GETTING INTO SHAPE:

A Comparison of Three Methods used to Characterize Personal Uniqueness of the Frontal Sinuses using Computed Tomography (CT) Data

by

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Abstract

Identification of unknown individuals is important in forensic cases to notify next of kin and to execute legal matters. Several areas in the skeleton have been proposed to aid in identification, including the frontal sinuses. The frontal sinuses have long been considered unique to each individual because of the high degree of observed morphological variation. Due to their location inside the skull, between the inner and outer tables of the frontal bone (Nambiar et al., 1999), visualisation of the frontal sinuses is achieved through radiographic imaging, typically X-Ray or computed tomography (CT).

Visual comparison and superimposition of an antemortem image over a postmortem image to identify a match is the most basic method for identifying if two frontal sinuses come from the same individual. This simple approach has given way to several methods that attempt to quantify observed morphological variation in the frontal sinuses. These methods can broadly be grouped into three categories: measurement, coding and outline methods. Recently, owing to the *Daubert* ruling, an increased emphasis has been placed on quantification and testing to develop accurate and replicable methods within forensic anthropology. In line with this ruling, it is crucial to test and validate all personal identification methods on independent samples.

This dissertation compares three methods for quantifying the personal uniqueness present in the frontal sinuses on an independent sample. The three methods tested here are a measurement method (Ribeiro, 2000), a coding method (Reichs and Dorion, 1992) and an outline method (Cox et al., 2009). The sample used in this study is a postmortem CT collection of 130 individuals from the University of Copenhagen. The protocols are described, including the adaptations made to the Ribeiro (2000) and Cox et al. (2009) methods which were originally designed to be used with X-ray image data rather than CT data. All methods were repeated using all individuals to identify intraobserver error. The three methodologies are evaluated and compared for their abilities to characterize individuality and produce unique matches in this sample. The results show that the weakest method is the coding system, while the strongest are the outline and measurement techniques. The aspects of frontal sinus morphology that made matching difficult will be discussed and recommendations for forensic anthropologists to increase standardization are made. Future directions, including the potential application of three dimensional renderings of the frontal sinuses for morphological comparison, are considered.

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Dedication

To my Lucy and all the girls who constantly ask "why?" this dissertation is dedicated to you.

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Chapter 1 Introduction

Forensic anthropology is the practical application of skeletal biology to address questions of medicolegal importance. The traditional focus is on personal identification (Steadman, 2013). Identification of decedents is crucial for a several reasons. Legally it is necessary for the completion of official documents such as death certificates, to probate wills and to settle estates (Kahana and Hiss, 1997). In addition, since many victims of crime know the perpetrator, the identification of the victim can be crucial to solving the crime. The FBI estimates that approximately 86% of victims know their killers (Haglund, 1993); to identify the victim is to identify the perpetrator. Moreover, the solution to homicide cases where the decedent is unidentified is relatively rare (Haglund, 1993) due to *corpus delicti* (Brogdon, 2012), or the requirement that that the prosecution must prove the crime charged has been committed (Gardner and Anderson, 2012). Identification becomes of paramount importance for legal proceedings and prosecution. Determining the identity of unknown human remains also permits notification of next-of-kin and enables family members to start the grieving process. Most human remains can be identified visually or with the aid of fingerprints or DNA (McCartney, 2006), while a small proportion of cases require other methods to attribute identity. It is the medical examiner or coroner who is responsible for declaring identification and issuing the death certificate. However, there are instances when the remains do not permit the use of these methods to establish identity. Skeletonised, burnt, mutilated, or decomposed remains present a challenge for identification and it is often at this point that the expertise of a forensic anthropologist is called upon.

In analysing human remains, forensic anthropologists construct an "osteobiography" providing data on age, sex, ancestry and stature. Although this information is helpful, alone it does not provide an identity for the remains and is limited to comparison with individuals who have been reported missing. To identify unidentified remains, forensic anthropologists must turn to known unique features of the skeleton. Since decomposition and completeness of the skeleton affect the number of skeletal elements recovered there must exist flexibility in techniques and features employable. Currently accepted forms of scientific identification include fingerprints, dental comparison and DNA analysis (Brogdon, 2012); however there are many instances when the remains or facilities available do not permit the use of these types of identification methods. There are many other anatomical features of the skeleton which have been used to base identification, and among these, the frontal sinuses, located in the forehead region of the skull between the inner and outer tables of bone, have been used extensively because they are stable over time, easily visible on radiographic images and accepted as unique to each individual (Nambiar et al., 1999). Although the unique morphology of the frontal sinuses has been employed in forensic anthropology since 1926 (Culbert and Law 1927), forensic anthropology is facing a critical point where the techniques and methods employed must meet guidelines established by various courts governing the admissibility of expert witness testimony (i.e. *R. v. Mohan, Daubert v. Merrell-Dow Pharmaceuticals, Inc*).

In North America several major courtroom decisions have had an impact on the admissibility of expert witness testimony. The critical Canadian case for admissibility of expert evidence is the case of *R. v. Mohan.* The *Mohan* ruling considers four factors: relevance, necessity in assisting the trier of fact, absence of any exclusionary rule, and the proper qualification of the expert (Glancy and Bradford, 2007:351). The *Mohan* findings emphasize the necessity of expert opinions, but indicate that testimony "... should be excluded if the potential for prejudice substantially outweighs the probative value, an important concern later reaffirmed in *R. v. B.M"*. (Glancy and Bradford, 2007:351). It is important to acknowledge the influence of the United States, which is particularly noticeable with regards to legal rulings. Skinner and Bowie (2009:88) remind us that "To discuss forensic anthropology as solely Canadian is parochial". The *Daubert* principles for acceptance of novel science are the primary decision affecting Canada (Glancy and Bradford, 2007). Rogers and Allard (2004) comment that Canadian law courts are finding *Daubert* increasingly important when deciding on admissibility of expert witness testimony. In American courts the *Frye* ruling, Federal Rules of Evidence 702, *Daubert* ruling, *General Electric Co. v. Joiner* and *Kumho Tire Co. v. Carmichael* are all key decisions; the last three form a trilogy of Supreme Court decisions (Christensen and Crowder, 2009). The most often cited are the *Daubert* guidelines, which are four principles stipulating that scientific methods should be empirically tested, subject to peer review, have known or potential error rates and have general acceptance by the relevant scientific community. The last clause incorporates the older *Frye* ruling.

The implication of these legal rulings is that forensic anthropologists are placing new emphasis on validation studies and standardisation of protocols with mathematical statements of certainty. Watamaniuk and Rogers (2010) note that *ad hoc* approaches are scientifically limited, generating little data to aid in application to future cases and lacking standardisation and validation which makes them dismissible under *Mohan* and *Daubert* rulings. Forensic anthropological methods must be conceived and tested within the rigors of evidentiary requirements to produce findings which fit within the stipulated requirements. While legal admissibility rules do not dictate how science is performed, the *Daubert* ruling and others have led to a realisation that scientific rigor may be lacking (Christensen and Crowder, 2009). In response to the demand for increased scientific rigor, forensic anthropologists have answered with a critical evaluation of their approaches and a call for increased standardised practice (i.e. Scientific Working Group for Forensic Anthropology, or SWGANTH and United States National Institute of Standards and Technology (NIST) formation of the Organization of Scientific Area Committees, or OSAC in Anthropology). In line with these changes, Christensen and Crowder (2009) and Christensen and Anderson (2013) advocate that as professionals and good scientists forensic anthropologists need to ensure that their methods are valid, transparent, and reliable. Steadman (2013:138) believes "One of the most important ramifications of the recent changes in the rules of evidence is greater attention to the scientific merit of traditional anthropological methods". A search by the author of the Daubert Tracker (www.dauberttracker.com), a database which tracks challenges to expert witness testimony under US federal and state gatekeeping authorities (including *Daubert, Frye, Joiner* and *Kumho*) reveals a temporal trend showing increasing challenges over time to anthropological testimony. Christensen and Crowder (2009) and Steadman (2013) believe that it is imperative to minimize the risk of error through quality assurance, including method validation, to establish method transparency and quantify method performance with measures of accuracy and reliability, which will provide a secure foundation for forensic anthropologists in the courtroom. When providing testimony, forensic anthropologists are under an ethical obligation; the strength of conclusions should not be overstated and limitations of the selected technique(s) should be considered and presented appropriately (Christensen and Anderson, 2013).

The frontal sinuses have been used extensively in forensic cases to determine personal identity. The most basic method is superimposition or side by side comparison to assess similarity. This involves the comparison of two radiographic images (typically X-ray images) to visualise the frontal sinuses since they are found inside the skull. The sinuses are evaluated by the observer for similarities or differences in overall structure and specific features including intersinus septa, loculations and location of sinuses. This technique is considered qualitative, although very effective. To be consistent with legal requirements recommending increased scientific rigor in forensic anthropology many methods have been published setting out quantitative ways of comparing two frontal sinuses to determine if they are from the same individual. These frontal sinus methods can broadly be grouped into three categories: measurement (Kirk et al., 2002; Ribeiro, 2000; Riepert et al., 2001; Harris et al., 1987), coding systems (Yoshino et al., 1987; Reichs and Dorion, 1992; Cameriere et al., 2005; Tatlisumak et al., 2007; Tang et al., 2009; Ubelaker, 1984) and outline (Cox et al., 2009; Christensen, 2005) methods. Considering the plethora of methods and in light of recent emphasis on scientific rigor imposed by the *Daubert* guidelines and other court rulings, it is important to assess the different morphological variations of the frontal sinuses in light of different methodological types. Conducting a study on a single sample allows for methodological strengths and weaknesses to be determined. With this in mind this dissertation project was formulated to compare three methods (Ribeiro, 2000; Reichs and Dorion, 1992; Cox et al., 2009) of quantifying the personal identification using frontal sinus morphology on a single sample.

1.1 Goals and objectives of this research

General goals of this study are twofold: to enhance standardisation within the field of forensic anthropology and to assess previously published research on the uniqueness of the frontal sinus morphology. As forensic anthropologists have entered a new era in the history of the discipline a noticeable change occurs as attention shifts from purely method generation to a focus on validation and quantification of existing methods. Ross and Kimmerle (2009:480) point out that "Much of the driving force behind the push for quantitative methods and research driven methodology stems from challenges to DNA and fingerprint evidence." In the case of the frontal sinuses, many published methods seek to quantify their unique morphology. In fact, there are currently 12 published methods on frontal sinus quantification for personal identification. All these methods are not created equal; they consider different aspects of morphology, some involve measurement, others combine this with feature scoring, while the latest methods assess frontal sinus outlines. In order to increase standardisation within forensic anthropology it is imperative to understand what our methods are capturing (or not capturing), potential sources of error and morphological variants in the frontal sinus which are problematic. This study will evaluate the factors contributing to and limiting positive identification using frontal sinus comparisons. The application of three different methods on the same sample provides a unique opportunity to compare these techniques on a common data set. This permits comments to be made about each method's performance and lead to recommendations which will in turn increase standardisation within the field. These aspects are important not only to respond to demands for increased scientific rigor in the forensic sciences for legal requirements but also as Tang et al. (2009:104e2) point out "If parameters of the frontal sinus and their classification were standardized, data of the frontal sinus could be stored as a database, and could be exchanged between different laboratories, and the frontal sinus patterns could be compared".

The frontal sinuses are considered an acceptable structure by forensic anthropologists on which to conclude personal identity and have been used for almost 90 years to do just this (Cox et al, 2009). This study will add to this body of research by increasing our understanding of the variation seen in the frontal sinuses and corroborate previous studies demonstrating the uniqueness of this structure between individuals and upon which to base personal identification.

The specific research objectives for this study are to test three types of methods previously proposed (Ribeiro, 2000; Reichs and Dorion, 1992; Cox et al., 2009) to capture and quantify the uniqueness of the frontal sinuses for the purposes of personal identification. Analysis will focus on the strengths and weaknesses of each method to provide information on method performance and recommendations for forensic anthropological standards of practice. More specifically, each method will be assessed for intraobserver error, its ability to produce unique scores and make unique matches, and accuracy and precision. The outcome of this dissertation project will be the quantification of method performance and objective assessment of their relative accuracy and reliability on a single sample. By testing each of a measurement, coding and outline methods, this research will provide answers on which of the existing method(s) is/are the best, information that contributes to the development and improvement of best practices within forensic anthropology. The research sample is composed of Computed Tomography (CT) data scans. Since two of the tested methods utilise traditional plane film, or X-ray, images as their data sets (Ribeiro, 2000; Cox et al., 2009), protocols will be created and described here to adapt these methods to CT scan data. The development of these additional protocols will provide greater flexibility by being able to utilise different image modalities for the application of frontal sinus methods.

1.2 Thesis organisation

This dissertation is organised into chapters. Chapter two presents background information on forensic anthropological assessment of personal identification including a detailed discussion of approaches using the morphological variation of the frontal sinuses. It also represents an overview of the relevant North American legal rulings affecting expert witness testimony. Chapter three details the materials and methods utilised in this study. Each of the three methods, including protocol adaptations to make the method usable on CT data, is described. Chapter four presents the results of this research. A discussion of the results, including method replication, intraobserver error, ability to individualise, and problematic cases is presented in Chapter five. Finally, Chapter six provides a summary and conclusions, including future directions of this research.

Identification of deceased individuals is crucial and forensic anthropologists, with our unique knowledge of the skeleton and its features, are in a unique position to be able to assist in providing this information for skeletonised, burnt, or incomplete human remains. Forensic anthropology as a discipline is rapidly evolving and current research interests promote standardisation and accreditation within the field. The current research study will add to our knowledge by identifying factors that both contribute to and limit positive identification employing frontal sinus comparisons. It will also corroborate the uniqueness of the frontal sinuses between individuals and verify their value for determining personal identity.

Chapter 2 Background

This chapter will begin with a discussion of some theoretical underpinnings surrounding personal identification and the current legal demands placed on forensic anthropologists. These requirements emphasize scientific rigor and repeatability for methods used by expert witnesses, something which the relatively new discipline of forensic anthropology lacks. This chapter takes a North American perspective and will include a discussion of the legal requirements in both Canada and the United States. A brief survey of the methods used in the field to aid in identification will be presented. This chapter will conclude with a more in-depth look at methods used to determine identification based on the morphology of the frontal sinuses.

In the course of studying human variation, anthropologists have identified methods to acquire biological information from skeletal remains. An "osteobiography" provides age, sex, ancestry and stature. These variables can then be compared with missing persons information, but this method is obviously limited to those individuals that have been reported missing. Osteobiographical information alone does not provide identity for the decedent, which is the focus of a forensic investigation.

Identification is typically categorised into one of three categories: tentative, circumstantial, and positive (Christensen and Anderson, 2013), the last being the ultimate goal. Tentative identification indicates that the identity of the decedent is suspected based on circumstances or associated materials, such as a wallet or driver's license. This designation is typically given to bodies entering the medicolegal system prior to establishing more substantial levels of identification. Circumstantial identification, also known as presumptive, possible, probable or putative identification (Christensen and Anderson, 2013), meets a higher standard than tentative, but a lesser standard than positive (Komar and Buikstra, 2008). With presumptive identification, circumstances or general characteristics provide investigators with a basis for identification and there is no exclusionary evidence. A death certificate may be issued based on a presumptive identification if it is satisfactory (Komar and Buikstra, 2008). Positive identification, also known as personal, biological or scientific identification (Christensen and Anderson, 2013) indicates that individualisation has been successfully demonstrated (Komar and Buikstra, 2008). Individualisation is based on features or characteristics that make each person unique – fingerprints, nuclear DNA, medical and dental history; a direct comparison of antemortem and postmortem data results in the conclusive demonstration of identity (Komar and Buikstra, 2008). Christensen and Anderson (2013) note that identification by exclusion may be used in mass fatality situations with a "closed" population, defined by having a list of occupants (e.g. a plane crash where the passenger manifest is available), when all other individuals have been identified.

Identification relies on matching known, antemortem information with unknown, postmortem observations and can be carried out in a number of ways depending on the state of preservation, skeletal elements recovered, the form of antemortem data and available time, money and equipment. The theoretical principle behind personal identification in forensic anthropology is based on knowing how rare a series of identifying features are in relation to the identification universe – the source from which the match will be made, usually the missing persons list (Skinner, 1988). Rogers and Allard (2004) state in practice such data are not yet available.

2.1 Forensic Anthropology: A North American context

The current situation in North American forensic anthropology shows a heavy American bias. In part this is explained by a lower Canadian population with historically lower crime rates and frequency of gunshot wounds, which has resulted in a demand for forensic anthropologists that is fundamentally less than that in the United States (Skinner and Bowie, 2009). In addition, there is a paucity of training programs (particularly at the graduate level) and funding in Canada for forensic anthropology (Skinner et al., 2010; Gruspier and Rogers, 2012). Almost exclusively forensic anthropologists in Canada are fee-for-service consultants working for coroners, medical examiners, pathologists and police; there is only one full-time salaried forensic anthropology position in a medicolegal laboratory in the entire country (Gruspier and Rogers, 2012:24).

In Canada there is no national professional body for forensic anthropologists and no guiding principles for professional standards (Gruspier and Rogers, 2012:23). Given this situation, many Canadian forensic anthropologists adhere to protocols published by SWGANTH in the United States, since there is no accreditation process or professional certification for Canadian forensic anthropologists (Gruspier and Rogers, 2012). Professional certification in North America is granted through the American Board of Forensic Anthropology (ABFA); Gruspier and Rogers (2012) report that there is one practicing forensic anthropologist in Canada with Diplomate status, although two practitioners in Canada are currently listed on the ABFA website (www.theabfa.org/diplomates. html). Christensen and Crowder (2009:1211) note that the American Board of Forensic Anthropology (ABFA) exists to examine and certify forensic anthropologists and set standards for their individual proficiency; this organization does not provide protocols to ensure consistency and reliability in the application of forensic anthropological methods. In January 2008 the first meeting of the Scientific Working Group for

Forensic Anthropology, or SWGANTH was held. This was established with co-sponsorship by Central Identification Laboratory and the Federal Bureau of Investigation. The purpose of SWGANTH is "... to develop consensus guidelines for forensic anthropology and to disseminate these guidelines as well as other relevant studies and findings to the forensic community" (Christensen and Crowder, 2009:1215). Christensen and Crowder (2009:1215) conclude "The guidelines are intended to be specific enough to ensure quality and consistency of practice, yet broad enough to be applicable across various jurisdictional types and laboratory settings, as well as be internationally relevant". Several topics have been identified for the development of standardisation, including but not limited to: qualifications and training, ethics, statistical methods, aspects of the biological profile, documentation and reporting. Currently, SWGANTH is comprised of 15 committees tasked with establishing best practice guidelines on a variety of topics. Steadman (2013:139) notes this is the first time that forensic anthropologists have protocols for their practice that can be referenced in court; she goes on to suggest that there is still a lack of fundamental understanding of the probative strength of different types of anthropological evidence for identification.

In addition to SWGANTH, the United States National Institute of Standards and Technology (NIST) formed the Organization of Scientific Area Committees (OSAC) and established 23 forensic science subcommittees. The subcommittee on Anthropology was established in October 2014 and focuses on standards and guidelines related to application of anthropological methods and theory – particularly those relating to the recovery and analysis of human remains – to resolve legal matters (www.nist.gov). The establishment of these committees illustrates that forensic anthropologists are currently concerned with addressing standardisation and protocols. Due to the present paucity of any Canadian counterparts, these working groups, although in the United States, represent current disciplinary and professional concerns for all North American forensic anthropologists.

This work chooses to take a North American perspective since this is relevant to the current disciplinary practice. With a larger cohort of practicing forensic anthropologists, dedicated training programs, several major legal rulings governing expert witness testimony, professional accreditation, organisations and working groups, forensic anthropologists in the United States exercises a direct influence on their Canadian counterparts, who are actively engaged in American-based publications, associations and training.

2.2 Forensic Anthropology in the Courtroom

Recent courtroom rulings in Canada and the United States outline standards for methods presented by expert witnesses in courtrooms. This section will begin by covering Canadian court rulings and then discuss American court rulings including the *Daubert* guidelines. Glancy and Bradford (2007) observe that recent decisions in Canadian law show the significant influence of American rulings. Christensen and Crowder (2009:1211) note that "Disciplines like forensic anthropology may be problematic in the eyes of the courts since they employ a combination of traditional scientific methodologies and less rigorous observational methodologies coupled with case study evaluations or casework experience". They report (in 2009) that currently there are no professionally agreed upon standards regarding the application of forensic anthropological methods, which leaves the individual or forensic institution responsible for developing their own guidelines and standards.

2.2.1 Forensic Anthropology in the Canadian Courtroom

In Canada the critical case for admissibility of expert evidence is the case of *R. v. Mohan.* In this case the judge ruled that the expert witness testimony evidence of a psychiatrist was not admissible because it did not fall within the proper sphere of expert evidence and went beyond the evidence of general reputation. The Ontario Court of Appeal (*R. v. Mohan*) found that the trial judge had based his decision on the sufficiency of the evidence, rather than its admissibility; they believed the trial judge had misapprehended the opinion of the witness. The Supreme Court has ruled that the admissibility of expert evidence is governed by four factors: relevance, necessity in assisting the trier of fact, absence of any exclusionary rule, and the proper qualification of the expert (Glancy and Bradford, 2007:351). However, the Court noted that the trial judge should determine this threshold requirement since it is a question of law. The *Mohan* findings emphasise the necessity of expert opinions, but indicates that testimony should be excluded if the potential for prejudice substantially outweighs the probative value, an important concern later reaffirmed in *R. v. B.M* (Glancy and Bradford, 2007:351). Glancy and Bradford (2007: 351) state "The Court went on to note that the influence of the testimony over the trier of fact may be out of proportion to its reliability ... [and]... expert evidence should not be admitted where there is a danger that it will be misused or will distort the fact-finding process." Expert evidence needs to be outside the experience and knowledge of the judge and jury to be considered necessary; evidence that advances a novel scientific theory or technique is subject to particular scrutiny to determine whether it satisfies the best basic threshold of reliability (Glancy and Bradford, 2007).

The *Mohan* ruling was tested in the case of *R. v. J. (J.-L.)*. In this case Justice Binnie allowed that the defense expert's evidence met the threshold requirement because the subject matter of the inquiry is beyond the knowledge of an ordinary person. The judge noted that the *Mohan* ruling admitted novel science but rejected the general acceptance theory of *Frye*. He went a step further and seemed to accept the reliable-foundation test laid down in the American *Daubert* ruling. Justice Binnie noted that while *Daubert* must be read in the light of the specific text of the U.S. Federal Rules of Evidence which are different in some ways from Canadian procedures, it is reasonable to rely on the *Daubert* criteria in evaluating the soundness of novel science (Glancy and Bradford, 2007:353). Glancy and Bradford (2007) note that it appears Canadian law now recognizes the *Daubert* principles for acceptance of novel science and Rogers and Allard (2004) comment that both the American and Canadian legal systems are finding *Daubert* increasingly valuable when deciding on admissibility of expert witness testimony.

2.2.2 Forensic Anthropology in the American Courtroom

In America several major court decisions have an impact on the admissibility of expert witness testimony. The first ruling was issued in *Frye v. United States,* where the Court gave an opinion on the admissibility standard for scientific expert witness testimony (Christensen, 2004a). This basic standard enunciated by the U.S. Circuit Court of Appeals in 1929 placed emphasis on general acceptance of new technical evidence by the appropriate scientific community (Gaensslen et al. 2008). The *Frye* ruling states that scientific expert testimony is considered admissible if the technique is ‘‘generally accepted’’ as reliable by the relevant scientific community (Grivas and Komar, 2008). Gaensslen et al. (2008) caution that although this sounds straightforward it can be difficult to decide which scientific community a test belongs to as multiple disciplines can use the same methods or techniques. The “*Frye* Rule” of general acceptance became the principal standard for determining admissibility of scientific evidence in the majority of courts. Christensen (2004a:427) notes this domination "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".

"Over time and with advancements in science, many courts and legal commentators began to modify or ignore the *Frye* standard prompting the eventual enactment of the Federal Rules of Evidence (FRE) in 1975, which was the first uniform set of evidentiary rules for the trial of civil and criminal cases in federal courts" (Christensen, 2004b:1211). Congress adopted the FRE in an attempt to clarify the trial process and formally standardize the federal judicial system, but made no mention of the *Frye* test (Grivas and Komar, 2008). Strictly speaking these rules only apply to federal courts for federal cases, and the individual states do not necessarily have to adopt the federal rules, although many have (Gaensslen et al., 2008). These rules emphasise the dual test of relevance and reliability as the appropriate standard for admissibility (Christensen, 2004a) and defined when scientific expert testimony is appropriate and who qualifies as an expert (Grivas and Komar, 2008). However, "The adoption of the Federal Rules of Evidence did not remove the confusion in the courts concerning the admissibility of scientific evidence" (Christensen, 2004a:472) because the text did not include the *Frye* ruling and the legislative history made no mention of *Frye* or the general acceptance standard. This resulted in the mixed use of *Frye*, the Federal Rules of Evidence or some hybrid of the two. The confusion is probably in part due to uncertainty regarding what exactly constituted a proper test for reliability and relevance (Gaesslen et al. 2008). Grivas and Komar (2008) contend that the lack of an official standard resulted in inconsistencies, ironically that the FRE was adopted to correct, and led to the admission of questionable scientific testimony, or ''junk science'', which may have needlessly confused, misled, and overwhelmed both judges and juries.

Confusion continued for almost 20 years until the United States Supreme Court ruled in the *Daubert v. Merrell-Dow Pharmaceuticals, Inc* case. In this decision the Supreme Court addressed the question of the *Frye* general acceptance test survived the passing of the Federal Rules of Evidence. They concluded that the Federal Rules of Evidence superseded *Frye* and therefore should govern admissibility, stipulating that a "rigid and absolute general acceptance test" should not be the standard so as to admit into evidence reasonable minority opinion, usually in the form of new and emerging research based on reliable, well-designed studies (Christensen, 2004a:473). The Court deemed that the language of Rule 702 set forth standards for the admissibility of scientific evidence regarding reliability and relevance. Reliability requires "scientific knowledge" be situated in the methods and procedures of science and should be more than subjective belief or speculation, while relevance necessitates that the information assist the fact-finder in reaching a conclusion in the case, i.e., that there is a valid scientific connection to the pertinent inquiry (Christensen, 2004a). Further principles were identified and collectively these standards are often referred to as the "*Daubert* guidelines".

Christensen (2004a) explains these guidelines. The first principle deals with whether the content of the testimony can be (and has been) empirically tested using the scientific method. This is based on Popper's (1989) conjectures that the scientific nature of a theory lies in its falsifiability, or refutability, or testability and Hempel's (1966) belief that statements composing a scientific explanation must be able to be empirically tested (Moenssens, 2009). The second guideline stipulates that the technique should be subject to peer review, preferably as a publication in peer-reviewed literature. Although publication is not required for testimony to be admissible and does not ensure absolute reliability, the review process can be considered to increase the likelihood that the scientific community will identify errors or flaws in the method or its application (Christensen, 2004a). The third guideline deals with applicable professional standards and known or potential error rates for the method. Such standards primarily refer to protocols that ensure reliability and consistency in methodological application. Finally, the Court must also consider general acceptance by ascertaining the appropriate scientific community and assessing the degree of agreement within that community (Christensen, 2004a).

Christensen and Crowder (2009:1212) state "It is important to understand that the *Daubert* decision instructs the judge to focus on principles and methods and not the conclusions that they generate." Under *Daubert* the judge is labelled the "gatekeeper", responsible for applying these rules (Gaensslen et al. 2008) and in charge of making sure evidence has a direct fit to the issues of the trial, while also responsible for keeping "junk science" out of the courtroom (Faigman et al. 1997). This is in an effort to prevent court cases from becoming a battleground for experts. Grivas and Komar (2008) note that although the *Daubert* decision theoretically put clear constraints on the admissibility of scientific expert witness testimony, in practice judges, lawyers, and expert witnesses have all experienced difficulty interpreting *Daubert* (Gatowski et al., 2001; Cecil, 2005).

Two other United States Supreme Court cases have clarified the admissibility criteria for admissibility of expert witness testimony (Christensen and Crowder, 2009). Christensen and Crowder (2009:1212) state *General Electric Co. v. Joiner* and *Kumho Tire Co. v. Carmichael* "... coupled with Daubert form the trilogy of Supreme Court decisions that set the legal standard for evaluating the admissibility of expert testimony." The outcome of the *Joiner* trial was to question and clarify the language in *Daubert* and solidify the burden of admissibility of testimony for trial courts. The *Kumho* trial tested the *Daubert* rulings, confirming the gatekeeper role of the judge and specifying that both scientific and non-scientific expert witness testimony needs to be relevant and reliable to be considered admissible. Whereas *Daubert* explicitly states several guidelines on expert witness testimony, *Kumho* represents an admission by the court that science is too complex to be evaluated using a single set of standards (Grivas and Komar, 2008). The Court realized given the variation in types of evidence across disciplines, that flexibility is needed in assessing expert testimony (Christensen and Crowder, 2009). Further the *Kumho* decision tied expert witness testimony to professional standards by dictating that the expert witness should employ the same intellectual rigor (Kassirer and Cecil, 2002). Lastly, the decision suggests the courts must to acknowledge that expert testimony may employ a combination of scientific methodology, less rigorous case studies and observational methodologies (Cecil, 2005; Christensen and Crowder, 2009).

In 2000, the Federal Rules of Evidence, including Federal Rule 702, were amended to further address expert witness testimony. The Rules state that (1) testimony must be founded upon sufficient facts or data, (2) the test is the product of reliable methods and principles and methods, (3) the expert witness has applied the methods and principles reliably to the facts of the case. This amendment considers the *Daubert* guidelines and clarifies issues of relevance and reliability which were previously confusing (Christensen, 2004a).

Although the *Daubert* standard has not been adopted in all American states, Moreno (2003) reports 94% of state court judges find these guidelines valuable to their decision-making. The outcome of the *Daubert*, *Joiner* and *Kumho* decisions emphasizes the importance of gate-keeping and the necessity for judges and legislators to set the standards the admission of expert witness testimony (Christensen and Crowder, 2009). Combined, these three rulings reinforce the standard of admissibility and decrease ‘‘soft’’ science and speculation-based experience in the courtroom (Slobogin, 2003). The amendments to the Federal Rules of Evidence following these landmark cases has led to a clarification in the legal language and eliminated loopholes regarding admissibility criteria for expert testimony.

Within the field of forensic science a debate is currently going on regarding the theory of identification regarding the use and value of the terms ‘uniqueness’, ‘identification’ and ‘individualisation’ (Champod, 2009; Tuthill and George, 2002; Saks and Koehler, 2008; Jayaprakash, 2013; Page et al., 2011; Cole, 2009; Kaye, 2007, 2009, 2010, 2012; Koehler and Saks, 2010). This debate impacts how forensic scientists, including forensic anthropologists, report their findings and present evidence in the courtroom. It also impacts the methods utilised by forensic practitioners. This section will present a brief discussion of this debate and how they impact forensic anthropologists.

A classic definition of criminalistics is that it constitutes the science of individualisation, a term set in a broader context by defining it as placing an object within a restricted class (Kirk, 1963). Definitions of individualisation in the forensic literature consistently refer to the capability of recognising the right source to the exclusion of all others (either objects or persons) (Champod, 2009). Although this seems straight forward enough, problems arise when trying to establish individualisation. Champod (2009:1508) suggests that “... by default, the size of the population of relevant sources considered is systematically set to its maximum, regardless of the circumstances of the case.” This is known as the earth paradigm. According to this paradigm, individualisation cannot be reached deductively, but is *de facto* probabilistic in nature since it would be impossible to examine every individual on the planet. Based on statistical probabilities involved some suggest that the concept of individualisation that forms the basis for of numerous subfields of forensic science is present only in a metaphysical or rhetorical sense and is in fact a fallacy (Champod 2009; Saks and Koehler 2008). Interestingly, the use of the earth paradigm is in contrast to other forensic practitioners who suggest that the missing persons database constitutes the “identification universe” (Skinner, 1988; Besana and Rogers, 2010). A less extreme opinion is presented by Tuthill and George (2002), who state that individualisation is established when agreement is found of such a number and significance of corresponding individual characteristics as to preclude the possibility (or probability) of their having transpired by coincidence. Jayaparakash (2013) states that there are three main criticisms of the use of individualisation in forensic science – i) uniqueness is unprovable, ii) every identification requires probabilistic quantification and therefore none can qualify as conclusive, and iii) individualisation is irrelevant because it amounts to fact finding, the prerogative of the judge and jury. Page et al. (2011) consider uniqueness as a pervasive cultural ideology and caution that forensic scientists should not use the terms unique and individualisation. Further, Cole (2009) states uniqueness is largely irrelevant to individualisation and cannot sustain claims of source attribution. Stoney (1991) attributes the process of individualisation to a ‘leap of faith’, a subjective extrapolation based on observations of highly variable traits. He states that we must look realistically at the individualising process, reminding us that statistics become less useful with rarer traits because with smaller frequencies larger populations are needed to estimate them.

When it comes to use of the term uniqueness, considerable confusion exists. The traditional viewpoint is articulated by Jayaprakash (2013:403.e4), a proponent of the use of the term, who believes that uniqueness “... forms the nucleus around which individualisation revolves as a major forensic activity.” He contends that individualisation based on pattern matching is the most positive and realistic method to arrive at a conclusive association. He goes on to state that “... individualisation qualifies as a prime tenet of forensic science.” (Jayaprakash, 2013:403.e4). While individualisation and identification are undoubtedly a focus in forensic science, others feel that it is not necessary to prove that structures, objects or their signatures are unique; in fact the belief in that everything is unique could be considered obvious in the sense that every entity is different and identical only to itself (Champod, 2009). What is important is the ability to distinguish two individuals from each other or determine whether two signatures originated from the same source. This belief removes the importance of uniqueness in identification theory and places the importance squarely on forensic science and its methods to detect and distinguish this variability to an acceptable degree of scientific certainty. The ability to perform this task depends not only on the intrinsic qualities of the material or biological structure being examined, but also on the examination method employed.

The so-called uniqueness of a particular structure does not guarantee the accuracy of the technique applied to it. Even if a feature is considered unique, practitioners must have an understanding of the accuracy and reliability of the methods being applied. Historically the judicial system has employed ‘uniqueness’, rather than ‘accuracy’ and ‘reliability’ as the relevant empirical data. Although, uniqueness has been exposed as untrustworthy by various legal challenges and rulings, the terminology persists and pervades in both testimony and research (Cole, 2009). Moreover, experiments cannot establish uniqueness, only corroborate that duplication is highly unlikely. Cole (2009) concludes that uniqueness is a useless term because it tells us nothing about why analysis is accurate or what makes one technique more useful than another.

Champod (2009) believes that practitioners should move away from reporting categorical opinions of individualisation and should instead report the strength of their findings and leave the integration of their information to the overall context of the case to the judge and jury. Other identification fields (e.g. fingerprint, footprint, tire impressions and DNA identification) have suggested the use of scales of conclusions that are focused on posterior probabilities by either following the Earth population paradigm or by applying other statistics (Champod, 2009). The changing requirements for the admissibility of scientific evidence in the U.S. and the probability-based treatment of DNA evidence are two factors cited (Kaye, 2003; Saks and Koehler, 2008; Saks and Faigman, 2008; Cole, 2009; Saks, 2010; Page et al., 2011) for the recommendation of imposing statistical methods to support identification in other areas of forensic science. It is apparent is that there is a need to study the areas of forensic science, such as forensic anthropology, that use observational methods to differentiate between human failure and system failure. A better understanding is required of the different types of methods and their strengths and weaknesses in relation to morphological variability and precision and accuracy. Jayaprakash (2013) argues that we need validation studies on the suitability of observational methods as well as those involving the conversion of observed details into numerical data.

Given this situation the question becomes how should we move forward. Typically specific structures (teeth, fingerprints, frontal sinuses) which are considered to be unique are used to establish identity. However, there are several issues with the ability to establish uniqueness of these biological regions. One obvious problem is the uniqueness of these traits cannot be proven per se as we cannot examine the morphology of every person alive to make sure that they are different. Moreover, arriving at an extremely low probability does not equal uniqueness (Page et al., 2011). Often courts rely on claims by forensic practitioners of ‘never having observed an identical structure’ to corroborate the uniqueness of a particular structure. Page et al. (2011) state that while these claims may be true, they depend on the assumption that every observer remembers the details of every object or structure they have examined. Such a proposition is questionable and relies on claims and observations that have neither been recorded, nor compiled, in a scientific or methodological manner. Attempts to infer uniqueness based on anecdotal and experiential bases rest purely on inductive reasoning (Page et al., 2011).

Statistical modeling of combinations of traits is used in odontology, DNA and some frontal sinus methods and is viewed as a gold standard after the 2009 NAS report (Page et al., 2011). One of the main concerns is that the derivation of the probability that a certain trait will occur is often dubious. There is a need to verify the frequency in particular populations which means it is often impossible to determine to what degree a model represents the true distribution of such traits in the real world. These studies represent possibilities, not probabilities. Further confounding this is that survey data is problematic: the samples are often not truly representative of the target population. Another problem with probability models is the reliance on the assumption that each individual trait is independent of any other and the use of the product rule to calculate the likelihood of that two or more features would occur in combination (Page et al. 2011). Foran and Berman (2014) explain the product rule as utilising frequency data of one given variable which is then multiplied by another variable and so on to create a probability value. However, there are several key considerations with the use of the product rule. Firstly, the states or variables must be truly independent as any linkage among them makes the method invalid. Secondly, there must be an accurate estimate of the frequency of each variable. These variables must not be so common that they have little utility, but not so rare that an accurate frequency cannot be placed on them (Foran and Berman, 2014:260).

The key issue is whether it is necessary to prove uniqueness to establish personal identification. While there are guiding principles about standard terminology use in other forensic identification disciplines, these are lacking in forensic anthropology. Forensic anthropologists have not yet weighed in on the use of terminology and still seem to be dually engaged in determining uniqueness and assessing methods. Whether the terms uniqueness, individualisation and identification fall into disuse in forensic anthropology in the future remains to be seen. What is important is that focus should be adjusted to understanding the strengths and weaknesses of particular methods with a view to standardisation, rather than determination of uniqueness of particular features. Cole (2009) states that contrary to what forensic examiners believe it is not uniqueness that makes methods powerful, but the ability to make correct source attributions. Steadman (2013:138) reflects "One of the most important ramifications of the recent changes in the rules of evidence is greater attention to the scientific merit of traditional anthropological methods". More research is needed into quantitative methods due to replacement of experiential testimony with standardised methods and realistic error rates that can scientifically justify opinion. Validation studies are used to measure the performance of a particular technique by objectively quantifying accuracy and reliability. The process of validation leads to refinement, improving the original method and also helping practitioners answer which of the methods currently available are the best; a process that culminates in the development of disciplinary best practices (Steadman, 2013).

The current study answers the call by various forensic scientists for validation studies by testing three quantitative methods to assess identification using the frontal sinuses. This type of validation represents a clear shift in emphasis to the method of detection of individualising attributes, rather than on establishing uniqueness of a biological structure. Testing Ribeiro's (2000) measurement method will provide insight into an acceptable window of detection (Ribeiro uses a 2mm window) to maximise the likelihood of correct matches and minimise the likelihood of incorrect or non-matches. A test of Reichs and Dorion's (1992) coding system method will address if the features of the frontal sinuses are independent enough for utilisation of the product rule. More broadly, the current study's utilisation of a modern postmortem sample from Denmark, rather than an archaeological sample, provides forensically relevant data on modern populations. Moreover, validation using populations different from the original establishes data on human variation. This type of method comparison establishes a measure of system strengths and an assessment of which morphological variants produce system failures, as well as the contribution of human error to method inaccuracy. One positive feature of this study is that it provides a measure of the relative strength of three types of methods, with comparable data statistical data on accuracy and precision. In addition, this research will provide an increased understanding of the frontal sinuses and the morphological aspects that are different among individuals.

