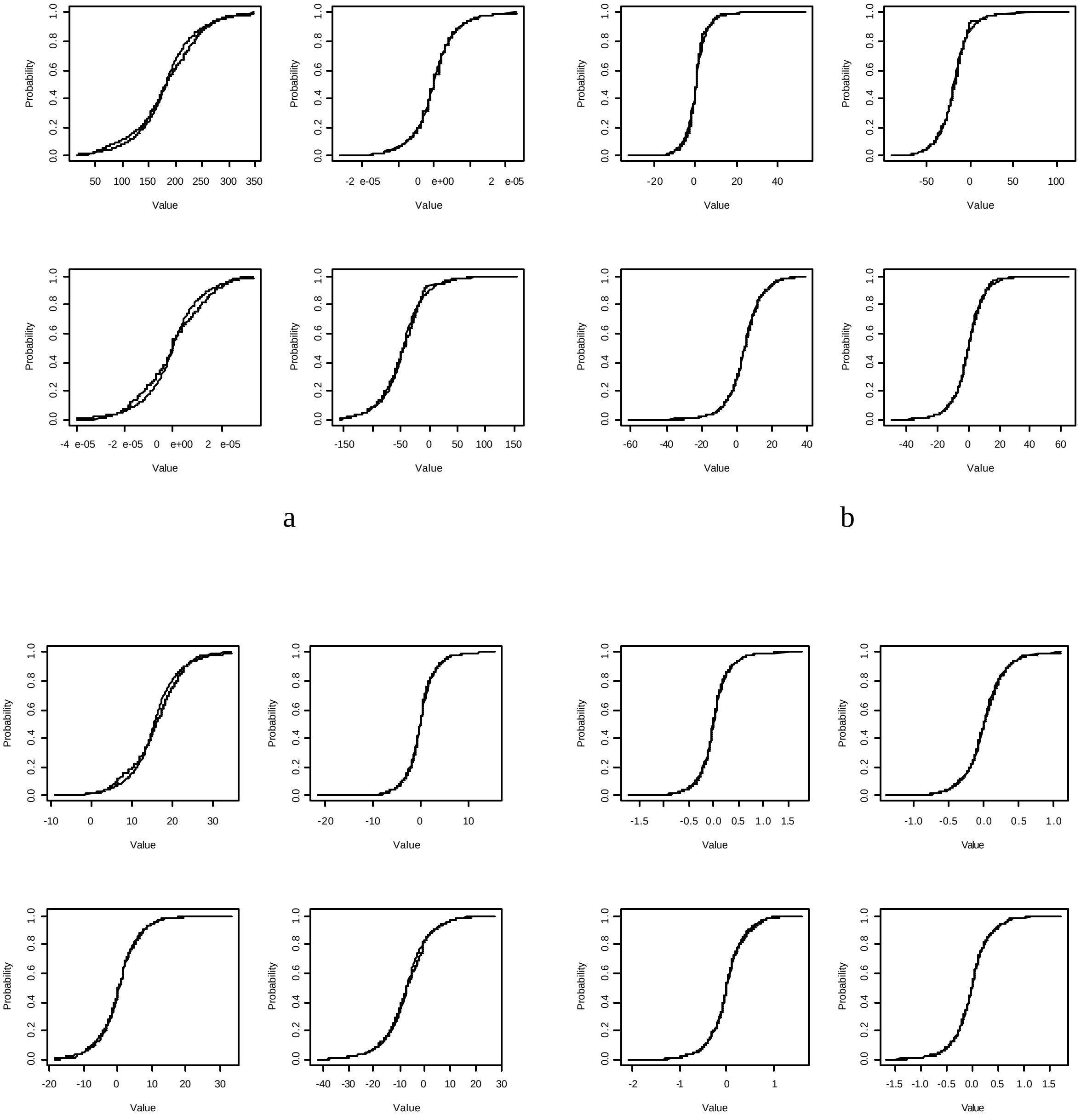
where:

$a =$ mean

$b = \sqrt{(\mathrm{var}/2)}$

To illustrate this, the Laplace distribution and distribution of the four EFA coefficients for singles for the first, second, third, and twentieth harmonics are shown in Figure 6.9.

A summary of the log likelihood ratios (likelihood ratios converted to log base-10 scale) for 1, 5, 10, 15 and 20 harmonics are shown in Table 6.4. A likelihood ratio of 1 would indicate that you would be equally likely to get that distance between duplicates of the same individuals as you would between different individuals. The average likelihood ratio for all harmonics in this study is fantastically high, and increases with increasing harmonics. Thus, the odds of a match given the correct identification are significantly higher than the odds of a match from the population at large. Indeed, on average, the odds are about 1.09E+84 to 1.



a b

c d

Figure 6.9: Laplace Distribution of EFA Coefficients.

Distribution of coefficients A_k, B_k, C_k, and D_k (left to right, top to bottom) for the (a) first, (b) second, (c) third, and (d) twentieth harmonics.

Table 6.4: Log Likelihood Ratios

Number of Harmonics	***Mean***	***Standard Deviation***
1	1.81	1.32
5	10.09	4.96
10	16.64	9.02
15	20.02	12.88
20	21.22	16.54

The posterior probabilities for 1, 5, 10, 15, and 20 harmonics are shown in Table 6.5 and Figure 6.10. For most cases, the posterior probability is 1 or very near 1. These results speak to the reliability of the technique, suggesting that the probability of a correct identification given a match would be nearly 1 in most cases, and about 96% on average. Comparing EFA coefficients using likelihood ratios and posterior probabilities, thus, provides a very reliable method for correctly identifying a match.

The Effect of Orientation

The posterior probabilities (using 5 harmonics) representing comparisons between the “standard” outlines and those that differed from it in orientation are shown in Table 6.6, and reproductions of the outlines obtained by the standard orientation versus the variants are shown in figures 6.11-6.13. The values highlighted in gray in Table 6.6 show very small posterior probabilities, suggesting that these variations in orientation significantly affected the projected shape of the frontal sinus outline. For 5° changes, there appears to be little effect on the projected outline, with only two comparisons showing significantly large deviations in shape. Tilting the skull more than 5° down appears to have had the largest effect, causing all observed cases to appear significantly different from the standard (i.e., posterior probabilities are very small).

It appears that the difference in the projection created may also be somewhat dependent on the shape of the frontal sinus itself, as specimen 2 showed greater deviation for more differences in orientation, while specimen 3 had high probabilities for all but two of the deviated positions. Strangely, tilting the skull superiorly appears to have increased the similarity to the standard.

Table 6.5: Posterior Probabilities

Number of Harmonics	***Mean***	***Standard Deviation***
1	0.88	0.23
5	0.96	0.18
10	0.94	0.22
15	0.92	0.25
20	0.90	0.29

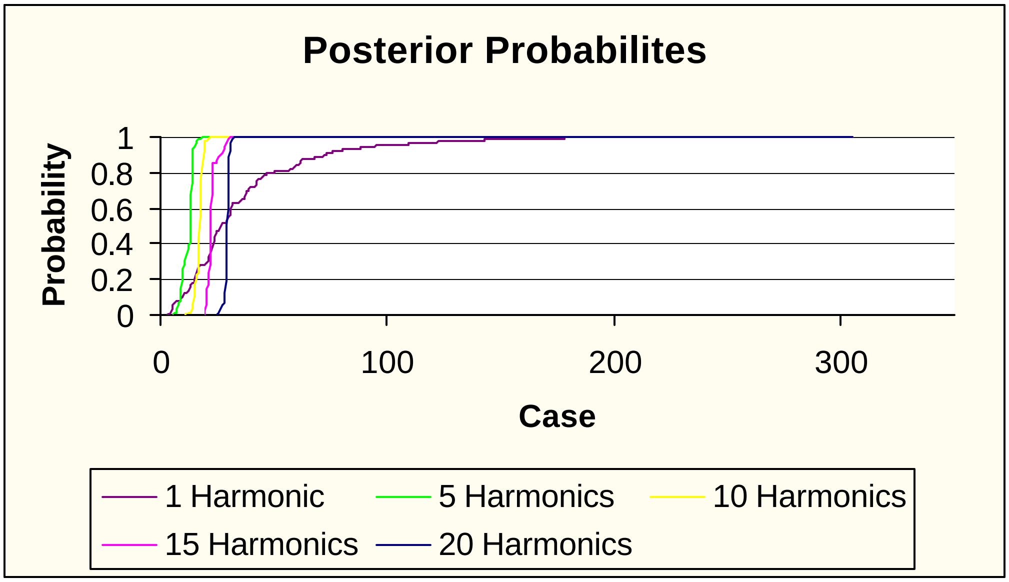
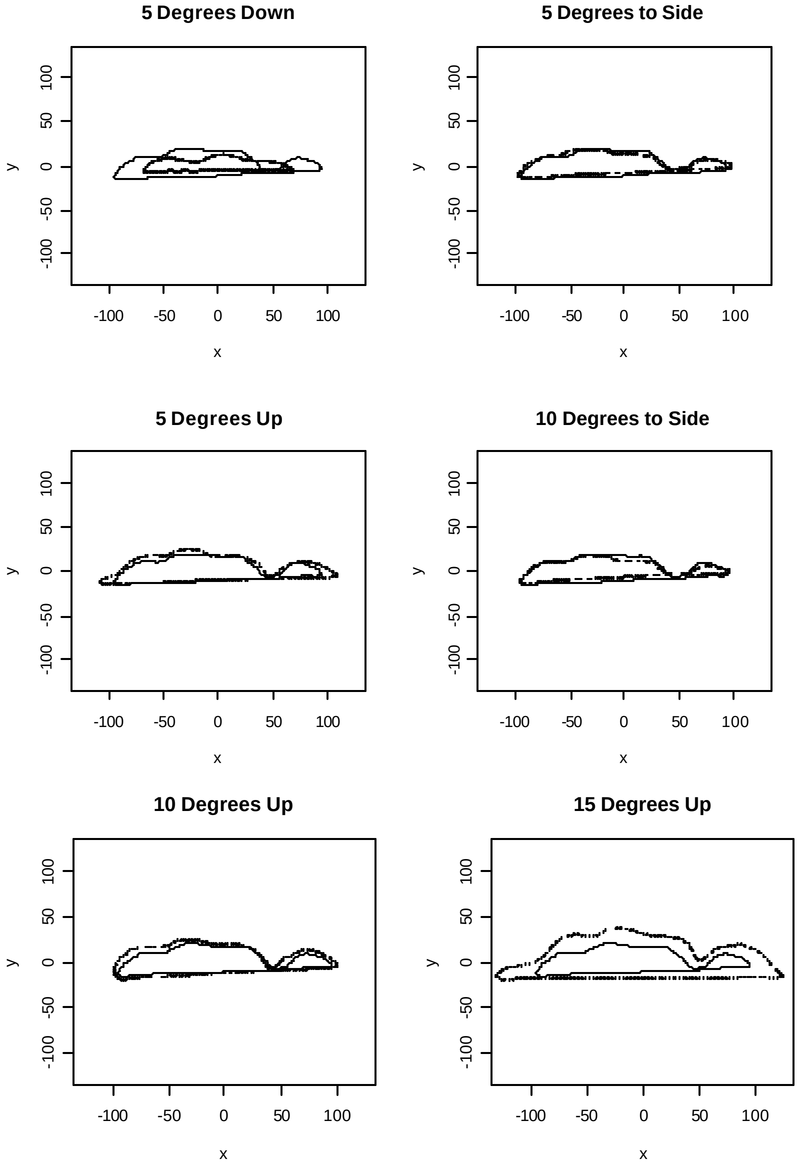