As forensic anthropologists increasingly find themselves required to provide expert witness testimony, knowledge and understanding of current admissibility guidelines is crucial. Forensic anthropological methods must be conceived and tested within the rigors of evidentiary requirements to produce findings which fit within the stipulated requirements. In addition to external influences, forensic anthropologists, like all scientists, are internally motivated by professional ethical responsibility to make sure that their methods are valid. While legal admissibility rules do not dictate how science is performed, the *Daubert* ruling and others have led to a realisation that scientific rigor may be lacking (Christensen and Crowder, 2009). Christensen and Crowder (2009:1213) note that "Conceptualizing methods within the rubric of evidentiary examination in disciplines like forensic anthropology is complicated, in that they employ a combination of traditional scientific methodologies and less rigorous observational methodologies." In line with this reality, Grivas and Komar (2008) suggest that the *Kumho* decision, rather than the *Daubert* guidelines, is more in line with anthropological inquiry because it allows for latitude in presenting evidence that cannot be empirically tested. While this may be the case, Christensen and Crowder (2009) point out that *Kumho* is not a stand-alone criterion. To this end, although anthropologists can endeavour to comply with the *Daubert* criteria, it is the courts that are responsible for determining if expert witness testimony has successfully met admissibility standards.

In evaluating the admissibility of forensic anthropological methods, Grivas and Komar (2008:4) suggest that in attempting to satisfy admissibility standards, anthropologists may be ‘‘trying needlessly to force powerful qualitative techniques into quantifiable categories’’. While some variables which rely on quantitative data can easily be assessed regarding their agreement with the *Daubert* criteria, it is more difficult to produce known or potential error rates and establish standards for qualitative methods. While some previously qualitative areas have been recently quantified (e.g. frontal sinuses) this is not possible for all areas of forensic anthropology and indeed should not be the goal. It is important to recognise though that the subjectivity that remains as part of these approaches does not equal unreliability (Christensen and Crowder, 2009)

However, forensic anthropologists need to critically evaluate their approaches in light of the scientific rigor required to present evidence in the courtroom and as part of this assess the ‘‘power’’ of our methods. Christensen and Crowder (2009) advocate that as professionals and good scientists we need to ensure that our methods are valid, reliable and transparent. Christensen and Crowder (2009:1214) believe that it is imperative to minimize the risk of error through quality assurance (i.e., proper training, method validation, accreditation, and certification), which will assist with establishing method transparency, and provide a secure foundation for forensic anthropologists in the courtroom. This belief provides a clear rationale for the validation of existing methods within forensic anthropology so that researchers can clearly testify to method reliability (accuracy and precision) in a way that is not only statistically significant, but forensically meaningful. Christensen and Crowder (2009) and Steadman (2013) advocate that forensic anthropology would profit from more validation studies aimed at addressing sample size, appropriate statistics, intra- and interobserver error.

The Daubert Tracker (www.dauberttracker.com) can be used to investigate challenges to expert witness testimony under federal and state gatekeeping authorities (including *Daubert, Frye, Joiner* and *Kumho*). This database is limited to cases in the United States and does not show how many cases there are in which anthropological expert witness testimony went unchallenged. Nevertheless, a search of the Daubert Tracker yields 95 cases in which expert witness testimony of anthropologists (including cultural anthropologists) was challenged; a search of "anthropology" combined with "criminal law" resulted in 49 challenges. Challenges in the area of forensic anthropology encompass testimony on time of death, cause of death, trauma analysis, toolmark and murder weapon determination, and ancestry estimation. One case in which forensic anthropological expert witness testimony was challenged included testimony on positive identification based on frontal sinus methods (Tennessee vs. Cosgrif, 2010). Of the challenges to anthropological testimony in criminal law, 63.27% were allowed, 26.53% were not allowed and 10.2% were undecided. Most of the testimony that was not admitted concerned cultural anthropology (10 of 13 cases), showing that in most cases forensic and biological anthropological testimony is passing gatekeeping review.

Although the majority of biological and forensic anthropology expert testimony is currently being admitted, it does not follow that this will always be the case. A temporal analysis of the Daubert Tracker data by the author illustrates there is an increasing trend in challenges to anthropological testimony from 1993 to the present (Figure 2.1). Holobinko (2012) reminds us that identification methods that have been used for decades and considered strong (such as fingerprint identification) have been challenged and deemed inadmissible (although later reversed) (*USA v Plaza, Acosta and Rodriguez, Cr. No.98-362-10,11,12 (2002*). Holobinko (2012) describe case of *Tennessee vs. Cosgrif* which involved comprehensive forensic anthropology testimony including identification based on frontal sinus morphology. Examination of the court documents shows that Dr Jantz made a positive identification based on at least eight points in the frontal sinuses; these observations were corroborated by several other researchers in the same laboratory. Dr Jantz testified that the frontal sinuses were unique to each individual and that based on Christensen's (2004) research misidentification based on the morphology of the frontal sinuses was highly unlikely. However, in the original court documents it is not mentioned which points or which method Dr Jantz used to determine a match. Christensen's (2004) method involves the comparison of frontal sinus outlines and it is unclear from the court documents if outline comparison was carried out in this case. Holobinko (2012) believes that the testimony in this case did not satisfy *Daubert* or *Mohan* criteria, although the conviction was upheld and challenge denied because witness firmly established her qualifications and expertise. Page et al. (2011) state law courts still appear extremely reluctant to deny admission to expert testimony because judges (gatekeepers) have developed a faith-based view of forensic sciences. Given the temporal trend in increasing challenges to anthropological testimony and greater public scrutiny there will likely come a time when this will change.

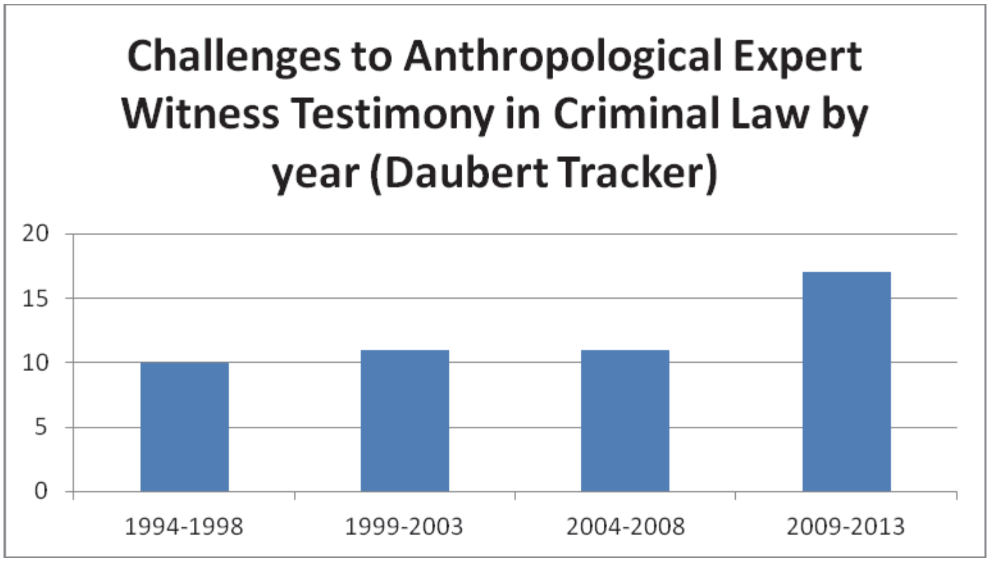


Figure 2.1: Challenges to Anthropological Expert Witness Testimony in Criminal Law by Year (Daubert Tracker)

Christensen and Crowder (2009:1214) note that "Forensic anthropology is fairly unique ... in that the techniques used are extremely variable and highly dependent on the evidence available (i.e., the completeness and condition of the skeletal remains)". Given the nature of the discipline there are several issues that need to be addressed. When considering identification, one issue is the criteria for minimum number of idiosyncratic anatomical points required for a match. Recommendations vary and include the establishment of one (Brogdon, 1998), two (Morse et al., 1983; Kuehn et al., 2002), four (Mann, 1998; Fischman, 1985) or thirteen (Singleton, 1951; Krogman and Iscan, 1986) "unique" traits. Currently among forensic anthropologists there is no accepted minimum number of matching points required for positive identification. Acharya and Taylor (2003) investigate the minimum number of concordant points needed to establish positive identification in forensic odontology. Their study of 680 cases found the incidence of identification more frequent with a minimum of twelve points. However, there were numerous instances in which the use of twelve or more points failed to produce an identification, as well as the inverse, in which the use of less than twelve produced a successful identification. They conclude that there appears to be no basis for utilising a minimum number of points, at least not for the dentition, and emphasize the view that each case is different and should be treated as such (Acharya and Taylor, 2003). This contradicts the more recent call for increased standardisation and warrants further investigation. In addition to the disagreement over the minimum number of points to used there is no agreement on what is meant by a "unique" feature (Cattaneo, 2007). Telmon et al. (2001) believe that the number of features required for positive identification depends on the presence of these in the general population, the rarer the feature, the smaller the number required for identification. However, feature uniqueness determined through experience-based observations renders expert opinion subjective and leads to inconsistent conclusions (e.g. Hogge et al., 1994), which would affect admissibility. Since not all forensic anthropologists share the same frame of reference, what is a rare trait to one, may not be rare to another (Rogers and Allard, 2004).

Another problem is the lack of established error rates for the many ‘‘unique’’ identifiers, such as anatomical anomalies, antemortem fractures, and surgical implants currently used for identification (Christensen and Crowder, 2009). Although, Grivas and Komar (2008) question the extent to which these types of data are testable and subject to error rates, Christensen and Crowder (2009) argue that probabilities can be established for these ‘‘unique’’ identifiers by determining how idiosyncratic these features are in a forensic population. Even if these data are lacking, these features may still be used in the interim to establish tentative identifications, to build a comprehensive identification based on multiple lines of evidence (Christensen and Crowder, 2009).

In response to this discrepancy between the legal requirements for scientific rigor and the reality of case-by-case approaches, some validation studies have been conducted (Besana and Rogers, 2010; Rogers and Allard, 2004; Christensen, 2005, Koot et al., 2005; Kuehn et al., 2002; Kahana et al., 1998; Kahana and Hiss, 1997; Kullman et al., 1990). However, these studies often create an artificial situation attempting to match simulated “antemortem” and “postmortem” data in a closed environment. Knowing the correct match is present within the data set increases the likelihood of an unreasoned correct guess by participants and falsely enhances a method’s effectiveness (as in Hogge et al., 1994). This is exacerbated by simulated “antemortem” and “postmortem” images captured at the same time, contrary to real world forensic identification, where images to be compared can be taken years or even decades apart. This raises the question of what constitutes an acceptable elapse in time since the acquisition of antemortem data. Sauer et al. (1988) state time spans from 10 to 23 years permit comparison of morphology in the vertebral column, but reliance on degenerative changes may not be advisable (Koot et al. 2005). Byers (2008) makes a safer suggestion of two years.

Despite the theoretical issues and obvious discrepancies evoked by the constraints of forensic work, researchers have reached some common ground. They agree the skeletal morphology must remain stable over time to permit comparison (Kahana and Hiss, 1997) and multiple identification techniques should be used where possible (Kahana et al. 1997; Clark, 1986; Prinz, 1993; Mulligan et al. 1988; Gregersen et al., 1995). Obstacles for forensic anthropological identifications pertain to the recovered postmortem remains, the antemortem data available, time, money and access to equipment. Due in parts to these factors, a range of techniques have been developed to establish personal identity. This chapter will now turn to a brief review of the methods used to determine identity.

2.3 Comparison of Dental Records

Teeth represent the most durable of human tissues and the material used in dental restorations is equally, if not more, resistant to destruction (Rogers, 1987). Dental identification continues to be one of the most reliable and frequently applied techniques for identification (Saxena et al., 2010). The practice of identifying individuals from their dental records is well accepted and considered well established (Pretty et al., 2012).

Dental radiographs are frequently taken for diagnostic purposes and provide a quick means for the comparison of dental features, resulting in this method being commonly used as a primary identification technique in mass disasters. The validity of dental radiographs comparisons has been demonstrated even with considerable time lapse between antemortem and postmortem film (Kogon and McLean, 1996). Pretty et al. (2003) demonstrated that experienced practitioners were able to perform identifications based on digitised radiographs with an accuracy rating of 91%. If radiographs are not available, comparisons can be made based on a dentist's notes. Unique characteristics include: hereditary anatomical details (tooth size, relative root length of the molars, jaw form, shovel shaped incisors and anomalous features such as Carabelli's tubercles), growth peculiarities and pathological indications (missing teeth, supernumary teeth, fused teeth, rotated teeth, transposed teeth, peg shaped, marked overbite, evidence of caries and periodontitis), conditions resulting from trauma, wear, personal habits and medication (broken teeth, teeth missing because of accidents, excessively worn teeth, wear resulting from bruxism, occupational practices and discolouration resulting from occupational exposure, smoking or the use of drugs) and evidence resulting from professional dental manipulation or orthodontic surgery (fillings, crowns, caps, bridges and dentures) (Rogers, 1987). The uniqueness of human anterior dentition has been demonstrated with a geometric morphometric study using landmarks and semilandmarks (Kieser et al., 2007). Kahana and Hiss (1997) state that these combinations of "unique" variables involving the 100 surfaces comprising the deciduous dentition and the 160 surfaces of the adult dentition provide the basis for dental identification (Buchner, 1985; Wood et al., 1994, Adams, 2003a & b). This is somewhat simplistic since certain surfaces are more susceptible to wear and more frequently restored. An agreement on the minimum number of points of similarity has not been established (Adams 2003b, Pretty et al., 2013).

In the case of endentulous individuals, Ohtani et al. (2008) investigated the uniqueness of the palatal rugae, which has been established as useful in dentate cases (English et al., 1988; Limson and Julian, 2004). By comparing casts taken of the hard palate to casts of dentures, Ohtani et al. (2008) were able to identify several unique points and reported a 90% median value of correct matched.

Problems with the use of dental records to establish personal identity includes the detail and availability of dental records. Schuller-Gotzburg and Suchanek (2007) report the initial identification of tsunami victims by dental status very high (54%), but after several months the success rate fell off, in part because of the poor quality of Thai dental records. Other issues pertain to the number of different systems in use to record the teeth, a complication in international situations.

The American Board of Forensic Odontology (ABFO) has established standards and guidelines for the practice of forensic odontology in the areas of human identification, bitemark investigation and analysis, dental age estimation, missing and unidentified persons and mass fatality incident dental identification team development. The Odontology Subcommittee of the

Forensic Science Standards Board (FSSB) was officially established in January 2015 (http://www.nist.gov/itl/iad/ig/odontology.cfm).

2.4 Other forms of identification

While pathological features of the teeth, such as dental caries and the corresponding dental manipulations are useful for identification, pathologies of other skeletal elements can also lead to identification. In some cases pathology can be linked to biological features such as age and sex (e.g. Devriendt et al., 2005). Klepinger (1999) presents a series of case studies in which skeletal anomalies and pathologies were used to resolve personal identification where techniques of dental comparison and DNA analysis were unsuccessful.

Medical records or information from family members about individual injuries can also lead to identification (Djuric, 2004). The latter is especially useful in countries where there is limited access to healthcare, inadequate documentation or destruction of records has taken place, prohibiting dental or x-ray comparison (Komar, 2003). The problems with this technique are many. Frequency data of pathological features for the study population is required, which is often lacking, especially in conflict situations (Komar, 2003). Interviewing family members to gain decedent information can be difficult. Aside from potential language and memory problems, family members are not trained physicians and can only describe the condition (Komar, 2003), which is why comparison of antemortem and postmortem radiographic images is preferred for identification.

2.5 Identification based on Radiographic Comparison

Following the establishment of presumptive identity, usually from the osteobiography, suitable antemortem radiographs are located and compared to postmortem radiographs taken at a similar orientation and magnification. They are compared for common anatomical features (Christensen, 2005), such as the presence and absence of different structures, size and shape of distinct elements or peculiarities (Campobasso et al., 2007). This type of comparison is routinely executed in a non-standardised, idiosyncratic (Cox et al., 2009).

Radiographic comparison was first used to confirm personal identity in 1926 (Culbert and Law, 1927) and is routine for identification of skeletonised or burnt remains and mass disasters (Campobasso et al., 2007) because it is considered effective, swift and easy. Radiographic comparison most often uses x-ray data, but with the increased sophistication of imaging modalities, the source of antemortem images has shifted to computed tomography (CT) and magnetic resonance imaging (MRI). Haglund (1993) states CT has largely replaced the use of radiographs to image the skull. Researchers have responded to these changes. Pfaeffli et al. (2007) compared antemortem x-rays to postmortem multi-slice CT images and found CT data eliminated the problem of matching the viewing angle. The most obvious problem with this approach is the need to acquire antemortem radiographs, without them the forensic anthropologist must turn to another technique. For example, in Manitoba there were a total of 161,924 CT scans and 70,962 MRIs performed in the 2013/2014 fiscal year (www.gov.mb.ca/health/waittime/diagnostic/ctcat.html); no data were available for plane film radiographs. The figures from Manitoba provide an indication regarding the availability of antemortem data.

In the skull, the morphology of mastoid air cells and paranasal sinuses were the first features on which comparison of radiographic images was used. Radiographic comparisons have also been conducted on normal anatomical variations (Rhine and Sperry, 1991), such as vascular grooves on the inner table of the skull, (Messmer and Fierro, 1986) ectocranial suture pattern (Sekaran, 1985; Rogers and Allard, 2004) and trabecular architecture (Van der Stelt et al., 1986).

Personal identity has also been established based on radiographic comparison of many bones and anatomical features of the postcranial skeleton. The scapula (Ubelaker, 1990) and clavicles (Adams and Maves, 2002) have been considered. Other features include: the shape of the vertebral body and pattern of the transverse and spinous processes of the vertebrae (Kahana et al., 1997), the vertebral column (Angyal and Derczy, 1998; Watamaniuk and Rogers, 2010), the shape and size of the ribs and their association to one another (Murphy and Gantner, 1982), the shape and length of the xiphoid process (Rouge et al., 1993), eminence of the manubrium and deformations of several thoracic vertebrae (Tsunenari et al., 1982), the vascular and trabecular and grooves on the innominates (Moser and Wagner, 1990), and the hands and feet (Greulich, 1960; Kahana and Hiss, 1994). Bone densities (Zugibe et al., 1985) and growth arrest lines (Gordon and Ross, 1977) have also been used (Mann, 1998).

Pathological and degenerative features can also be compared using radiographs. Examples include: osteophytic lipping and vertebral body crushing (Kahana et al., 1997), vertebral anomalies (Frayer and Bridgens, 1985), costal cartilage calcifications (Martel et al., 1977), bony bridges between the vertebrae and bony spiculae on the innominate, disc herniations (Rouge et al., 1993), deformation of the pelvis (Angyal and Derczy, 1998) and bilateral clubfoot (Sudimack et al., 2002). Indications of healed trauma and medical intervention can be considered individualizing markers (Varga and Takacs, 1991; Evans et al., 1981) as can non-metric features, such as sternal foramina and metopic sutures (Hunter et al. 1996), which have been suggested as unique characteristics.

2.6 Frontal sinus methods

The frontal sinuses are one anatomical region that has been used extensively as a basis for personal identification. Before surveying the different methods it is useful to consider the growth and development of these anatomical structures. The frontal sinuses are one of the four paranasal sinuses, air-filled cavities located around the nose. The others are maxillary, sphenoid and ethmoid, each named for the bones they inhabit. Rae and Koppe (2008:1414) state "These hollow spaces develop as outgrowths of the mucosa that line the nasal capsule; traditional anatomical definitions (e.g., Negus, 1958) of the sinuses are derived from the distinctive placement of their openings, or ostia, into the nasal cavity, although other classificatory systems have been proposed (e.g., Rossie, 2006)".

The development of the paranasal sinuses was of interest to some of the earliest researchers and is well chronicled (Koppe et al., 1994; Libersa et al., 1981; Szolar et al., 1994; van Alyea, 1939, 1941; Anon et al., 1996). In humans, the paranasal sinuses begin to develop during the tenth and twelfth fetal weeks, but undergo their major expansion after birth. The air cells making up the ethmoidal labyrinth start to develop as expansions of the nasal epithelium, which gives rise to all the other sinuses. From this labyrinth, two recesses originate: the ethmofrontal and the ethmomaxillary. These recesses expand later into the frontal bone and the maxilla respectively, which they pneumatise, later becoming the frontal and maxillary sinuses. The most posterior cells form the sphenoid recess (Weiglein, 1999). The sphenoid sinus forms slightly differently; the primitive sphenoid sinus is apparent as an invagination of the nasal mucosa and eventually expands backward and downward to form a pouch in the cartilage. Pneumatisation happens in two stages – primary and secondary pneumatisation. Primary pneumatisation occurs when pockets of nasal epithelium spread into the cartilaginous nasal capsule; secondary pneumatisation happens when the pockets colonise the bony elements (Nambiar, 1999). Both maxillary and frontal sinuses grow in bones of intramembranous origin, the sphenoid and ethmoid sinuses develop by endochondral ossification (Koppe and Nagai, 1999). Weiglein (1999) reminds us that the embryonic development of the nose and the paranasal sinuses is closely tied to facial development and their ultimate morphology is influenced by both environmental and epigenetic factors (Koppe and Nagai, 1999).

In a newborn human the developing frontal sinus has not yet reached the frontal bone. By the age of four, the frontal sinus has grown vertically to the nasofrontal suture and at twelve years of age, it has expanded into the frontal squama, although left and right sinuses develop independently (Weiglein, 1999). By adulthood, the paranasal sinuses are fully grown and exhibit great morphological variation. Asymmetry is common and often marked (O'Higgins et al., 2006). Unfortunately, as Zollikofer and Weissman (2008:1447) point out that, "... beyond issues concerning growth and allometry of sinus volumes (i.e., size), relatively little is known about how their often complex and highly variable shape is formed during development, and only a few studies attempt to quantify sinus morphology beyond volume measurements and description of anatomical variants (Krennmair et al., 1999; Farke, 2007)".

Theories of the function performed by the paranasal sinuses abound. Despite our knowledge of their morphological distribution in primates and centuries of study, their functional role remains elusive. Theories can be divided into structural (architectural), functional (or physiological) (Blaney, 1990) and non-functional roles (Marquez, 2008). There are many reasons to account for this surplus of theories. Blanton and Biggs (1969) point out that most of the explanations for the role performed by the paranasal sinuses are based merely on speculation. Numerous problems exist with attempts to narrow down their role. Many theories exist in part because few have been empirically tested (Zollikofer et al., 2008; Blanton and Biggs, 1969; Blaney, 1990). No hypothesis can be indisputably supported given the evidence available and several hypotheses directly contradict each other. Rae and Koppe (2004) point out that the paranasal sinuses are made up of a lack of bone, further compounding the determination of their function. This lack of research has contributed in part to the failure to determine the functional role of the paranasal sinus pneumatisation and led some researchers (Ingersoll, 1906; Negus, 1957, 1958; Takahashi, 1983; Lund, 1988) to conjecture that there is no function for these air-filled cavities and that they represent evolutionary remnants.

The frontal sinuses were first used to establish personal identity in 1926 (Culbert and Law, 1927) and since then the frontal sinuses have been widely utilised because of their noted individual variation (Asherson 1965) and their stable morphology throughout life. Twin studies focusing on the frontal sinus (Schuller, 1943; Asherson, 1965; Dillon and Gourevitch, 1936; Maresh, 1940) illustrate morphological differences between monozygotic twins, but especially between fraternal twins, which increase with age until adulthood when growth is completed. In a more recent study Cameriere et al. (2008) set out to test if kinship can affect identification success and verify if frontal sinuses can be employed to uniquely identify individuals belonging to family groups. The authors report that kinship does not increase the proportion of false-positive identifications when using a modification of Yoshino et al.'s (1987) method. These studies, although most are rather dated, form the basis for the consensus regarding the uniqueness of the frontal sinuses. Christensen (2004b) comments that most of the claims put forth concerning the unique nature of frontal sinus morphology are based on anecdotal observations of hundreds of radiographs, which report that no two frontal sinuses were identical (Asherson, 1965; Cryer, 1907; Culbert and Law, 1927; Poole, from Mayer, 1935; Schuller, 1943). She goes on to say that "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..." (Christensen, 2004b:291).

Nevertheless the morphology of the frontal sinuses is accepted as unique with some researchers going as far as to describe the "frontal sinus print" which they compared to the individuality of fingerprints (Murphy et al., 1980). Comparison of the pattern of the frontal sinus depicted on antemortem and postmortem radiographs has been used to determine positive identification in a number of forensic cases (Stewart, 1979; Murphy and Gantner, 1982; Ubelaker, 1984; Yoshino et al., 1987; Marlin et al., 1991; Reichs and Dorion, 1992; Reichs, 1993; Haglund and Fligner, 1993; Owsley, 1993; Quatrehomme et al., 1996; Angyal and Derczy, 1998; Smith et al., 2002; Tatlisumak et al., 2007).

Superimposition of antemortem and postmortem radiographs of the frontal sinuses is the most basic method used to confirm identity. For individuals with a suspected identity, antemortem records are acquired and compared to postmortem radiographs taken at a similar angle and orientation. Sinus patterns are compared either side by side or more commonly by superimposing one over the other. This form of visual comparison has been used in several documented cases (Campobasso et al., 2007; Marlin et al., 1991; Nambiar et al., 1999; Quatrehomme et al., 1996; Angyal and Derczy, 1998; Ubelaker, 1984; Haglund and Fligner, 1993) and it has been reported to have a very high success rate regardless of age, sex, cause of death and time elapsed between image capture (Kirk et al., 2002). Constraining factors in the application of superimposition include image quality and orientation when using X-ray images (Kirk et al., 2002; Kullman et al., 1990). Despite low error rates and being simple to carry out, superimposition is criticised for being a highly subjective method which lacks the statistical evidence required for admissibility in court (Cox et al., 2009).

Several methods have been developed which go beyond basic superimposition in an attempt to introduce more objective techniques suitable for the courtroom. These methods can be grouped into linear measurements, scoring systems and outlines.

The simplest objective method for characterising the uniqueness of the frontal sinuses involves taking and comparing linear measurements. Kirk et al. (2002) combined superimposition and quantitative measurements of the width and height of the frontal sinuses. In all 35 cases they report it was possible to superimpose antemortem and postmortem tracings and positively match the outline of the frontal sinuses. Utilizing sinus height and width 16 (46%) of the cases could be matched quantitatively (Kirk et al. 2002). Any discrepancy greater than 5 mm between antemortem and postmortem values was classified as a "metric nonmatch." Several cases presented problems because of mixed projections for comparisons. In these cases no metric superimposibility was noted. The authors report that it was difficult to compare and quantify dimensions taken from two differing projections. Kirk et al. (2002:323) suggest that intraobserver error may play a role in the ability to obtain a metric match, and query the arbitrary error value of 5 mm as being "… too small a margin to account for differences in inter-operator variability and measurement error". Ribeiro (2000) developed a metric method which measures four distances of the frontal sinuses on plain film x-rays. The system was tested using a subsample of the original data set to attempt to match the sinuses based on the measurements.

Although the author reports 100% accuracy, visual comparison was required in cases where more than one film was found with identical measurements (Ribeiro, 2000). Ribeiro's system was used to verify identification in a forensic case (da Silva et al. 2009).

While metric methods are among the easiest to execute, classification systems have also been employed in an attempt to objectively characterise the uniqueness of the frontal sinuses by reducing subjectivity with the introduction of code numbers. Yoshino et al.'s (1987) method, reported to be one of the most widespread (Cameriere et al., 2005), is a classification system based on seven morphological characteristics: area size, bilateral asymmetry, superiority of area size, outline of superior borders, partial septa, and supraorbital cells. According to its creators, this system means that there are more than 20,000 possible combinations of class numbers, meaning there is a very remote chance of two people having a similar pattern of frontal sinuses. As a result, Yoshino et al. (1978) believe their method can safely be relied upon. Several researchers have sought to improve on the Yoshino et al. (1987) method. Reichs and Dorion (1992) used a slightly modified approach and applied it to transverse computed tomography images. They considered similar characteristics of the sinuses: bilateral dimension, bilateral asymmetry, superiority of side, distribution and number of partial septa, and distribution and number of complete cells. Their method involves scoring these features on two or three separate transverse images and combining the scores into a 14- or 21-digit code number. The authors state that this will produce a high number of possible score combinations: 240 billion for a 14 digit code (seven variables scored on two separate transverse slices and combined) and over 118 quadrillion for a 21 digit code (using three separate transverse slices). However, the probability that two different individuals share an identical code is much higher than the values reported by Yoshino et al. (1987) and Reichs and Dorion (1992) because of significant correlations between the seven characteristics used (Cameriere et al., 2005). Cameriere et al. (2005) also modified the Yoshino et al. (1987) method by substituting ratios (frontal sinus area/orbital area for each sinus) to counter the error introduced by skull position in the X-ray beam; using this system they report that each individual was characterized by a unique frontal sinus pattern. Like Reichs and Dorion (1992) and Reichs (1993), Tatlisumak et al. (2007) also utilise CT images; their FSS system combines metric features with coding numbers. They found that measurements were prone to bias and state the criteria of the FSS to be more objective. Although these researchers report high rate of success at individualising (93% based on FSS scores and 98% with the addition of measurement data), a closer examination of the published data shows many duplicates in scores; a total of 45 of the 100 individuals in the sample had a non-unique FSS identifier, including one formula possessed by seven different individuals. A three-dimensional analysis combining measurement and coding systems was undertaken by Kim et al. (2012). Their findings suggest a three-dimensional approach offers a greater ability to differentiate individuals in their sample (98% produced different codes) using variables from all three dimensions of the frontal sinuses.

Although several researchers have tried to utilise metric and coding systems to quantify uniqueness of the frontal sinuses, these studies fall short in a number of ways. Christensen (2005) points out that these investigations typically employ very small sample sizes (Harris et al., 1987, N = 32; Ubelaker, 1984, N = 35), although more recent studies, (Ribeiro, 2000; Tang et al., 2009; Tatlisumak et al., 2007) have employed more individuals. Christensen (2005) criticises the coding system methods of Yoshino et al. (1987) and Reichs and Dorion (1992) for addressing only general characteristics of the frontal sinuses and not their complete morphology. There has been no research to support the uniqueness of these specific frontal sinus features. Although Yoshino et al. (1987) suggest the possible number of combined variables is very large, permitting characterisation of individuality, Cameriere et al. (2005) point out that correlations exist among the different variables, greatly increasing the probability that two individuals will have similar frontal sinus patterns and be assigned identical code numbers. They report that on four occasions a pair of X-rays which belonged to two different individuals produced the same code number and the frontal sinus patterns of a set of three individuals could be expressed by the same code numbers using the Yoshino et al. (1987) method (Cameriere et al., 2005:772). Indeed it is likely because of these correlations between variables that when validating a combination of the Yoshino et al. (1987) and Cameriere et al. (2005) methods on an independent sample, Tang et al. (2009) report the same 12-digit combined code was found in three different individuals. Although Reichs and Dorion (1992) suggest a low probability of misidentification in forensic contexts based on their observations, they were neither able to estimate this probability, nor assess what proportion of the population possess a particular pattern. Christensen (2005b) states that other identification methods, such as fingerprints, have carried out more rigorous estimating attempts (Pankanti et al., 2001) and are consequently more accepted.

Both metric and classification systems have shown varying degrees of success, but frequently require visual comparison as a final confirmatory step (Cox et al., 2009). Cox et al. (2009) suggest that this is likely due to the reduction of information as a result of grouping features and assigning class numbers or when basic linear measurements, such as height and breadth, are used. The ensuing data fail to capture enough variation in the frontal sinuses to permit reliable identification. Cox et al. (2009) caution that at best, coding and measurement systems provide a means to perform quick searches in order to narrow down identity of suspect remains and eliminate non-matches within a sample.

To deal with some of these issues, methods using the outline of the frontal sinuses have been proposed. Christensen's (2004b, 2005) method uses elliptical Fourier analysis and Euclidean distances. She reports that the differences in outlines generated using elliptical Fournier analysis of different individuals were significantly larger than those of replicates of the same individual. In addition, the probability of a different individual having a smaller Euclidean distance than the distance between that individual's own replicate is very small (Christensen, 2004b). Cox et al. (2009) simplified Christensen's outline approach, testing it on archaeological, clinical and contemporary samples. They report extremely encouraging results: a high level of agreement in patterns achieved between observers and combined error rates for both observers showed 0% false positive, and 0% false negatives for 18 same skull pairs and 42 different skull pairs. Empirical testing of the ability of the odds ratio to discriminate same skull from different skull logTD values yielded 100% correct discrimination of same skull pairs (n = 9) and 97% correct discrimination of different skull pairs (n = 36). Christensen (2005) concluded that frontal sinus outlines are quantifiably different at a highly significant level, confirming uniqueness in this structure. However, although these outline methods are promising, they warrant further investigation and testing.

It is important to bear in mind the terminology employed when comparing studies of personal uniqueness because it can be misleading. Many studies (Cameriere et al., 2005; Tatlisumak et al., 2007; Kim et al., 2012) indicate they are identifying individuals when in fact these methods are actually differentiating individuals from each other. Identification involves comparison of known information to unknown information. Typically in forensic cases, this involves comparison of antemortem information (e.g. photograph, dental records) from a known individual to postmortem data from an unknown individual. One illustration of the incorrect use of terminology comes from Kim et al. (2012) who state that their method is able to identify 98% of the individuals in their sample (n=110). In this example and other studies there is no comparison of data, either through the use of antemortem and postmortem images for the same person (as in Kirk et al., 2002) or through the use of multiple data collection carried out on the same sample (as in the current study). Therefore, these studies are not identifying individuals in their sample set, but merely differentiating them and establishing whether their system is able to produce unique codes. Moreover, there is no replication of the method in the form of either intra- or inter-observer error testing. These studies reflect the ability of a particular method to differentiate individuals, not match (or identify) them which is required in forensic situations.

2.7 Summary

Ultimately the goal in a forensic context is individualization, which is conducted for both legal and humanitarian purposes. This chapter has outlined the theoretical principles on which forensic identification is based. Forensic anthropologists are finding themselves at a critical juncture between the requirements of the legal profession which they must answer to as expert witnesses and the realities of a young discipline whose methods necessitate testing to meet these legal standards. Methods of identification involve comparison of known information collected during an individual's life to data acquired from an unidentified decedent. Numerous sources of information can be employed and this chapter has discussed the commonly used data sources – dental records, pathology and radiographs. Although radiographic comparison can be conducted using any stable skeletal structure, the frontal sinuses have been used in a large number of forensic cases because of their accepted morphological uniqueness. Several techniques have been developed and these can broadly be grouped into measurement, scoring and outline approaches. Currently, there remains no standardised approach to the comparison of antemortem and postmortem radiographic images of the frontal sinus. This is due in part to a lack of testing of existing methods on independent samples. To respond to this and address legal requirements for increased scientific rigor this thesis will test three methods from each category of approaches – measurement (Ribeiro, 2000), scoring (Reichs and Dorion, 1992) and outline (Cox et al, 2009) on an independent sample.

Chapter 3 Materials and Methods

3.1 Materials

This study utilized an anonymised postmortem CT sample of 130 individuals (males n= 70, females n=57, unknown n=3) from University of Copenhagen to examine the frontal sinuses. Computerised tomography imaging allows for the visualisation of internal structures of the skeleton. The age range of the sample based on medical records is 19 to 88 years (mean for males is 49.88 years, mean for females is 54.93 years) shown in Figure 3.1.

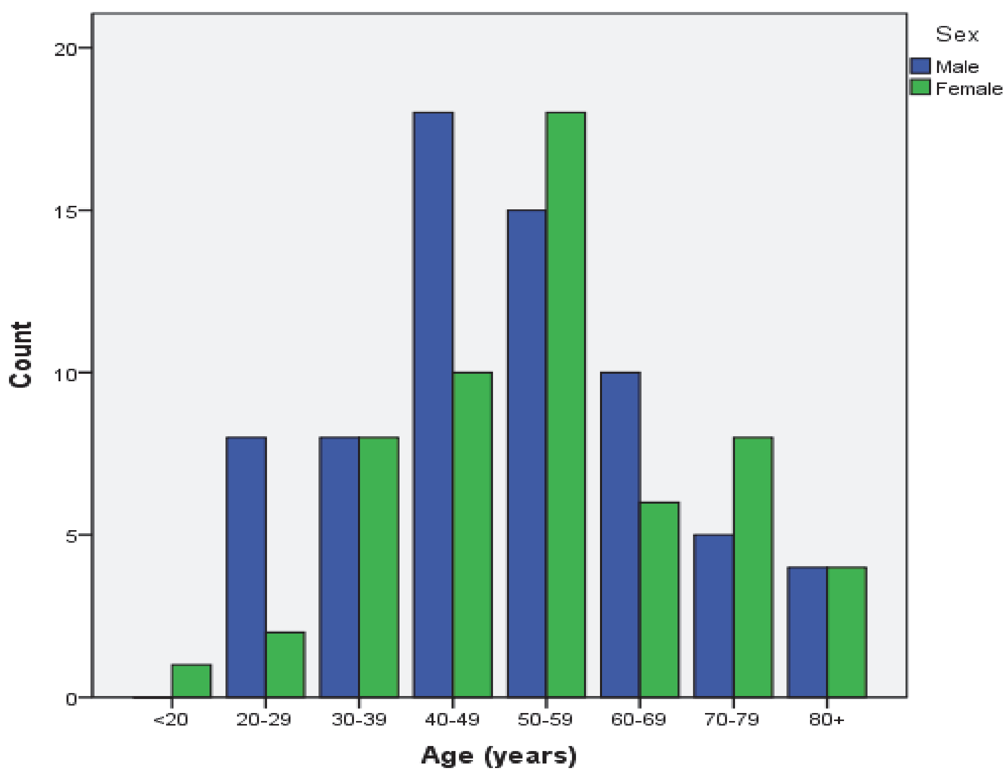


Figure 3.1: The age range of the sample by sex.

The CT scans were obtained using a multislice Siemens Somatom Sensation 4 scanner. Axial images covering only the skull were obtained using the following parameters: matrix: 512 x 512, kV: 120, mAs: 169.5, algorithm: H20s. The slice thickness of the scans is typically 2 mm, but varies from 0.5 mm to 2 mm; the average is 1.704 mm (Figure 3.2).

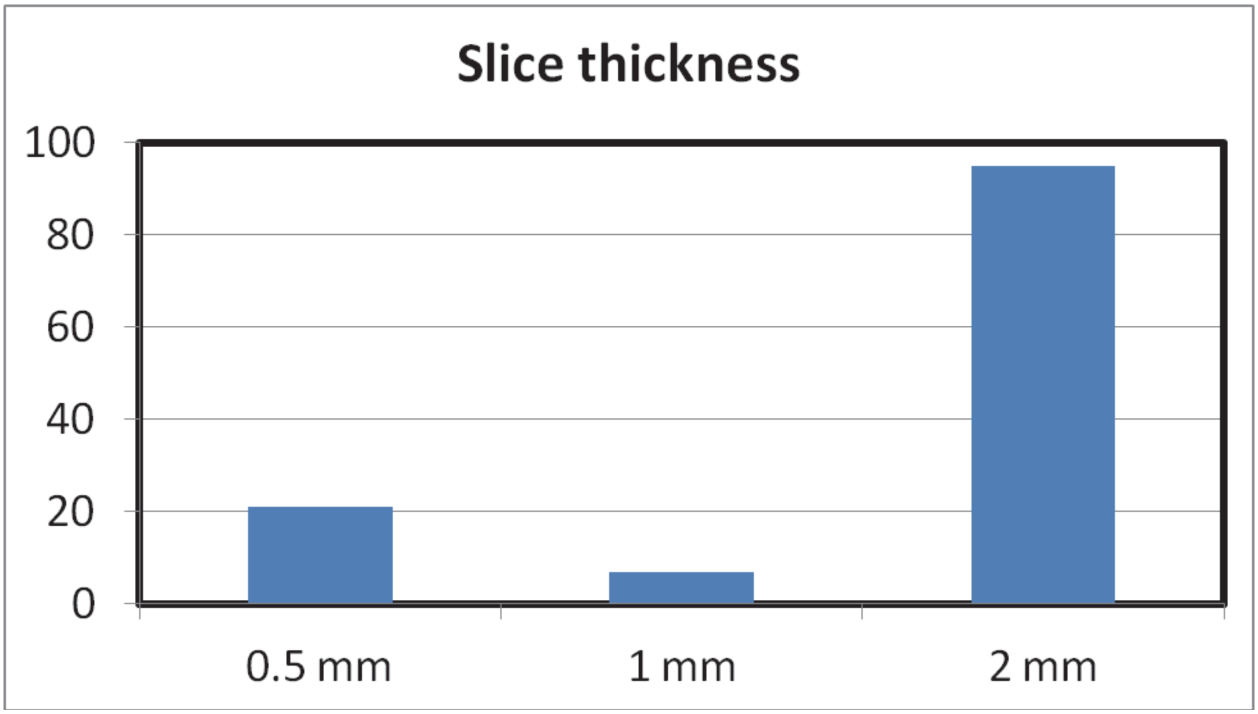


Figure 3.2: Range of slice thickness in the sample

3.2 Method testing

Three previously published methods for personal identification using the frontal sinuses are being tested on an independent sample to validate these techniques. The methods being examined fall into three categories: measurement (Ribeiro, 2000), coding (Reichs and Dorion, 1992) and outline (Cox et al. 2009) techniques. Methods were tested following as closely as possible to the original protocol, however, some alterations were used for the Ribeiro (2000) and

Cox et al. (2009) techniques to adapt them to CT images from traditional plane film radiographs (or X-rays). All CT data were viewed and analysed using the Materialise MIMICS™ x64 software (Belgium: Materialise). This software is designed for medical image processing and can take both two and three dimensional measurements, view slices in different orientations and create three dimensional models. Intraobserver error analysis and method validation for unique matches was conducted for each method.

3.3 Ribeiro (2000) method validation

Ribeiro's (2000:28) method involves taking four measurements on anterior-posterior X-rays. The film is placed on a viewer and a horizontal line connecting the upper limit of the orbits is drawn. This is the baseline. Four more lines are drawn perpendicular to the baseline. These lines are drawn at the lateral limits of the right (E) and left (H) frontal sinuses and the highest (most superior) point of the right (F) and left (G) frontal sinuses. Once these lines are established the four primary measurements are drawn. Measurement A is the diameter of the frontal sinuses at the widest point (from lines E to H). Measurement B is the distance between the highest (most superior) points of the right and left frontal sinuses (from lines F to G). Measurement C is the distance between the lines marking the maximum lateral limit and the highest point of the right frontal sinuses (lines E to F). Measurement D is the distance between the lines marking the maximum lateral limit and the highest point of the left frontal sinuses (lines G to H) (See Figure 3.3).

Figure 3.3: Figure 1 from Ribeiro (2000). "A baseline is drawn horizontally along the upper limit of both orbital cavities. Four lines are then drawn perpendicular to the baseline. One line (E) delineates the maximum lateral limit of the right frontal sinus. Another line (F) passes through the highest point (the most distant from the baseline) of the right frontal sinus. A third line (G) is drawn through the highest point of the left frontal sinus. The fourth line (H) defines the most lateral limit of the left frontal sinus. Measurement A is the diameter of the frontal sinuses at the widest point – that is, the distance between the projected lines that delineate the maximum lateral limits of the right and left sinuses (line E to H). Measurement B is the distance between the projected lines marking the highest points of the right and left sinuses (F to G). Measurement C is the distance between the lines marking the maximum lateral limit and the highest point of the right frontal sinus (E to F). Measurement D is the distance between the lines marking the maximum lateral limit and the highest point of the left frontal sinus (G to H)."

For frontal sinus anatomy that does not fit the classic architectural pattern, Ribeiro (2000:28) developed nine rules to follow:

1. Take measurements only of the air-containing cavities of the frontal sinuses
2. When one sinus has two equally high points, measure the one closest to the intersinus septum.
3. When the highest point is difficult to determine, measure the point at the middle of the lobulation.
4. When the highest point is not evident because of a plateau lobulation, measure the middle of the plateau.

5. Any air-containing cavity of the frontal bone is considered to be part of the frontal sinus and should be measured.
6. When the frontal sinus is triangular in shape and there are no two distinct highest points because they coincide with the vertex of the triangle, measure and notate the highest point on the vertex and list measurement B as zero.
7. When the points delineated by lines E, F, G and H are above the baseline they are classified as positive, when they are below the baseline they are classified as negative. Points are classified as null when they are on the baseline.
8. If a skull has only one frontal sinuses, make measurement A the distance between the projections of its lateral and medial limits. Denote measurement B as zero. Measurement C remains the same and measurement D is the distance between the highest point and the medial limit.
9. If a skull has no frontal sinuses, measure only the distance between the projection of the lines that pass through the medial borders of the orbit cavity (measurement X) (Figure 3.4).

[redacted]

Figure 3.4: Figure 8 from Ribeiro (2000). If a skull has only one frontal sinus, measurement A is the distance between the projections of its lateral and medial limits. Measurement B is zero. Measurement C remains the same. Measurement D is the distance between the highest point and the medial limit.

Ribeiro's (2000) measurements for individualization were applied to each individual using a modified protocol for the CT dataset as follows. Data were thresholded with a setting between 220-3071 Hounsfield units. The bone threshold in MIMICS is 226-3071 Hounsfield units; this was reduced to 220 Hounsfield units to maximise the visualisation of bone. The resulting skull was rendered as a 3D object. The 3D object was viewed on the full screen. To align the skull to the Frankfurt Plane it was viewed in left profile and oriented so that the left and right mandibular rami were aligned. Using the measure distance feature a line was drawn connecting inferior margin of the left orbit to the upper margin of external auditory meatus. The skull was aligned so this line was straight and then rotated to right using the right arrow key to the frontal view. Following Ribeiro (2000), a "baseline" was drawn across the superior borders of the eye orbits on the skull. The transparency setting was applied to view the frontal sinuses and four lines were drawn on the skull corresponding to Ribeiro's lines E, F, G and H at the highest points and lateral limits of each sinus (Figure 3.5). Measurements A (maximum dimension, lines E-H), B (distance between highest points of right and left sinuses, lines F-G), C (distance between lateral limit and highest point of right sinus, lines E-F) and D (distance between lateral limit and highest point of left sinus, lines G-H) were taken and recorded (Figure 3.3). This method was later repeated independent of the first data collection. To do this the CT data were re-thresholded with the same values, the lines were re-drawn and measurements re-taken. This was done to assess intra-observer error and as a proxy for testing the reliability of individualization.

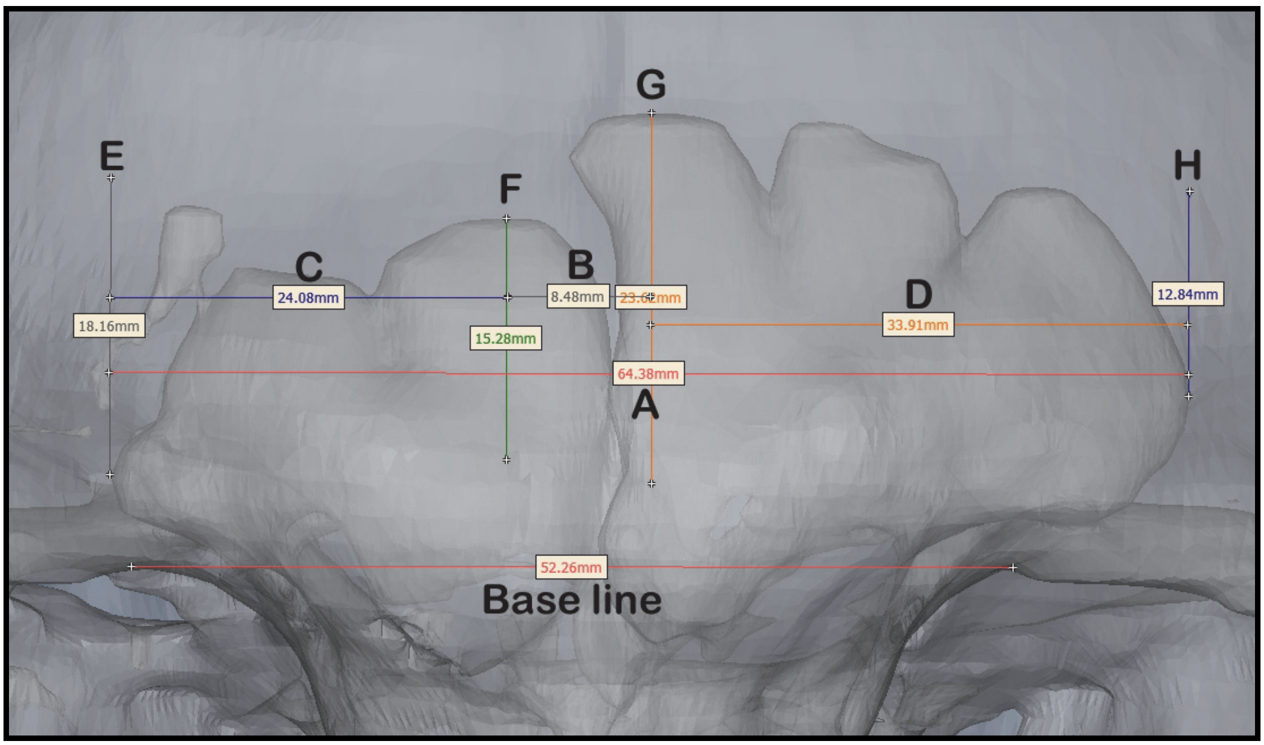


Figure 3.5: Ribeiro's (2000) measurements applied to an individual in the current sample

3.4 Reichs and Dorion (1992) method validation

Reichs and Dorion (1992) method scores seven features: bilateral dimension, bilateral asymmetry, superiority of side, distribution of partial septa, number of partial septa, distribution of complete cells and number of complete cells. Each of these features is classified on two, or if possible three, different slice levels, resulting in a fourteen (for two levels) or twenty one (for three levels) digit code. The original method description does not provide criteria for slice selection.

Reichs and Dorion (1992) define bilateral dimension as the measure of the maximum diameter of both the right and left frontal sinuses including all independent cells. Reichs and Dorion (1992) use a 2 mm acetate grid laid over the scan to take measurements (Figure 3.6). With MIMICS this is not necessary as measurements can be taken using the software. A class number (0 through 4) is assigned based on the maximum diameter measurement (see Table 3.1).

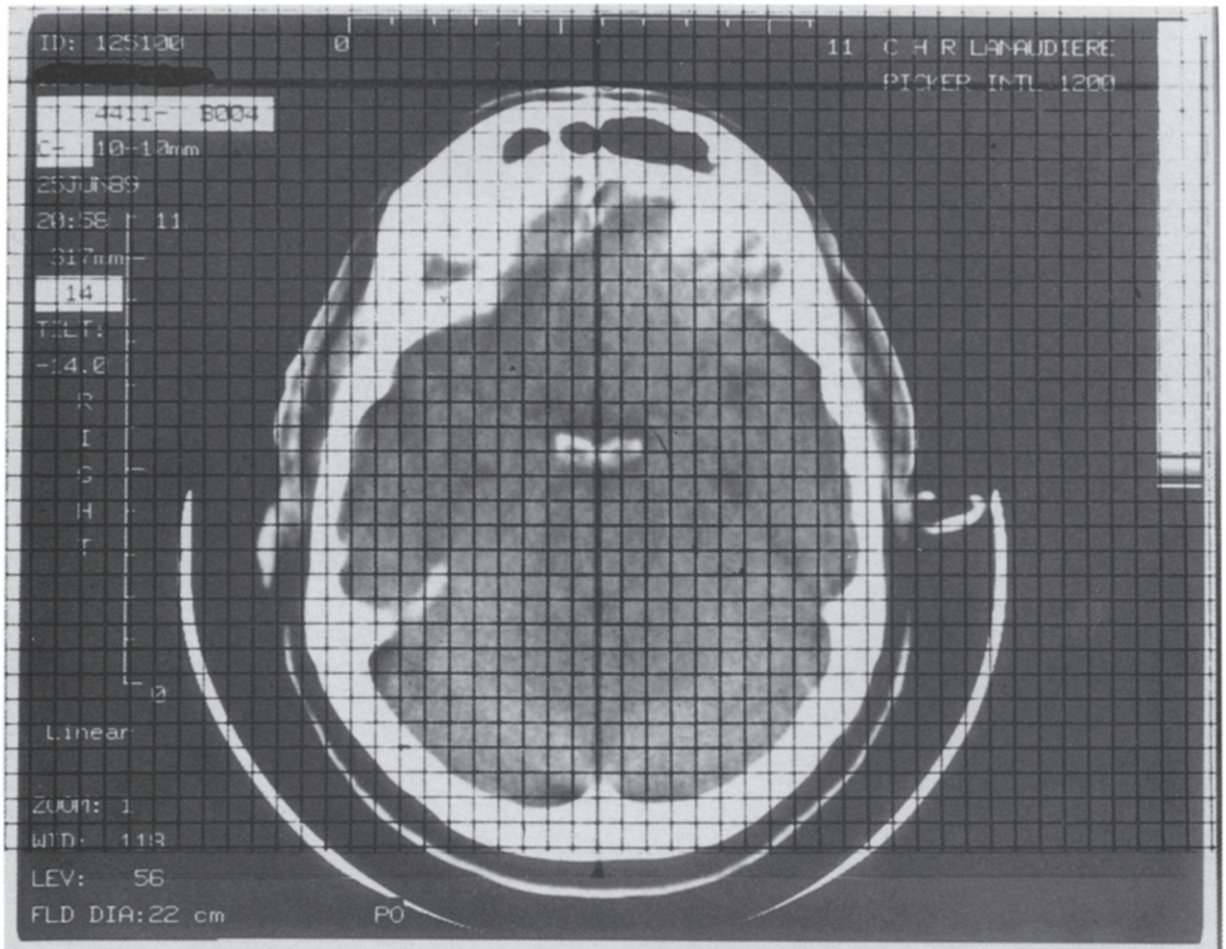


Figure 3.6: Figure 2 from Reichs and Dorion (1992). "CT scan with 2 mm grid superimposed."

Bilateral asymmetry according to Reichs and Dorion (1992:4) "... is a measure of the degree of unilaterality in the expression of sinuses on the left and right sides" and is expressed through the index below. A class number is assigned (0 through 5, see Table 3.1) based on the degree of asymmetry.

$$\frac{\text{Maximum diameter of smaller sinus (MDS)}}{\text{Maximum diameter of larger sinus (MDL)}} \times 100 = \text{Bilateral asymmetry index (BAI)}$$

Reichs and Dorion (1992) define superiority of side as the feature that describes the direction of the asymmetry seen in the right and left frontal sinuses. This is scored as 0 through 3.

Reichs and Dorion (1992:4) describe partial septa as "... a segment of bone projecting from the superior border into the sinus and dividing it, incompletely, into compartments". To qualify a partial septum must measure at least 1 mm and not divide the sinus completely into separate cavities. Scoring (0 through 7, see Table 3.1) is based on the location. In addition the number of partial septa is scored (0 through 7, see Table 3.1 and Figure 3.7).

Figure 3.7: Fig 3 from Reichs and Dorion (1992). "Partial septa. A partial septa is defined as a segment of bone which projects 1 mm or more from the superior border of the sinus, dividing it, incompletely, into compartments. Two septa, dividing the sinus into three compartments, are shown."

Complete cells are defined as a "... self-containing cavity or compartment formed by a bony dividing wall within in the sinus" (Reichs and Dorion, 1992: 5). Class numbers (0 through 7) are assigned separately for both location and number of complete cells (see Table 3.1 and Figure 3.8).

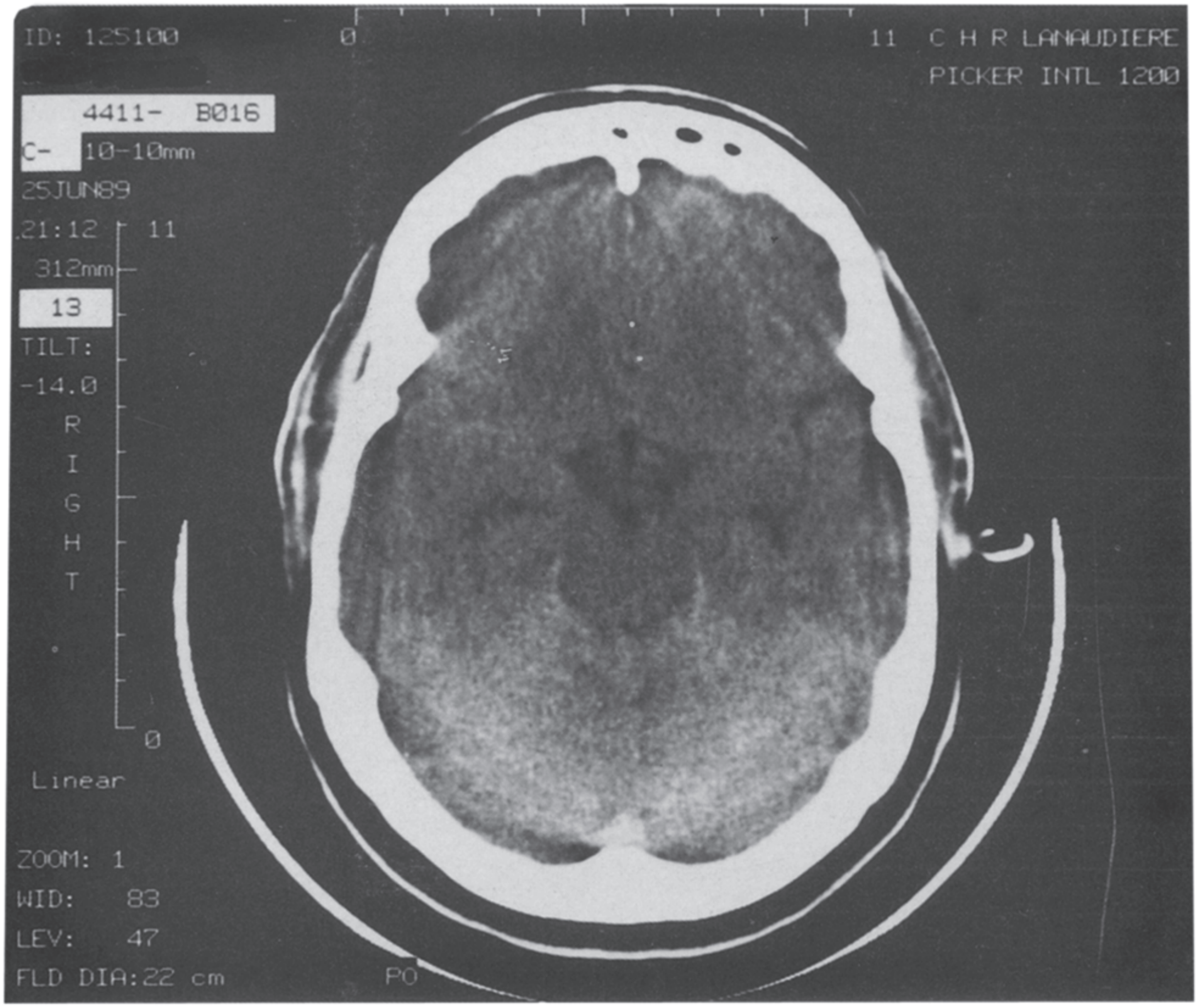


Figure 3.8: Fig 4 from Reichs and Dorion (1992) "A complete cell. A complete cell is defined as a self-contained cavity or compartment within the sinus. Three complete cells are shown."

Table 3.1: Reichs and Dorion (1992) classification guide

	Bilateral dimension	
Size category	Maximum dimension	Class number
Absent		0
Small	< 5 mm	1
Medium	5 mm - 10 mm	2
Large	10 mm - 15 mm	3
Very large	> 15 mm	4

	Bilateral asymmetry (BAI)	
Degree	Range asymmetry index	Class number
Absent		0
Symmetrical/almost	B AI $\geq$ 80	1
Slight	60 $\leq$ BAI > 80	2
Moderate	40 $\leq$ BAI > 60	3
Strong	20 $\leq$ BAI > 40	4
Extreme	BAI < 20	5

Superiority of side	
Superiority of side	Class number
Absent	0
L = R	1
L > R	2
R > L	3

Distribution of partial septa	
Partial septa	Class number
Absent	0
L only	1
R only	2
Midline only	3
L and R	4
R and midline	5
R and midline	6
L, R and midline	7

Number of partial septa	
Partial septa	Class number
Absent	0
1	1
2	2
3	3
4	4
5	5
6	6
7 +	7

Distribution of complete cells	
Complete cells	Class number
Absent	0
L only	1
R only	2
Midline only	3
L and R	4
R and midline	5
R and midline	6
L, R and midline	7

Number of complete cells	
Complete cells	Class number
Absent	0
1	1
2	2
3	3
4	4
5	5
6	6
7 +	7

The Reichs and Dorion (1992) method was applied to the current data set. Due to difference in head position all individuals were resliced in MIMICS™, using the reslice project function. A line was drawn on the transverse image connecting the frontal crest to the internal occipital protuberance, around this line a box appears. The head was then rotated so that it was straight. The box was widened to include the whole skull. The analysis was later repeated on all individuals using the resliced images. The first slice was chosen to represent a transverse section in the lower third of the sinus and the second slice was chosen to represent a transverse section in the upper third of the frontal sinus. Data were collected two more times to compare the results to original scores. The first time data were collected blind ('unknown slice' scores), without any previous information, the second time they were recollected the original slice number was provided ('known slice' scores); this removed variation introduced by difference in slice choice and enabled evaluation of intraobserver error. Basic descriptive statistics on the effect of slice number and scoring of variables were performed as well as the comparison of measurement trials to investigate intraobserver error and individualisation performance.

Figures 3.9 and 3.10 illustrate the Reichs and Dorion (1992) method applied to individual 02271145d. The score for the first slice (Figure 3.9) is 4330000 (Table 3.2). The score for the second slice (Figure 3.10) is 4000022 (Table 3.3). The combined 14-digit score for individual 02271145d is 43300004000022.

Table 3.2: Reichs and Dorion (1992) method applied to individual 02271145d first slice.

Variable	Score	Description
Bilateral dimension	4	≥ 15 mm (45.58 mm)
Bilateral asymmetry index	3	40 ≤ BAI < 60 (12.79/31.8 * 100 = 40.22)
Superiority of side	3	Right (31.8 mm) is greater than left (12.79 mm)
Distribution of partial septa	0	Absent
Number of partial septa	0	Absent
Distribution of complete cells	0	Absent
Number of complete cells	0	Absent

Table 3.3: Reichs and Dorion (1992) method applied to individual 02271145d second slice.

Variable	Score	Description
Bilateral dimension	4	≥ 15 mm (25.58 mm)
Bilateral asymmetry index	0	Absent
Superiority of side	0	Absent
Distribution of partial septa	0	Absent
Number of partial septa	0	Absent
Distribution of complete cells	2	Present on right only
Number of complete cells	2	2 cells present

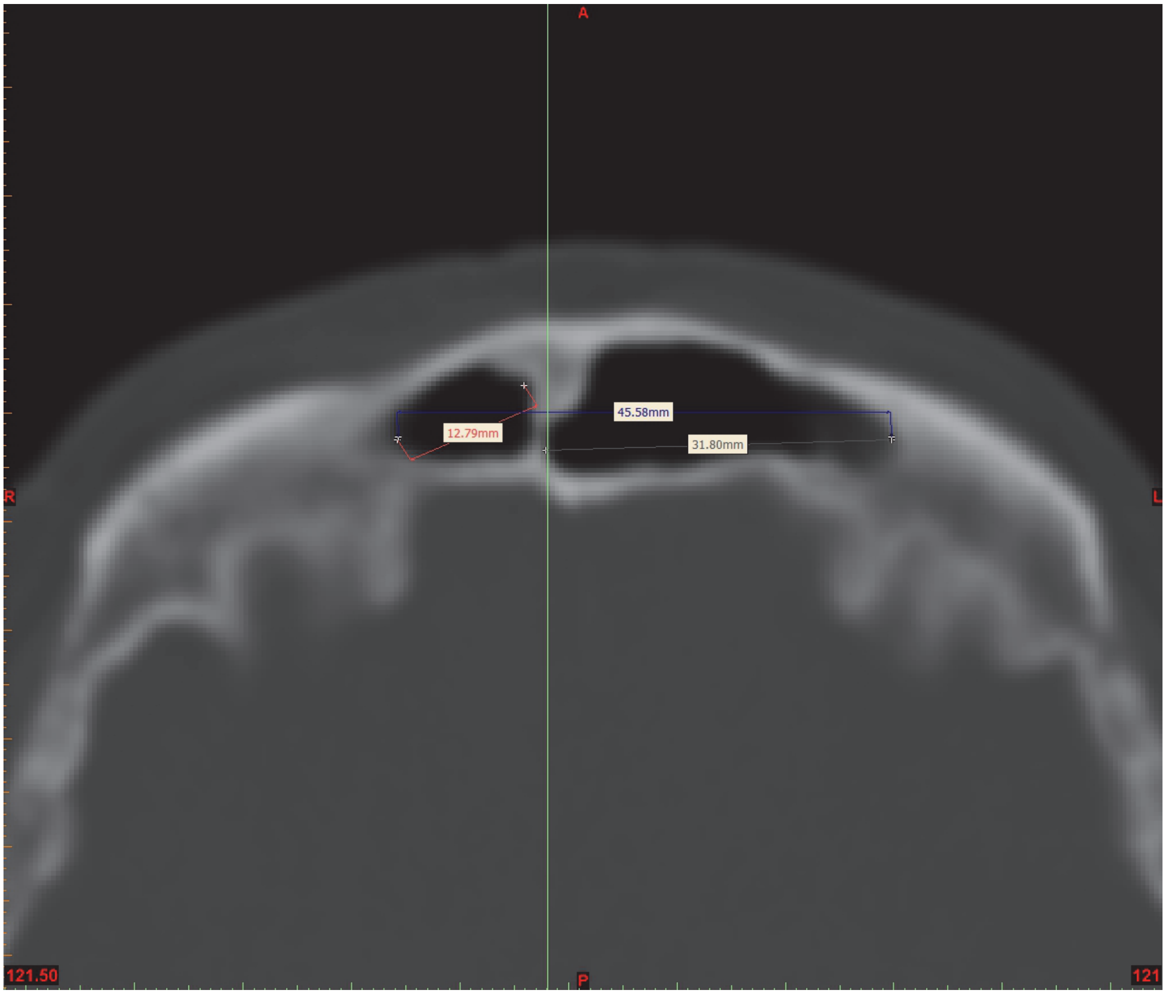


Figure 3.9: Axial image of individual 02271145d. Reichs and Dorion (1992) method scoring on original first slice = 4330000.

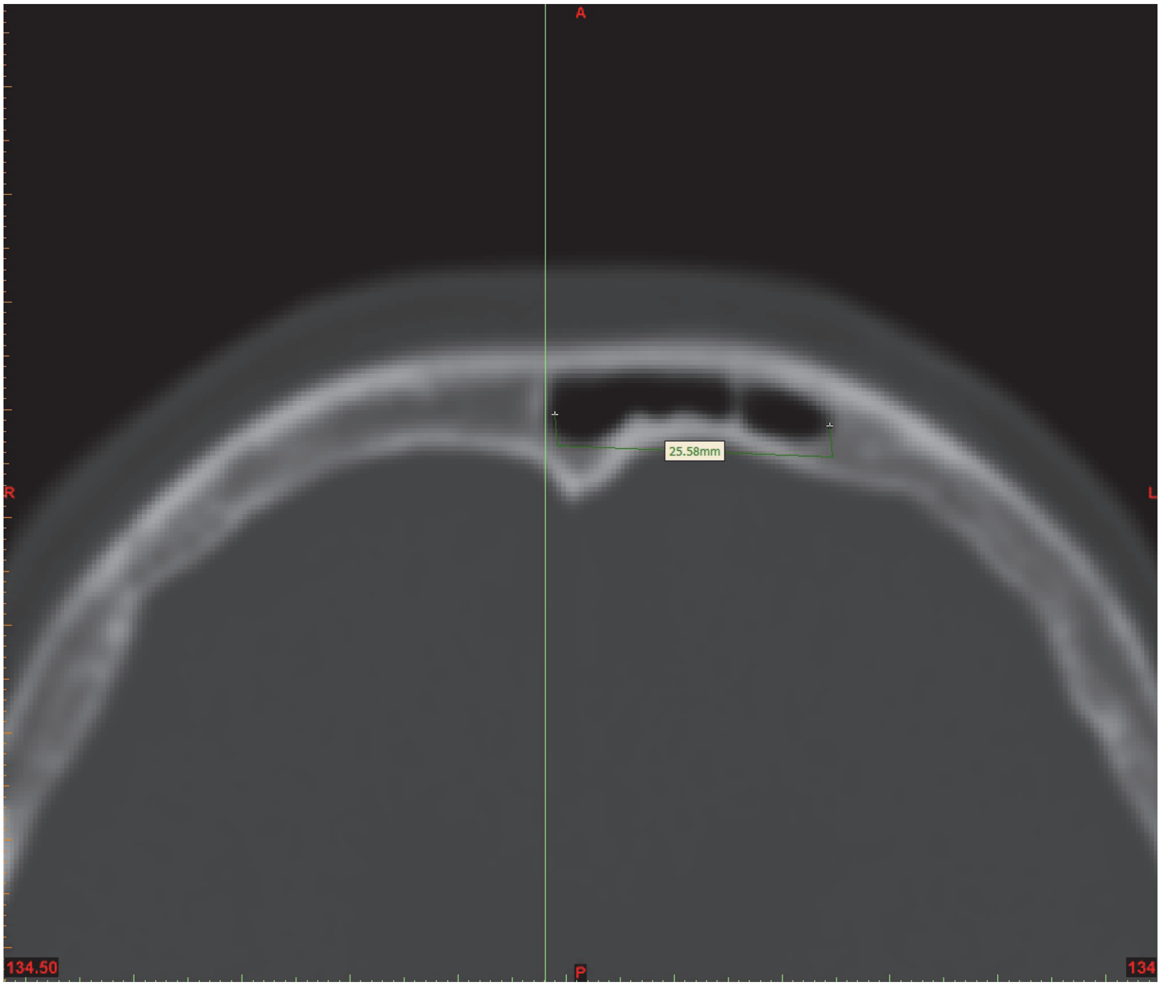


Figure 3.10: Axial image of individual 02271145d. Reichs and Dorion (1992) method scoring on original second slice = 4000022.

3.5 Cox and colleagues (2009) method validation

Cox et al. (2009) method involves capturing the outline of the frontal sinuses for comparison. The frontal sinuses were traced by placing a sheet of acetate over a radiograph (taken in the standard Caldwell or occipitofrontal view) over an illumination box. The left edge of the acetate was aligned with the left edge of the radiograph. A clear line was used to draw the baseline of the frontal sinuses tangential to the superior borders of the orbits using a fine-tipped indelible marker. The midline of the skull was established using a clear ruler to align mid-sagittal landmarks such as the nasion, nasospinale, the frontal crest and crista galli. The intersection of the midpoint and the midline and baseline were termed the origin. The outer border of frontal sinuses was traced onto the acetate (see Figure 3.11).

Figure 3.11: Figure 1 from Cox et al. (2009). "A radiograph from the Archaeological sample with a corresponding traced acetate."

The acetates were scanned at 300 dpi and saved as Tagged Image File (.tif). Each file was duplicated and these duplicates were used as the working files. In Adobe Photoshop™ CS2 the *Magic Wand* tool was used to delineate an unambiguous dashed outline on the interior border of the sinus outline to which all measurements were taken. The *Ruler* tool was used to measurement the length of the baseline by zooming in an extending the ruler from one end to the other, overlapping the dashed *Magic Wand* line. The length of the baseline (indicated on the top of the window as D1:) and the angle (displayed as A:) were recorded. The ruler was then shorted by dragging the left terminus to the origin, ensuring that the angle remained the same. The length of this new line was recorded. These data were recorded to allow for precise reposition if the placement happened to be lost. Pressing <alt> and clicking on the terminus of the baseline at the origin established a second line (D2:) originating from the origin. The terminus of the measuring line was then dragged around the dashed outline, this origin-to-border distance was recorded every 3° from 3° to 177° (Figure 3.12).

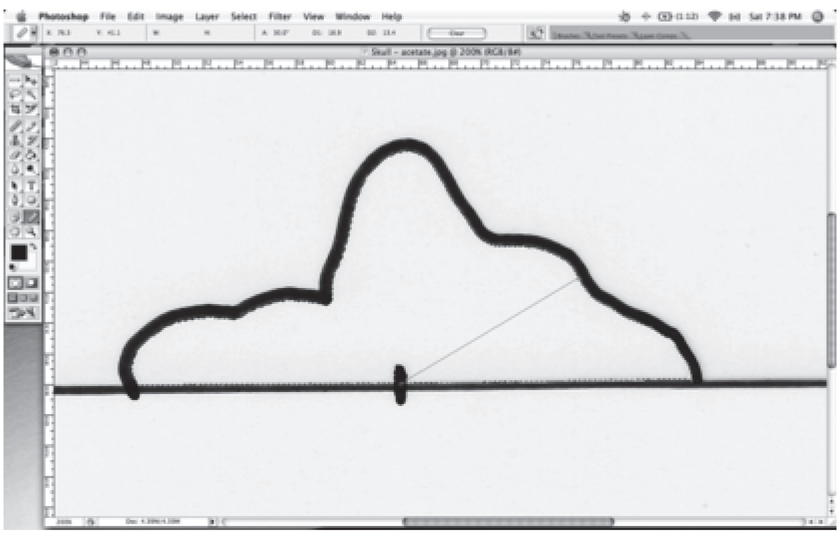


Figure 3.12: Figure 2 from Cox et al. (2009). "A scanned traced acetate opened in Adobe Photoshop CS2®. The baseline and point of origin for measuring have been established. The measurement line extends out from the origin laterally to the outline."

Cox et al.'s (2009) method was applied to the sample using a modification for use on computed tomography scans, rather than traditional plane film X-ray. The data were thresholded with a setting between 220-3071 Hounsfield units to maximise the visualisation of bone using Materialise MIMICS medical imaging software. The resulting skull was rendered in 3D. The 3D model was viewed on the full screen and oriented in the Frankfurt Plane. A line was drawn across superior borders of the orbits and the skull was oriented so that this line was straight. The transparency function was used to visualise the frontal sinuses on the 3D model and the baseline was adjusted to correspond with the diameter of the frontal sinuses. This measurement was recorded. A screenshot was taken of the 3D model and was opened in Adobe Photoshop™ 6.0. A new layer was applied and the baseline was traced using the ‘line’ tool. Another layer was applied and the outline of the frontal sinuses was traced using the ‘pencil’ tool. This was done on a WACOM™ monitor (Cintiq 21UX 6.1.7-3) directly on the viewed images using the stylus tool.

The outline image file was further modified in Adobe Photoshop CS6™. The zoom function was set to 500% and the measurement scale was calibrated with the ruler tool using the baseline measurement previously recorded. The ruler was shortened by dragging the left terminus to the origin. The <alt> key was pressed while hovering over the centre-point to establish a second line originating from the origin. The length of this line and the angle between it and the baseline were displayed at the top of the screen as A: and D2: (D1: always indicated the length of the baseline after being shortened). Figure 3.4 is an example of the Adobe Photoshop CS6 user window with an outline image opened and the lines established.

The terminus of the measuring line was then dragged around the outline, and the origin-to-border distance (D2) was recorded every 3° from 3° to 177° as per Cox et al.’s (2009) method. This produced 59 measurements per outline which were recorded in a spreadsheet. The measurement was always recorded at the outermost intersection with the outline (Figure 3.13) as per Cox et al.’s (2009) instructions.

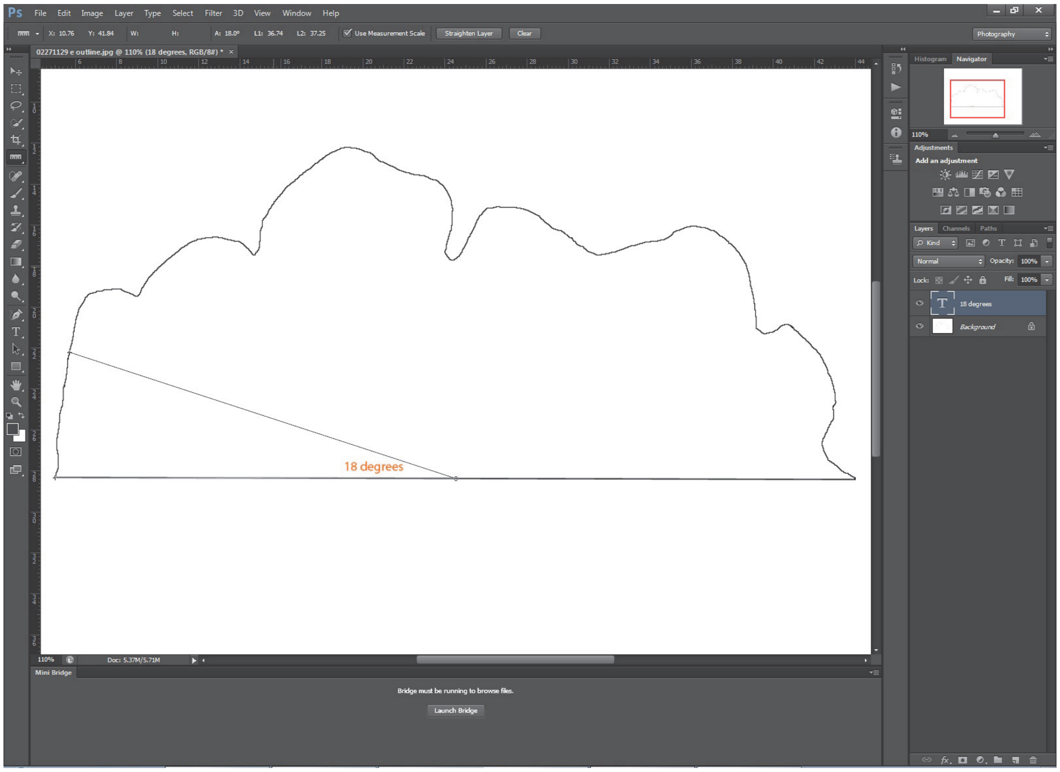


Figure 3.13: Adobe Photoshop™ CS6 user window with an outline image opened and the lines established

To repeat the measurements the outline images were imported into Matlab R2012a. Matlab was used to speed up the data acquisition. The image was first rotated 90°, then it was converted into a black and white image and the outline was extracted. Then the centre of the baseline of the image was found manually using the data cursor and points were found around the outline. These were plotted on a graph. Lastly, the angles were found for every three degrees and the corresponding maximum distance between the centre of the baseline and the border. The final points were plotted.

To determine the difference between any two outlines, the difference of the origin-to-border distance (D2) was found for each measurement from 3° to 177° and the absolute value of each difference was summed to produce the total difference in Microsoft Excel 2010. The total difference scores for same skulls (SS) and different skulls were compared for the whole sample.

Binary logistic regression analysis was performed in SPSS 20 using the total difference scores for both the same skull and different skull pairs.

3.6 Assessing method identification success

The efficacy of individualisation for each of the three methods was investigated. For the Ribeiro (2000) method, repeated data collection values were used as proxy for postmortem data. Using SPSS 20, second measurements were entered with a +/- 2 mm window (Ribeiro's suggestion) and compared to all individuals. This step was repeated using +/- 1 mm. All match combinations were recorded.

For the Reichs and Dorion (1992) method the 14-digit "unique" scores were compared for the whole sample using Excel. The original scores were compared first to 'unknown slice' (when the data were re-collected without any information) and second to 'known slice' (when data were collected on the original slice number) re-collected data. All match combinations were recorded.

The Cox et al. (2009) method was repeated on all individuals. Raw CT data were re-thresholded and re-oriented as 3D models using MIMICS. The baseline was drawn on the skull and the sinuses viewed in 3D using the transparency function. The screenshot was retaken and the outline of the sinuses was traced in Photoshop. The steps followed to acquire the origin-to-border distances every three degrees were acquired using Matlab. The total difference scores were calculated and a logistic regression analysis was performed using SPSS using a 0.5 cut off. Group probabilities and group membership were recorded.