Figure 6.10: Posterior Probabilities

Table 6.6: Angle Variations and Corresponding Posterior Probabilities (5 Harmonics)

Angle Variation	***Specimen 1***	***Specimen 2***	***Specimen 3***
5° inferior	0.999	1	1
5° lateral	1	1	1
5° superior	2.4E-48	6.6E-148	1
10° inferior	N/A	6.3E-135	1.7E-8
10° lateral	1	1.4E-24	.999
10° superior	2.7E-47	8.3E-159	1
15° inferior	N/A	2.6E-24	3.0E-27
15° superior	.999	1	1


5 Degrees Down

5 Degrees to Side

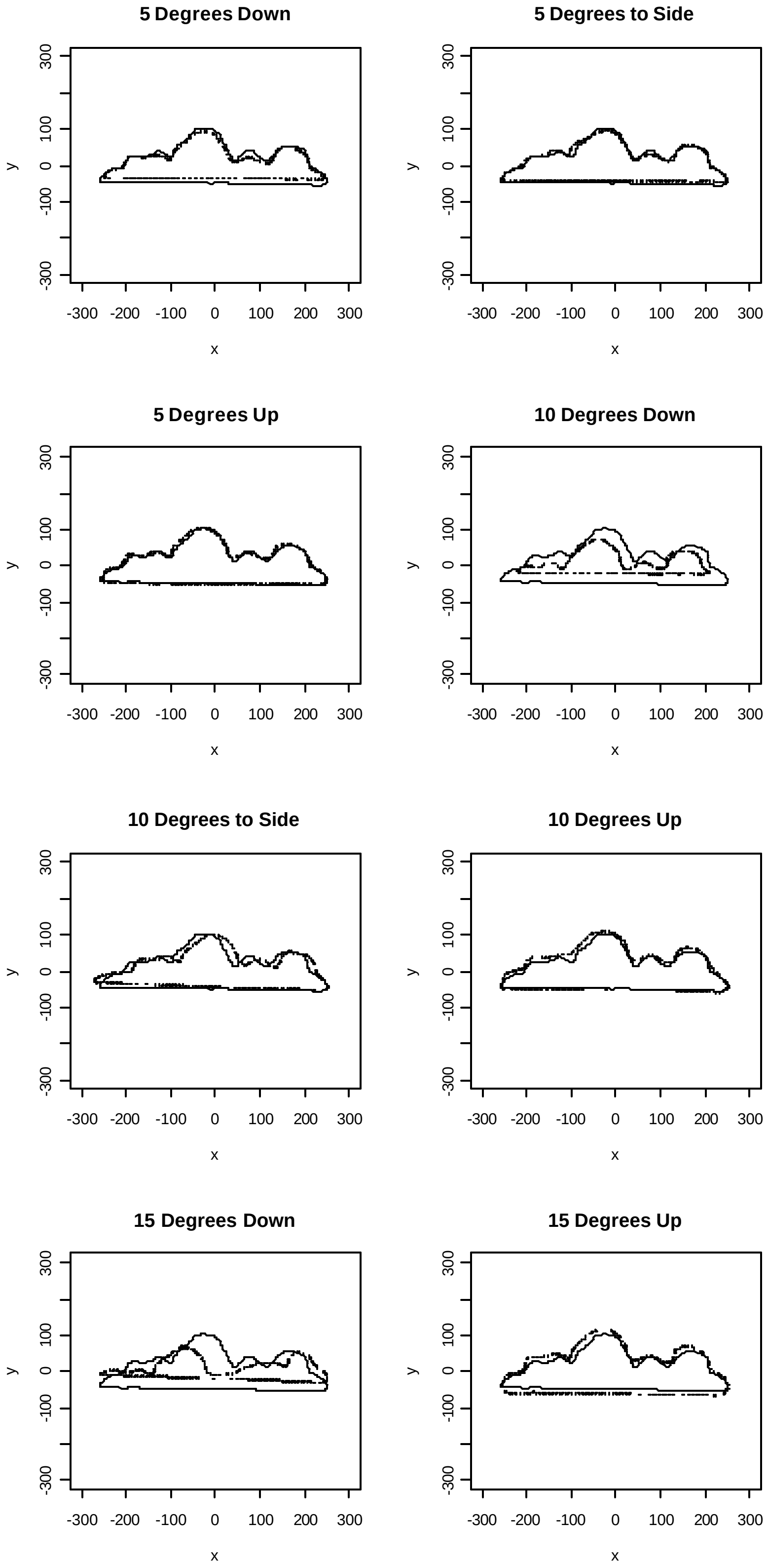
5 Degrees Up

10 Degrees to Side

10 Degrees Up

15 Degrees Up

Figure 6.11: Angle Variations and Resulting Projection Changes for Specimen 1



5 Degrees Down

5 Degrees to Side

5 Degrees Up

10 Degrees Down

10 Degrees to Side

10 Degrees Up

15 Degrees Down

15 Degrees Up

Figure 6.12: Angle Variations and Resulting Projection Changes for Specimen 2

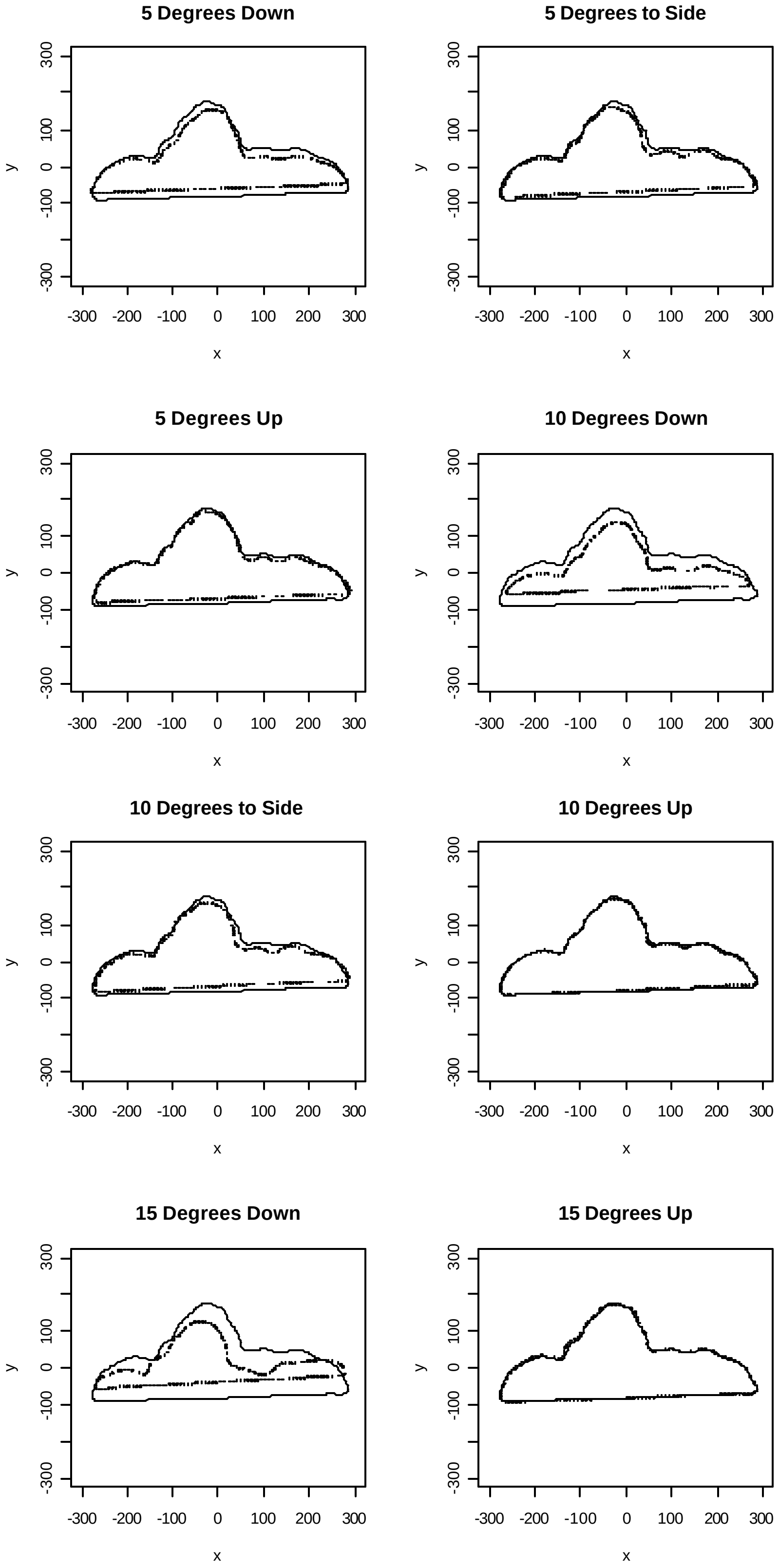


Figure 6.13: Angle Variations and Resulting Projection Changes for Specimen 3

To present the relevant point (considering a forensic context), while large deviations in orientation between the antemortem and postmortem radiographs appear to create significant differences in the projected shape of the frontal sinus, smaller deviations may not affect the application of the technique in question.

Chapter 7: Discussion

Significance of Findings (and Bayes' Theorem)

Are frontal sinus outlines unique and reliable in confirming or refuting that two radiographs belong to the putatively same individual? The results presented in the previous chapter quantitatively support previous notions of the individualized quality of frontal sinus outlines and their reliability in forensic identifications.

One question that forensic anthropologists (or other forensic specialists making the identification) must consider is: what probability is acceptable for an identification? In other words, with what degree of certainty would you feel comfortable in claiming that you have correctly identified the remains of a previously unidentified individual? Since neither the courts nor the discipline of forensic anthropology (or for that matter, any forensic discipline involved in personal identification) recognize an objective standard for confirming or rejecting a frontal sinus-based identification, this remains a judgment call for the expert. It is also important to bear in mind a number of important considerations when interpreting the significance of these findings.

Consider the fallacy of the transposed conditional, or what has become known as the "prosecutor's fallacy" (Thompson and Schumann, 1987). The "prosecutor's fallacy" is the error of confusing conditional probability $P(A|B)$ with $P(B|A)$. Consider the examples "the card is a diamond" and "the card is red"; the probabilities of one given the other are not equal. The probability that the card is a diamond given that it is red is ½, while the probability that the card is red given that it is a diamond is 1. An error often committed by prosecutors (particularly in DNA cases) is confusing the following two conditional probabilities and alleging that they are equal: (1) The probability that a DNA sample taken from a person matches that found at the scene of a crime given that the person is innocent, and (2) The probability that the person is innocent given that his/her DNA sample matches that found at the scene of the crime. The two probabilities are *not* the same, and it is clearly the second one that is of interest. The probability of the first may be very small, and the error committed is in declaring that the probability of the second must also be very small when in fact it may be much larger.

With regard to frontal sinus morphology and the results obtained here, this amounts to confusing the following two probabilities: (1) The probability of a frontal sinus match given that the identification is correct and (2) the probability that the identification is correct given a frontal sinus match. The preceding study addressed the first, and showed the average probability to be about 96%. Again, however, it is the second of these probabilities that is of interest in a forensic context. Arriving at probability (2) requires the application of Bayes' Theorem (Bayes, 1763), which tells us how to update our knowledge by incorporating other information. Bayes' Theorem states:

$$P(A|B) = P(B|A) \bullet P(A)/P(B)$$

The configuration of Bayes' Theorem of interest for this investigation would be:

$$\frac{P(\text{Correct ID} \mid \text{Match})}{P(\text{Incorrect ID} \mid \text{Match})} = \frac{P(\text{Match} \mid \text{Correct ID})}{P(\text{Match} \mid \text{Incorrect ID})} \bullet \frac{P(\text{Correct ID})}{P(\text{Incorrect ID})}$$

or

$$\textit{Posterior Odds} = \textit{Likelihood Ratio} \bullet \textit{Prior Odds}$$

The prior odds represent an initial body of information which we use to estimate a final posterior odds that represents the confidence that the identification is correct. The posterior odds are what we want to know—the odds in favor of a correct identification after taking other evidence into account. The two will only be equal if the prior odds are equal to 1, i.e., if the probability that the identification is correct is equal to the probability that it is incorrect. This is clearly not the case, since there is always some other reason or evidence to suggest that the identification may be correct (or else why would you be comparing the radiographs in the first place?). Thus, the prosecutor's fallacy is no fallacy if there is no initial body of information, and the prior odds of a match is equal to 1. The fallacy consists in the prosecutor's claim of a small probability of a match while failing to mention that conveniently omitted information (prior odds) may have led to a significantly different estimate.