All three methods tested here to determine if two frontal sinuses images belong to the same or different individuals, however they all use different data: four linear measurements for Ribeiro, a combination of measurements and feature scoring for Reichs and Dorion and outline comparisons for Cox and colleagues. To compare the ability of each method to identify unique matches, accuracy, sensitivity and specificity were calculated. These measures are starting to be utilised in forensic anthropology (Koot and Sauer, 2005; Stephan et al., 2011) and represent important results in validation studies (Koot and Sauer, 2005). Accuracy is a measure of the overall correct identification rate from the total number of trials; sensitivity quantifies the rate at which examiners correctly found a match, the true positive, and specificity measures the rate at which examiners correctly did not find a match, the true negative (Stephan et al., 2011). A false negative occurred when the examiner incorrectly rejected a match between a postmortem and antemortem image; in this case the examiner failed to recognize the existing match because they stated there was no match. A false positive occurred when the observer incorrectly matched a postmortem to an antemortem image, when the postmortem did not have a match in the antemortem pool or was matched incorrectly (Koot and Sauer, 2005).

The frontal sinus is considered to be a structure within the skeleton that is unique to each individual. This study validates the three published methods intended to capture this uniqueness on an independent sample of computed tomography images taken of 130 individuals. The next chapter will present the results of these validation studies.

Chapter 4 Results

This chapter presents the results of this study. The results of each method validation are detailed including intraobserver error results and individualising ability. Problematic cases for matching will be discussed in the next chapter.

4.1 Ribeiro (2000) method validation

Three individuals were not included because their sinuses did not extend above the baseline (bilateral absence 2.31%). Unilateral absence is seen in 5 individuals (3.85%) (4 right, 1 left sinus absent). 127 individuals were scored, although one individual was scored in the first trial but not the second due to different decisions about presence of the frontal sinus.

4.1.1 Variation

Measurement A is total bilateral dimension of both frontal sinuses and will be used to examine variation since Measurements B, C and D represent different segments of Measurement A. Variation in frontal sinus size (bilateral dimension) for the current sample is shown in Figure 4.1. While there is a strong degree of overlap between the sexes, mean dimensions of the sinuses are larger in males than females ($t=2.682$; $df=122$; $p=0.008$). The summary statistics of all measurements is presented in Table 4.1.

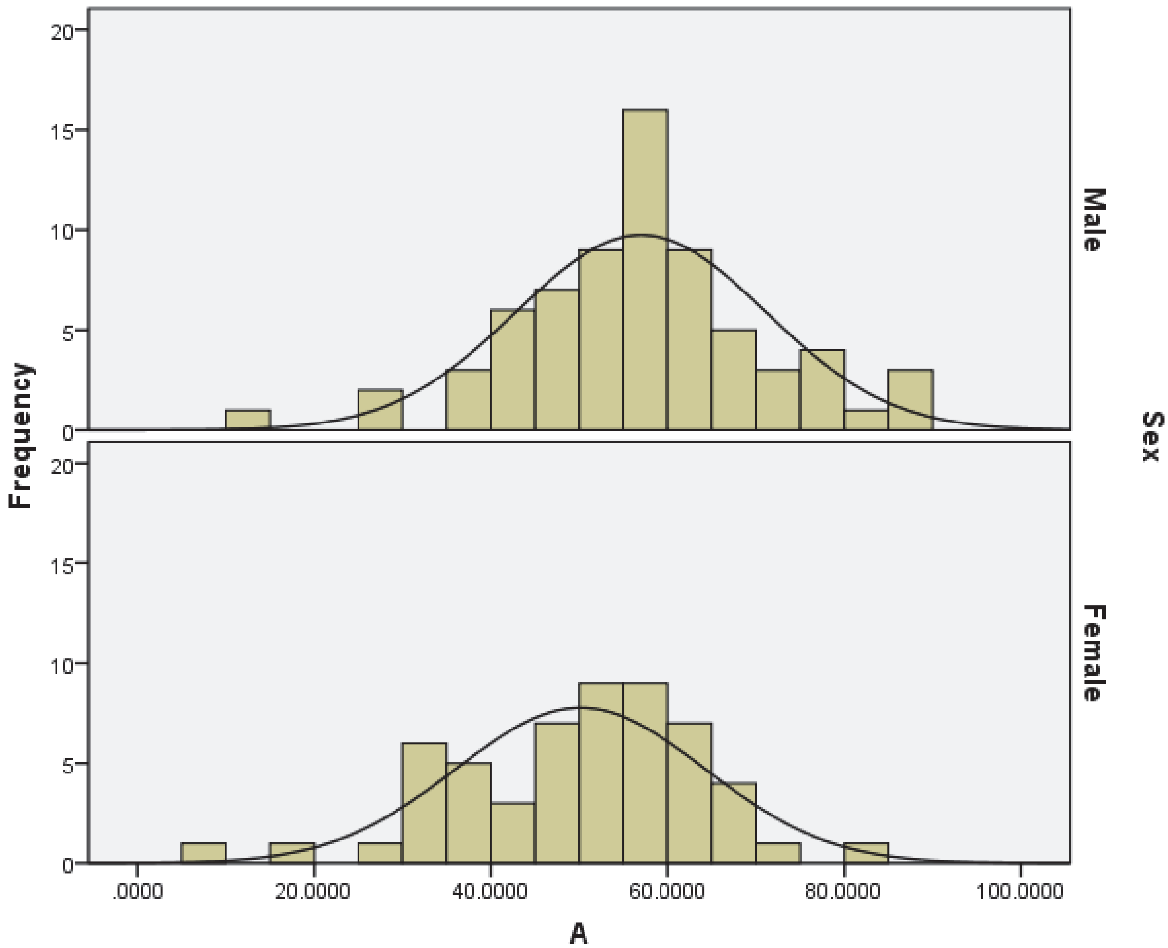


Figure 4.1: Distribution of Measurement A by sex

Table 4.1: Summary statistics of Ribeiro (2000) method

Measurement	Range (mm)	Mean	Standard deviation
A	5.81 - 89.44	54.74	14.04
B	0 – 46.09	17.96	8.71
C	0.97 – 50.38	18.18	10.43
D	1.89 – 46.3	20.66	10.16

No statistically significant difference in the age distribution was observed between males and females in the sample, and no correlation was found between age and Measurement A in the sample. The distribution of Measurement A by age group is presented in Figure 4.2.

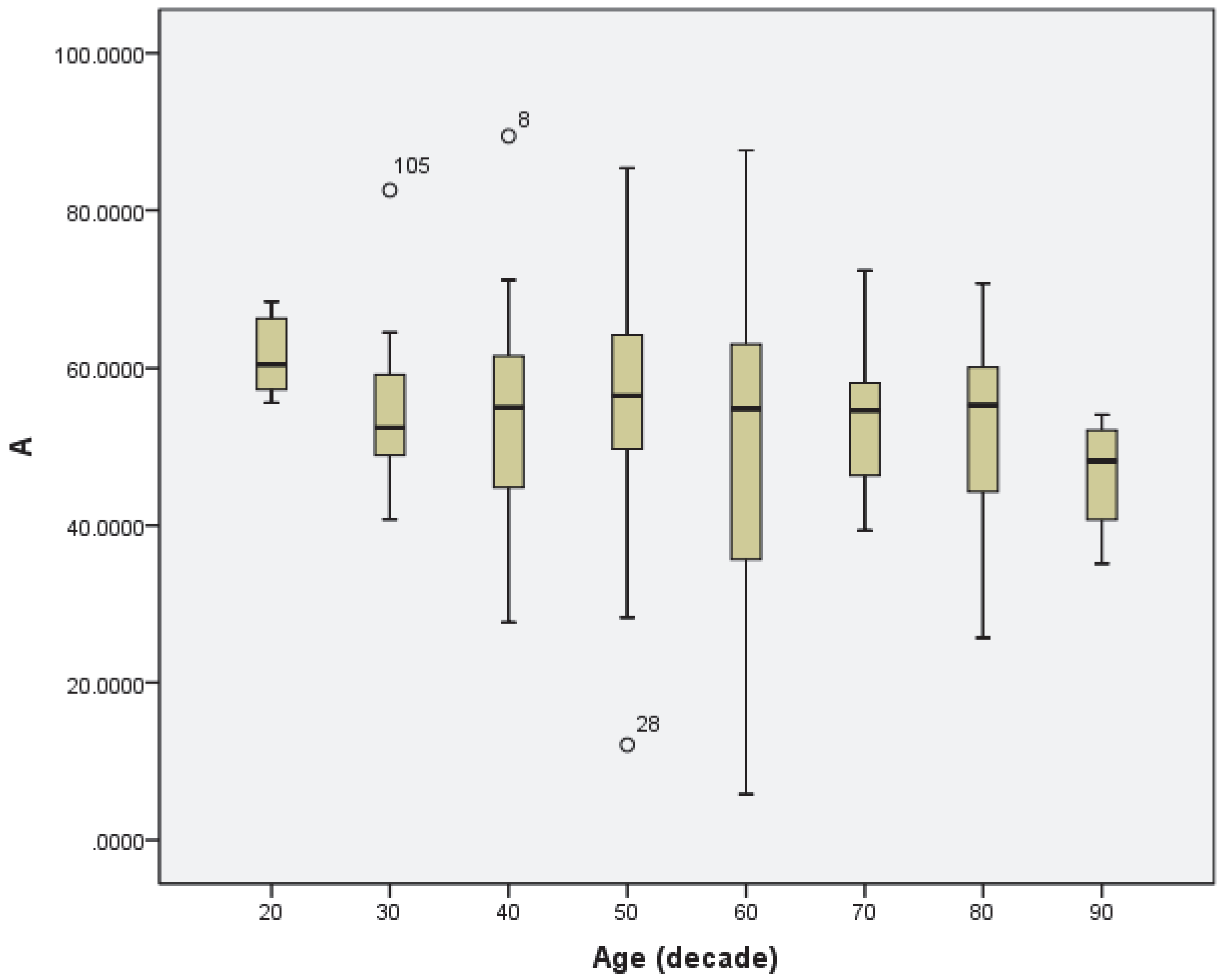


Figure 4.2: Distribution of Measurement A by age group

4.1.2 Intra-observer error

Each measurement was collected from the CT scan a second time two weeks later on all individuals to assess replicability of the method; the order of analysis remained the same. The mean difference between first and second trials for all measurements of all individuals was calculated by summing the absolute difference between the first and second trials for all measurements (A-D) and dividing this by the number of individuals. The mean difference between first and second trial measurements for all individuals is 0.67 mm. This is lower than the average slice thickness which is 1.70 mm and slightly greater than the minimal slice thickness of 0.5 mm. No significant differences were observed between any of the repeated measurements. Table 4.2 shows the mean average difference between first and second measurements by slice thickness (the six anomalous individuals discussed below were not included) and Figure 4.3 shows a box plot of the average difference by slice thickness.

Table 4.2: Mean average difference between first and second measurements by slice thickness

Slice thickness (in mm)	Mean average difference between first and second measurements	Standard deviation
0.5 (n=17)	0.17	0.14
1 (n=7)	0.40	0.20
2 (n=97)	0.30	0.15

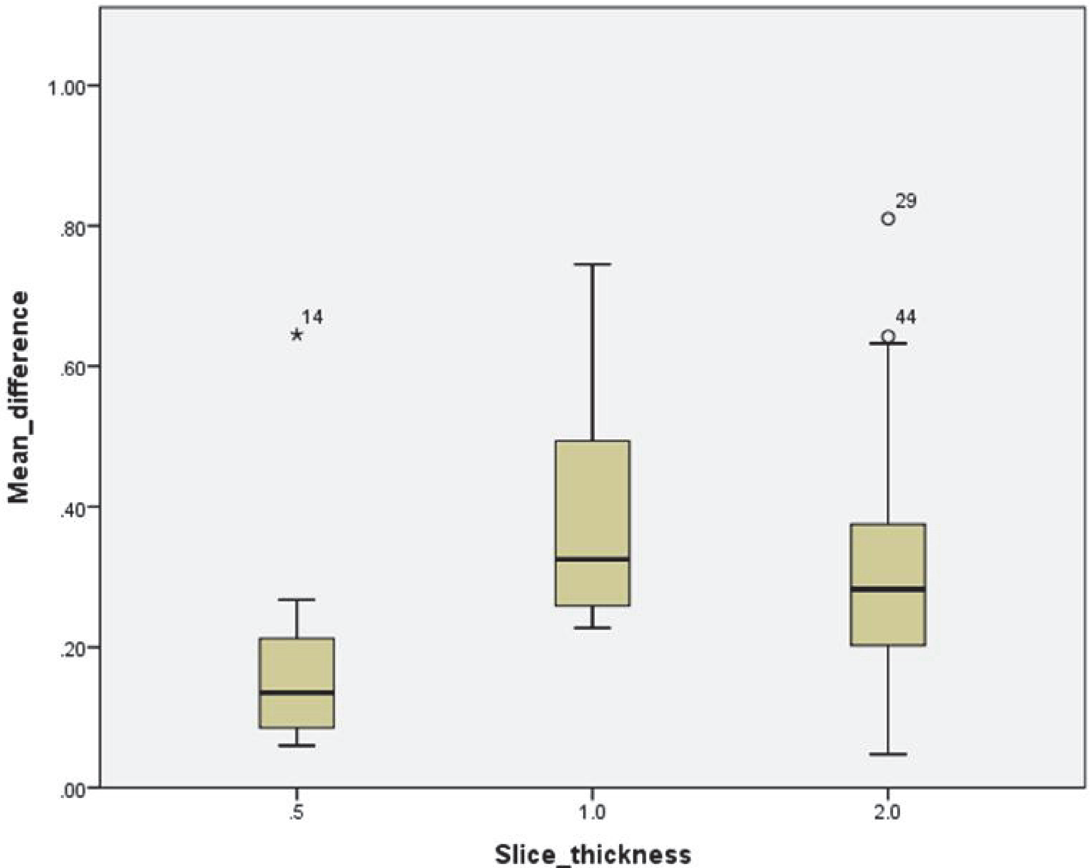


Figure 4.3 Box plot of average difference by slice thickness

Analysis of variance (ANOVA) shows that there is significant difference between the means ($F = 7.28$, $p < .05$). The effect size ($r = 0.33$) is not substantive. *Post hoc* tests (Table 4.3) show that there is significant difference between mean average difference of those scans with a slice thicknesses of 0.5 mm and the mean average difference of those scans taken with slice thicknesses both 1 mm (.003) and 2 mm (.006).

Table 4.3: ***Post hoc*** **tests of mean average difference by slice thickness**

Multiple Comparisons

Dependent Variable: Mean_difference

	(I) Slice_thickness	(J) Slice_thickness	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Hochberg	.5	1.0	-.22653*	.06637	.003	-.3872	-.0659
		2.0	-.12355*	.03886	.006	-.2176	-.0295
	1.0	.5	.22653*	.06637	.003	.0659	.3872
		2.0	.10299	.05784	.214	-.0370	.2430
	2.0	.5	.12355*	.03886	.006	.0295	.2176
		1.0	-.10299	.05784	.214	-.2430	.0370
Games-Howell	.5	1.0	-.22653	.08122	.052	-.4553	.0022
		2.0	-.12355*	.03673	.007	-.2156	-.0315
	1.0	.5	.22653	.08122	.052	-.0022	.4553
		2.0	.10299	.07541	.411	-.1234	.3294
	2.0	.5	.12355*	.03673	.007	.0315	.2156
		1.0	-.10299	.07541	.411	-.3294	.1234

*. The mean difference is significant at the 0.05 level.

A few individuals (n=6) with abnormal or difficult to see sinus morphology showed differences when the two sets of measurements were compared. The average difference between first and second measurement trials for all measurements for this group is 8.39 mm, which is well above the average slice thickness. If these outliers are removed the average difference between the two sets of measurements for the rest of the sample drops to 0.29 mm. The morphology of these individuals will be looked at further in the discussion chapter.

4.2 Validation of Ribeiro's (2000) individualization technique

The second trial measurements were used as a proxy for a post-mortem scan to emulate a real world forensic situation. Each case was assessed for matches relative to all individuals in the sample. Following Ribeiro's criteria, a successful match required all 4 measurements to fall within ±2 mm window of the original measurements. Ribeiro (2000) method accuracy, precision, false positive and false negative data are presented in Table 4.4. Accuracy was considered to be the amount of times the second trials matched the original, producing a unique match. Precision was calculated by including the number of times the second trial matched the original including matches to other individuals in the sample, non-unique matches. False positives were when an individual (other than the correct individual) is identified, while false negatives are when the correct individual is rejected.

Table 4.4 Summary of Ribeiro (2000) method performance

Accuracy	77.16%
Precision	97.64%
False positives	21.26%
False negatives	3.94%

The results show that a unique match was found in 98 of 127 cases. In cases where a unique match was not found, the results varied. Most commonly two matches were found where one was the correct individual and the other was not (n=22). In a few cases several matches were returned, where one was the correct individual and the others were not (three matches, n=2; four matches, n=2). In five cases no match was returned and in one case three matches were returned with none being the correct individual. Analysis of the cases of no match shows that the morphology of these individuals' frontal sinuses was atypical. This anomalous morphology included two individuals that appeared to have two intersinus septa (one is the expected). The group in which multiple matches were returned (including the correct individual) is made up of 13 males, with an average age 51.31 years and 10 females, with an average age of 52.8 years. Tests of significance using an independent T-test combining the individuals with no match and the individuals that produced multiple matches showed no significant difference for age for these mismatched individuals (t = -0.655, p>0.05). Chi-squared test showed no significant difference for sex $X^2(1) = 0.175$, $p < 0.5$).

4.3 Reichs and Dorion (1992) method validation

Six individuals could not be scored using this method because their frontal sinuses did not extend above the orbital cavities. In total 123 individuals were scored because one additional individual (8281236) could only be scored on one transverse slice because the sinuses were of diminutive height.

To assess reproducibility each individual was rescored a second time on the same slice. 40 individuals (32.52%) showed a difference in 14-digit scores, resulting in low repeatability for this method. Most of the individuals that differed only did so by one digit (57.5%). Table 4.5 shows the breakdown of difference between 14-digit scores.

Table 4.5: Breakdown of difference between 14-digit scores

Number of digits different between scoring first and second time	Number of individuals
0	83
1	23
2	10
3	2
>3	5

When slice number was unknown and the method repeated even poorer results were seen (different scores in 80.64% of individuals). Table 4.6 shows the comparison of male and female ages for mismatched re-collected data when the original slice number was known or unknown.

Table 4.6: Comparison of male and female ages for mismatched re-collected data when original slice number was known or unknown

Method	Reichs & Dorion mismatched known slice (n=40)	Reichs & Dorion mismatched unknown slice (n=99)
# of males	22 (55%)	53 (53.53%)
Mean age of males	49.23	49.18 (2 unknown age)
# of females	16 (40%)	46 (46.47%)
Mean age of females	48.31	55.46
# of unknown	2 (5%)	0

To measure the effect of slice number all individuals were re-scored. The average slice difference is 1.34 mm (1.47 mm first slice and 1.21 mm second slice). For first slice 78.86% (97/123) of individuals were re-scored on a different slice. Of those 73.2% (71/97) resulted in a different score. For second slice 64.23% (79/123) of individuals re-scored on a different slice. Of those in 58.23% (46/79) resulted in a different score.

A trait analysis (Table 4.7) shows that the number of partial septa and bilateral asymmetry are the variables that produced the most difference in scores when a different slice is used, although other variables (number of complete cells, distribution of partial septa) show a high degree of difference.

Table 4.7: Frequency of differences between original score and rescoring for known and unknown slice number by trait

Trait	Freq. of difference between original and known slice (N = 123)	Freq. of difference between original and unknown slice (N = 123)
Bilateral dimension	2	12
Bilateral asymmetry	17	**62**
Superiority of side	5	39
Distribution of partial septa	14	41
Number of partial septa	**24**	52
Distribution of complete cells	2	43
Number of complete cells	4	52

4.4 Validation of Reichs and Dorion (1992) individualization technique

To test the ability of the Reichs and Dorion method to individualise each case was assessed for matches relative to all individuals in the sample by comparing the original 14-digit score to the repeated score on the same slice number. Reichs and Dorion (1992) method accuracy, precision, false positive and false negative data for all scorable individuals (n=123) are presented in Table 4.8. Accuracy was considered to be the amount of times the second trials matched the original, producing a unique match. Precision was calculated by including the number of times the second trial matched the original including matches to other individuals in the sample, non-unique matches. False positives are when an individual other than the correct individual is identified, while false negatives are when the correct individual is rejected.

Table 4.8 Summary of Reichs and Dorion (1992) method performance

Accuracy	63.41%
Precision	67.48%
False positives	11.38%
False negatives	32.54%

Matches between the 14-digit scores were found in 67.48% of 123 individuals this method could be performed on (n=83). However, when the slice number was unknown and compared to the original score matches were reduced to 18.7% (n=23) of individuals.

A pivot table report was generated in Excel™ to organise and group the data generated by the application of the Reichs and Dorion (1992) method to the current sample. The pivot table was used to look for duplicate scores. The results show that this method does not produce entirely unique identifiers. In the context of the original scoring there are ten individuals (8.13%) which share 14-digit codes (five codes, each of which have two individuals possessing the same number). Codes with two individuals possessing the same number were common.

When slice number was known there were twelve individuals (9.75%) (six codes, each with two individuals possessing the same number) and when slice number was unknown there were fourteen individuals (11.38%) (seven codes, each with two individuals possessing the same number). These code numbers are shown below in Table 4.9. Interestingly the original assessment and known slice assessments share three of the same repeated scores (40000004000012, 44211004000012, 43200004000000), whereas the known and unknown slice assessments share two repeated scores (42200004000012 and 4100004320012).

Table 4.9: Non-unique 14-digit codes for original data collection and re-collected data when slice number was known and unknown

Non-unique codes for original assessment	Non-unique codes for repeated scores where slide number is known	Non-unique codes for repeated scores where slide number is unknown
40000004000012	40000004000012	40000003000000
44211004000012	44211004000012	41300004330000
43200004000000	43200004000000	41200004000012
41300004110044	44200004000012	44200004000012
42200004420012	41100004320012	41100004320012
	41111004220044	40011004000012
		43211004000012

It was noted that in 98.6% of first slice and 87.8% of second slice scores bilateral dimension was scored ‘4’ (>15mm). In this sample the average bilateral measurement is 49.66mm on the first slice (lower third) and 32.68mm on the second slice (upper third). It was hypothesised that the frequent occurrence of a score of 4 for bilateral dimension could be contributing to the lack of unique scores. To test this all individuals in the sample were rescored using a new system for bilateral dimension variable (Table 4.10).

Table 4.10: New scoring system compared to original system for bilateral dimension variable

Score	Old system	New system
0	Absent	Absent
1	< 5 mm	<10 mm
2	5 - 10 mm	10 - 20 mm
3	10 - 15 mm	20 - 30 mm
4	>15 mm	30-40 mm
5		40 - 50 mm
6		50 - 60 mm
7		>60 mm

With the changes to the scoring of bilateral dimension, the five duplicate 14-digit scores are reduced to one duplicate. Both individuals with original scores of 40000004000012 produced duplicate scores of 30000002000012. While this removed four of the five (80%) original duplicates it illustrates that this small change to one variable cannot entirely resolve the problems the Reichs and Dorion method produced with unique identifiers.

4.5 Cox et al. (2009) method validation

A total of 107 same skull (SS) comparisons and 5671 different skull (DS) comparisons were made. The mean average total difference score for SS was 46.40 mm (SD = 46.22), while the mean average score for DS was 461.20 mm (SD = 286.02). Logistic regression analysis was chosen because with certain information it can be used to predict which of two groups a person is likely to belong to. In this case, given the total difference (TD) value, are two scans from the same individual (SS) or a different individual (DS). In a binary situation, 100% probability is the correct identification. The predicted probabilities are the probabilities of something occurring given the values of the predictor (Field, 2005).

Initial logistic regression analysis in SPSS 20 using the raw TD scores showed an over dispersion in the top tail due to the large number of different skull comparisons (Figure 4.4). The *Hosmer and Lemeshow goodness-of-fit* statistic was used to assess how well the model fits the data. This model does not fit the data well (Table 4.11). The classification table illustrates that overall 99.8% of cases were correctly classified (Table 4.12), 89.7% of SS and 99.9% of DS using a 0.5 cut off.

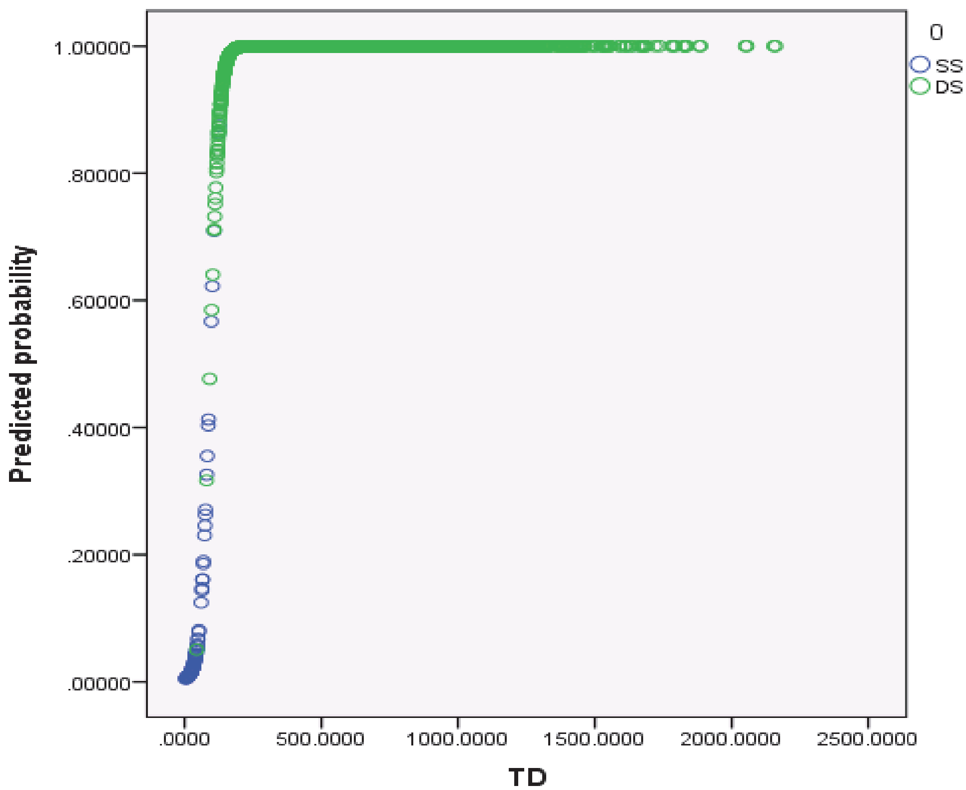


Figure 4.4: Initial logistic regression analysis using raw scores shows over dispersion in the top tail

Table 4.11: Hosmer and Lemeshow Test results of initial logistic regression

Hosmer and Lemeshow Test

Step	Chi-square	df	Sig.
1	115.012	8	.000

Table 4.12: Percent classified for same skull (SS) and different skull (DS) total difference scores (TD scores) for initial logistic regression analysis

Classification Table[a]

			Predicted		
			0		Percentage Correct
	Observed		SS	DS	
Step 1	0	SS	96	11	89.7
		DS	3	5668	99.9
	Overall Percentage				99.8

a. The cut value is .500

A log transformation was performed to rectify the over dispersion visible at the top of Figure 4.4 produced by having so many more different skull (N=5671) comparisons than same skull (N=107) comparisons. The log transformation produced an even distribution in the two tails (Figure 4.5). The *Hosmer and Lemeshow goodness-of-fit* is not significant (Table 4.13) and the classification table still reports an overall correct classification of 99.8% of cases (Table 4.14).

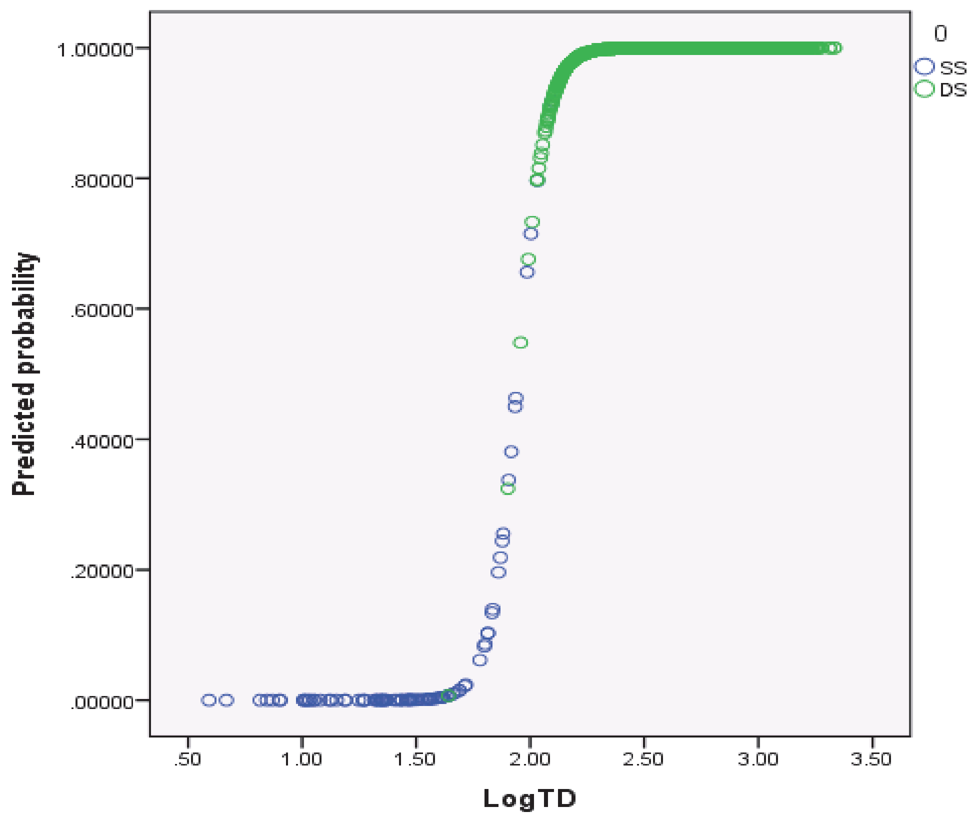


Figure 4.5: Logistic regression results using log transformed data

Table 4.13: Hosmer and Lemeshow Test results using log transformed data

Hosmer and Lemeshow Test

Step	Chi-square	df	Sig.
1	10.172	8	.253

Table 4.14: Percent classified for same skull (SS) and different skull (DS) total difference scores (TD scores) for log transformed logistic regression analysis

Classification Table[a]

Observed			Predicted 0 SS	Predicted 0 DS	Percentage Correct
Step 1	0	SS	96	11	89.7
		DS	2	5669	100.0
	Overall Percentage				99.8

a. The cut value is .500

4.6 Validation of Cox et al. (2009) individualization technique

Accuracy, precision, false positive and false negative data for the Cox et al. (2009) method are presented in Table 4.15 for all scorable individuals (n=107). Accuracy was calculated using the same skull matches and precision included the same skull and different skull matches and captures when the results are correct.

Table 4.15 Summary of Cox et al. (2009) method performance

Accuracy	89.7%
Precision	99.8%
False positives	10.28%
False negatives	1.87%

4.6.1 Different skull comparisons

Using LogTD values only 2 scores were misclassified employing a cut off of 0.5, which corresponds to a TD score of approximately 90 (Table 4.16).

Table 4.16: Different skull (DS) misclassified scores

TD Score	Probability	Individuals
43.8204	0.00689	02271223f / 8281236
79.7693	0.32412	10221246 / 02271146a

4.6.2 Same skull comparisons

For the same skull comparisons 11 individuals were misclassified using the LogTD values and a cut off of 0.5 (Table 4.17).

Table 4.17: Same skull (SS) misclassified scores

TD Score	Probability	Individuals
96.9759	0.65618	8291405
100.8045	0.71507	12879119
107.316	0.79621	11031243
123.0257	0.91124	02271223
124.7242	0.91877	8281230
161.7515	0.98613	8291430
162.4853	0.98656	02271223e
164.982	0.98777	8281222
179.5364	0.99332	9051203
257.5865	0.99948	02271222
259.4805	0.99950	8291439

This chapter has detailed the results of the validation of three methods to quantify the uniqueness seen in the frontal sinuses. The next chapter will discuss each method's ability to be replicated and repeated, as well as its ability to produce individual identifiers. In addition, cases of method failure will be presented and analysed for potential causes.

Chapter 5 Discussion

This thesis presents the results of an independent validation of three methods designed to establish personal identification using the frontal sinuses: one measurement method, one coding system method and one outline method. Validation studies enable statements to be made on method reliability (including accuracy and precision) for current legal requirements regarding expert witness testimony. This chapter will discuss the primary criteria of method validation, including issues with replication, repeatability and ability to individualise. It will also examine instances where each method failed and present any discernible patterns. The chapter concludes with a discussion of the results of the current study within the context of previous research.

5.1 Method replication

Method replication deals with the basic application of the published methods to the current dataset, including ease of use, since it is important in forensic cases to be able to apply methods and produce results quickly (Derrick et al, 2015). Of all the methods, Ribeiro's (2000) was the easiest and most expedient to apply. This method involves the visualisation of the frontal sinuses so that four lines corresponding to the lateral and most superior points of the left and right sinuses can be drawn. From these lines, four measurements were taken. In general the most lateral and superior features were the easiest to visualise and determine which made measurement taking straightforward. Due to its simplicity and few required measurements, this method was also quick to carry out. This method can also be considered flexible since it can be applied to both plane film radiographs and CT images.

The Reichs and Dorion (1992) scoring system method was the most difficult to replicate. The original paper contained sparse descriptions of the variables and only a few, low quality images were provided for illustration. The most difficult variables to assess were the distribution and number of partial septa and the distribution and number of complete cells. Within the current dataset the inconsistent position of the head further added to these difficulties. In an attempt to counter variation in head position all individuals were resliced to a standard position, but this process involves the use of interpolation and affected image slice clarity in some areas, making assessment of some frontal sinus features more challenging. Inconsistencies are also seen in the choice of transverse slice to score features because no clear instructions are provided in the original publication about which slices should be used. It is concluded that improvements to this method are needed in order to apply it to forensic cases with any consistency. Successful application of this method would greatly be aided by a consistent head position during scanning, in addition to clearer definitions with well-illustrated examples of all features to be assessed. Since this method requires transverse images of the frontal sinuses it cannot be applied to plane film X-ray images of the skull, which are typically taken in the anterior-posterior and sagittal planes.

The Cox et al. (2009) outline method was well described in the original article, but was very time consuming to conduct on the current dataset. In addition to taking extensive time to carry out, additional software (in this study Adobe Photoshop CS6) was required to acquire the origin to border distances on which total difference is based. On average, measuring the origin to border distance using the methodology laid out in the original article took 15- 20 minutes for each outline depending on its complexity. A Matlab script was created specifically for this purpose and reduced the time taken for each outline significantly. However, this script would require additional work to be applied routinely to forensic investigations. Among the challenges for this program was the lack of automation, meaning the user was required to enter several numbers for each individual at different lines of the computer code. It is noted that development of an entirely automated program would speed up comparisons of outline data (Christensen, pers. comm.).

5.2 Intraobserver error

Method repeatability encapsulates intraobserver error or the ability to repeat the method by the same observer. Low intraobserver error is a sign of high precision, an important indicator of good methods. In this validation study interobserver error (between observers) was not measured. The following section discusses the intraobserver error for each method.

The Ribeiro (2000) method produced an intraobserver error on average of 0.67mm for all four measurements. However, intraobserver error differed for each of the four distances taken with measurement A producing the lowest error (A = 0.56 mm, B = 0.93 mm, C = 0.62 mm, D = 0.58 mm). This is explained by looking at the measurements. Measurement A is the total diameter of the frontal sinuses, which is the most straightforward measurement and least susceptible to user interpretation relative to the other measurements (Measurement B = distance between highest points of right and left sinuses, Measurement C = distance between lateral limit and highest point of right sinus, and Measurement D = distance between lateral limit and highest point of left sinus). The intraobserver error score of 0.67 mm is less than the average slice thickness (1.74 mm) for the sample. A closer look at the intraobserver error showed that six individuals produced much higher differences than expected. The average difference for all four measurements for these individuals is 8.39 mm (compared with 0.67mm for the whole sample). Individual examination of these cases is considered below, however these individuals all had showed various morphological anomalies which contributed to the high intraobserver error between trials. If these morphologically anomalous individuals are removed from the greater sample, the average intraobserver error for the remaining sample is 0.29 mm, a value less than the minimum slice thickness of 0.5 mm.

It is interesting to examine these six morphologically anomalous individuals in greater detail to see why they were inconsistently measured. A comparison of the first and second trials for two individuals (02271101b and 901339) shows the intersinus septum was drawn in different places. Both individuals possessed two septa and it was difficult to identify which was the intersinus septum from the anterior-posterior view alone. By looking at the transverse slices for these individuals it is possible to identify the intersinus septum. The intersinus septum was correctly identified in the second trial for both individuals 02271101b and 901339. The drawing of the intersinus septa in different places for these two individuals between the different trials results in different high points for the left and right sinuses (lines F and G), leading to different results for measurements B, C and D. Measurement A is consistent; in the case of individual 02271101b it is identical in both trials (47.12mm) (Figure 5.1). Figure 5.2 depicts the differences for individual 901339.

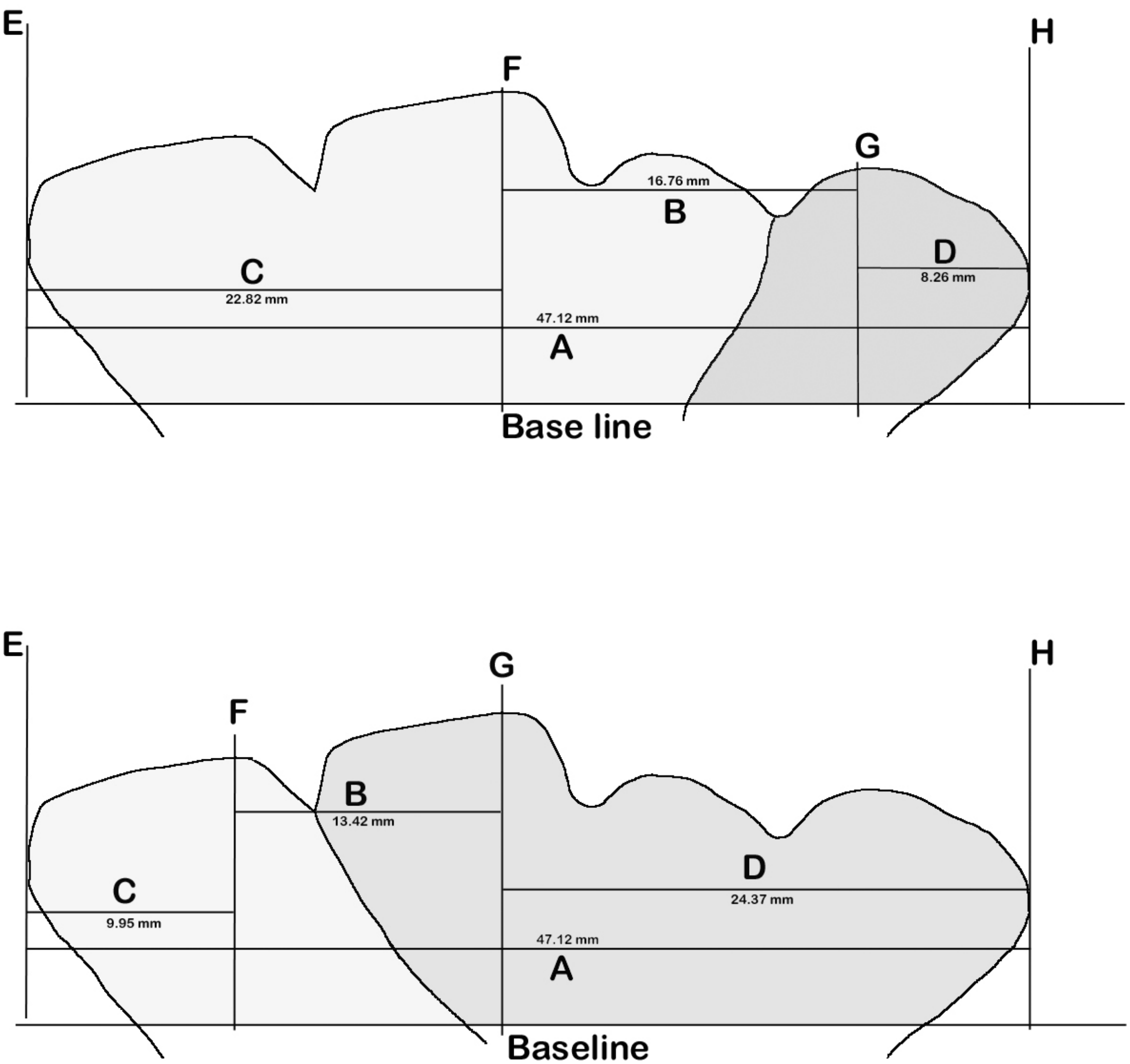


Figure 5.1: Individual 02271101b first and second trial comparisons showing different position of the intersinus septum

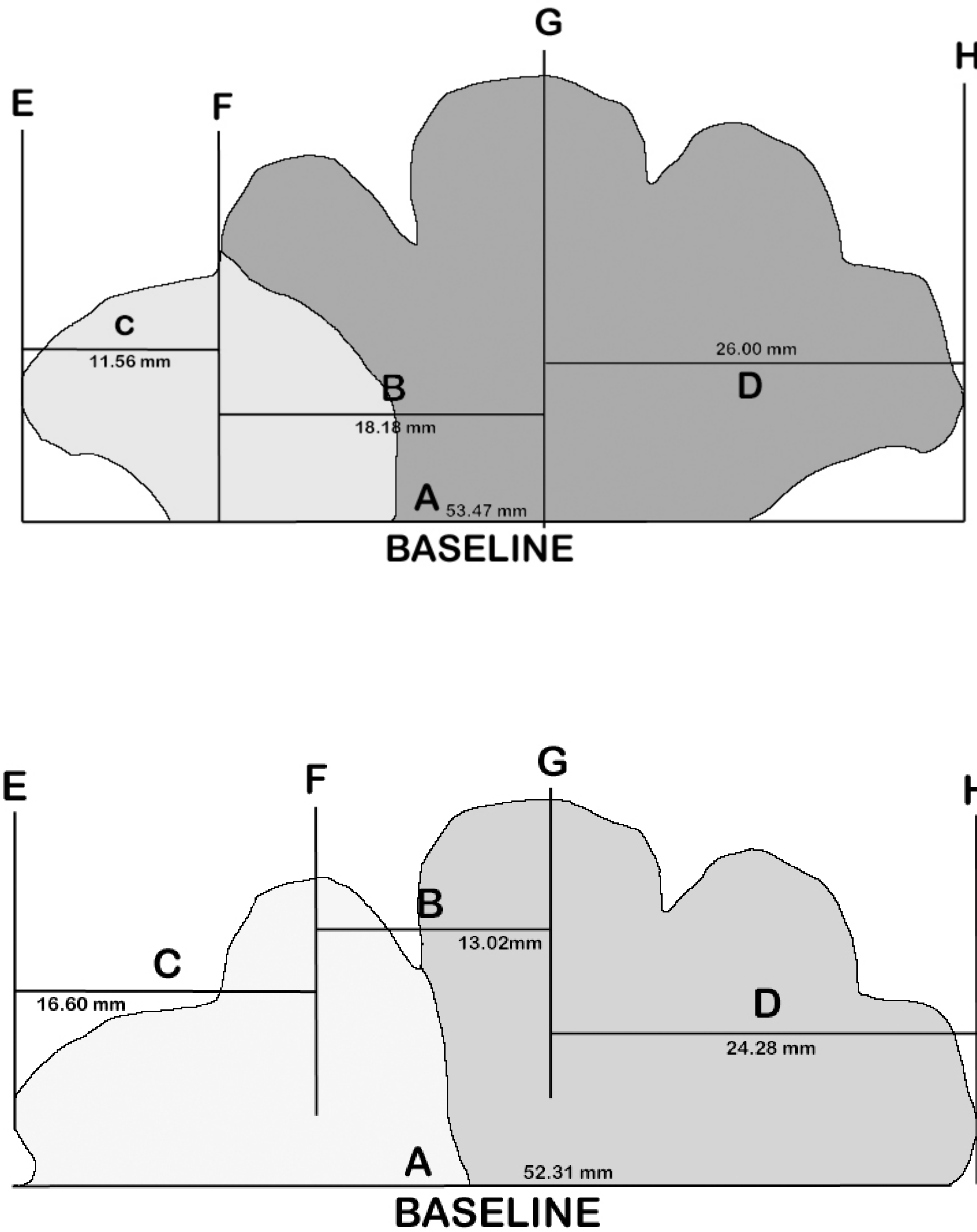
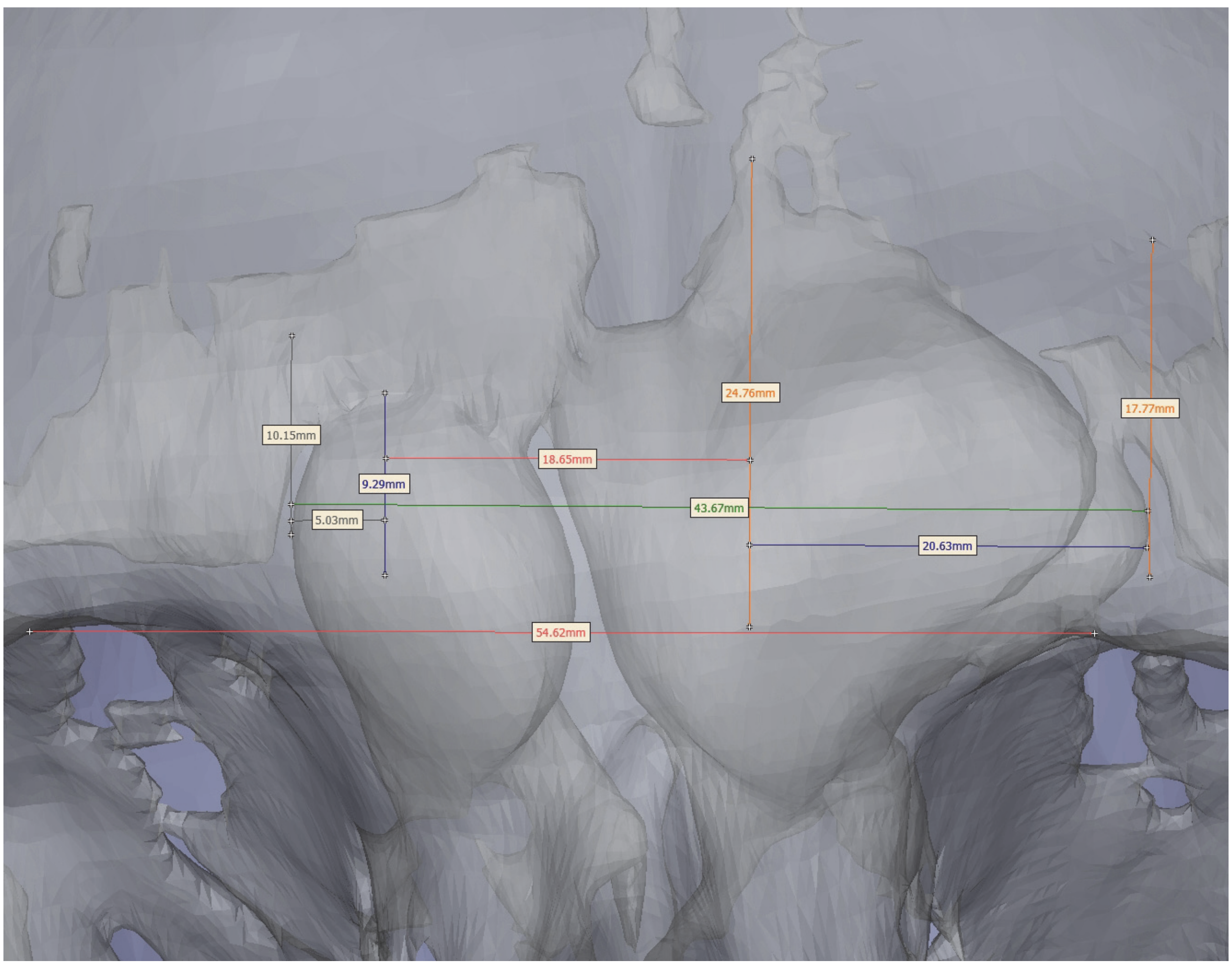


Figure 5.2: Individual 901339 first and second trial comparisons showing different position of the intersinus septum

Individual 11031258b has distinct left and right frontal sinuses so no difficulties were experienced with the intersinus septum, but it is the anomalous morphology in the superior portion of the sinuses that has led to different results (Figure 5.3). It is unclear from the anterior-posterior view whether the superior portion of both the left and right frontal sinuses characterizes true pneumatisation. This variation was difficult to assess and no mention was made of how to address features such as these in the original article. With no guidelines to follow this has led to differing evaluation in this case.



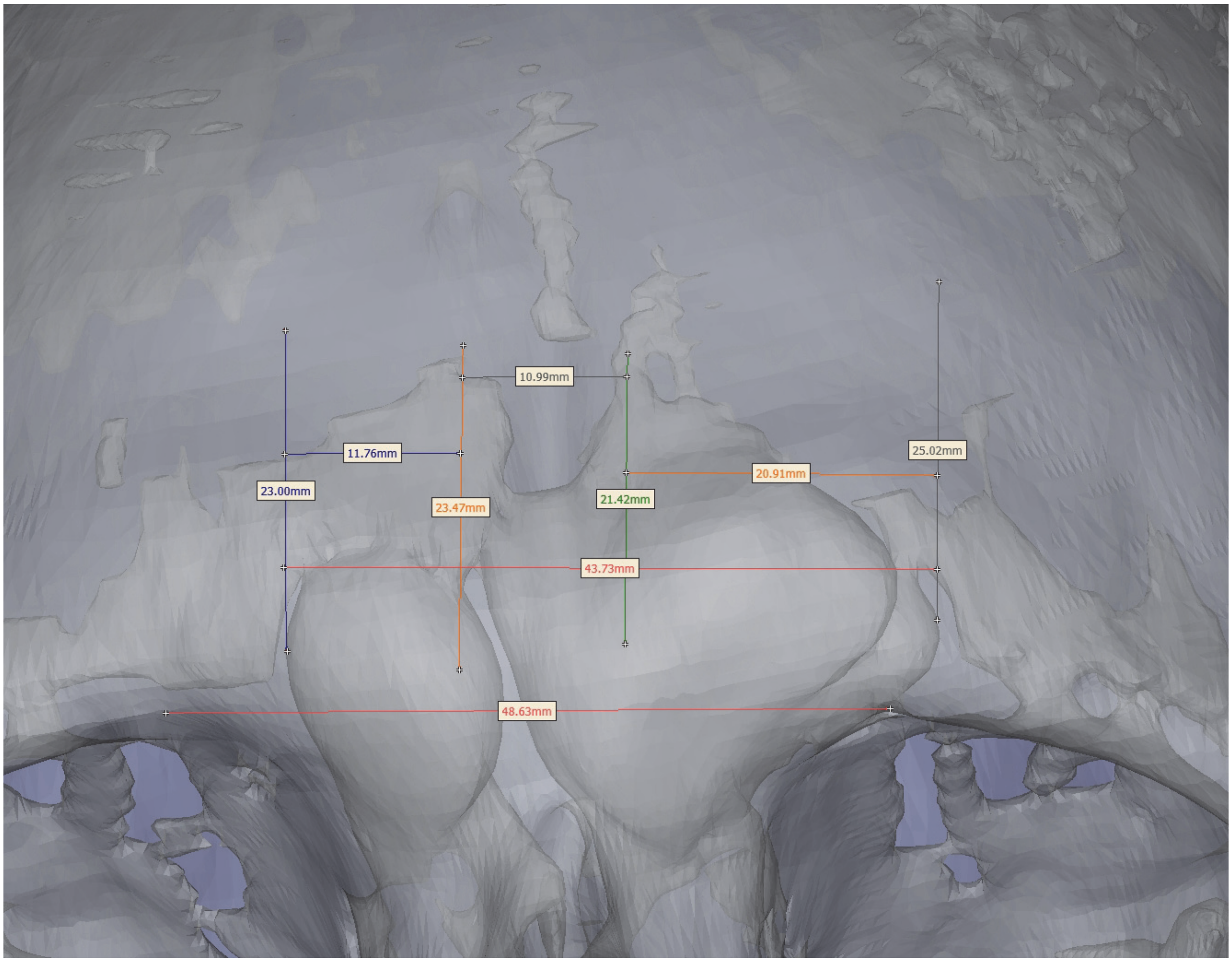


Figure 5.3: Individual 11031258b first and second trial comparisons showing anomalous morphology in the superior portion of the frontal sinuses.

In the last example, individual 12987108 (Figure 5.4), the small right frontal sinus has been classified differently between the two trials. In the first trial, the right frontal sinus had been measured, but in the second case it was not. The original article was confusing because it did not define the presence of a frontal sinus. A suggestion to reduce misunderstanding would be to classify the frontal sinuses as "present" and therefore measurable using this method if they extend above the baseline connecting the superior borders of the orbits.

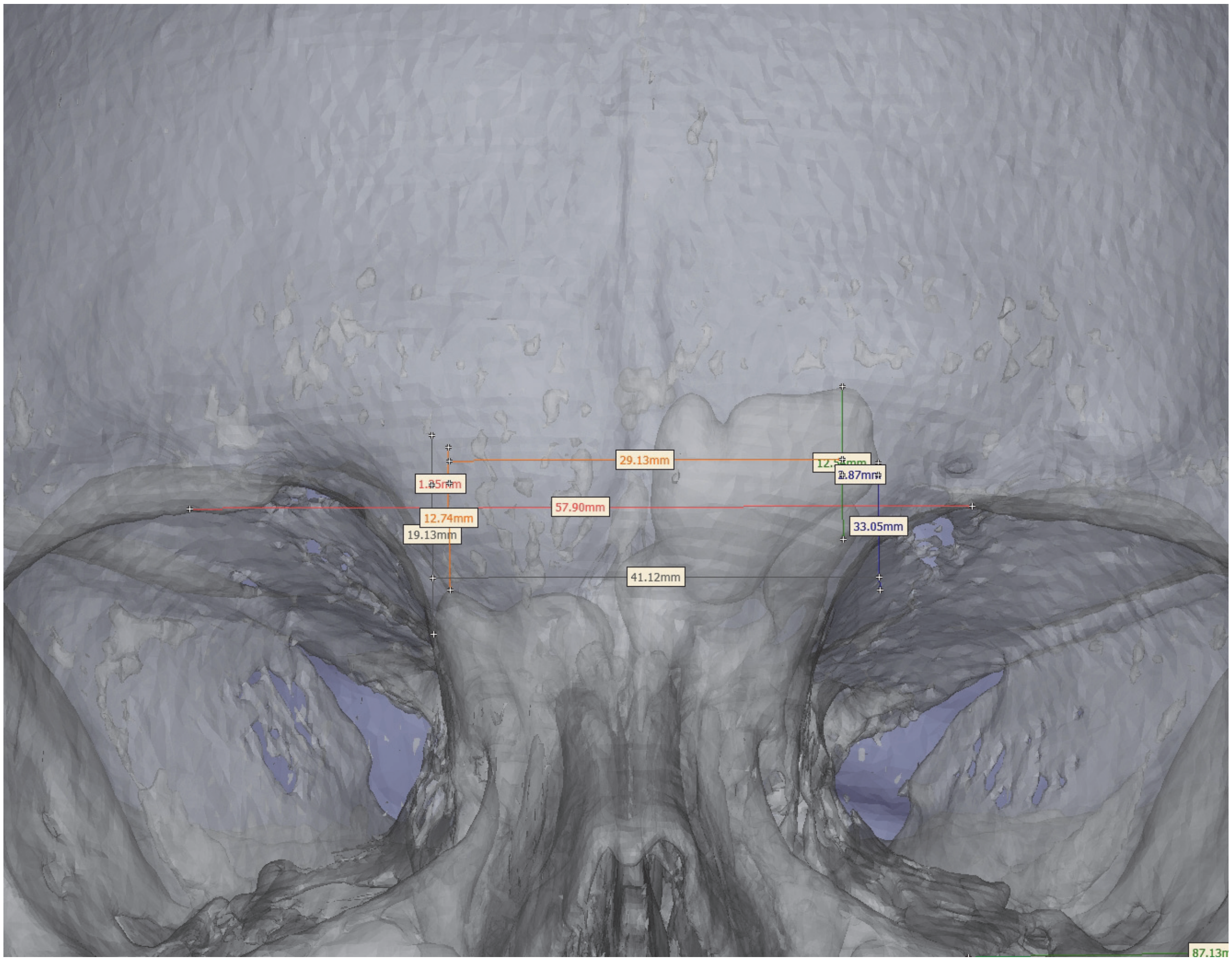


Figure 5.4: Individual 12987108. The small right frontal sinus was classified differently between the two trials, present in one trial and absent in the other.

Analysis of variance (ANOVA) shows that there was a significant difference for intraobserver error between the three different slice thicknesses comprising the current sample. 0.5 mm slice thickness produced intraobserver error differences that were significantly lower than both 1 mm and 2 mm slice thicknesses. These findings suggest that 0.5 mm slice thickness represents the "gold standard" for minimization of intraobserver (and potentially interobserver) error. It is recommended that where possible the Ribeiro (2000) method protocol developed and described in the current study be applied to CT data utilizing 0.5 mm slice thickness.

The intraobserver error for the Reichs and Dorion (1992) scoring method was very high compared to the other methods. Using the Reichs and Dorion (1992) method 40 individuals (32.52%) showed a difference in 14-digit scores, resulting in low repeatability for this method. Most of the individuals had a 1 digit difference (23 of 40 or 57.5%). A trait analysis showed that the number of partial septa is the feature with the most variation when scored a second time, although other variables (bilateral asymmetry and distribution of partial septa) also show a high degree of difference. This method was found to be confusing to apply because of poor explanation of the variables; better explanations with clear illustrations may reduce the intraobserver error. One example of a confusing variable is superiority of side. This scoring feature describes the "... direction of asymmetry with regard to left and right sides. A case is scored 0 through 3, based on the measure of maximum diameter relative to the midline." (Reichs and Dorion, 1992:4) Table 4 in the original publication outlines the class numbers as absent = 0, left equal to right = 1, left greater than right = 2, and right greater than left =3. The problem here is classification group 1, "left and right frontal sinuses equal" since the authors do not quantify this. Must the measurements be exactly equal or within a certain window? MIMICS™ provides measurements to two decimal places so it would be extremely unlikely that two measurements would be equal at this level of precision. In the current study it was determined that the left and right frontal sinuses were considered equal if they were within 1 mm of each other.

The high intraobserver error for this method is concerning and seems to be method driven unlike the intraobserver differences with the other two methods which seem to be due to certain morphological variations. Due to such inconsistent repeatability it is not recommended this method be applied to forensic situations. Table 5.1 and Figures 5.5 to 5.16 provide some of the examples of inconsistent scoring with explanations.

Table 5.1: Examples of inconsistent scoring using Reichs and Dorion (1992) method

Individual	Original score	Known slice score	Unknown slice score	Match between original & known	Match original between & unknown
11251047	41245224321112	41245224**4**21112	41244224**4**21112	No	No
10221311	42200002000000	42200002000000	4**11**00**22422**0000	Yes	No
11181204	41200004420000	4**2**200004420000	41200004**00**00**12**	No	No
8291430	41343004320013	41343004320013	4134**4**004320013	Yes	No

Individual 11251047

Original score = 41245224321112

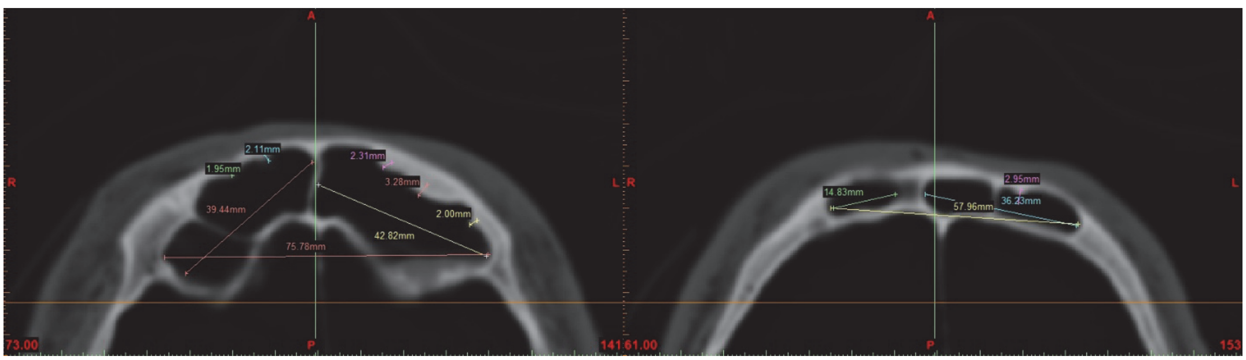


Figure 5.5: Individual 11251047 Reichs and Dorion (1992) method original score

Variable	First slice (141)	Second slice (153)
Bilateral dimension	4 is ≥ 15 mm (75.78 mm)	4 is ≥ 15 mm (57.96 mm)
Bilateral asymmetry	1 is ≥ 80 (92.11 = 39.44/42.82 *100%)	3 is 40 ≤ BAI < 60 (40.93 = 14.83/36.23*100)
Superiority of side	2 (L > R)	2 (L > R)
Classification/distribution of partial septa	4 (present on L and R)	1 (present on L only)
Number of partial septa	5	1
Classification/distribution of complete cells	2 (present on R only)	1 (present on L only)
Number of complete cells	2	2

Known score= 41245224**4**21112

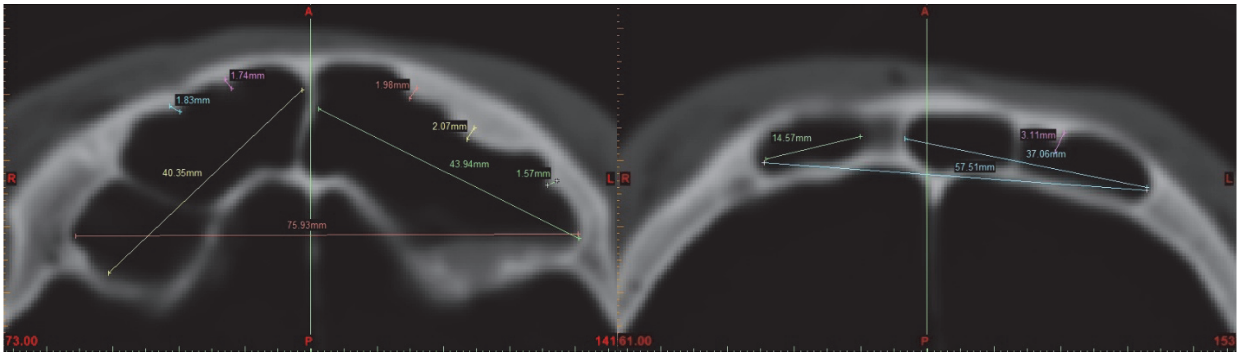


Figure 5.6: Individual 11251047 Reichs and Dorion (1992) method known score

Variable	First slice (141)	Second slice (153)
Bilateral dimension	4 is $\geq$ 15 mm (75.93 mm)	4 is $\geq$ 15 mm (57.51mm)
Bilateral asymmetry	1 is $\geq$ 80 (91.83 = 40.35/43.94*100%)	**4 is 20 $\leq$ BAI <40 (39.31 = 14.57/37.06*100)**
Superiority of side	2 (L > R)	2 (L > R)
Classification/distribution of partial septa	4 (present on L and R)	1 (present on L only)
Number of partial septa	5	1
Classification/distribution of complete cells	2 (present on R only)	1 (present on L only)
Number of complete cells	2	2

Unknown score = 4124422**4**421112

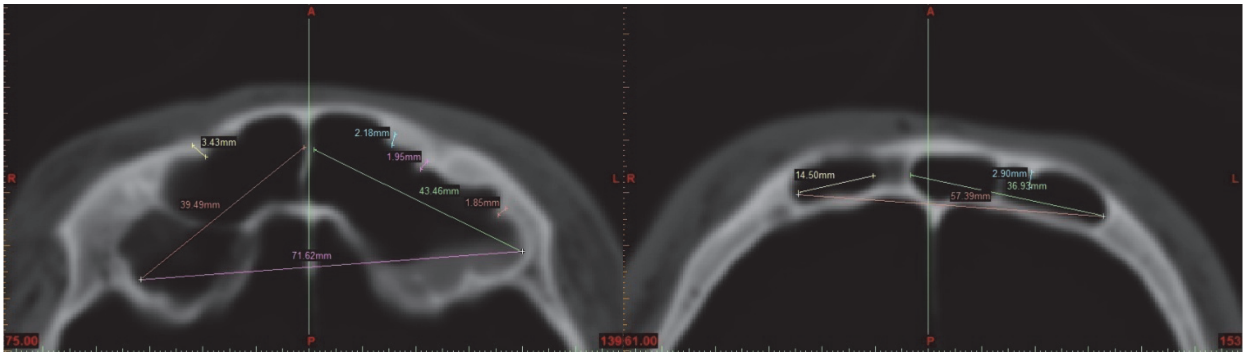


Figure 5.7: Individual 11251047 Reichs and Dorion (1992) method unknown score

Variable	First slice (139)	Second slice (153)
Bilateral dimension	4 is ≥ 15 mm (71.62 mm)	4 is ≥ 15 mm (57.39 mm)
Bilateral asymmetry	1 is ≥ 80 (90.87 = 39.49/43.46 *100%)	**4 is 20 ≤ BAI < 40 (39.26 = 14.5/36.93*100)**
Superiority of side	3 (R > L)	2 (L > R)
Classification/distribution of partial septa	4 (present on L and R)	1 (present on L only)
Number of partial septa	4	1
Classification/distribution of complete cells	0 (none)	1 (present on L only)
Number of complete cells	0 (none)	2

For individual 11251047 the only variable different between the original and both known and unknown slice trials is the score for bilateral asymmetry index taken on the second slice (slice 153 in all trials). With closer inspection it can be seen that in the original trial the bilateral asymmetry index was 40.93, resulting in a score of 3; in the known slice trial the index was 39.31 and in the unknown slice trial it was 39.26, both of which resulted in a score of 4 according to the Reichs and Dorion (1992) method, which has a cut off of 40. Even though the absolute difference between the original and the known and the original and unknown slice trials index scores is small (1.72 for the known slice trial and 1.67 for the unknown slice trial) because the original score has a bilateral asymmetry index over 40 while the known and unknown slice trials both have bilateral asymmetry indices under 40 (although barely) they are receive a different score for this variable and result in a different 14-digit score and subsequent non-match. This example illustrates the innate issue with scoring methods – the reduction of anatomical variation into feature based "individual identifiers", in this case a 14-digit score. This reduction of measurement data into numerical codes introduces error due to morphological oversimplification.

Individual 10221311

Original score = 42200002000000

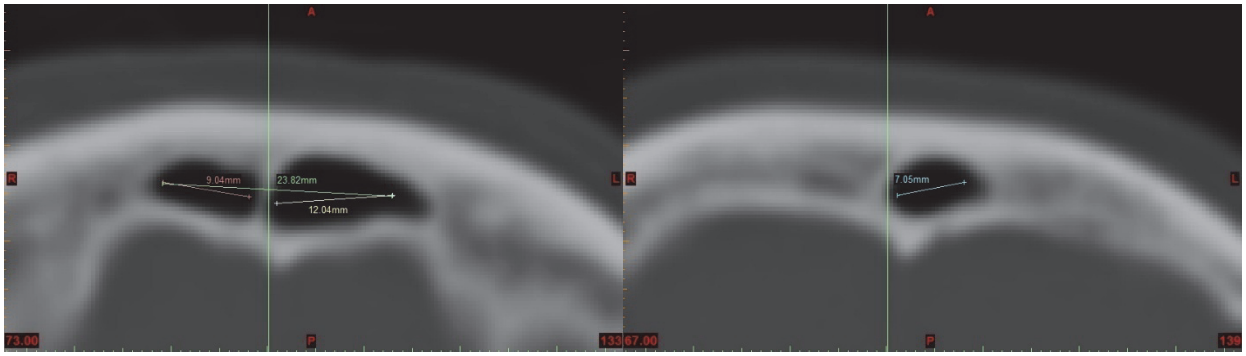


Figure 5.8: Individual 10221311 Reichs and Dorion (1992) method original score

Variable	First slice (133)	Second slice (139)
Bilateral dimension	4 is ≥ 15 mm (23.82 mm)	2 is 5 - < 10 mm (7.05 mm)
Bilateral asymmetry	2 is 60 ≤ BAI< 80 (75.08 = 9.04/12.04 *100%)	0 (absent)
Superiority of side	2 (L > R)	0 (absent)
Classification/distribution of partial septa	0 (none)	0 (none)
Number of partial septa	0	0
Classification/distribution of complete cells	0 (none)	0 (none)
Number of complete cells	0	0

Known score = 42200002000000

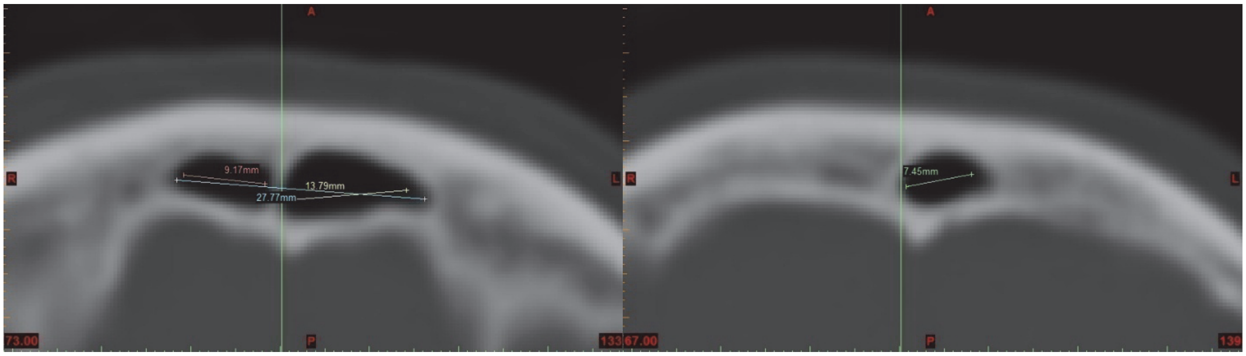


Figure 5.9: Individual 10221311 Reichs and Dorion (1992) method known score

Variable	First slice (133)	Second slice (139)
Bilateral dimension	4 is ≥ 15 mm (27.77 mm)	2 is 5 - < 10 mm (7.45 mm)
Bilateral asymmetry	2 is 60 ≤ BAI < 80 (66.5 = 9.17/13.79 *100%)	0 (absent)
Superiority of side	2 (L > R)	0 (absent)
Classification/distribution of partial septa	0 (none)	0 (none)
Number of partial septa	0	0
Classification/distribution of complete cells	0 (none)	0 (none)
Number of complete cells	0	0

Unknown score = 4**11**00**22422**0000

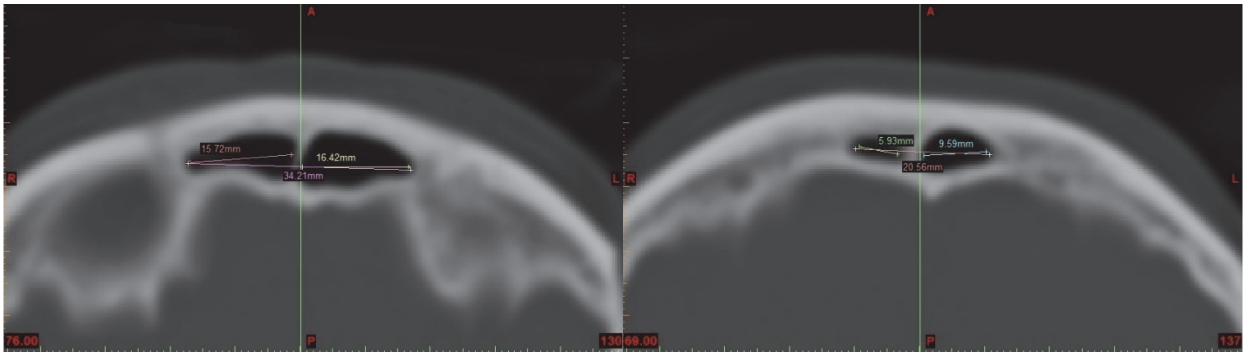


Figure 5.10: Individual 10221311 Reichs and Dorion (1992) method unknown score

Variable	First slice (130)	Second slice (137)
Bilateral dimension	4 is ≥ 15 mm (34.21 mm)	**4 is ≥ 15 mm (20.56 mm)**
Bilateral asymmetry	**1 is ≥ 80 (= 95.74 15.72/16.42*100%)**	**2 60 ≤ BAI < 80 (= 61.83 5.93/9.59 *100)**
Superiority of side	**1 (L = R) see note about this variable**	**2 (L > R)**
Classification/distribution of partial septa	0 (none)	0 (none)
Number of partial septa	0	0
Classification/distribution of complete cells	**2 (R only)**	0 (none)
Number of complete cells	**2**	0

For individual 10221311 the difference in 14-digit scores is seen between the original (and known slice trial) and unknown slice trial and is explained by slice choice. In the original slice (and known slice trial) the first slice is 133 and the second is 139. In the unknown slice trial the first slice is 130 (three below the original) and the second is 137 (two below). This difference in slice selection accounts for the differences seen in five variables (bilateral dimension (second slice), bilateral asymmetry (first and second slices), superiority of side (first and second slices), distribution and number of complete cells (first slice)).

Individual 11181204

Original score = 41200004420000

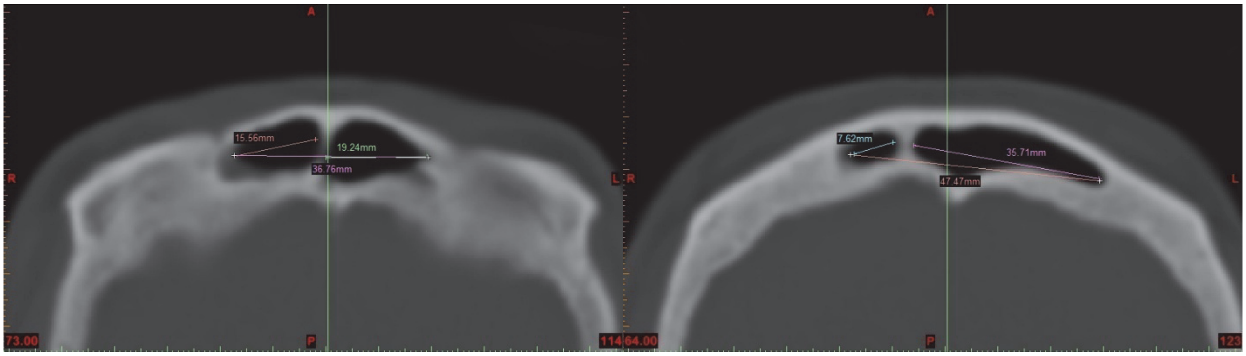


Figure 5.11: Individual 11181204 Reichs and Dorion (1992) method original score

Variable	First slice (114)	Second slice (123)
Bilateral dimension	4 is ≥ 15 mm (36.76 mm)	4 is ≥ 15 mm (47.47 mm)
Bilateral asymmetry	1 is ≥ 80 (80.87 = 15.56/19.24 *100%)	4 is 20 ≤ BAI <40 (= 21.34 7.62/35.71*100)
Superiority of side	2 (L > R)	2 (L > R)
Classification/distribution of partial septa	0 (none)	0 (none)
Number of partial septa	0	0 (none)
Classification/distribution of complete cells	0 (none)	0 (none)
Number of complete cells	0 (none)	0 (none)

Known score = 4**2**200004420000

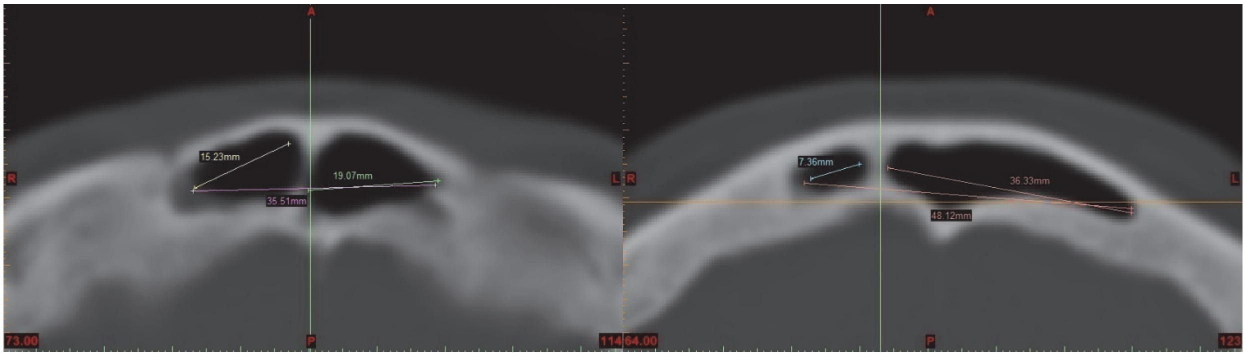


Figure 5.12: Individual 11181204 Reichs and Dorion (1992) method known score

Variable	First slice (114)	Second slice (123)
Bilateral dimension	4 is ≥ 15 mm (35.51 mm)	4 is ≥ 15 mm (48.12 mm)
Bilateral asymmetry	**2 is 60 ≤ BAI < 80 (79.86 = 15.23/19.07 *100%)**	4 is 20 ≤ BAI < 40 (= 20.26 7.36/36.33*100)
Superiority of side	2 (L > R)	2 (L > R)
Classification/distribution of partial septa	0 (none)	0 (none)
Number of partial septa	0	0 (none)
Classification/distribution of complete cells	0 (none)	0 (none)
Number of complete cells	0 (none)	0 (none)

Unknown score = 41200004**00**00**12**

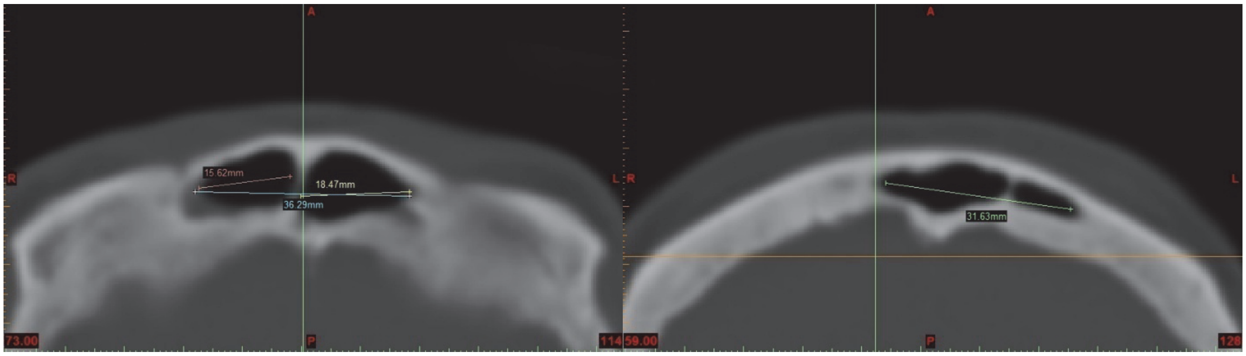


Figure 5.13: Individual 11181204 Reichs and Dorion (1992) method unknown score

Variable	First slice (114)	Second slice (128)
Bilateral dimension	4 is ≥ 15 mm (36.29 mm)	4 is ≥ 15 mm (31.63 mm)
Bilateral asymmetry	1 is ≥ 80 (84.57 = 15.62/18.47 *100%)	**0 (absent)**
Superiority of side	2 (L > R)	**0 (absent)**
Classification/distribution of partial septa	0 (none)	0 (none)
Number of partial septa	0	0 (none)
Classification/distribution of complete cells	0 (none)	1 (L only)
Number of complete cells	0 (none)	2

For individual 11181204 the 14-digit score for original slice and known slice only differs for bilateral asymmetry on the first slice. On the original slice the bilateral asymmetry is 80.87 (15.56 mm/19.24 mm * 100) which receives a score of 2, whereas on the known slice the bilateral asymmetry is 79.86 (15.23 mm/19.07 mm * 100). The difference here is the very small, less than 1 mm difference for all measurements, but results in a different classification because the cut off is 80. This is the same situation as with individual 11251047 and illustrates the problem with arbitrary cut off points utilized by this method. For the unknown slice trial difference are seen between the original and unknown slice trials regarding the second slice. Slice number for the original trial is 123, whereas for the unknown slice trial it is 128, 5 slices different. The differences between the 7-digit scores (4420000 for the original slice and 4000012 for the unknown slice trial) are explained by the different choice of slice number.