Prior odds are always greater than 1 in such cases because there is already some reason that the two radiographs are being compared, presumably because there is already other evidence to suggest that they belong to the same individual (medical records, of course, were not pulled at random from the population at large). Such evidence increases the prior odds, though quantification of these odds may not be straightforward.

In sum, assuming a prior odds of 1 provides only the *absolutely most conservative* estimate of a correct identification in the absence of any other information or evidence. In this study, even this most conservative estimate provides a posterior probability of about 96%. When prior odds are considered, this posterior probability is likely to increase to an even higher level. The technique, therefore, should be considered a (more than) sufficiently reliable method for confirming or rejecting a positive identification.

Possible Sources of Error in the Research Method

As with any research endeavor, there are several potential sources of error that may affected these results. The first of these is the sample itself, since the radiographs were taken by different individuals for varying reasons—the forensic and donated samples were taken (or at least oriented) by me specifically for the present study, the student sample was taken by (possibly multiple) UT Student Health X-ray Technicians, and the Arikara sample was taken by two others. While each sample was taken to produce a Caldwell view, they may differ slightly with regard to orientation and distance since a Caldwell view may vary within several degrees. Moreover, one subset of the sample consisted of radiographs of live individuals, while the other two consisted of radiographs of skeletal material.

All of the tracings were done by me, requiring my interpretation of the location of the orbital margins and the outer border of the frontal sinuses. There may, therefore, have been some error involved in interpreting the color gradation and features of the radiographs, and thus in identifying the precise locations and boundaries of the frontal sinuses. However, since one individual did them all, error in this area (if present) should be considered consistent.

The precision of the resulting digital outlines may have been affected by at least two factors. First, the use of pencil for the tracings resulted in outline images that varied in color within the image, which may have contributed to precision limitations. Second, the resolution of the scanner may have resulted in some loss of precision. Either of these may have the effect of producing digital images that did not precisely reflect the outlines as seen in the radiographs.

Some of this error could undoubtedly be reduced through some fine-tuning to facilitate data processing. Methods for tracing the outline from scanned (digital) radiographs using computer-aided programs were explored, but it seems that radiographs themselves have too much color gradation and computer programs were not able to isolate the outline of interest. Tracings could also have been done in ink or some other medium with a more consistent color tone thus producing a more precise outline.

Limitations of the Technique

Despite the encouraging results presented in the previous chapter, the technique of identification by EFA comparison of frontal sinus outlines as seen in standard radiographs unfortunately suffers from several possible limitations relating primarily to the availability, applicability and quality of radiographic records. Radiographic comparison of any feature presupposes two sets of films, one antemortem taken during life, and one taken of the postmortem remains. The technique, therefore, is highly dependent on the accuracy and availability of hospital and/or mortuary records; inadequate, unreliable or unavailable antemortem or postmortem data can prove a great hindrance to identification using this method.

There are several reasons that records may not be available. First and foremost, while an increasingly utilized diagnostic tool, not everyone has had an antemortem radiograph of his or her skull or sinuses taken. Obviously, those without such a record created are not candidates for this method of identification. However, the practice of taking radiographs has become increasingly frequent due to decreases in the cost of the technology as well as the fact that it has become an obligatory procedure preceding many treatments of the frontal sinuses. Some have even suggested that deliberate radiographs should be taken and kept specifically for the purposes of identification (Law, 1934). In many countries, unfortunately, radiography is not used as routinely in the investigation of medico-legal cases due to the scarcity of x-ray equipment in mortuaries. As a result, postmortem films may be difficult to obtain and radiology may only be used in special cases (Fatteh and Mann, 1969).