<u>Individual 08291430</u>

Original score = 41343004320013

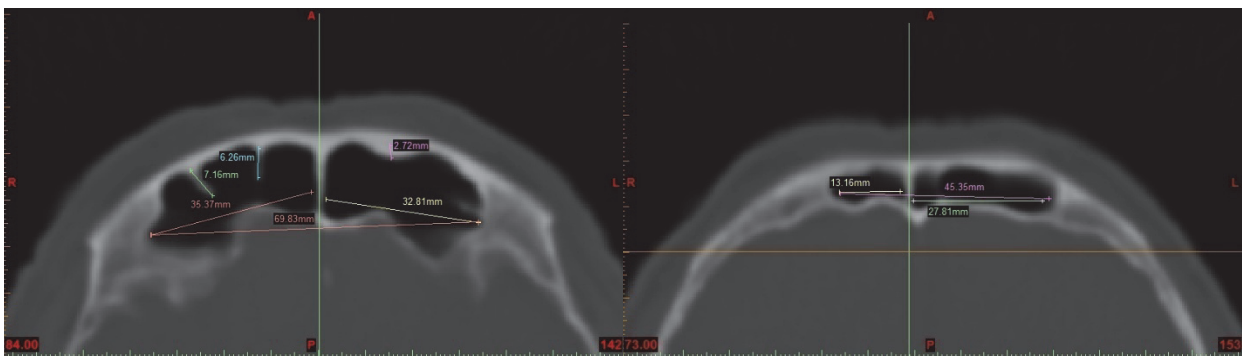


Figure 5.14: Individual 08291430 Reichs and Dorion (1992) method original score

Variable	First slice (142)	Second slice (153)
Bilateral dimension	4 is ≥ 15 mm (69.83 mm)	4 is ≥ 15 mm (45.35 mm)
Bilateral asymmetry	1 is ≥ 80 (92.7 = 32.81/35.37 *100%)	3 is 40 ≤ BAI < 60 (47.32 = 13.16/27.81*100)
Superiority of side	3 (R > L)	2 (L > R)
Classification/distribution of partial septa	4 (present on L and R)	0 (none)
Number of partial septa	3	0 (none)
Classification/distribution of complete cells	0 (none)	1 (present on L only)
Number of complete cells	0 (none)	3

Known score 41343004320013

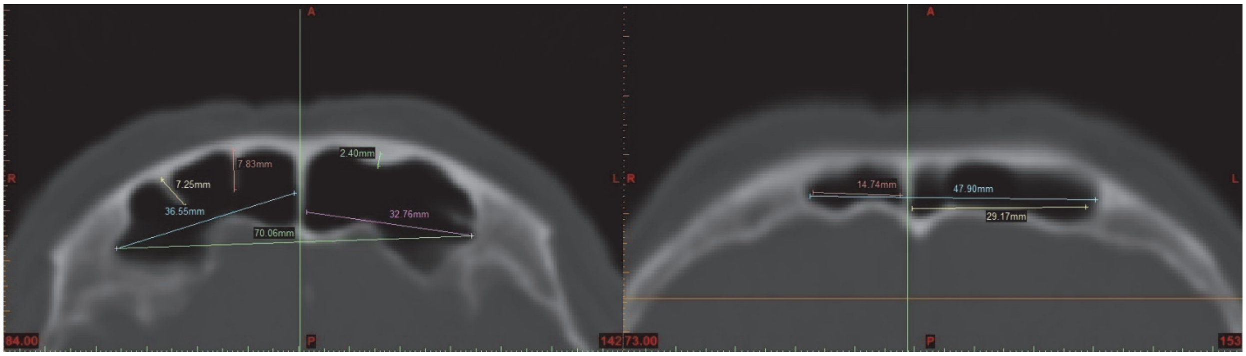


Figure 5.15: Individual 08291430 Reichs and Dorion (1992) method known score

Variable	First slice (142)	Second slice (153)
Bilateral dimension	4 is ≥ 15 mm (70.06 mm)	4 is ≥ 15 mm (47.9 mm)
Bilateral asymmetry	1 is ≥ 80 (89.63 = 32.76/36.55 *100%)	3 is 40 ≤ BAI < 60 (50.53 = 14.74/29.17*100)
Superiority of side	3 (R > L)	2 (L > R)
Classification/distribution of partial septa	4 (present on L and R)	0 (none)
Number of partial septa	3	0 (none)
Classification/distribution of complete cells	0 (none)	1 (present on L only)
Number of complete cells	0 (none)	3

Unknown score 4134**4**004320013

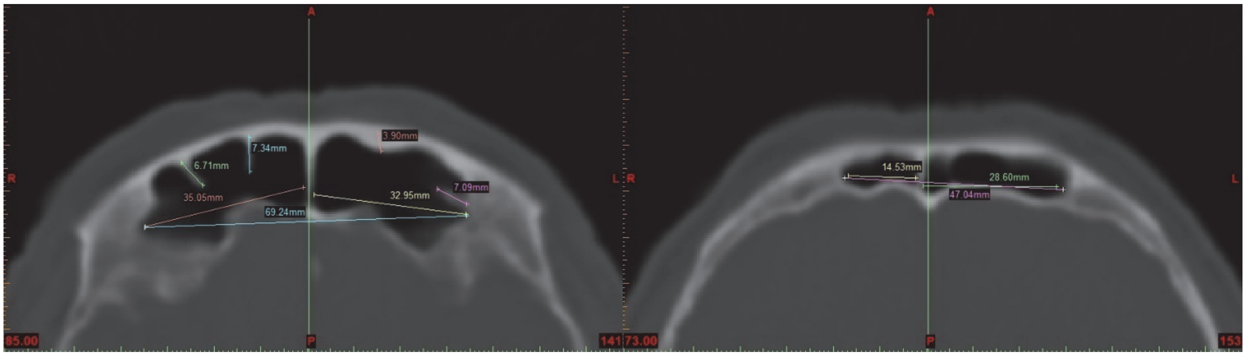


Figure 5.16: Individual 08291430 Reichs and Dorion (1992) method unknown score

Variable	First slice (141)	Second slice (153)
Bilateral dimension	4 is ≥ 15 mm (69.24 mm)	4 is ≥ 15 mm (47.04 mm)
Bilateral asymmetry	1 is ≥ 80 (94.0 = 32.95/35.05 *100%)	3 is 40 ≤ BAI < 60 (50.8 = 14.53/28.6*100)
Superiority of side	3 (R > L)	2 (L > R)
Classification/distribution of partial septa	4 (present on L and R)	0 (none)
Number of partial septa	**4**	0 (none)
Classification/distribution of complete cells	0 (none)	1 (present on L only)
Number of complete cells	0 (none)	3

For individual 08291430 there is no difference between the original and known slice trials. The only difference between the original slice and the unknown slice trials is the number of partial septa. Reichs and Dorion (1992:4) describe partial septa as "... a segment of bone projecting from the superior border into the sinus and dividing it, incompletely, into compartments". A partial septum must measure at least 1 mm and not divide the sinus completely into separate cavities. However, there was no stipulation as to width of partial septa and consequently this variable was often scored inconsistently. Slice number may also contribute to the difference, the original and known first slice trial were both scored on slice 141, whereas the first slice of the unknown slice trial was 142. The second slice chosen was 153 for all trials and all these 7-digit scores are the same.

The Cox et al. (2009) method produced an average total difference score (TD) of 46.40 mm for the same skull comparisons, which is much lower than the average total difference score for the different skull comparisons (461.20 mm) As with the Ribeiro (2000) method, some same skull comparisons produced a much higher TD score than expected. There are 10 individuals with total difference scores above 100. Table 5.2 shows the two measurements of the baseline (trial one and two) and the total difference score for these individuals. There seems to be several factors contributing to the large TD scores between trials one and two in certain individuals – baseline measurement, placement of the baseline and outline tracing,

It seems that differences in the measurement of the baseline connecting the superior borders of the orbits for the frontal sinuses are contributing to large total difference scores in four cases (8291430, 8291439, 12879119 and 02271222, Table 5.2). Interestingly, the two largest total difference scores between the same skull comparisons have differences between the baseline measurements (individual 02271222, Figure 5.17). It seems that differences in the baseline measurement between the compared images have the potential to produce large total difference scores with this method. This warrants further investigation through application of this method to larger samples to see if the findings from the current study are corroborated.

Table 5.2: Individuals with TD scores > 100

Individual	Baseline 1	Baseline 2	Difference in baseline score	TD score
8291439	40.26	44.59	4.33	259.4805
02271222	49.51	44.3	5.21	257.5865
9051203	48.68	49.13	0.45	179.5364
8281222	42.67	42.36	0.31	164.6982
02271223e	47.98	47.99	0.01	162.4853
8291430	39.7	47.59	7.89	161.7515
8281230	44.83	43.05	1.78	124.7242
02271223	69.53	70.61	1.08	123.0257
11031243	50.26	50.47	0.21	107.316
12879119	37.95	41.08	3.13	100.8045

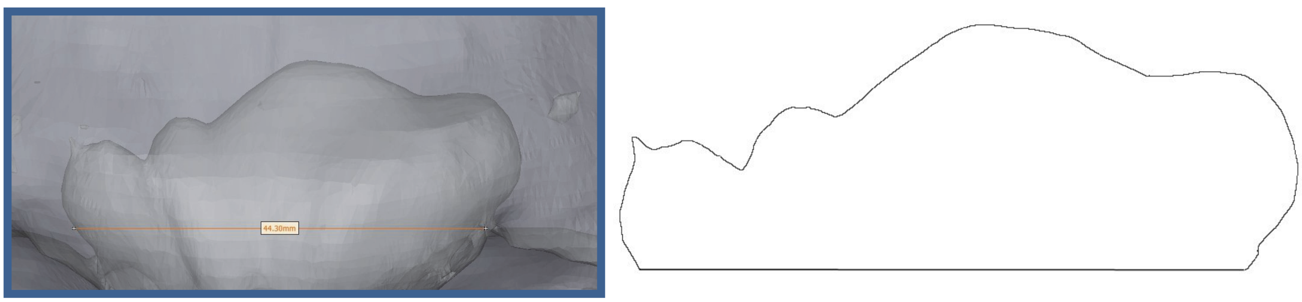


Figure 5.17: Individual 02271222 TD = 257.5865

Baseline 1 = 44.3mm Baseline 2 = 49.51mm

However, the absolute difference between the baseline measurements between the two trials does not seem to explain all the high total difference scores among all the same skull comparisons. In several cases the placement of the baseline is driving the dissimilar in scores. In the case of individual 02271223e the baseline was drawn in a slightly different position (Figure 5.18) and although the overall shape of the outline is the same the measurements are slightly skewed (Figure 5.19). In the first trial the line is drawn above the supraorbital notches and the other trial it is drawn below. In Cox et al.'s (2009) original article there is no mention about where the baseline should be drawn in regards to the variation seen in the supraorbital notches; a set of procedures regarding this would rectify these inconsistencies.

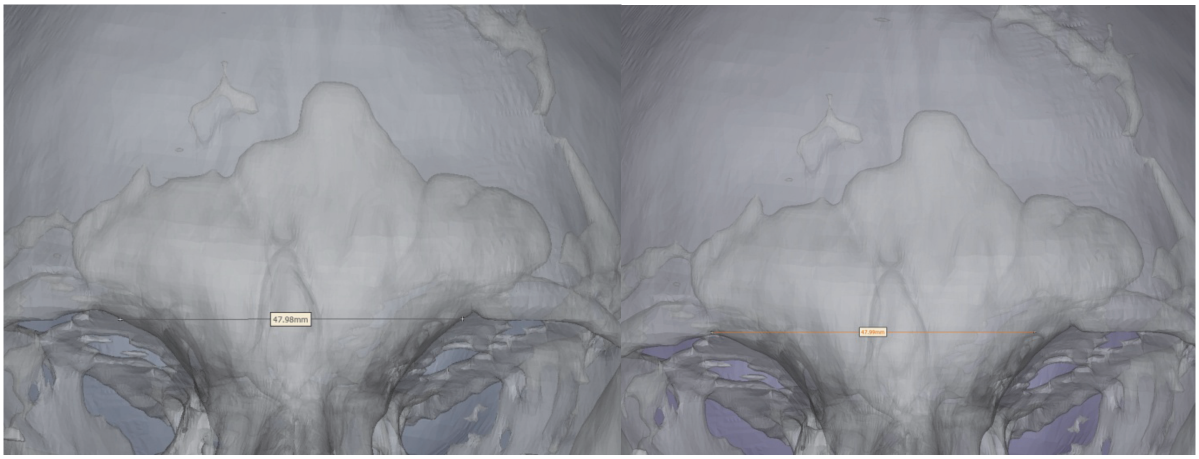


Figure 5.18: Individual 02271223e showing baseline drawn in different positions

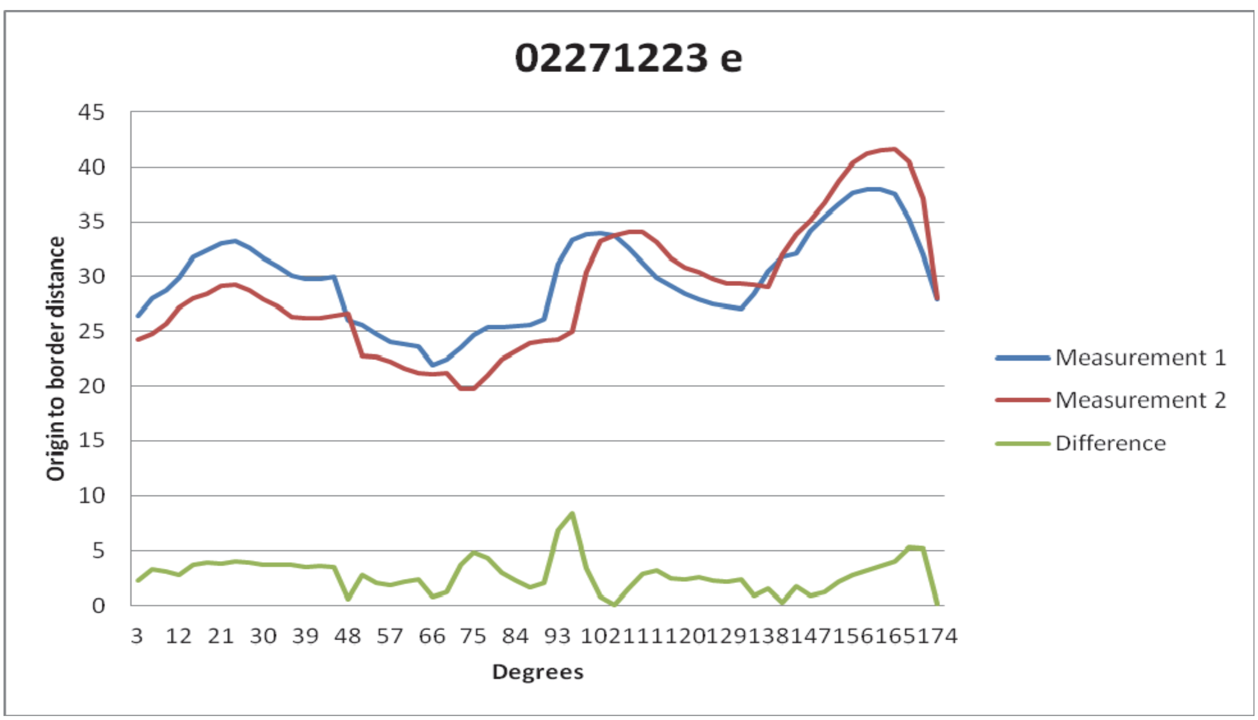


Figure 5.19: Individual 02271223e showing difference in outline measurements between the two trials

In a few individuals parts of the frontal sinus outline seems to be traced differently. Individual 8281222 has some anomalous morphology on the left frontal sinus which has contributed to differences in drawing the outline (Figures 5.20 and 5.21). Individual 8291430 shows a difference in the tracing on the right frontal sinus, corresponding to decisions made about air cells. The total difference scores in these two cases are 164.70 for individual 8281222 and 161.75 for individual 8291430. This boils down to judgments made on the part of the observer. Clearer protocols with descriptions of anomalous morphology and guidelines for practitioners would reduce inter- and intraobserver error, making results more consistent and increasing the potential for unique matches.

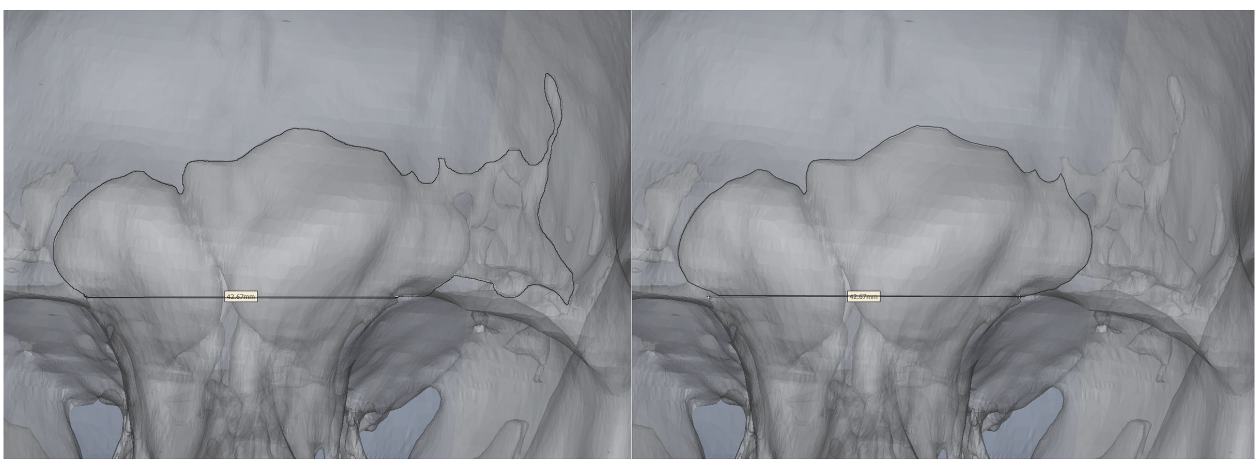


Figure 5.20: Individual 8281222 with anomalous morphology on the left frontal sinus which has contributed to differences in drawing the outline

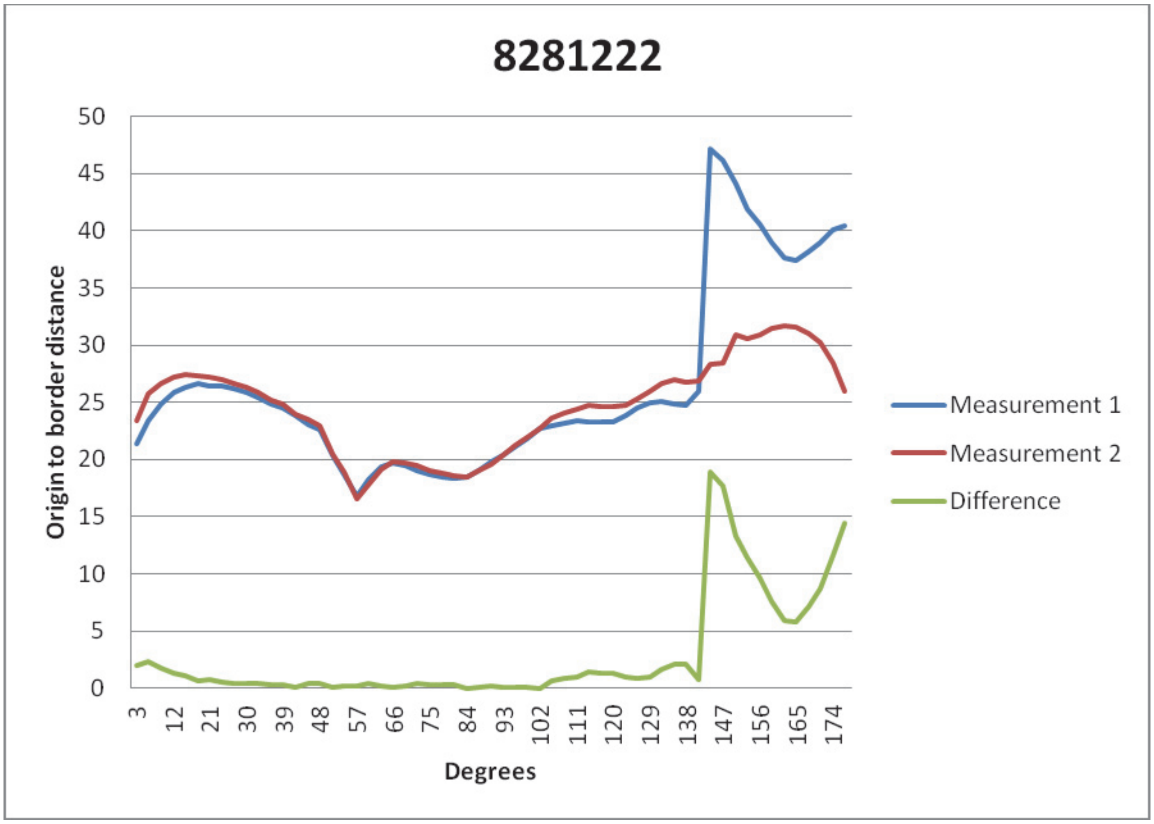


Figure 5.21: Individual 8281222 with anomalous morphology in the left frontal sinus

The methods that showed the lowest intraobserver error are the measurement method (Ribeiro, 2000) and the outline method (Cox et al. 2009). These methods are both described satisfactorily in the original publications and involve taking measurements, rather than scoring variables. That being said, for both these methods a small percentage of the sample shows morphologically anomalous individuals that were difficult to assess consistently between measurement trials. There is potential that this difficulty could result in unfavorable results when applied to forensic cases to assess personal identification. The Reichs and Dorion (1992) method showed the highest intraobserver error, attributable to difficulties replicating the method due to unclear descriptions of the variables combined with inconsistent head position within the sample. Clearer descriptions of variables with images illustrating the different scores would potentially counter these errors, although it is unclear without further validation whether these improvements would put this method in line with the other two.

5.3 Ability to individualise

To be considered for use for personal identification, methods must not only be able to be replicated from the original published method and be repeated consistently, but must also show an ability to capture individual variation to produce unique matches. It is difficult to compare the three methods to each other in this regard since they assess uniqueness in different ways. While they all seem good at capturing idiosyncratic features, none of the methods does this perfectly for the dataset used. It is difficult to tell whether a larger sample would show similar results, but this would need further investigation to validate the findings presented here. In this study, different scans were not available for the same person so original measurements were treated as a proxy for antemortem observations while repeated measurements taken at a different time using the same image served as postmortem observations. However, it is important to note that this is not an accurate representation of a real world forensic situation where different scans would be used, sometimes taken several years apart.

The Ribeiro (2000) method recommends using a plus or minus 2 mm window for each measurement to assess a match using all four measurements. The results show that a unique match was found in 98 of 127 scorable cases (77.16%). In cases where a unique match was not found (n=26), the most common result was two matches, where one was the correct individual and the other was not (n=22). In a few cases several matches were returned, where one was the correct individual and the others were not (three matches, n=2; four matches, n=2) (Figure 5.22). Figures 5.23A through 5.24B illustrate some examples of non-unique matches.

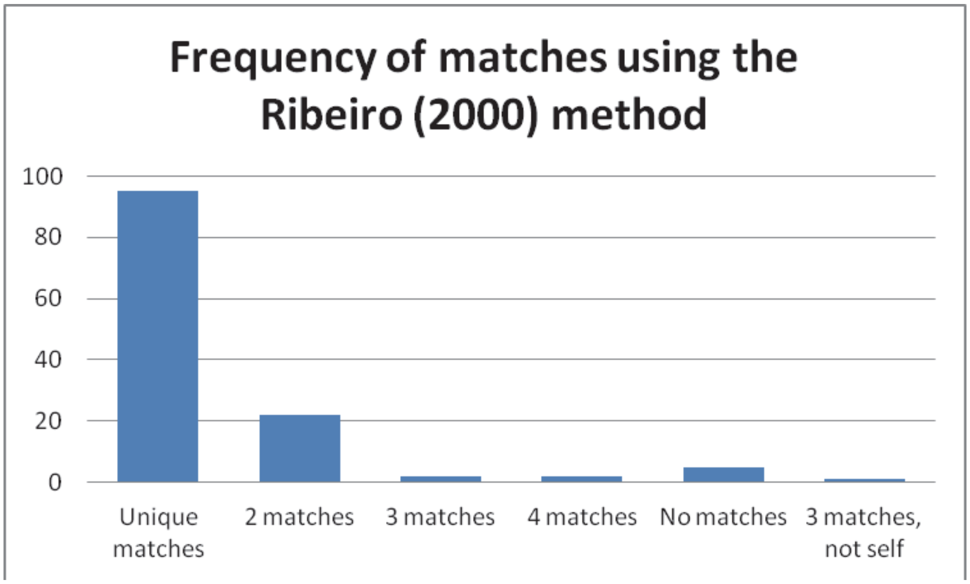


Figure 5.22: Chart illustrating the frequency of matches for Ribeiro (2000) method

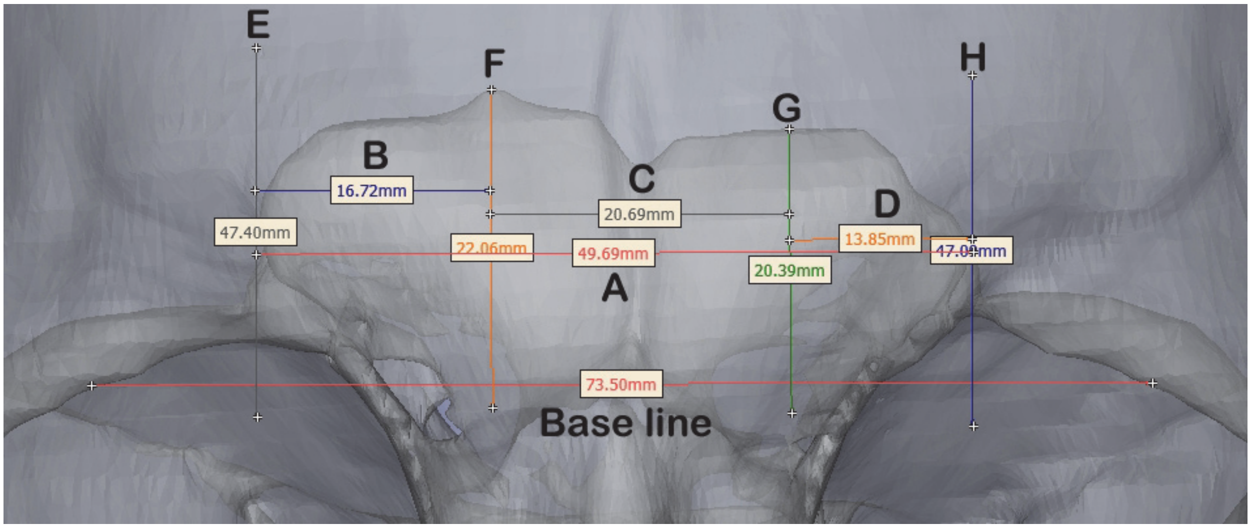


Figure 5.23A: Individual 9051203 a match to individual 10221252a pictured below

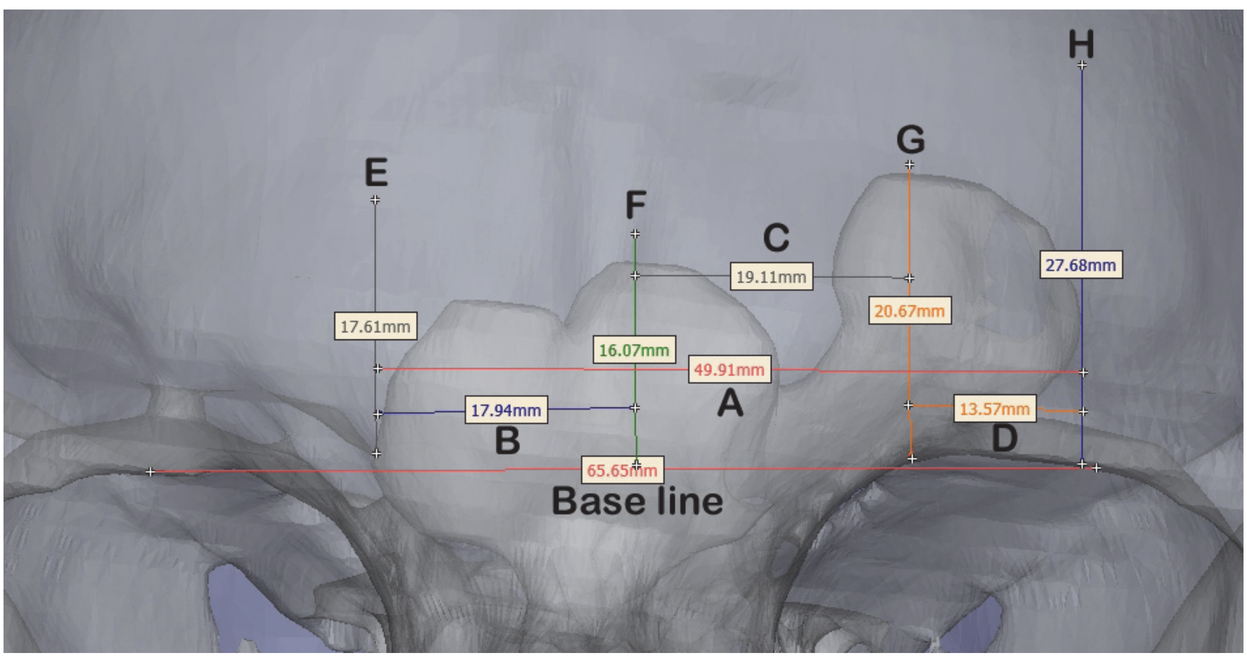


Figure 5.23B: Individual 10221252a a match to individual 9051203 pictured above

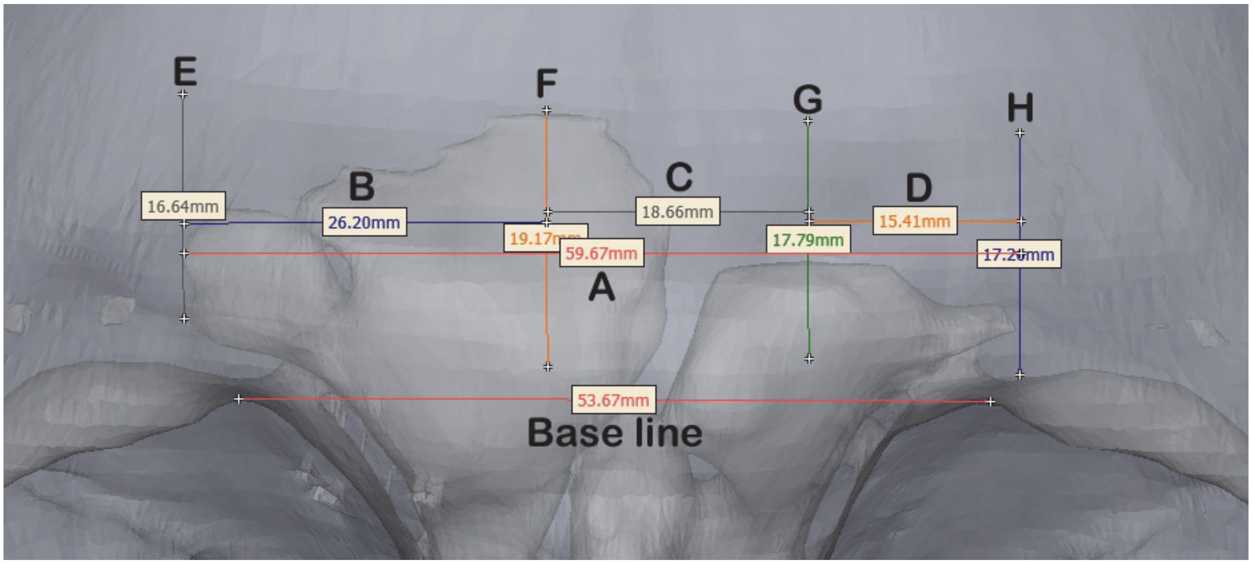


Figure 5.24A: Individual 10231229 a match to individual 11031232 below

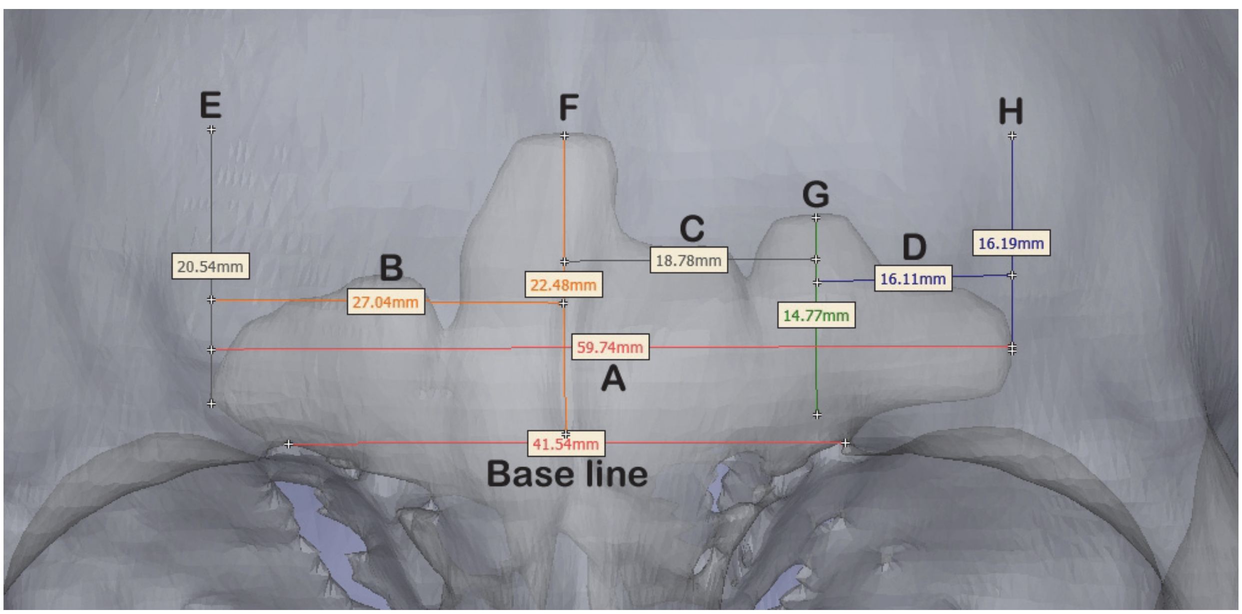


Figure 5.24B: Individual 11031232 a match to individual 10231229 above

Although these individuals produced similar numbers based solely on four measurements of the frontal sinuses the absolute number of non-unique matches can be considered to be few, compared to the Reichs and Dorion (1992) method. The highest number of individuals matched in any case was four. With multiple match situations the correct match can be determined from the match pool by visual comparison (see figures above). An exception to this would be individual 12798112 (Figure 5.25A and B) where a false negative was produced (measurements for the first trial did not match measurements from the second trial). In this case the second measurements for this individual matched three other individuals in the sample. The confusion in this instance arose because of lack of a definition of frontal sinus presence not defined in the original paper.

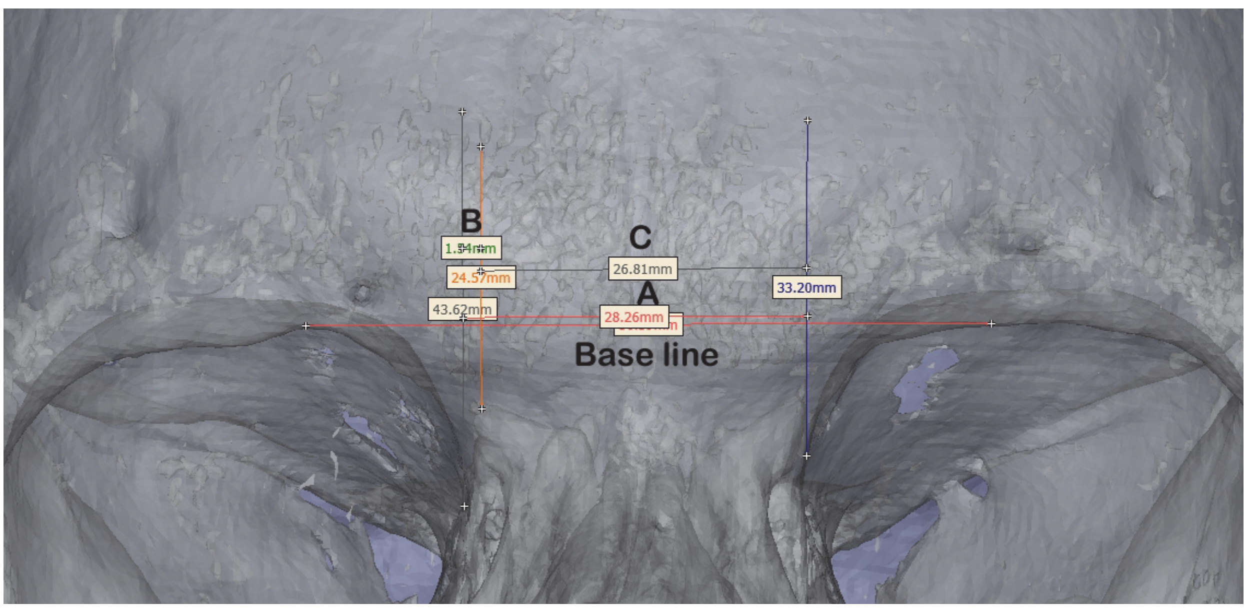


Figure 5.25A: Individual 12798112 measurements from trial 1

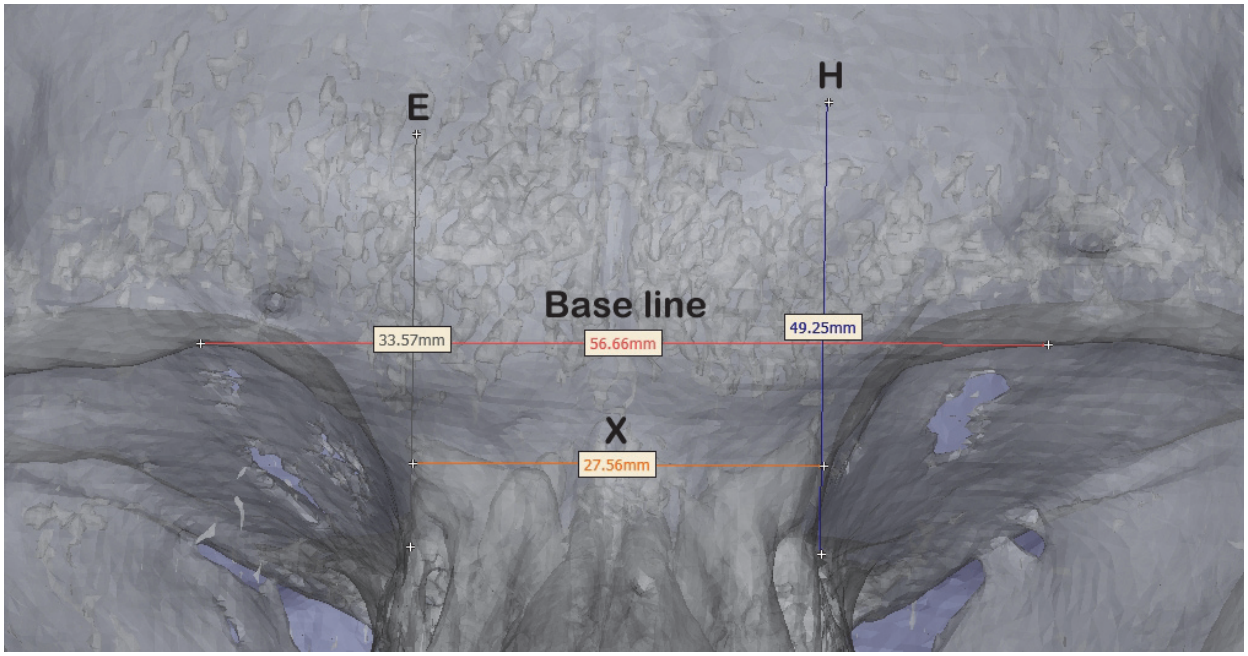


Figure 5.25B: Individual 12798112 measurements from trial 2

In five additional cases, no match was returned and in one case three matches were returned with none being the correct individual. Analysis of the cases of no match shows that the morphology of these individuals' frontal sinuses was different than expected. This anomalous morphology included one individual (02271101b) that appeared to have two intersinus septa, where one is considered normal (Figure 5.1) and individual 9011339 (Figure 5.2) for which it was difficult to determine where the intersinus septum was. In both cases, the intersinus septa were assigned differently in the two trials leading to non-matches. From the frontal views of the skull on which the Ribeiro (2000) method was scored it was difficult to determine the intersinus septum, but by looking at the transverse slices of the original scans it is possible to establish the correct septum for both individuals. In both cases, the intersinus septa were correctly assigned in the second trial. It is possible that this can be explained by observer experience, greater familiarity with both the method and sinus morphology resulted in determination of the correct morphology in the second trial. Observer experience is especially pertinent for individual 02271101b which was the first individual scored in the sample set. Table 5.3 illustrates the measurements of the individuals which produced no matches using the Ribeiro (2000) method. Figures 5.3 and 5.4 illustrate individuals 11031258b and 12987108.