Second, for a number of reasons, even if such a record was produced and available at one time, it may no longer be available. In most countries, radiographs pertaining to the inactive files of patients are stored for at least five years (Marek, 1983; Mason, 1983; Messmer, 1986). In the U.S., medical records are usually retained until the statute of limitations for acts of medical malpractice has run out (Kahana and Hiss, 1997). The decision to retain radiographic records and for what period of time is often dependent on economical considerations; the cost of storage may make it difficult to maintain radiographs indefinitely and sheer bulk of storage has been cited as a reason not to retain radiographs. Yet another reason is that radiograph film contains significant amounts of recoverable silver so there are monetary incentives to periodically trim files (Messmer, 1986). However, with recent advances making it possible to store the images digitally, perhaps this will become less of a concern. Due to their forensic potential, some have suggested that for identification purposes, all anterior/posterior skull radiographs, and all radiographs of the frontal sinuses should be stored and arranged according to a classification system (Marek et al., 1983), and others insist that clinical radiologists should be made aware of the importance of storing radiographs for extended periods of time and developing efficient record keeping methods to enable prompt retrieval of films for identification purposes (Kahana and Hiss, 1997).

Even if a record of a cranial radiograph is available for comparison, it may still fail to be applicable for the purpose of identification using this technique for a number of reasons. Recall that a certain subset of the population lacks radiographically demonstrable frontal sinuses. These individuals, though possessing the proper antemortem records, may not be suitable for this identification method. However, given that they comprise only a small percent of the population, significant likelihood ratios may still result. If, for example, *p* represents the proportion of individuals without frontal sinuses (which in the sample used here was 81 out of 584 or about 14%), then the likelihood ratio for a sinus-less individual would be 1/*p*, or 1/(81/584) or 7.3. Thus, even for comparisons of sinus-less individuals, likelihood ratios would be significantly greater than one and may still be used in forensic comparisons, though with somewhat less strength than for more remarkable frontal sinuses.

Cases of subadults or those whose frontal sinuses have been affected by pathology or trauma also present potential applicability problems and should be considered with caution as changes in the size and shape of the frontal sinuses may have occurred. Antemortem frontal sinus films are not usually taken unless to aid in the investigation and diagnosis of a medical problem, so there is a good chance that many antemortem films may have been affected by trauma or pathology (however, this did not appear to affect the ability to make a match in a study by Kirk et al. (2002)). Moreover, as the preceding study showed, even if radiographs are available and the frontal sinus is present, it may be too small or unremarkable to apply the technique considered here. This problem is similar to one experienced in dental identifications – those who have a dental record but who lack teeth or have unremarkable dentition (i.e. have no restorations, gaps, etc.) would not be suited for dental comparisons for confirming identification (Adams, 2003).

Another concern is the quality of both the antemortem and postmortem records. Obviously, the greater the quality of the records, the more reliable the conclusions drawn from them. It is widely recognized that the quality of films for comparison is greatly enhanced with the use of trained personnel in a properly equipped center. Specifically, a comparison is enhanced by sufficient clarity, similar orientation and distances, and minimal deformation and magnification.

Finally, one should consider the consequences (i.e. limitations) of using conventional radiography. All structures in the path of the x-ray beam appear superimposed on the image and cannot be distinguished from each other, "collapsing" three-dimensional structures into two dimensions provides only limited information on structures such as frontal sinuses (Spoor et al., 2001). The method used here to investigate variability further reduces the representation of the structure to that portion located above the established baseline. Recently, a number of researchers have used CT scans for comparison (Haglund and Fligner, 1993; Reichs and Dorion, 1992; Smith et al., 2002), arguing that CT scans provide a dimension to the analysis that is not present in standard A-P radiographs and that it may afford greater precision because it can reveal greater detail. Perhaps such comparisons will become increasingly frequent due to the increased applications of CT scans and MRIs in medicine and dentistry, but this technique will no doubt also need to be tested for reliability and such tests will likely be significantly more complex than the current investigation.

Developing an Objective, Standardized Methodology

Another important issue in identification by frontal sinus radiographs is: who is qualified to do it? In most instances, only a board certified expert will be asked to testify and these individuals ostensibly have sufficient education, training and experience to be qualified to make assessments of identity and testify as to the result. Indeed, it is highly advisable to employ the expertise of a certified radiologist to examine the radiographs for comparison. While some note that mismatches could be rare, even by observers with limited training and experience (Kullman et al., 1990), many (including Hogge et al., 1993; Koot, 2003; Messmer, 1986; Murphy et al., 1980) support the need for trained interpreters in identification cases, and find that those with more experience fared better in comparisons. Although the results of the orientation test suggest that slight changes in orientation do not significantly affect the projected shape of the frontal sinus outline, many suggest that radiological and anatomical training can compensate for a slight change in orientation and help avoid technical traps caused by both position and exposure, thereby facilitating comparison.

Perhaps, however, the technique would be enhanced by a methodology that did not depend solely on the expertise of the user, but which was standardized and repeatable by other reputable forensic scientists. Ubelaker (1984) once questioned in preparing for a court testimony positively identifying an individual by frontal sinus morphology comparison: What is the precedent for making a positive identification from a radiographic comparison? As previously underscored, to date there are no objective, reproducible comparison methods recognized within forensic radiology or anthropology, with comparisons based on subjective visual comparison by a qualified (usually certified) expert. In light of recent decisions regarding the admissibility of expert witness testimony, however, it seems imperative that a quantified system of objectifying comparisons is established if conclusions are to withstand cross-examination.

Ubelaker (1984) noted that an “exact match” of details of frontal radiographs, especially in the frontal sinus area, is sufficient basis for positive identification. But what is an “exact match”? It is suggested here, based on the results of this study, that a “match” be considered two frontal sinus outlines possessing sufficiently similar EFA coefficients so as to result in a convincing posterior probability. This method, like no other investigated before it, can be applied objectively and quantitatively to frontal sinus identification cases. Especially when prior odds are factored in, the probability of correctly identifying a match (or rejecting one) is sufficiently high.

Another question to consider is: Is the proposed technique worthwhile? Should forensic scientists bother with this method of frontal sinus-based positive identification? Given the acceptance that visual assessments have gained in the past and the success with which they have been applied, it may be redundant (if not overkill) to perform EFA on all frontal sinus comparisons in forensic contexts. A visual assessment can be performed quickly and easily, while an EFA will require more time and resources, which may make it seem significantly less appealing. However, where the EFA technique may prove particularly valuable is in cases that may go to trial and therefore will likely be challenged by another expert and/or opposing council. In such cases, the results of an EFA comparison may significantly strengthen the expert’s argument by demonstrating that the comparison technique meets *Daubert* guidelines in 1) having been empirically tested, 2) having known error rates established, and 3) having been applied via an objective, standard method. Perhaps the technique could be further enhanced (and made somewhat less cumbersome) by the development of a software package designed to specifically address and facilitate forensic EFA comparisons.

Keeping it in Perspective

All of the above said, there are a few important ideas to keep in mind regarding statistical probabilities and “proving” positive identifications. While the *Daubert* guidelines require statistical estimates of reliability and objective methods (and not unjustly so), it is a misconception that any statistical probabilities exist independently of human judgment. Even in the case of DNA evidence (which is widely regarded as unique, objective, and reliable for establishing identity), there is no complete objectivity since DNA comparisons, too, exist only within a framework of assumptions (Evett and Weir, 1998).

In testifying as to whether two pieces of evidence (fingerprints, DNA samples, or frontal sinus radiographs) came from the same individual, experts often report that “the two are identical”, when indeed, two of anything will inevitably be somewhat different. The task of the forensic anthropologist, thus, is not to answer whether two frontal sinus outlines are identical, but whether there is sufficient evidence to suggest that they originated from the same individual.

Moreover, as previously quoted: “…it is for the jury, not the expert, to decide on the identity of a skeleton; it is for the expert to show whether the identity is possible or probable” (Dwight, 1878). While the research presented here has contributed to the quest for objectivity, quantification, and estimating potential rates of error (misidentification), the ultimate decision as to whether a positive identification has been made is still up to the triers of fact. While the expert plays a role in determining the degree or state of belief in the minds of the jurors, it is ultimately the jurors’ belief in the probability of the identification that matters. In other words, an expert in no way “proves” a positive identification; the issue is proven only when the jury decides that an expert can be believed. This believability, however, can be enhanced through processes of inference that are less subjective and more objective.

Conclusion

To reiterate, the purposes of the preceding study were:

1. To emphasize the need for objectivity and a standardized methodology for identification using frontal sinus outlines, especially in light of recent rulings in admissibility law;

2. To empirically assess frontal sinus outline variability using Elliptic Fourier Analysis (EFA);

3. To investigate the reliability of the EFA method for identification, and estimate the probability of misidentification (at least in a forensic context).

The current state of admissibility law as reviewed in Chapter 4, coupled with observed methodological shortcomings of visually comparing frontal sinus outlines clearly illustrates the need for objectivity and standardization when comparing frontal sinus radiographs in a forensic context. Given the courts' history of emphasizing the *Daubert* guidelines (such as in the case of fingerprint evidence), a strong case can be made for the need of forensic identification techniques to satisfy these guidelines. Moreover, the history and current state of frontal sinus-based positive identifications clearly fail in this regard, as shown in the review of previous studies on uniqueness and the subjective visual comparison method typically used in forensic cases.

The need for an empirical assessment of frontal sinus outline variability was satisfied by the preceding study, which demonstrated that the Euclidean distances between EFA-generated outlines of different individuals were significantly larger than those between replicates of the same individual, and thus that each individuals' frontal sinus outline is distinctly (and quantifiably) different.

Finally, the EFA method was concluded to be a reliable method for comparing frontal sinus outlines to confirm or reject a putative identification based on the fact that posterior probabilities of a match given the correct identification were very high, with higher probabilities expected when prior odds are taken into consideration.

It is hoped that this dissertation will serve to encourage the use of EFA or similar objective method when attempting frontal sinus-based identifications, and stimulate further discussion in forensic anthropology and other forensic sciences regarding the reliability of identification methods, and perhaps encourage evaluation of the extent to which other techniques satisfy the *Daubert* guidelines.

LIST OF REFERENCES

List of References

Adams BJ. 2003. Establishing Personal Identification Based on Specific Patterns of Missing, Filled, and Unrestored Teeth. Journal of Forensic Sciences 48(3):1-10.

Adams BJ. 2002. Personal Identification Based on Patterns of Missing, Filled, and Unrestored Teeth. [dissertation]. Knoxville (TN): The University of Tennessee.

Adams BJ, Maves RC. 2002. Radiographic Identification Using the Clavicle of an Individual Missing from the Vietnam Conflict. Journal of Forensic Sciences 48(2):369-373.

American Academy of Forensic Sciences Home Page. 2003. http://www.aafs.org.

American Board of Forensic Anthropologists Home Page. 1996. http://www.csuchico.edu/anth/ABFA.

Angual M, Derczy K. 1998. Personal Identification on the Basis of Antemortem and Postmortem Radiographs. Journal of Forensic Sciences 43:1089-1093.

ArcSoft PhotoImpression. 1998. Version 3.0. Wal-Mart.com Photo Center.

Asherson N. 1965. Identification by Frontal Sinus Prints: A Forensic Medical Pilot Survey. London: H.K. Lewis & Co. Ltd.

Atkins L, Potsaid MS. 1978. Roentgenographic Identification of Human Remains. Journal of the American Medical Association 240:2307-2308.

Bacon AM. 2000. Principal components analysis of distal humeral shape in Pliocene to recent African hominids: The contribution of geometric morphometrics. Am J Phys Anthropol 111(4):479-487.

Bass WM. 1984. Is it Possible to Consume a Body Completely in a Fire? In Rathbun TA, Buikstra JE, editors. Human Identification: Case Studies in Forensic Anthropology. Springfield: Charles C. Thomas. p 159-167.

Baute P. 2000. Expert Witnessing & Daubert. The Forensic Examiner March/April:15-20.

Bayes T. 1763. An Essay Towards Solving a Problem in the Doctrine of Chances. Philosophical Transactions of the Royal Soc. of London 53:370-418.

Baylor College of Medicine. 1996. The Bobby R. Alford Department of Otorhinolarungology and Communicative Sciences. www.bcm.tmc.edu/oto/studs/nose.html.

Beggs GJ. 1995. Novel Expert Evidence In Federal Civil Rights Litigation. American University Law Review 45(1):1-76

Blanton PL, Biggs NL. 1969. Eighteen Hundred Years of Controversy: The Paranasal Sinuses. American Journal of Anatomy 124:135-148.

Bono JP. 1981. The Forensic Scientist in the Judicial System. Journal of Police Science and Administration 9:160-166.

Bookstein FL. 1982. Foundations of morphometrics. Annu Rev Ecol Syst 13:451-470.

Bookstein F, Schäfer K, Prossinger H, Seidler H, Fieder M, Stringer C, Weber G, Arsuaga JL, Slice D, Rohlf FJ, Recheis W, Mariam A, Marcu L. 1999. Comparing frontal cranial profiles in archaic and modern *Homo* by morphometric analysis. Anatomical Record (New Anatomist) 257: 217-224.

Bookstein FL, Strauss RE, Humphries JM, Chernoff B, Elder RL, Smith GR. 1982. A comment upon the uses of Fourier methods in systematics. Syst. Zool. 31:85-92.

Brogdon BG. 1998. Radiological identification of individual remains. In: Forensic radiology. Boca Raton: CRC Press. p 149-187.

Brothwell DR, Molleson T, Metreweli C. 1968. Radiological aspects of normal variation in earlier skeletons: an exploratory study. In: Brothwell DR, editor. The Skeletal biology of earlier human populations. New York: Pergamon Press. p 149-172.

Brown WAB, Molleson TI, Chinn S. 1984. Enlargement of the frontal sinus. Annals of Human Biology 11:221-226.

Buckland-Wright JC. 1970. A Radiograhic Examination of Frontal Sinuses in Early British Populations. Man 5:512-517.

Caffey J. 1993. Caffey's Pediatric X-ray Diagnosis: An Integrated Imaging Approach Vol 1. 8th ed. Silverman FN, ed. Chicago: Year Book Medical Publishers, Inc.

Caldwell EW. 1918. Skiagraphy of the accessory sinuses of the nose. American Journal of Radiology 5:569-574.

Camps FE. 1969. Radiology and its forensic application. In: Camps FE, editor. Recent Advances in Forensic Pathology. London: J. & A. Churchill. p 149-160.

Carmody TE. 1929. The development of the sinuses after birth. The Annals of Otology, Rhinology & Laryngology 38:130-134.

Cheevers LS and Ascencio R. 1977. Identification by skull superimposition. International Journal of Forensic Dentistry 13:14-16.

Christensen AM, Slice D. 2002. New Morphometric Approaches to Positive Identification from Frontal Sinuses. Proceedings of the 71st annual meeting of the American Association of Physical Anthropologists. April 9-13; Buffalo (NY).

Cornwell WS. 1956. Radiology and photography in problems of identification: a review. Medical Radiography and Photography 32:32,34.

Cryer MH. 1907. Some variations in the frontal sinuses. Journal of the American Medical Association 48:284-289.

Culbert WL, Law FL. 1927. Identification by Comparison of Roentgenograms of Nasal Accessory Sinuses and Mastoid Processes. Journal of the American Medical Association 88:1634-1636.

Currey J. 1984. The Mechanical Adaptations of Bones. Princeton: Princeton University Press.

Cwik CH. 1999. Guarding the Gate: Expert Evidence Admissibility. Litigation 25:6-12,66-67.

Daubert v. Merrell Dow Pharmaceuticals, Inc., 509 U.S. 579 (1993).

Davis WB. 1918. Anatomy of the Nasal Accessory Sinuses in Infancy and Childhood. The Annals of Otology, Rhinology & Laryngology 27:940-967.

DiMaio DJ, DiMaio VJ. 1989. In DiMaio DJ, DiMaio VJM, editors. Forensic Pathology. New York: Elsevier Saina Publishing Co. p 332-333.

Dolan KD. 1982a. Paranasal sinus radiology part 1A: Introduction and the frontal sinuses. Head & Neck Surgery 4:301-311.

Dolan KD. 1982b. Paranasal sinus radiology part 1B: The frontal sinuses. Head & Neck Surgery 4:385-400.

Donald PJ, Gluckman JL, Rice DH. 1994. The Sinuses. New York: Raven Press.

Dossel O. 2000. Bildgebende Verfahren in der Medizin: von der Technik zur medizinischen Anwendung. Berlin: Springer Verlag. Pp. 11-12.

Dutra FT. 1944. Identification of person and determination of cause of death from skeletal remains. Archives of Pathology 38:339-349.

Dwight T. 1878. The Identification of the Human Skeleton: A Medicolegal Study. Boston: Massachusetts Medical Society.

Eckert WG. 1997a. Introduction to the Forensic Sciences. In: Eckert WG, editor. Introduction to Forensic Sciences. 2nd ed. New York: CRC Press. p 1-10.

Eckert WG. 1997b. Historical Development of Forensic Sciences. In: Eckert WG, editor. Introduction to Forensic Sciences. 2nd ed. New York: CRC Press. p 11-21.

Eckert WG, Garland N. 1984. The History of the Forensic Applications in Radiology. American Journal of Forensic Medicine and Pathology 5:53-56.

Eckert WG, Wright RK. 1997. Scientific Evidence in Court. In: Eckert WG, editor. Introduction to Forensic Sciences. 2nd ed. New York: CRC Press. p 69-80.

Evans M, Hastings N, Peacock B. 1993. Statistical Distributions. 2nd ed. New York: John Wiley & Sons, Inc.

Evett IW, Weir BS. 1998. Interpreting DNA Evidence: Statistical Genetics for Forensic Scientists. Sunderland: Sinauer Associates, Inc.

Faigman D, Porter E, Saks M. 1994. Check Your Crystal Ball at the Courthouse Door, Please: The Future of Scientific Evidence. Cardozo Law Review 15:1799-1835.

Farrell WL. 1979. Forensic Identification of Burn Victims. Journal of the American Dental Association 99(1):51-56.

Fatteh AV, Mann GT. 1969. The role of radiology in forensic pathology. Medicine, Science and the Law 9:27-30.

Federal Rules of Evidence. 1975; 2000.

Ferrario VF, Sforza C, Guazzi M, Serrao G. 1996. Elliptic Fourier Analysis of mandibular shape. Journal of Craniofacial Genetics and Developmental Biology 16(4):208-217.

Ferson SF, Rohlf FJ, Koehn RK. 1985. Measuring shape variation of two-dimensional outlines. Systematic Zoology 34:59-68.