Table 5.3: Illustrating first and second trial measurements for the individuals with no matches using the Ribeiro (2000) method

Individual	A	B	C	D	Sex	Age
02271101 b FIRST	47.12	16.76	22.82	8.26	F	56
SECOND	47.04	13.42	9.95	24.37		
9011339 FIRST	53.27	13.02	16.6	24.28	M	73
SECOND	53.47	18.18	11.56	26		
11031258 b	43.73	10.99	11.76	20.91	M	54
SECOND	43.67	18.65	5.03	20.65		
12789102 FIRST	51.73	30.63	17.05	5.32	F	78
SECOND	51.76	40.19	7.03	5.22		
12987108 FIRST	41.12	29.13	1.35	2.87	F	60
SECOND	16.84	0	2.8	13.86		
12798112 FIRST	28.26	26.81	1.54	0	F	49
SECOND (Fig 5.25A&B)	0	0	0	0		

If the window for matches is reduced from +/- 2 mm to +/- 1 mm this transforms 20 of the 26 non-matches into unique matches, however, in three cases the window becomes too narrow and excludes the original measurements. The obvious problem here is to balance the window so that it is small enough to capture only the original measurements. If it is too small it could potentially exclude the original measurements due to intraobserver error and anomalous morphology which was scored differently between trials, if it is too large and it will include too many individuals. When multiple matches are returned using the Ribeiro (2000) method, the researcher can go back and compare the screenshots side by side or by superimposing one on top of the other to confirm or rule out matches. A more serious situation is produced when no matches are returned. The current research situation is artificial since it is known that the original individual is present in the database and when no matches are returned the results can be investigated. In a forensic case situation, if a database such as this was employed and no matches were returned this could lead to a false negative that the individual is not present in the database and prevent identification. However, the typical forensic case size is one, performing this method to collect measurements on the antemortem scan image and comparing these to the same measurements taken on the postmortem scan image to assess a match seems based on the results of this validation study to lead to a reliable means of establishing identification with only a small percentage of false results.

The Reichs and Dorion (1992) method produced matches to the original in 67.48% of 123 cases (n=83). When the slice number was unknown, matches to the original score were reduced to 18.7% (n=23). The Reichs and Dorion method produced nine cases (7.32%) of false positive matches (Table 5.4). Of these cases, four (3.25%) instances were seen where the second measurements (as a proxy for measurements taken from a postmortem scan) do not match with the first measurements (as a proxy for measurements taken from an antemortem scan). One of these cases matches with two incorrect individuals, whereas the remaining three cases match with one incorrect individual. Of the nine cases, there are five instances (4.07%) where the second measurements match with the correct individual and also with one other individual. Figures 5.26A to 5.29B illustrate the morphology of some of these individuals. Similarities can plainly be seen between these individuals. In some cases the individuals can be distinguished based on differences in depth of the frontal sinus, a parameter which is not considered in the Reichs and Dorion (1992) method. It is not as easy to perform a visual determination of a match or exclusion images utilising transverse CT slices as it is to use frontal views as employed by both the Ribeiro (2000) and Cox et al. (2009) methods. This is because less morphological variation is apparent on transverse slices.

Table 5.4: Reichs and Dorion (1992) method false positives

Individual	Match with	Match with first measurements?	Sex	Age
10221252b	11181214 & 02271222	No	F	38
10231251	11181145	No	M	51
11031243	12798118	No	M	31
11181214	02271145d	No	F	81
02271129b	02271129d	Yes	M	52
02271129d	02271129b	Yes	M	63
02271222	11181214	Yes	M	54
08281218	02271101g	Yes	M	41
10221221	12978116	Yes	F	60

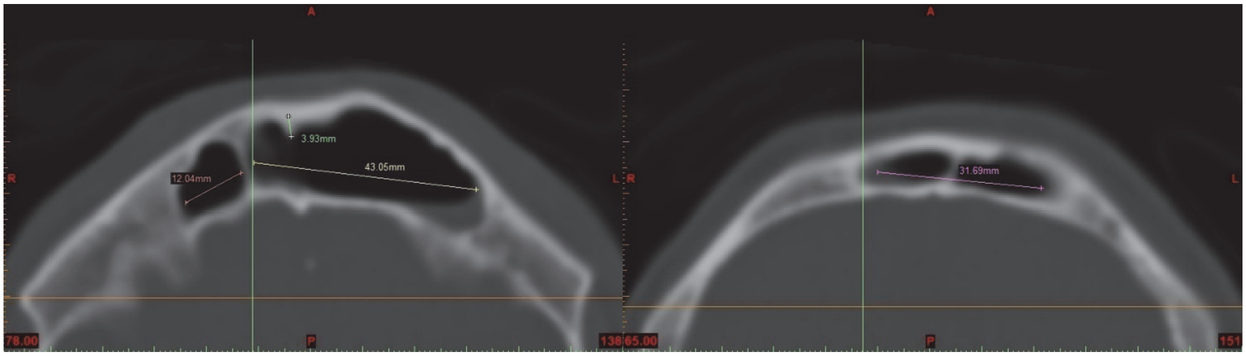


Figure 5.26A: Individual 10221252b matches with individual 11181214 below

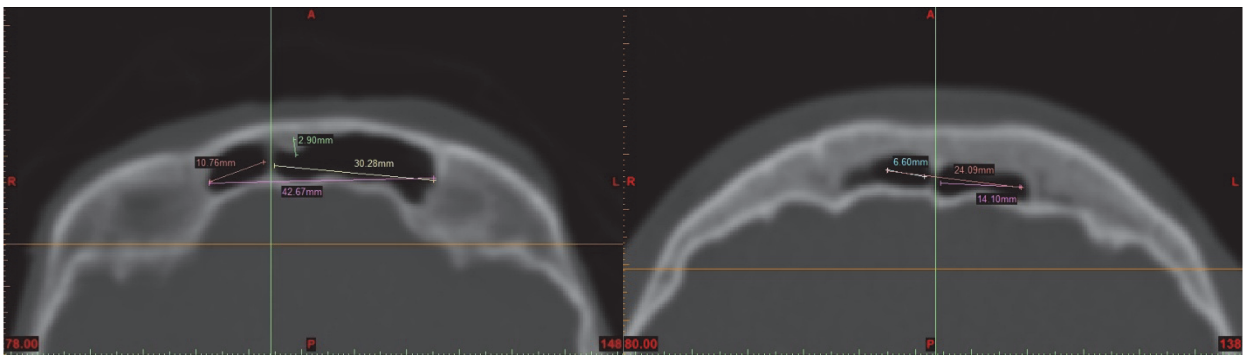


Figure 5.26B: Individual 11181214 matches with individual 10221252b above and individual 02271222 below

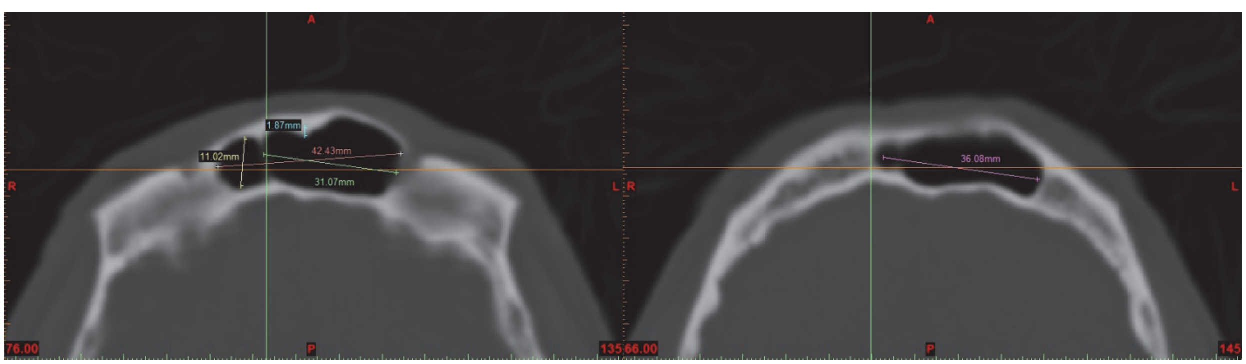


Figure 5.26C: Individual 02271222 matches with individual 11181214 above

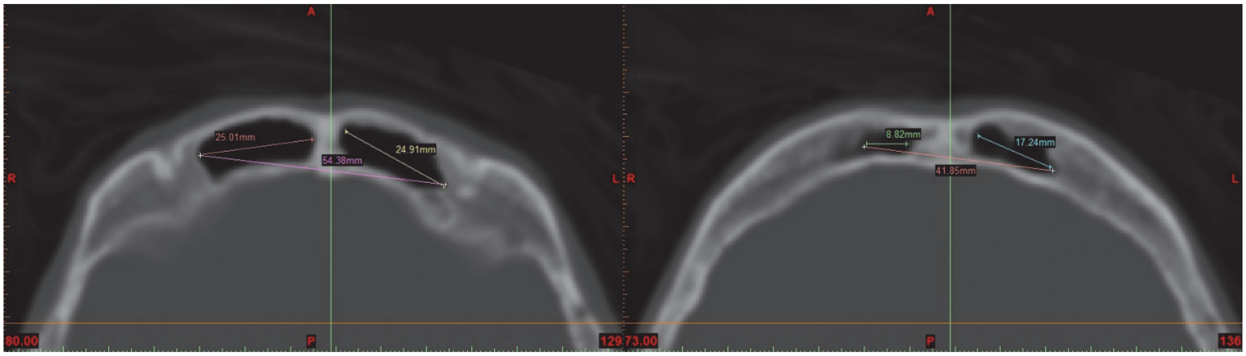


Figure 5.27A: Individual 10231251 matches with individual 11181145 below

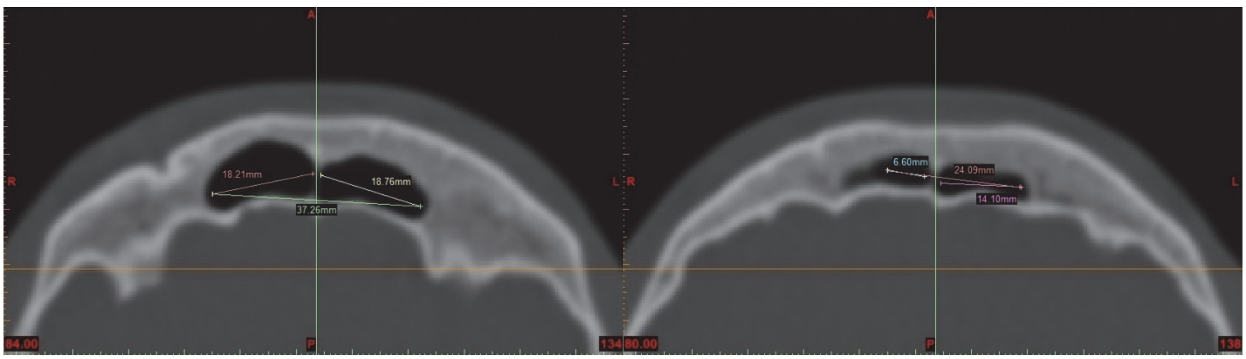


Figure 5.27B: Individual 11181145 matches with individual 10231251 above

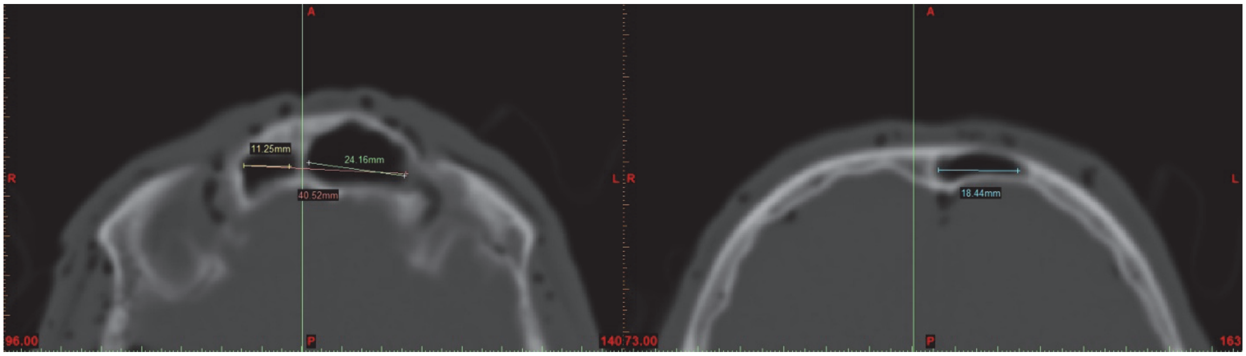


Figure 5.28A: Individual 02271129b matches with 02271129d below

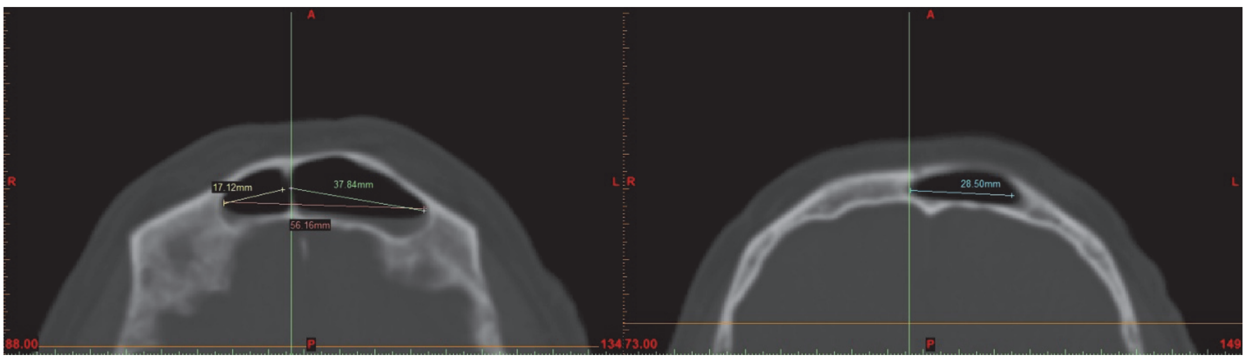


Figure 5.28B: Individual 02271129d matches with individual 02271129b above

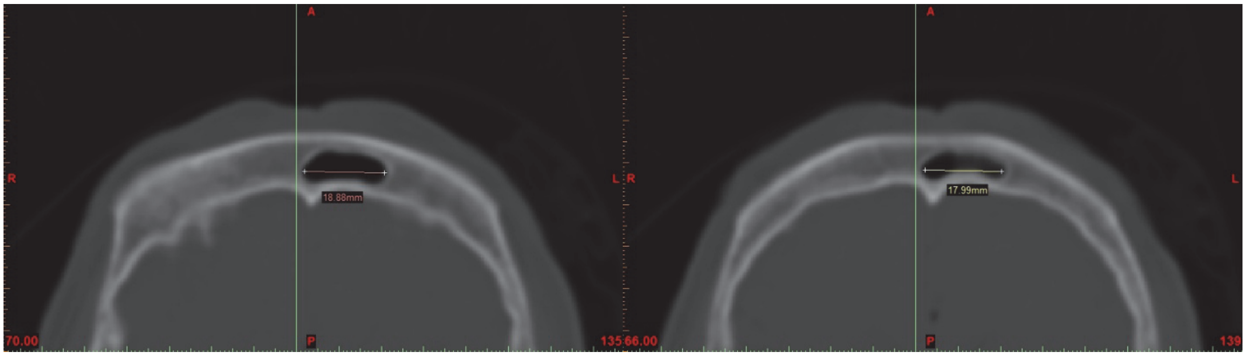


Figure 5.29A: Individual 10221221 matches with individual 12978116 below

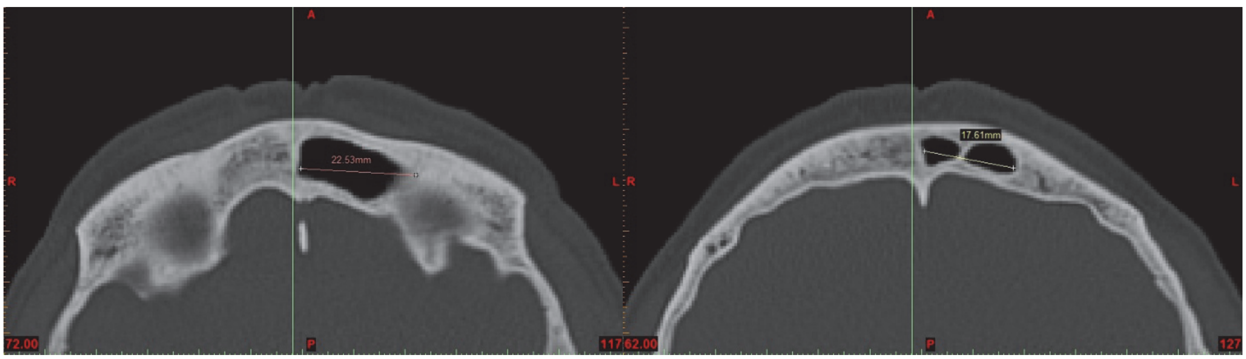


Figure 5.29B: Individual 12978116 matches with individual 10221221 above

These poor results are likely the result of high intraobserver error and the Reichs and Dorion (1992) method itself, rather than for morphological reasons. It is unclear from the original publications whether the authors developed and tested their method using a sample group. Although they do apply the method to a forensic case for personal identification, there are no published error rates for comparison with the results of this study. Further research is needed to investigate interobserver error. The results of the current project indicate that the Reichs and Dorion (1992) method should not be applied to forensic cases.

The logistic regression analysis of the Cox et al. (2009) method produced a small number of same skull (11 of 107 or 10.3%) and different skull (2 of 5671 or 0.03%) comparisons that were misclassified; overall 99% of the skull comparisons were correctly discriminated. This method does not, however, produce unique identifiers, which can be compared within the sample like the previous two methods. In their original publication Cox et al. (2009) report extremely encouraging results: a high level of congruency in patterns achieved between observers and combined error rates for both observers showed 0% false positive, and 0% false negatives for 18 same skull pairs and 42 different skull pairs. Empirical testing of the ability of the odds ratio to discriminate same skull from different skull logTD values yielded 100% correct discrimination of same skull pairs (n = 9) and 97% correct discrimination of different skull pairs (n = 36).

Although overall 99% of the comparisons in the current study were correctly classified, it is the cases that were incorrectly assigned that are perhaps the most interesting and deserve discussion in terms of forensic applications. The same skull comparisons have already been discussed in terms of intraobserver error. It has already been mentioned that the baseline measurement, baseline placement in regards to the superior border of the orbits and differences in the drawing of the outline are responsible for the eleven incorrect classifications.

The two misclassified different skull comparisons indicate these individuals have outlines which are similar enough to be classified as belonging to the same individual. The first misclassified different skull pair produced a total difference score of 43.82, which is below the average total difference score for the same skull comparisons (46.40). The probability that these two outlines were from the same individual was 0.99 (or 0.007 probability they were from different individuals). Further investigation shows these two individuals (02271223f and 8281236) both possess only left frontal sinuses. The baseline measurements are 5.82 mm and

10.18 mm respectively and the outlines are similar in overall shape, both being featureless (Figures 5.30A and 5.30B).

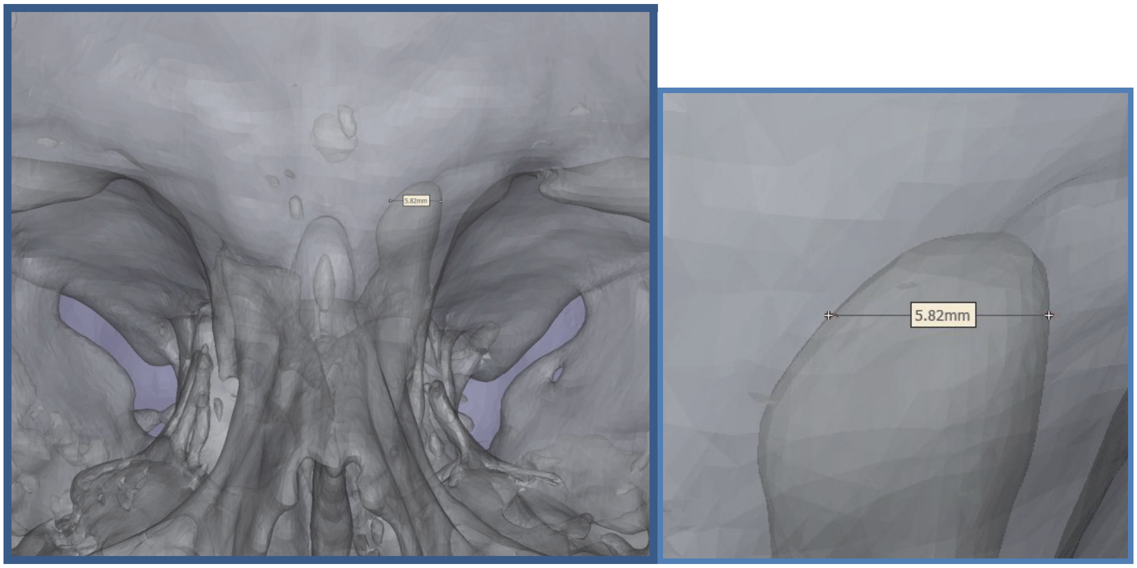


Figure 5.30A: Individual 02271223f

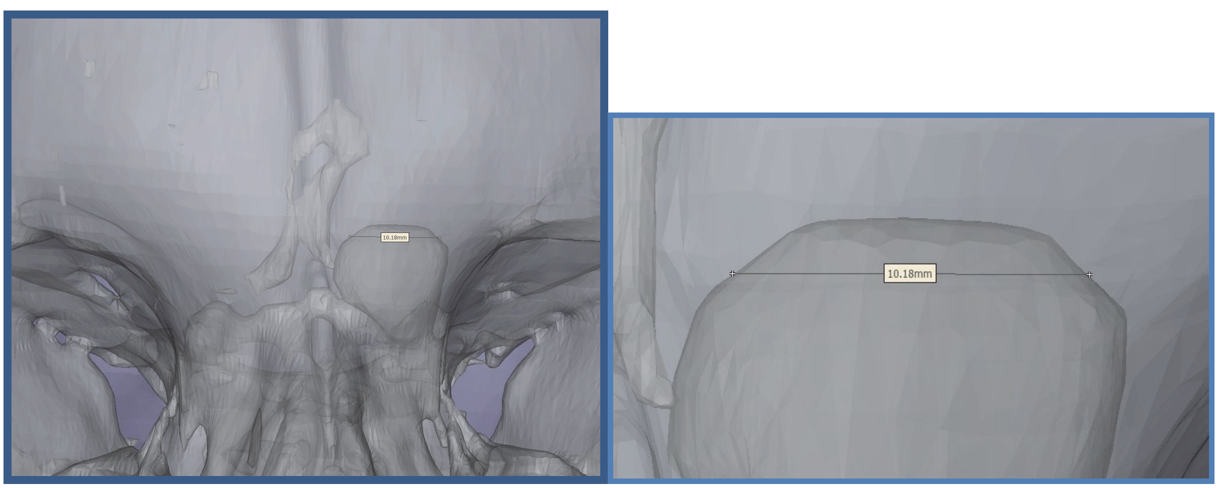


Figure 5.30B: Individual 8281236

The second misclassified different skull comparison had a total difference score of 79.77 and had a probability of 0.32 of being from different individuals. In this case, the baseline measurements were very similar (41.69 mm and 39.57 mm). A comparison reveals both individuals to have relatively featureless outlines (Figure 5.31). Although the total difference score is low for this different skull comparison and within the probability of same skull pairs, a side by side comparison of the CT image screenshots shows the sinuses are clearly distinct and belong to different individuals.

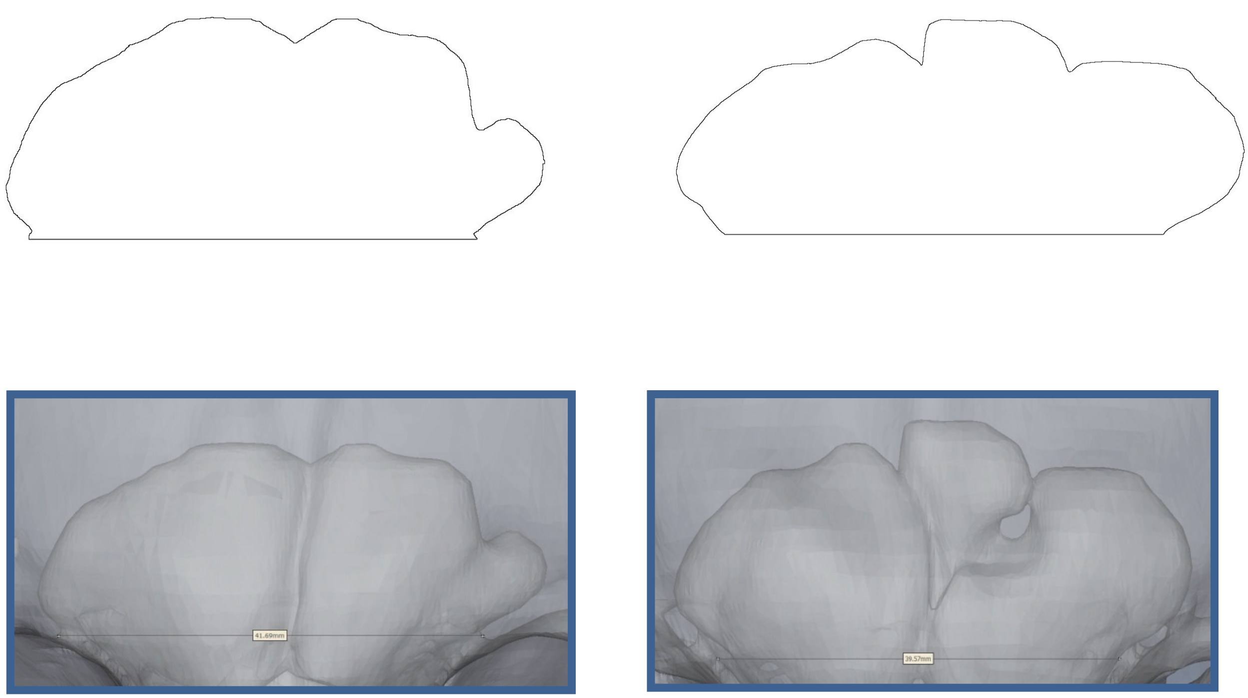


Figure 5.31: Comparison of individuals 02271146a (right) and 10221246 (left) with a total difference score of 79.77

5.4 Limitations of methods: mismatches

All mismatched individuals were examined to investigate if there were any patterns regarding age and sex information and to determine if the same individuals were being consistently mismatched by all methods. The results of the Ribeiro (2000) method produced only one true mismatch, where matches were returned but the target individual was not one of them. In this case the first measurements were taken of the sinuses, but in second trial it was determined that there was no frontal sinuses so measurements were not taken. When matching analysis was run this individual matched with several others which had no frontal sinuses. Below is a screenshot illustrating the morphology of this individual (Figure 5.32). It can clearly be seen that this individual has no frontal sinuses and according to Ribeiro (2000) only measurement X (the distance between the projections of lines that pass through the medial borders of the orbital cavities) should be taken. This error is easily rectified with correct application of the original method and illustrates the learning curve with applying methods to the frontal sinuses.

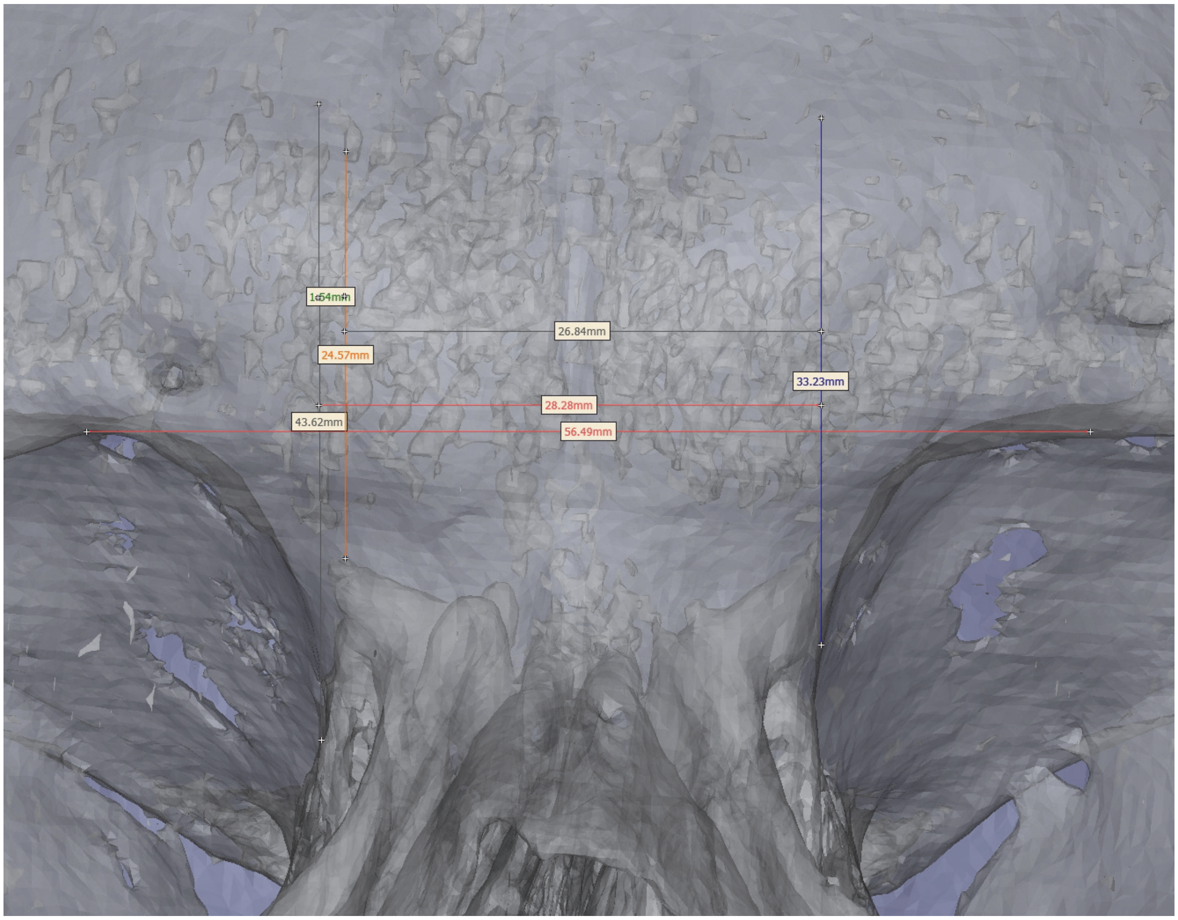


Figure 5.32: Individual 12798112 with no frontal sinuses

The five individuals where no match was returned are not true mismatches because the sinus measurements did not produce a match with another individual. However, these results represent false negatives. In this study it is known that the match is present within the database, but this would impact a real forensic situation where identification is being tested.

Of the six non-match individuals for the Ribeiro (2000) method there are four females and two males; the average age of these individuals is 61.67 years (Table 5.5), average age of the males is 66 years and 60.25 years for the females, both of which are higher than the average age for the sample (mean age for males is 49.88 years, mean age for females is 54.93 years). The average age for the 127 individuals of known age in the sample is 52.1 years.

Table 5.5: Age and sex of the individuals with no match using the Ribeiro (2000) method

Individual	Sex	Age
12798112	F	47
02271101b	F	56
12987108	F	60
12789102	F	78
11031258b	M	54
9011339	M	73

The Ribeiro (2000) method produced 26 instances of multiple matches. Table 5.6 presents the age and sex information for these individuals; 11 males (average age 51.18 years), 12 females (average age 49.25 years) and three unknown individuals made up these multiple matches. There appears to be no age or sex pattern for the multiple matches; the distribution is almost equal between males and females and represents all age groups. In general individuals of similar age or sex are not being matched up; however there are three instances, individuals 8291439, 9090930 and 10221307, where the age and sex profile of the original individual and the mismatched individuals are similar. These instances are forensically significant because age and sex information of unknown individuals are produced in the biological profile and if this information were used to eliminate potential matches it could lead to false positives. It is recommended that age and sex data not be used exclusively to eliminate possible matches, but instead side by side comparison of images of the frontal sinuses be used to assess matches in instances where multiple matches are produced. Tests of significance using an independent T-test combining the individuals with no match and the individuals that produced multiple matches showed no significant difference for age for these mismatched individuals (t = -0.655, p>.05). Chi-squared test showed no significant difference for sex $X^2(1) = 0.175$, $p < 0.5$). Odds ratio shows that males are 1.194 times more likely to be mismatched.

Table 5.6: Age and sex of individuals that produced multiple matches using the Ribeiro (2000) method

Original individual	Sex	Age	Matches Individual(s)	Sex	Age
02271101e	F	35	11031230	F	51
02271223b	M	83	11251046	F	83
02271223d	F	47	10231228	Unknown	Unknown
8281228	F	57	10221307	M	51
8291401	F	41	10221221 10221311	F F	60 58
8291433	M	43	11031232 12879113	M F	28 78
	M	50	10221307	M	51
8291502	F	72	9021234	M	42
9011340	M	87	11031228	F	44
9021234	M	42	8291502	F	72
9051203	M	29	10221252a	F	52
9090930	M	39	8291439 02271223d 10231228	M M Unknown	50 47 Unknown
9101255	M	60	10221248	F	39
10221221	F	60	8291401	F	41
10221252a	F	52	9051203	M	29
10221307	M	51	8281228	M	57
10221311	F	58	8291401	F	41
10231228	Unknown	Unknown	9090930 8291439 02271223d	M M M	39 50 47
10231229	Unknown	Unknown	11031232	M	28
10231251	M	51	9051201	F	74
11031228	F	44	9011340	M	87
11031230	F	51	02271101e	F	35
11031232	M	28	10231229	Unknown	Unknown
11181201	Unknown	Unknown	12798107	F	37
12798107	F	37	11181201	Unknown	Unknown
12879113	F	78	8291433	M	43

Mismatches and non matches using the Reichs and Dorion (1992) method are very prevalent. Forty (40) individuals can be classified as non-matches (where the score for the original slice was different from the score for the known slice), indicating very high intraobserver error. Of these 40 non-matches, 22 were males, 16 were females and 2 were of unknown sex. The average age for these males is 49.23 years and average age for these females is 48.31 years. Tests of significance using an independent T-test showed no significant difference for age for these mismatched individuals (t =0.081, p>0.05). Chi-square test showed no significant difference for sex $\chi^2(1) = 0.210$, p <0.5). The Odds ratio shows that males are 0.833 times more likely to be mismatched with the Reichs and Dorion (1992) method.

Four true false positives exist where a match was made to someone else in the sample but not to the actual individual (Table 5.7). Of these individuals, two are male (aged 31 and 51 years) and two are female (aged 38 and 81 years).

Table 5.7: Age and sex of false positive individuals with the Reichs and Dorion (1992) method

Original individual	Sex	Age	Matches individual(s)	Sex	Age
10221252b	F	38	11181214& 02271222	F, M	81, 54
10231251	M	51	11181145	M	31
11031243	M	31	12798118	F	69
11181214	F	81	02271145d	F	72

Four other multiple matches occurred where they matched the actual individual but also a match to another individual in the sample (Table 5.8). Table 5.8 illustrates two instances (original individuals 02271129d and 10221221) which are forensically significant. These cases matched with individuals of the same sex and similar age; both age and sex are used in forensic anthropology to include or exclude potential matches from missing persons information. As with the Ribeiro (2000) cases of multiple matches, this can be rectified by employing visual comparison and not relying on age and sex data to confirm or eliminate potential matches. The more serious problem with the Reichs and Dorion (1992) method is the high intraobserver error which resulted in so few matches being made between the scores in the first trial and those of the second, even when the slice number was known. The individuals making up the false positive and multiple match subsets are evenly distributed between males and females and show no specific age distribution.

Table 5.8: Age and sex of individuals with multiple matches using the Reichs and Dorion (1992) method

Original individual	Sex	Age	Matches	Sex	Age
02271129d	M	63	02271129b	M	52
02271222	M	54	11181214	F	81
08281218	M	41	02271101g	M	67
10221221	F	60	12897116	F	65

Cox et al (2009) mismatches are represented by incorrectly classified same skull comparisons (those with a TD score > 96.98). There are a total of 11 individuals: 8 males and 3 females (Table 5.9). The average age for males is 49.25 years; the average age for female is 57.67 years. It is important to note that the use of logistic regression with the Cox et al. (2009) method produces match probabilities which would be useful for court testimony.

Table 5.9: Age and sex of individuals producing a TD score greater than 96.9759 for SS comparisons

Individual	SS score	Sex	Age
8291405	96.98	M	60
12879119	100.80	F	60
11031243	107.32	M	31
00271223	123.03	M	51
8281230	124.72	F	58
8291430	161.75	M	68
02271223e	162.49	F	55
8281222	164.70	M	51
9051203	179.54	M	29
02271222	257.59	M	54
8291439	259.48	M	50

Tests of significance using an independent t-test showed no significant difference for age for these mismatched individuals (t =0.138, p>0.05). The Chi-square test showed no significant difference for sex $\chi^2(1)$= 1.510, p < 0.25). Odds ratio shows that males are 0.431 times more likely to be mismatched. Since age and sex values are not significant for the mismatched individuals for any of the methods it suggests these variables are not responsible for the correct match not being returned. Table 5.10 shows a comparison of mismatches by sex for each method.

Table 5.10: Breakdown of mismatches by sex for each method

Method	Whole sample	Ribeiro correct match not returned (n=6)	Ribeiro multiple matches returned (incl. correct) (n=26)	Reichs & Dorion mismatched (n=40)	Cox mismatched SS (n=11)
# of males	70	2	13	22	8
Mean age of males	49.88	60.25	51.31	49.23	49.25
# of females	57	4	10	16	3
Mean age of females	54.93	66.0	52.8	48.31	57.67
# of unknown	3	0	3	2	0

5.5 Limitation of methods: problematic individuals

No single individual produced problematic results for all three methods. There are however several individuals which were misclassified by two methods (Table 5.11). The Ribeiro (2000) method and Reichs and Dorion (1992) method show the most overlap in misclassified individuals (n=5), although these methods assess frontal sinus features quite differently. Table 5.12 illustrates the sex of these misclassified individuals. Figures 5.33 through 5.38 illustrate the frontal view of a selection of these individuals.