Fischman SL. 1985. The use of medical and dental radiographs in identification. Int. Dent. J. 35:301-306.

Frankel MS. 1989. Ethics and the Forensic Sciences: Professional Autonomy in the Criminal Justice System. Journal of Forensic Sciences 43:763-771.

Friess M, Baylac M. 2001. Assessing the effects of artificial cranial deformation using Elliptic Fourier Analysis. Am J Phys Anthropol Suppl 32:66.

Frye v. United States, 54 App.D.C. 46, 293 F. 1013 1923.

Gianelli P. 1993. Forensic Science, Frye & Daubert. Criminal Law Bulletin 29:428-436.

Gray H. 1901. Gray's Anatomy. London: Longmans.

Greulich WW. 1960. Skeletal Features Visible in the Roentgengrams of Hand and Wrist Which Can be Used for Establishing Individual Identification. American Journal of Roentgen. Rad. Therapy and Nuclear Medicine 83(4):756-764.

Greulich WW, Pyle SI. 1959. Radiographic Atlas of Skeletal Development of the Hand and Wrist. Palo Alto: Stanford University Press.

Gulisano M, Pacini P, Orlandini GF, Colosi G. 1987. Anatomico-radiological Findings on the Frontal Sinus: Statistical study of 520 human cases. Arch. Ital. Anat. Embriol. 83:9-32.

Haglund WD, Fligner CL. 1993. Confirmation of Human Identification Using Computerized Tomography (CT). Journal of Forensic Sciences 38:708-712.

Hajek M. 1926. Normal Anatomy of the Frontal Sinuses. In: Hajek M, Heitger JD, eds. Pathology and Treatment of the Inflammatory Diseases of the Nasal Accessory Sinuses. 5th edition. St. Louis: The C.V. Mosby Company. p 35-43.

Hanson CL, Owsley DW. 1980. Frontal Sinus Size in Eskimo Populations. American Journal of Physical Anthropology 53:251-255.

Harris AMP, Wood RE, Nortje CJ, Thomas CJ. 1987a. The Frontal Sinus: A Forensic Fingerprint?—A Pilot Study. Journal of Forensic Odonto-stomatology 5:9-15.

Harris AM , Wood RE, Nortje CJ, Thomas CJ. 1987b. Gender and Ethnic Differences of the Radiographic Image of the Frontal Region. The Journal of Forensic Odonto-stomatology 5:51-57.

Havarti K, Reddy D, Marcus L. 2002. Analysis of the posterior cranial profile morphology in Neanderthals and modern humans using geometric morphometrics. Am J Phys Anthropol Suppl 34:150.

Hennessy RJ, Stringer CB. 2002. Geometric morphometric study of the regional variation of modern human craniofacial form. Am J Phys Anthropol 117(1):37-48.

Herman R. 1990. Allowing the Jurors to Decide: Evidence Review. National Law Journal July 30:15.

Hempel CG. 1966. Philosophy of Natural Science. Englewood Cliffs: Prentice Hall.

Hodgson G. 1957. A text-book of x-ray diagnosis, Volume 1. 3rd edition. London: H.K. Lewis.

Hogge JP, Messmer JM, Fierro MF. 1995. Positive Identification by Post-Surgical Defects from Unilateral Lambdoid Synostectomy: A Case Report. Journal of Forensic Sciences 40(4):688-691.

Hogge JP, Messmer JM, Doan QN. 1993. Radiographic Identification of Unknown Human Remains and Interpreter Experience Level. Journal of Forensic Sciences 39:373-377.

Hooton EA. 1930. Indians of the Pecos Pueblo: A study of their skeletal remains. Andover: Yale University Press.

Hounsfeld GN. 1973. Computerized transverse axial scanning (tomography): Part I. Description of the system. British Journal of Radiology 46, 1016–1022.

Hunter J, Roberts C, Martin A. 1996. Studies in Crime: An Introduction to Forensic Archaeology. London: B.T. Batsford Ltd.

Hylander WL, Picq PG, Johnson KR. 1991. Masticatory stress hypotheses and the supraorbital region in primates. American Journal of Physical Anthropology 86:1-36.

Ikeda J. 1980. Interpopulation variations of the frontal sinus measurements: comparison between the Jamon and Recent Japanese population. J. Anthrop. Soc. Nippon, 90 Suppl.

Isaev M. 1995. EFAWin. Morphometrics at SUNY Stony Brook. http://life.bio.sunysb.edu/morph/.

Iscan MY. 1988. Rise of Forensic Anthropology. Yearbook of Physical Anthropology 31:203-230.

Jensen S. 1991. Identification of human remains lacking skull and teeth. A case report with some methodological considerations. American Journal of Forensic Medicine and Pathology 12(2):93-97.

Joblanski NG, Shum BS. 1989. Identification of unknown human remains by comparison of antemortem and postmortem radiographs. Forensic Science International 42:221-230.

Kade H, Meyers H, Wahlke JE. 1967. Identification of skeletonized remains by X-ray comparison. The Journal of Criminal Law 58:261-264.

Kahana T, Goldin L, Hiss J. 2002. Personal Identification Based on Radiographic Vertebral Features. American Journal of Forensic Medicine and Pathology 23(1):36-41.

Kahana T, Hiss J. 1997. Identification of human remains: forensic radiology. Journal of Clinical Forensic Medicine 4:7-15.

Kahana T, Hiss J. 1994. Positive Identification by means of trabecular bone pattern comparison. Journal of Forensic Sciences 39:1325-1330.

Kahana T, Hiss J, Smith P. 1998. Quantitative Assessment of Trabecular Bone Pattern Identification. Journal of Forensic Sciences 43(6):1144-1147.

Kahana R, Ravioli JA, Urroz CL, Hiss J. 1997. Radiographic identification of fragmentary human remains from a mass disaster. American Journal of Forensic Medicine and Pathology 18(1):40-44.

Kerley ER. 1977. Forensic Anthropology. In: Tedeschi CG, Eckert WG, Tedeschi LG, eds. Forensic Medicine Vol 2. Philidelphia: W.B. Saunders Company.

Kerley ER, Snow CC. 1979. Authentification of John F. Kennedy Autopsy Radiographs and Photographs. Final Report to the Select Committee on Assassinations, U.S. House of Representatives March 9.

Kids ENT Home Page. 2002. The ear, nose and throat site for parents. www.kids-ent/sin_pic.html.

Kirk NJ, Wood RE, Goldstein M. 2002. Skeletal Identification Using the Frontal Sinus Region: A Retrospective Study of 39 Cases. Journal of Forensic Sciences 47(2):318-323.

Koertvelyessy T. 1972. Relationships between the frontal sinus and climatic conditions: a skeletal approach to cold adaptation. American Journal of Physical Anthropology 37:161-172.

Kondrat JW. 1995. Frontal Sinus Morphology: An analysis of craniometric and environmental variables on the morphology of modern human frontal sinus patterns. [thesis]. Dekalb (IL): Northern Illinois University.

Koot MG. 2003. Radiographic Human Identification Using the Bones of the Hand: A Validation Study. Proceedings of the 55th annual meeting of the American Academy of Forensic Sciences February 17-22; Chicago.

Koppe T, Nagai H. 1999. Factors in the Development of the Paranasal Sinuses. In: Koppe T, Nagai H, Alt KW, eds. The Paranasal Sinuses of Higher Primates: development, function and evolution. Chicago: Quintessence Publishing Co, Inc. p 133-150.

Krogman WM, Iscan MY. 1986. The Human Skeleton in Forensic Medicine. 2nd ed. Springfield: C.C. Thomas.

Kuhl FP, Giardina CR. 1982. Elliptic Fourier features of a closed contour. Computer Graphics and Image Processing 18:236-258.

Kumho Tire Co., Ltd. v. Carmichael, 526 US 137 1999.

Kullman L, Eklund B, Grundin R. 1990. The Value of the Frontal Sinus in Identification of Unknown Persons. The Journal of Forensic Odonto-stomatology 8:3-10.

Lang J. 1989. Clinical anatomy of the nose, nasal cavity and paranasal sinuses. New York: Thieme.

Law FM. 1934. Roentgenograms as a means of identification. American Journal of Surgery 26:195-198.

Libersa C, Faber M. 1958. Etude Anatomo-radiologique du Sinus Frontal Chez L'enfant. Lille Med. 3:453.

Lockwood CA, Lynch JM, Kimbel WH. 2002. Quantifying temporal bone morphology of great apes and humans: an approach using geometric morphometrics. Journal of Anatomy 201(6):447-464.

Lustre AB. 2003. Post-Daubert Standards for Admissibility of Scientific and Other Expert Evidence in State Courts. American Law Reports 5th 450.

Lynch JM, Wood CG, Luboga SA. 1996. Geometric morphometrics in primatology: Craniofacial variation in Homo sapiens and Pan troglodytes. Folia Primatol 67(1):15-39.

Mahle S. 1999. The Impact of Daubert v. Merrell Dow Pharmaceuticals, Inc. on Expert Witness Testimony: With Applications to Securities Litigation. Florida Bar Journal 73:36-43.

Majmudar KB. 1993. Daubert v. Merrell Dow: A flexible approach to the admissibility of novel scientific evidence. Harvard Journal of Law & Technology 7:187-205.

Mann RW. 1998. Use of bone trabeculae to establish positive identification. Forensic Science International 98(1-2):91-99.

Marciniak R, Nizankowski C. 1959. Metopism and its correlation with the development of the frontal sinuses. Acta Radiol. 51:343-352.

Marek Z, Kusmiderski J, Lisowski Z. 1983. Radiograms of the paranasal sinuses as a principle of identifying catastrophe victims and unknown skeletons. Arch Kriminol 172(1-2):1-6.

Maresh MM. 1940. Paranasal Sinuses from Birth to Late Adolescence. American Journal of Diseases of Children 60:55-78.

Marlin DC, Clark MA, Standish SM. 1991. Identification of Human Remains by Comparison of Frontal Sinus Radiographs: A Series of Four Cases. Journal of Forensic Sciences 36:1765-1772.

Martel W, Wicks JD, Hendrix RC. 1997. The Accuracy of Radiological Identification of Humans Using Skeletal Landmarks: A Contribution to Forensic Pathology. Radiology 124:681-684

Mason JK. 1983. Radiology in Forensic Medicine. In: Mason JK, editor. Forensic Medicine for Lawyers. 2nd ed. London: Butterworths. p 285-290.

Mayer J. 1935. Identification by Sinus Prints. Virginia Medical Monthly 62:517-519.

McCormick CT. 1972. McCormick's Handbook of the Law of Evidence. 2nd ed. Cleary EW, editor. St. Paul: West Publishing Company.

McCormick WF, Stewart JH, Langford LA. 1985. Sex determination from chest plate roentgengrams. American Journal of Physical Anthropology 68:173-195.

McKeown AH. 1999. Investigating intracemetery variation at the Sully site (39SL4), South Dakota, via the "New Morphometry". Am J Phys Anthropol Suppl 32:66.

Messmer JM. 1986. Radiographic Identification. In: Fierro MF, ed. CAP Handbook for Postmortem Examination of Unidentified Remains. Skokie: College of American Pathologists. p 68-75.

Microsoft Excel. 1999. Version 9.0.2719. Microsoft Corporation.

Mitterocker P, Gunz P, Takehisa-Silvestri G, Seidler H. 2001. Human cranial growth reassessed using New Geometric Morphometrics. Am J Phys Antrhopol Suppl 32:109-110.

Montiero H, Pinto S, Ramos A, Taveres AS. 1957. Aspects morphologiques des sinus para-nasaux. Acta Anatomica 30:508-522.

Morgan TA, Harris MC. 1953. The use of X-rays as an aid to medicolegal investigations. Journal of Forensic Medicine 1:28-38.

Murphy WA, Gantner GE. 1982. Radiologic Examination of Anatomic Parts and Skeltonized Remains. Journal of Forensic Sciences 27:9-18.

Murphy WA, Spruill FG, Gantner GE. 1980. Radiologic Identification of Unknown Human Remains. Journal of Forensic Sciences 25:727-735.

Novelline RA. 1999. Squire's Fundamentals of Radiology. 5th ed. Cambridge: Harvard University Press.

O'Malley JF. 1924. Evolution of the Nasal Cavities and Sinuses in Relation to Function. Journal of Laryngology and Otology 39:57-64.

Owsley DW. 1993. Identification of the Fragmentary, Burned Remains of Two U.S. Journalists Seven Years After Their Disappearance in Guatemala Journal of Forensic Sciences 38(6):1372-1382.

Owsley DW, Mann RW. 1989. Positive identification based on radiographic examination of the leg and foot. J Am Pod Med Assoc 79(10):511-513.

Owsley DW, Mann RW, Chapman RE, Moore E, Cox WA. 1993. Positive Identification in a case of intentional extreme fragmentation. Journal of Forensic Sciences 38(4):985-996.

Page R. 1998. tpstoefa. Fourier Analysis of Outlines. http://taxonomy.zoology.gla.ac.uk/rod/docs/fourier/fourier.html.

Pais A. 1986. Inward bound: Of matter and forces in the physical world. Oxford: Clarendon Press. pp. 37–38.

Pankanti S, Prabhakar S, Jain AK. 2001. On the Individuality of Fingerprints. Proc. IEEE CVPR, Hawaii Dec. 805-812.

Penalver JJ, Kahana T, Hiss J. 1997. Prosthetic devices in positive identification of human remains. Journal of Forensic Identification 47:400-405.

Petrie WMF. 1898. Deshasheh 1897. Mem 15. London: Egyptian Exploration Fund.

Phrabhakaran N, Naidu MDK, Subramaniam K. 1999. Anatomical Variability of the Frontal Sinuses and Their Application in Forensic Identification. Clinical Anatomy 12:16-19.

Popper K. 1989. Conjectures and Refutations: The Growth of Scientific Knowledge. New York: Harper & Row.

Prossinger H, Bookstein FL. 2003. Statistical Estimators of Frontal Sinus Cross-Section Ontogeny From Very Noisy Data. Journal of Morphology 257:1-8.

Prossinger H, Bookstein F, Schäfer K, Seidler H. 2000. Reemerging stress: Supraorbital torus morphology in the mid-sagittal plane? Anatomical Record (New Anatomist) 261: 170--172.

Quatrehomme G, Fronty P, Sapanet M, Grevin G, Bailet P. 1996. Identification by frontal sinus pattern in forensic anthropology. Forensic Science International 83(2):147-153.

Quatrehomme G, Sapanet M, Bailet P, Gravin G, Boublenza A, Ollier A. 1995. Identification by Frontal Sinus: Performance and Difficulties. Proceedings of the 6th Annual Meeting of the International Association for Craniofacial Identification; Nov 8-11; Boca Raton, (FL).

R. 2003. Version 1.7.1. www.r-project.org.

Ravosa MJ, Vinyard CJ, Hylander WL. 2000. Stressed out: masticatory forces and primate circumorbital form. Anatomical Record (New Anatomist) 261:73-175.

Reichs KJ. 1993. Quantified Comparison of frontal sinus patterns by means of computed tomography. Forensic Science International 61:141-168.

Reichs KJ, Dorion RBJ. 1992. The use of computerized axial tomography (CAT) scans in the comparison of frontal sinus configurations. Canadian Society of Forensic Science Journal 25:1-16.

Rhine S, Sperry K. 1991. Radiographic Identification by Mastoid Sinus and Arterial Pattern. Journal of Forensic Sciences 36:272-279.

Ribeiro FA. 2000. Standardized measurements of radiographic films of the frontal sinuses: An aid to identifying unknown persons. Ear, Nose & Throat Journal 79:26-33.

Richtsmeier JT, Deleon VB, Lele SR. 2002. The Promise of Geometric Morphometrics. Yearbook of Physical Anthropology 45:63-91.

Riddick L, Brogdon BG, Laswell-Hoff J, Delmas B. 1983. The Accuracy of Radiologic Identification of Charred Human Remains Through Use of the Dorsal Defect of the Patella. Journal of Forensic Sciences 28(1):263-267.Robertson B, Vignaux GA. 1995. Interpreting Evidence: Evaluation Forensic Science in the Courtroom. New York: John Wiley and Sons.

Rontgen WC. 1895. Über eine neue Art von Strahlen. Sitzungsberichte der physikalisch-medizinischen Gesellschaft zu Würzburg. P 137

Rohlf FJ. 1997. tpsDig Version 1.07. Morphometrics at SUNY Stony Brook. http://life.bio.sunysb.edu/morph/.

Rohlf FJ. 1996. Introduction to Outlines. In Marcus LF, Corti M, Loy A, Naylor GJP, Slice DE, eds. Advances in Morphometrics. New York: Plenum. p 209-210.

Rohlf FJ. 1990. Fitting Curves to Outlines. In: Rohlf FJ, Bookstein FL, editors. Proceedings of the Michigan morphometrics workshop. Ann Abor: University of Michigan Museums of Zoology, Special Publication 2.

Rohlf FJ, Archie JW. 1984. A comparison of Fourier methods for the description of wing shape in mosquitoes (Diptera Culicidae). Systematic Zoology 33:302-317.

Rohlf FJ, Marcus L. 1993. A revolution in morphometrics. Trends in Ecology and Evolution 8:129-132.

Ross AH, McKeown AH, Konigsberg LW. 1999. Allocation of crania to groups via the "new morphometry." Journal of Forensic Sciences 44(3):584-587.

Rouge D, Telmon N, Arrue P, Larrouy G, Arbus L. 1993. Radiographic Identification of Human Remains Through Deformities and Anomalies of Post-Cranial Bones: A Report of Two Cases. Journal of Forensic Sciences 38(4):997-1007.

Rowe JH. 1953. Technical aids in anthropology: a historical survey. In: Kroeber AL, ed. Anthropology Today: An Encyclopedic Inventory. Chicago: University of Chicago Press. p 895-940.

Sainio P, Syrjanen SM, Komakow S. 1990. Positive identification of victims by comparison of ante-mortem and post-mortem dental radiographs. The Journal of Forensic Odonto-stomatology 8:11-16.

Sampson PD, Bookstein FL, Sheehan FH, Bolson EL. 1996. Eigenshape Analysis of Left Ventricular Outlines from Contrast Ventriculograms. In Marcus LF, Corti M, Loy A, Naylor GJP, Slice DE, eds. Advances in Morphometrics. New York: Plenum. p 209-210.

Samuel E. 1952. Clinical radiology of the ear, nose and throat. London: H.K. Lewis.

Samuel E, Lloyd GAS. 1978. Clinical Radiology of the Ear, Nose and Throat. 2nd ed. Philadelphia: W.B. Saunders Company.

Sanders I, Woesner ME, Ferguson RA, Noguchi TT. 1972. A New Application of Forensic Radiology: Identification of Deceased from a Single Clavicle.

American Journal of Roentenology, Radium Therapy and Nuclear Medicine 115(3):619-622.

SAS. 2001. SAS Institute, Inc. Cary, NC.

Sassouni V. 1959. Cephalometric identification: a proposed method of identification of war dead by means of radiographic cephalometry. Journal of Forensic Sciences 4:1-10.

Sauer NJ, Brantley RE, Barondess DA. 1988. The Effects of Aging on the Comparability of Antemortem and Postmortem Radiographs. Journal of Forensic Sciences 33(5):1223-1230.

Schaeffer JP. 1916a. The Genesis, Development and Adult Anatomy of the Nasofronal Region in Man. American Journal of Anatomy 2:125-145.

Schaeffer JP. 1916b. Further Observation of the Anatomy of the Sinus Frontalis in Man. Annals of Surgery Dec:665-671.

Schaeffer JP. 1915. The embryology and anatomy of the nasofrontal region in man. Antomical Record 10:238-241.

Schmidt G, Kallieris D. 1982. Use of Radiographs in the Forensic Autopsy. Forensic Science International 19:263-270.

Schuller A. 1943. A note on the identification of skulls by X-ray pictures of the frontal sinuses. Medical Journal of Australia 1:554-557.

Schuller A. 1921. Das Rontgenogram der Stirnhohle: ein Hilfsmittel fur die Identitatsbestimmung von Schadeln. Monatsschrift feur Ohrenheilkunde und Laryngo-Rhinologie 5:1617-1620.

Shapiro R, Schorr S. 1980. A Consideration of the Systematic Factors that Influence Sinus Pneumatization. Investigative Radiology 15:191-202.

Shapiro R, Janzen AH. 1960. The Normal Skull: A Roentgen Study. New York: Paul B. Hoeber, Inc.

Singleton AC. 1951. The roentgenological identification of victims of the “Noronic” disaster. American Journal of Roentg. 66:375-384.

Sivaloganathan S, Butt WP. 1988. A foot in the yard. Medicine, Science and the Law 28(2):150-156.

Smith DR, Limbird KG, Hoffman JM. 2002. Identification of Human Skeletal Remains by Comparison of Body Details of the Cranium Using Computerized Tomographic (CT) Scans. Journal of Forensic Sciences 47:937-939.

Sopher IM. 1972. The Dentist, the Forensic Pathologist, and the Identification of Human Remains. Journal of the American Dental Association 85(6):1324-1329.

Spoor F, Jeffery N, Zonneveld F. 2001. Imaging Skeletal Growth and Evolution. In: O’Higgins P and Cohn MJ, editors. Development, Growth and Evolution. San Diego: Academic Press. p 123-161.

Stevens PJ. 1966. Identification of a body by unusual means. Medicine, Science and the Law 6:160-161.

Stewart TD. 1979. Essentials of Forensic Anthropology. Springfiled: Thomas.

Strek P, Kaczanowski K, Skawina A, Pitynski K, Kitlinski Z, Mrowka D, Naklicka B. 1992. The morphological evaluation of frontal sinuses in Human Skulls. Folia Morphol. (Warsz.) 51:319-328.

Sudimack JR, Lewis BJ, Rich J, Dean DE, Fardal PM. 2002. Identification of Decomposed Human Remains from Radiographic Comparisons of an Unusual Foot Deformity. Journal of Forensic Sciences 47(1):218-220.

Szilvassy J. 1973. Stirhohlenvariatoinen in Ostosterreich (Wein, Nienderosterreich und Bergenland). Mitt Anthrop Ges Wein 102:48-59.

Tanaka H, Lestrel PE, Uetake T, Kato S, Ohtsuki F. 2000. Sex differences in proximal humeral outline shape: Elliptical Fourier functions. Journal of Forensic Sciences 45(2):292-302.

Terracol J, Guerrier Y. 1958. Les Sinusites de l'enfance. Paris: Libraires de l'Academie de Medecine.

Thomas F. 1974. Milestones in Forensic Science. Journal of Forensic Sciences 19:241-254.

Thompson WC, Schumann EL. 1987. Interpretation of statistical evidence in criminal trials: The prosecutor's fallacy and the defense attorney's fallacy. Law and Human Behavior 11:167-187.

Thorne H, Thyberg H. 1953. Identification of children (or adults) by mass miniature radiography of the cranium. Acta Odontol. Scandinavica 11(2):129-140.

Torgersen J. 1950. A roentgenological study of the metopic suture. Acta Radiol. 33:1.

Travis WJ. 1974. Impartial Testimony Under the Federal Rules of Evidence: A French Perspective. International Lawyer 8:492-522.

Turner AL. 1902. The Accessory Sinuses of the Nose. New York: Longmans, Green & Co.

Turner AL, Porter WG. 1922. The structural type of mastoid process, based upon the skiagraphic examination of one thousand crania of various races of mankind. J. Laryng. Otol. 37:115-121,161-175.

Ubelaker DH. 1990. Positive Identification of American Indian Skeletal Remains from Radiographic Comparison. Journal of Forensic Sciences 35(2):466-472.

Ubelaker DH. 1984. Positive Identification from the Radiographic Comparison of Frontal Sinus Patterns. In: Rathbun TA, Buikstra J, eds. Human Identification: Case Studies in Forensic Anthropology. Springfield: Charles C. Thomas. p 399-411.

United States of America v. Carlos Ivan Lleva Plaza, Wilfredo Martinez Acosta, and Victor Rodriguez Cr. No. 98-362-10, 11, 12 2002.

University of Calgary Medical Clinic. 2000. Otolaryngology- Head and Neck Surgery. www.skullbase.ca/postop_nose.htm.

University of Tennessee Forensic Anthropology Center 2003. Forensic Case Archives. Knoxville, TN.

Valenzuela A. 1997. Radiographic comparison of the lumbar spine for positive identification of human remains. A case report. American Journal of Forensic Medicine and Pathology 18(2):215-217.

Van Alyea OE. 1951. Nasal sinuses: an anatomic and clinical consideration. 2nd ed. Baltimore: The Williams & Walkins Company.

Varga M, Takacs P. 1991. Radiographic personal identification with characteristic feature in the hip joint. American Journal of Forensic Medicine and Pathology 12:328-331.

Walander A. 1965. Consideration of variation of size of frontal sinuses. Acta Otol Laryngol 60:15-22.

Weinert H. 1925. Die Ausbildung de Stirnhohlen als Stammesgeschichtliches Merkmal. Z. Morphol Anthropol. 25:243-359,365-418.

Wentworth B, Wilder HH. 1932. Personal Identification: Methods for the Identification of Individuals, Living or Dead. Chicago: T.G. Cooke.

Witmer LM. 1999. The phylogenetic history of paranasal air sinuses. In: Koppe T, Nagai H, Alt KW, eds. The Paranasal Sinuses of Higher Primates: development, function and evolution. Chicago: Quintessence Publishing Co, Inc. p 21-34.

Wolfowitz BL. 1974. Pneumatization of the skull of the Southern African Negro. [dissertation]. Johannesburg: University of Witwatersrand.

Yoshino M, Miyasaka S, Sato H, Seta S. 1987. Classification system of frontal sinus patterns by radiography: Its application to identification of unknown skeletal remains. Forensic Science International 34:289-299.

Zollikofer CPE. 2002. A computation approach to paleoanthropology. Evolutionary Anthropology 11:64-67 Suppl 1.

Zonnefeld FW. 1987. Computed tomography of the temporal bone and orbit: Technique of multiplanar, high-resolution CT and correlative cryosectional anatomy. Munich: Urban & Schwarzenberg.

Zuckerkandl E. 1895. Anatomie des sinus frontaux. In: Anatomie Normale et Pathologique des Fosses Nasales et de Leurs Annexes Pneumatiques. Paris: G. Masson. p 349-361.

APPENDIX A

Appendix A consists of an outside folder called “outlines”, containing the *.jpg images of all of the original outlines used for this study. There are five folders within the “outlines” folder, each containing individual files of outlines (including duplicates if applicable) sampled from the W.M. Bass Donated Skeletal Collection (“UT Donated”), the University of Tennessee Forensic Skeletal Collection (“UT Forensic”), the Arikara Collection (“UT Arikara”), and the University of Tennessee Student Health Center (“UT Student”), as well as the outlines used for the test of orientation (“Angles”).

Vita

Angi M. Christensen was born on January 9, 1975 at McChord Air Force Base in Washington State. She attended elementary through high school in East Wenatchee, Washington, graduating from Eastmont High School in 1993. She enrolled at the University of Washington, Seattle, in the fall of 1993 in pursuit of a degree in Civil Engineering before discovering her interest in anthropology as a result of an elective course taken in physical anthropology. After changing majors, she received a Bachelor of Arts in Anthropology in 1997. She came to the University of Tennessee in the fall of 1998 to pursue a graduate degree in Anthropology with an emphasis on forensic anthropology, receiving a Master of Arts in the spring of 2000, and a Doctor of Philosophy in the summer of 2003. She has hopes of a career in death investigation in either a medicolegal or law enforcement setting.