Table 5.11: Common misclassified individuals

Ribeiro / Reichs and Dorion	Ribeiro / Cox et al.	Reichs and Dorion / Cox et al.
8291401 (F 41)	8291405 (M 60)	8291439 (M 50)
8291433 (M 43)	11031243 (M 31)	9051203 (M 29)
10231228 (unknown)		
10231229 (unknown)		
10231251 (M 40)		

Table 5.12: Common misclassified individuals by sex

Males	6	66.67%
Females	1	11.11%
Unknown	2	22.22%

These images suggest it would appear that these mismatched individuals from multiple methods typically possess frontal sinus morphology where the left and right sinuses are similar in size and the superior borders are relatively flat. This morphological variant is common and suggests that any method, be it measurement, coding or outline, needs to be able to distinguish individuals with this pattern. The majority (66.67%) of these individuals are male.

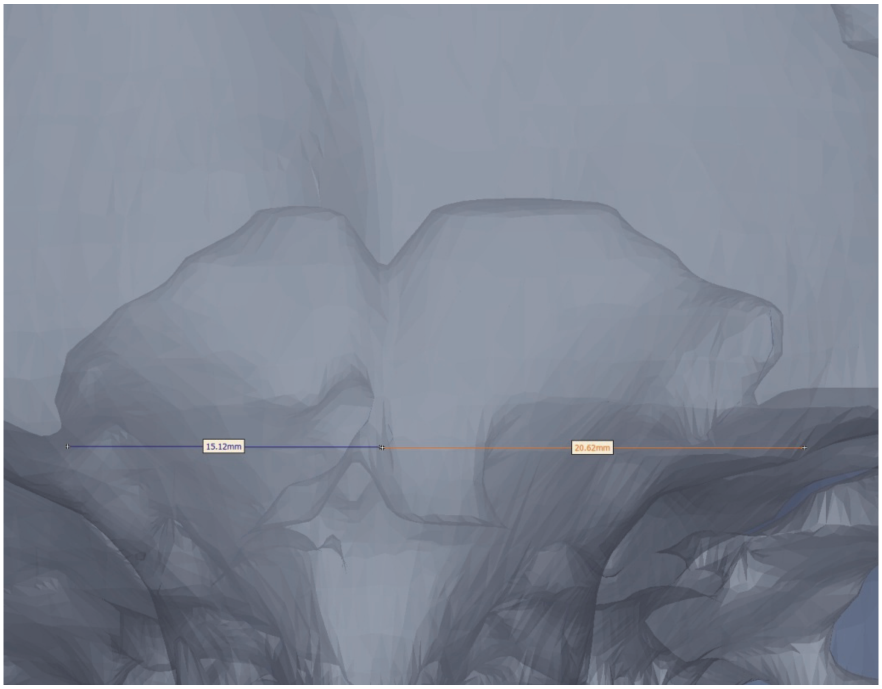


Figure 5.33: Individual 8291401; mismatched using both Ribeiro (2000) and Reichs and Dorion (1992) methods.

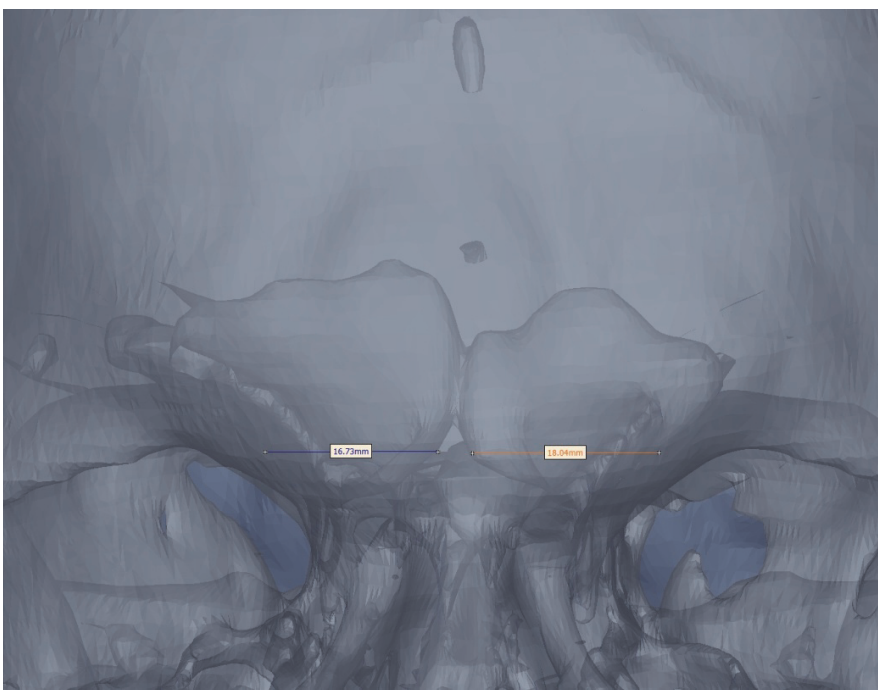


Figure 5.34: Individual 8291433; mismatched using both Ribeiro (2000) and Reichs and Dorion (1992) methods.

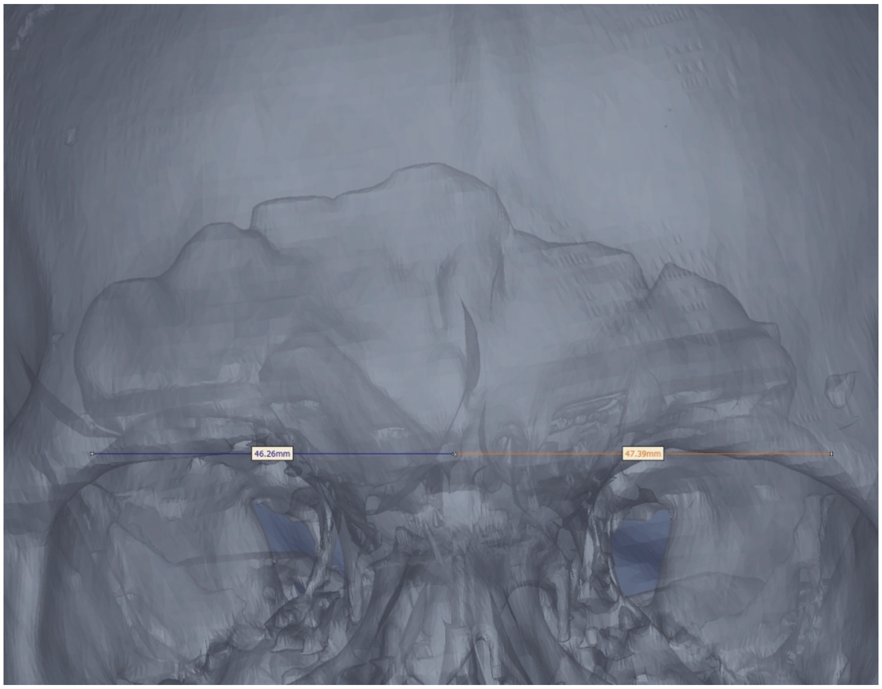


Figure 5.35: Individual 8291405; mismatched using both Ribeiro (2000) and Cox et al. (2009) methods.

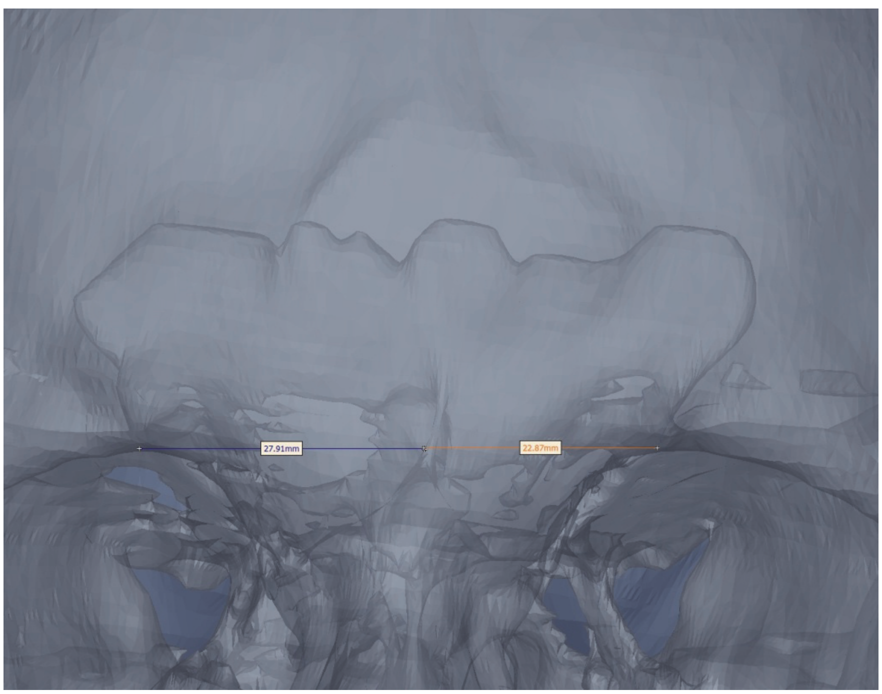


Figure 5.36: Individual 8291439; mismatched using both Reichs and Dorion (1992) and Cox et al. (2009) methods.

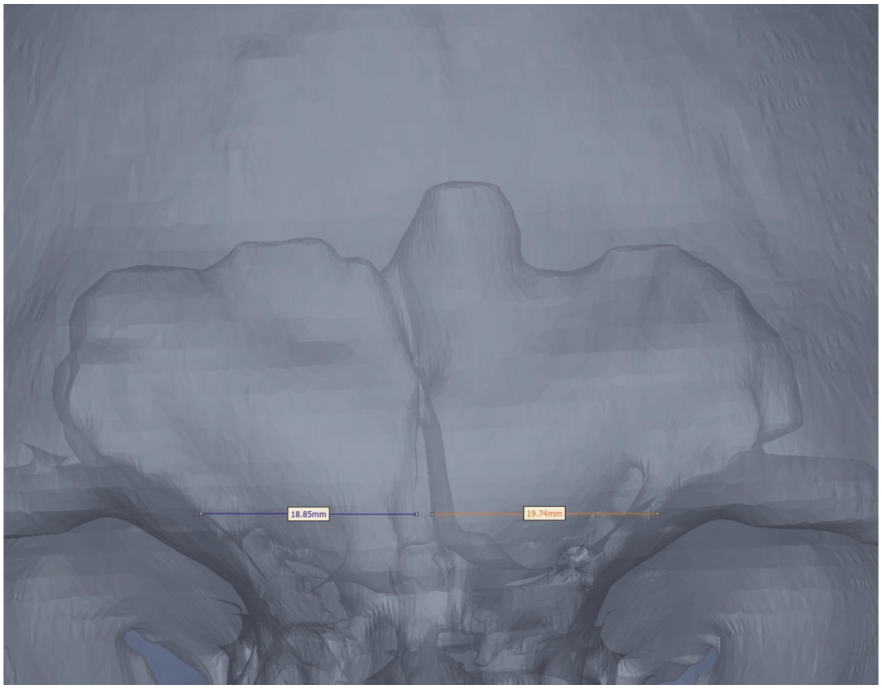


Figure 5.37: Individual 10231228; mismatched using both Ribeiro (2000) and Reichs and Dorion (1992) methods.

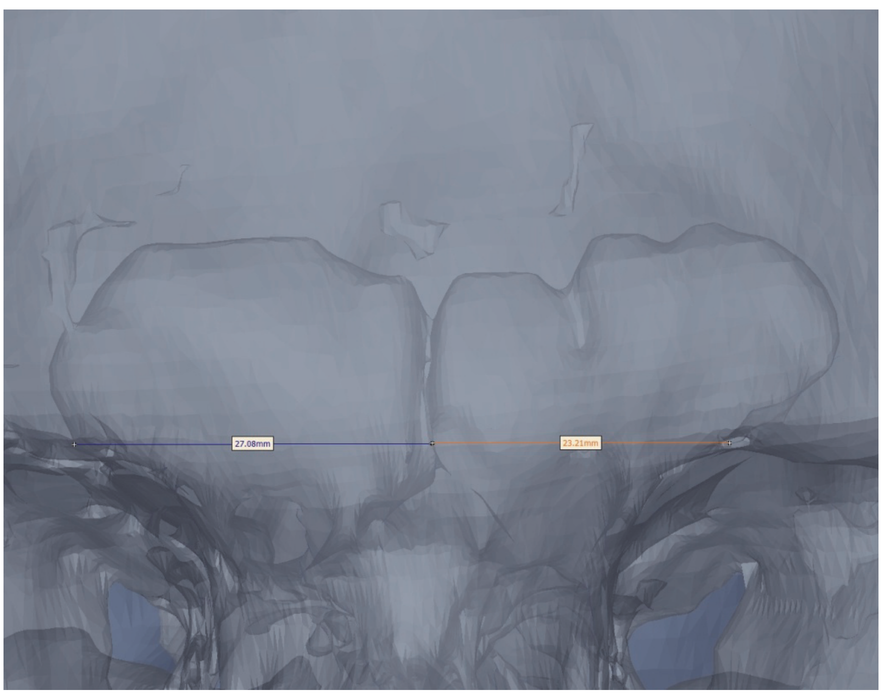


Figure 5.38: Individual 11031243; mismatched using both Ribeiro (2000) and Cox et al. (2009) methods.

5.6 Accuracy and precision

Christensen and Crowder (2009) examine evidentiary standards for forensic anthropology. They (2009:1214) believe "... it is not necessary to demonstrate that every technique we use is highly reliable, but rather it is important to show that we are (scientifically, statistically) sure of *how* reliable a technique is". Accuracy and precision are important measurements for evaluating method performance (Christensen and Crowder, 2009). Christensen and Crowder (2009: 1214) state "Precision refers to the absence of random error... which affect(s) method accuracy, the distance between estimated and observed values to the true value". Validation studies of analytical methods can establish quality assurance in order to determine method reliability (precision and accuracy) (Christensen and Crowder, 2009:1215). In this study, accuracy and precision data provide a way of comparing the three methods applied in the current study. Table 5.13 and Figure 5.39 present a comparison for all three methods for accuracy, precision, false positives and false negatives. Accuracy was calculated for the Ribeiro (2000) and Reichs and Dorion (1992) methods by the amount of times the second trials matched the original, producing a unique match. Precision was calculated for these two methods by including the number of times the second trial matched the original including matches to other individuals in the sample, non-unique matches. For the Cox et al. method (2009), accuracy was calculated using the same skull matches. Precision included the same skull and different skull matches and captures when the results are correct, indicating high replicability between first and second trials.

Table 5.13: Accuracy, precision, false positives and false negatives for each method

Method (n=scorable individuals)	Ribeiro (n=127)	Reichs & Dorion (n=123)	Cox et al. (n=107)
Accuracy	77.16%	63.41%	89.7%
Precision	97.64%	67.48%	99.8%
False positives	21.26%	11.38%	10.82%
False negatives	3.94%	32.52%	1.87%

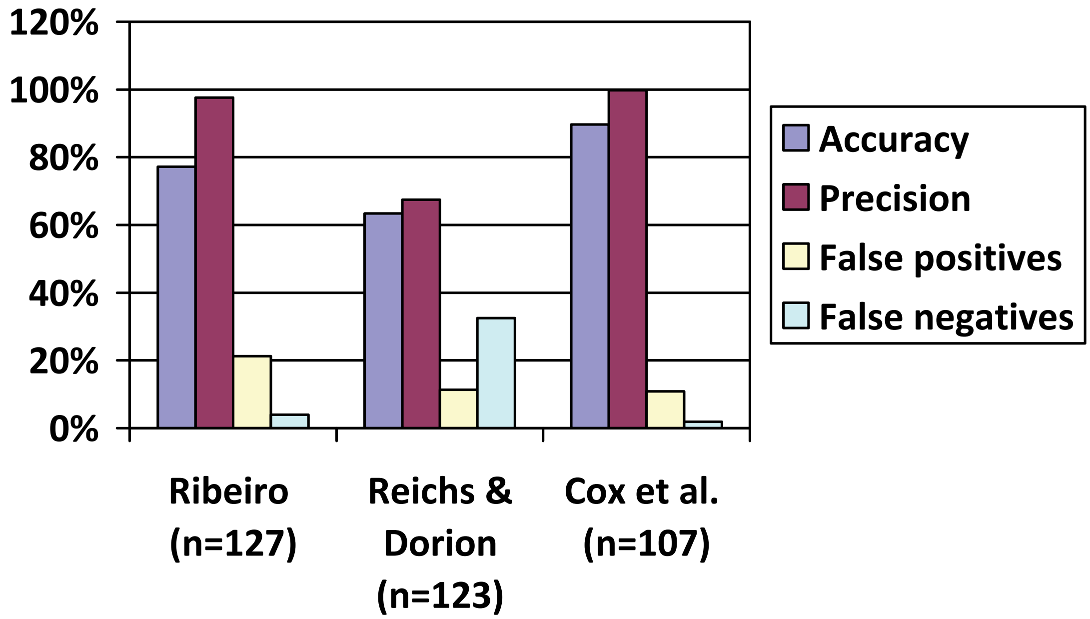


Figure 5.39: Accuracy, precision, false positives and false negatives for each method

All methods show higher precision than accuracy, suggesting that repeatability is better than accuracy. However, Table 5.13 clearly illustrates that Reichs and Dorion (1992) method is the weakest of the three methods tested in this study.

5.7 Contextualisation of findings

Many methods have been developed in an attempt to quantify the variation seen in the frontal sinuses and applied to personal identification for forensic purposes. This study has evaluated only three of the published methods, one in each of the major categories (measurement, coding and outline). Superimposition, which constitutes the most basic way of comparing frontal sinuses, was not directly considered because of its perceived lack of quantification (Cox et al., 2009). However, this technique can prove useful as a means of confirming identity when multiple matches are returned. In the current study, superimposition would be applicable to either the measurement or scoring system methods to offer a double check or eliminate mismatches and identify the correct match in situations where multiple matches were returned.

Several measurement methods have been developed. The findings in the current validation of Ribeiro's (2000) method are consistent with the original results. Using a subsample to test matching capabilities of his method, Ribeiro (2000) reported 100% accuracy, although visual comparison was required in cases where more than one film was found with identical measurements. In the current study 98 of 127 cases produced unique matches and a further 26 cases produced non unique matches, where one was the correct individual and the other(s) was/were not. Side by side comparison of images would be useful in these cases to identify the correct match. Quantitative measurements and superimposition were combined in a method by Kirk et al. (2002). They report that using sinus height and width led to matches in only 16/35 (46%) cases, but using superimposition they were able to match all 35 cases used in the subsample. It must be noted that Kirk et al.'s (2002) sample is made up of antemortem and postmortem radiographs obtained from the radiographic archives of the Chief Coroner's Office for Ontario and contains two types of radiographic film exposures (Caldwell and Waters). An arbitrary cut-off value of 5 mm was used (in the Ribeiro (2000) method this was reduced to 2 mm). Using CT images, this study found that 2 mm suggested by Ribeiro was enough to capture a unique match in 98 cases (75.38%). An even narrower 1 mm window was able to produce matches in 115 cases (88.46%). The Kirk et al. (2002) study indicates that utilization of only the frontal sinus height and width is not enough to produce unique matches. It is important to bear in mind that both the current study and the original study use only one set of images. The comparison of actual antemortem and postmortem images, sometimes taken many years apart, in Kirk et al.'s (2002) study is more relevant to an applied forensic situation than the simulated situation employed by the current study. Perhaps the simulated scenario is artificially enhancing the number of unique matches by taking separate measurements using the same images whereas a comparison of antemortem and postmortem images would reduce the cases of unique matches.

Scoring systems have been developed by a handful of researchers. The Reichs and Dorion (1992) system tested here is a modification of Yoshino et al.'s (1987) method. Unfortunately, neither Yoshino et al. (1987) nor Reichs and Dorion (1992) have published tests of their methods on a large sample, so the findings from the current study cannot be compared.

Tatlisumak et al. (2007) combined metric features and coding numbers in their FSS system, which evaluates F (presence or absence of frontal sinus), S (septum) and S (scalloping). The authors state that 93% of the cases could be negatively identified, yet a closer examination of the raw data shows that 45 of the 100 individuals in the sample had a non-unique FSS identifier (Table 1, Tatlisumak et al. (2007)). The authors state that measurement data allowed the discrimination of 98% of cases, however the measurement data are not included so further comparisons cannot be made. The current study found that the validation of Reichs and Dorion

(1992) method produced 10 of 123 individuals with non-unique 14-digit identifiers. This suggests that utilising more features (seven in Reichs and Dorion (1992) scored on two separate slices versus three for Tatlisumak et al. (2007)) offers more individualising power. Tang et al. (2009) report three individuals in their study had the same code. In all three cases the individuals were missing the right frontal sinus and had a left frontal sinus that was scalloped with a single arcade. The lack of features produced poor discrimination power for Tang et al.'s (2009) method.

One of the key aspects emphasized by numerous scoring systems is the potential number of unique identifiers possible. Yoshino et al. (1987) state that their code permits more than 20,000 possible combinations, while Reichs and Dorion (1992) suggest a 14 digit code (seven variables scored on two separate transverse slices and combined) would have over 240 billion combinations and a 21 digit code (using three separate transverse slices) would theoretically produce over 118 quadrillion combinations. Cameriere et al. (2005) state the probability that two different individuals have an identical code is much higher than these estimates because of significant correlations between the characteristics. In performing a validation of the Yoshino et al. (1987) method, Cameriere et al. (2005) reported 11 individuals out of 98 individuals with non-unique identifiers (four pairs with the same score and one group of three with the same score). "Significant correlations between code items greatly increase the probability that two individuals may have similar frontal sinus patterns, and therefore also that they are assigned identical code numbers" (Cameriere et al., 2005:773). To address this the authors alter the Yoshino system to substitute ratios (frontal sinus area divided by orbital area) for area size and bilateral asymmetry and report that using this method each individual was characterized by a unique pattern because these variables are quantitative continuous characteristics. They estimate the probability of the potential error of positive identification as was less than $7x10^{-6}$, but because their ratios vary according to skull position at X-ray, the same skull will not always show an identical value. While Cameriere et al.'s (2005) suggestion of including ratios with scored features may increase individualising potential of scoring methods, the correlation between variables used in these methods will nevertheless produce identical scores among some individuals in the sample, in particular those with relatively featureless frontal sinuses. The use of quantitative continuous variables with scoring methods is essentially employing a measurement method augmented by feature classification. With the success of simple measurement methods, such as Ribeiro's (2000), it remains to be seen if complicated scoring systems are adequate at capturing uniqueness of the frontal sinuses. To do this they must be tested more extensively on much larger samples.

Coding systems have been criticized for addressing only general features and not morphology per se (Christensen, 2005). Outlines have been employed in two separate studies and show promising results. But as demonstrated in the current study, this approach is not entirely able to capture individuality. Cox et al. (2009) report a high level of congruency in patterns achieved between observers and combined error rates for both observers showed 0% false positive, and 0% false negatives for 18 same skull pairs and 42 different skull pairs. Empirical testing of the ability of the odds ratio to discriminate same skull from different skull logTD values yielded 100% correct discrimination of same skull pairs (n = 9) and 97% correct discrimination of different skull pairs (n = 36). In a validation of the Cox et al.(2009) method the current study produced 89.7% correct discrimination for 107 same skull pairs and 99.9% correct discrimination for 5671 different skull pairs using logTD values. This seems to disagree with Cox et al.'s (2009) results, although the sample size in the current study is larger. Issues with the outline method as applied in this study have been already discussed (baseline measurement value, baseline placement, small, featureless or singular sinuses) and are contributing to the differences seen between the validation of Cox et al.'s (2009) method on the current sample and the original. Christensen (2004b) employed Elliptical Fourier Analysis and Euclidean distance models on frontal sinus outline images and reports a 96% accuracy rate. The combined same skull and different skull rates of correct identification capable of outline methods are greater than those of the measurement (although with a +/- 1mm window the Ribeiro method was able to slightly achieve higher accuracy than the matching accuracy in the same skull group) and scoring methods tested here. However, both outline methods, especially Christensen's (2004b) method, are more involved than either the measurement or scoring methods tested in this study. The time needed to collect data in the current research was greater because of the number individuals in the sample; in a forensic situation where the sample is typically one individual twenty minutes to acquire data is reasonable. Despite yielding high accuracy and precision the major problem with the Cox et al. (2009) method is that it could be applied to the fewest number of individuals in the current sample data set, which is a significant weakness. The methods in this analysis were deliberately chosen because are not overly complicated (thereby reducing intra- and interobserver error) and did not require specialised equipment, other than what is available at most morgues or hospitals.

Like previous research (Cameriere et al., 2005; Tatlisumak et al., 2007; Kim et al., 2012), the current study is limited by the unavailability of different scans for the same person. However, the current research does investigate intraobserver error and method matching ability by utilizing the original measurements as a proxy for antemortem observations, while repeated measurements, taken at a different time using the same image, served as postmortem observations. The author acknowledges that this is unlike a real world forensic situation where antemortem and postmortem scans would be used, sometimes taken several years apart. This use of different scans introduces additional error associated with scan data captured using different machines, with different scan parameters or from different orientations which is not seen in the current study. While the current work is not set up as a true measure of method performance in forensic anthropological case study, it can be considered to represent method simulation in its purest form by preventing the introduction of additional errors and providing a true measure of method repeatability and performance. One potential effect is that the artificial situation created by the similarity between original and repeated scan images produced enhanced measures of method accuracy and precision. To truly test whether this is the case, additional images taken during life would need to be acquired for the individuals in this study to mimic a forensic case. Given this limitation, the results presented here can be considered to represent best case scenarios for the performance of the three methods tested.

The frontal sinuses are considered useful for determining personal identification because of their noted variation, which is apparent even in this relatively small research sample. However, some sinus morphologies present difficulties for the establishment of personal identification. Frontal sinuses that are small and relatively featureless were difficult for all the methods considered in the current work, a finding reported in other studies. Smith and Christensen (2010:1413) comment that the 4% incorrectly identified in Christensen's previous study "… largely represented the inability of the computerized models to correctly match small, less featured frontal sinuses using an outline approach". Small, less featured sinuses suffer a greater effect of the loss of information which occurs when characteristics are grouped and given class numbers or when basic linear measurements, such as height and breadth, are employed. The result is an oversimplification of the morphology which does not capture the degree of variation and individuality required for reliable identification. Other problematic morphological types include frontal sinuses with a flat superior border; which showed a high proportion of mismatches from multiple methods (Figures 5.33, 5.37 and 5.38). Morphological variations, such as additional areas of pneumatisation (Figure 5.3) or apparent double intrasinus septa (Figures 5.1 and 5.2), which were not incorporated into the protocols of the original methods produced mismatches and non-matches. These features show high potential for identification, but the failure of both Ribeiro (2000) and Reichs and Dorion (1992) methods to incorporated these sinus variants suggests that a much better understanding of frontal sinus morphological variation is needed, particularly for measurement and feature-based systems.

Since coding and measurement systems are prone to an oversimplification of information, Cox et al. (2009) caution that at best, such methods provide a way to perform quick searches to narrow down suspect remains and eliminate non-matches within a sample. One option with these cases is to resort to visual comparison as a confirmatory step, but this negates the quantitative aspect of trying to implement standardised methods. Cox et al. (2009) suggest using an outline approach, although it has been shown here that this is not immune to the same problems in quantifying outlines of small sinuses with few features. Moreover, in the current study morphological variants with separate left and right frontal sinuses were unable to be included in the outline approach, meaning that the Cox et al. (2009) method could only be conducted on 107 of the 130 individuals in the sample.

All the methods discussed in this chapter, including the three tested in this study, assess the frontal sinuses in two dimensions, either using outlines or transverse slices. More recently a three-dimensional analysis has been undertaken by Kim et al. (2012). While the authors apply measurements and coding systems, which have already been critiqued here, their findings suggests a greater ability to differentiate individuals in their sample (98% produced different codes) using variables from all three dimensions of the frontal sinuses. The failure of previous approaches to differentiate among small, less featured frontal sinuses highlights the need for a greater understanding of the morphology of the frontal sinuses. A three-dimensional shape analysis of the frontal sinuses would increase our understanding of the areas of greatest morphological variation and would result in an improved ability to develop methods that can capture this variation to be applied to personal identification.

5.8 Summary

This chapter has discussed the results of the application of three methods to quantitatively assess the frontal sinuses. The three methods have been discussed with regard to method replication, including ease of use, intraobserver error and their ability to individualise. In all criteria the Reichs and Dorion (1992) method ranked the lowest, which is seen in the accuracy and precision scores. Ribeiro's (2000) measurement method was the easiest and quickest to replicate and produced low intraobserver error; however, the Cox et al. (2009) outline method produced the best accuracy and precision scores, although was applicable to the fewest individuals in the sample. Despite the encouraging results of some techniques, all methods produced mismatches. Analysis indicates that age and sex of the individual does not appear to be contributing to mismatches, which suggests that morphology and/or methodology are the causal agents. The next chapter will present the summary and conclusions.

Chapter 6 Summary and Conclusions

This research has tested three previously published methods to quantify variation in frontal sinus morphology. The aim is to extrapolate the findings to make recommendations for the application of these types of techniques to increase standardisation within forensic anthropological methods for personal identification and to comply with standards for expert witness testimony concerning method testing and comprehension of error rates. The following is a brief summary of the conclusions of this research.

- The method that fit with the most criteria for application to forensic casework was the Ribeiro (2000) technique. It was the simplest and easiest to apply and produced a unique correct match in 75% of comparisons utilising four measurements with a window of ± 2 mm (90% accuracy with a ± 1 mm window).
- Coding methods, such as Reichs and Dorion (1992), were found to be the least suitable because of the high intraobserver error rate due to ill-defined frontal sinus features. In addition a lack of independence of features produced several instances were 14-digit codes were not unique to each individual.
- Outline methods, such as Cox et al. (2009), offer the most precision and accuracy and the employment of logistic regression provided a measure of match probability, which would be useful if courtroom expert witness testimony is required. However, due to morphological constraints this method was applicable to the least amount of individuals in the current study.

Forensic anthropologists are at the point of re-evaluating and refining many of the existing methods, providing an appropriate opportunity to review what is needed from our methodologies. We require robust methodologies that fulfill legal stipulations but also are true to forensic anthropology data to provide meaningful information. There are several key criteria which methods should meet in order to be useful to forensic casework. Methods need to be relatively easy to employ without requiring extensive experience either with the method or with the anatomical region. They should be applicable to the wide variety of sinus morphologies and be straightforward enough to be communicated to a judge and jury should expert witness testimony be required.

In this case Ribeiro's (2000) method was the simplest to understand because it is the most basic of the three methods tested here. It required only few lines to be drawn and a total of four measurements to be taken. It was easy to apply to individuals with normal frontal sinus morphology. In this validation study, the most challenging aspect of application was how to adapt the protocol developed for X-ray radiographs to CT images. With increased familiarity with the Ribeiro method, application became more consistent and this can be seen in the one case where in the first instance cavities which were not true sinuses where measured. However, as the technique continued to be applied and familiarity was gained, more consistent results were achieved, illustrating a small learning curve for this approach. The morphological features of the frontal sinuses necessary to apply the Ribeiro method were easy to recognise. The methods proposed by Reichs and Dorion (1992) required more knowledge of the frontal sinus region and the method itself was more complicated, because of poorly explained variables. To apply this method more consistently, variables need to be better illustrated and more guidelines need to be developed so that the same anatomical regions of the frontal sinuses are being employed for scoring. This would permit more reliable intraobserver and inter-individual comparisons. The Cox et al. (2009) method was the most involved method of the ones validated in this study. While the acquisition of the outlines was relatively easy, the procedure to acquire the total difference data was labour intensive and required specialised computer software. As stated previously, the use of the Matlab software greatly reduced the time required to collect the initial data, but without this processing each individual outline took up to 20 minutes, depending on the outline's complexity.

To be applicable to forensic case situations methods used should also be relatively quick to apply and gain results (Derrick et al., 2015). More complicated methods increase the time to carry out and may be considered less desirable by busy forensic personnel. Methods need to be simple to understand and not require extensive equipment or processing software. In this validation study, Ribeiro's method was the easiest to understand, quickest to execute and only required four measurements to be taken. Where multiple matches are returned, final conclusions about a match could be performed using side by side or superimposition comparisons. The Reichs and Dorion method was the most difficult to apply because of poorly defined features in the original publication. Cox et al.'s method was found to be the most time consuming to apply because it required the employment of multiple software packages.

To be forensically relevant a method must also be applicable to the variety of sinus morphologies. All of the methods tested here could only be used on a subset of the available dataset, which limited their ability to be tested. The Ribeiro method was applied to the most individuals of the sample (n=127), whereas the Cox et al. method could be applied to the least (n=107). The Cox et al. method required the outline of the sinuses to be a continuous closed object; individuals that possessed distinct left and right sinuses could not be considered for this method. A potential alteration would be to apply the Cox et al. method separately to the left and right sinuses, but this requires testing to ensure this amendment captures the variation present in the frontal sinuses.

Obviously the 130 individuals comprising the current dataset do not represent all the morphological types of frontal sinuses and so more validation studies utilising sinuses belonging to different populations are needed to provide a better understanding of the morphological variation upon which to base personal identification. A better understanding of the variation of frontal sinus morphology is required to continually refine existing techniques and develop new methods as appropriate.

Lastly, to be widely applicable to the legal aspects of forensic anthropology, techniques should preferably be easy to understand by, and communicate to, a judge and jury. Overly complicated methods can make forensic anthropologists seem unfavourable in the eyes of a judge or jury and even alienate them and their testimony. While it is not suggested that the courtroom drive how science is carried out or that all the approaches used by forensic anthropologists should be simplified these are important aspects to be mindful of when applying methods. Going hand in hand with the complexity of methods, is the technique's ability to describe both the accuracy and precision of the matches. Being able to assign a probability to the match is an advantage over methods which are simply a "yes" or "no" to the match. This validation study has shown that all these methods produce mismatches of different types, but being able to quantify these would be helpful. Byers (2011) states that levels of probability can be attached to expert witness testimony to convey a level of certainty. Methods that have been tested on independent samples are important. Although Christensen (2005) has established the uniqueness of the frontal sinuses using elliptical Fourier analysis, other methods used to establish personal identity based on this structure still need to be quantified. To do so, more independent samples must be used.

The method that fits the most of the above criteria is Ribeiro's measurement method. This method is easy to apply and did not require extensive experience to successfully execute. It is also quick to carry out the analysis because it only requires four measurements. These factors make it easy to explain in a courtroom, especially with the aid of visual images. It was also applicable the most individuals in the sample and easily adaptable from X-ray film on which it was developed to CT images comprising the current dataset. The number of mismatches was low with this method and where multiple matches are returned, a true match could be determined using visual comparisons, either side by side or superimposed. The Reichs and Dorion method required extensive familiarity with the frontal sinus features because of poor explanations in the original publication. Due to difficulties repeating the original method, high intraobserver error and low matching ability it is recommended that the Reichs and Dorion method not be applied to forensic cases. Even with reclassification of the bilateral dimension variable to better capture the variation in the current sample, these issues could not be resolved. The Cox et al. method was the most labour intensive to apply. As stated this method was problematic because it could only be applied to individuals with connected right and left frontal sinuses, those with distinct cavities could not be considered, which greatly reduced the sample size. Moreover, individuals with similar baseline measurements produced lower total difference scores, which is concerning since it suggests that the size rather than the shape of the frontal sinuses is driving much of the variation captured with this method. This needs to be investigated further. However, despite concerns with some of the aspects of this method, the probability values produced by logistic regression are more forensically meaningful than strictly inclusion or exclusion results.

6.1 Future directions

The most basic approach to compare the morphology of the frontal sinuses for personal identification purposes is either side-by-side comparison or superimposition of radiographic images taken of the frontal sinuses from similar angles and with similar magnification. Quantification methods for comparing similarities in morphology and assessing the uniqueness of the frontal sinuses can broadly be grouped into three categories: measurement methods, coding methods and outline methods. Outcomes of the current research study indicate that none of the three tested methods representing these categories was perfect at producing unique matches or completely consistent with the above criteria for application to forensic case work. One explanation for this could be that almost all methods to quantitatively evaluate the frontal sinuses rely on two-dimensional data. This has been in the form of X-ray and several more recent studies employing CT image data (e.g. (Reichs and Dorion, 1992; Reichs, 1993; Haglund and Fligner, 1993; Smith et al., 2002; Tatlisumak et al., 2007; Pfaeffli et al., 2007; Kim et al., 2012) and only one study has used MRI (Swingler, 2005). Although CT and MRI scans can provide three-dimensional data, to date the three-dimensional variation in the frontal sinuses has only been explored in a single study (Kim et al. 2012). This sole investigation into three-dimensional variation in the frontal sinuses considers both metric and non-metric characteristics and applies a coding system method which draws on earlier work by Yoshino et al. (1987). Although Kim et al.'s (2012) study appears successful; two individuals in the sample produced the same 10-digit code revealing that this method is not entirely effective at individualising the frontal sinuses using a simple coding system. In the current research, the validation of Reichs and Dorion's (1992) coding system method produced the greatest number of non-unique scores. Moreover, Kim et al.'s (2012) study was not repeated to test for intra- or inter- observer error regarding their variables or methodology. When considered together the current state of this research demonstrates unique variation in the frontal sinuses, which although considered acceptable for the basis of personal identification, is not yet understood well enough to be effectively captured using existing measurement, coding or outline methods. The morphological variation existing between the frontal sinuses of different individuals needs more investigation in order to improve forensic anthropological methods to quantify this.

An exploratory study (described in Appendix One) conducted during this research provides tantalizing evidence for capturing morphological variation in the frontal sinuses for the purpose of comparison and identification of unique individuals. It is hypothesized that a greater understanding of morphological variation will enhance quantitative methods aimed at capturing individual variation in these structures. This preliminary exploration illustrates the potential for three-dimensional quantification of variation and uniqueness seen in the anatomy of the frontal sinuses. As demonstrated by this study, previously developed measurement, coding and outline methods aimed at quantifying the morphological variation in these structures are not entirely successful because they attempt to boil the variation seen in the frontal sinuses down to a certain number of variables or regions. Preliminary differences in the different skull comparisons illustrate that the variation is a function of both size and shape in all three dimensions and is not confined to specific regions of frontal sinus anatomy, viewable on two dimensional images. These findings highlight an important limitation to consider when developing and assessing methods to quantify frontal sinus variation and establish an explanation for why two-dimensional methods are not fully capable of capturing the individual uniqueness present in these structures. The promising results of the three-dimensional exploration suggest that the inclusion of the extra data afforded by the additional dimension can be used to quantify frontal sinus variation more accurately and inform forensic anthropological methods intended to document individuality and form a basis for positive identification.

6.2 Final comments

This research has evaluated three types of methods on a small sample of CT images. Not surprisingly the simplest and easiest method to apply was the measurement method by Ribeiro (2000), what was surprising was that 75% of comparisons produced a unique match using only four measurements with a ± 2 mm window (90% accuracy with ± 1 mm). Feature-based methods were found to be the most difficult to apply because of intraobserver differences in feature recognition and poor descriptions of variables in the initial publication. In addition to high intraobserver error there was a lack of independence of features producing several instances where individuals shared 14-digit codes that were intended to be unique identifiers. The Cox et al. (2009) method produced the best matching ability overall and the use of logistic regression is useful for establishing match probabilities. However, due to morphological constraints this method could be used on the least amount of individuals from the current sample, limiting its applicability in a forensic context. Three-dimensional approaches to evaluating the uniqueness of frontal sinus morphology show promising results and represent future directions for research on personal identification.

References

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

Federal Rules of Evidence (1975; 2000).

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

General Electric Co. v. Joiner (1997).

Kumho Tire Co. v. Carmichael (1999).

R. v. Mohan (1992).

R. v. Mohan O.C.A. (1992).

R. v. B.M. (1998).

R. v. J. (J.-L.) (1999).

State v. COSGRIF, No. E2009-02547-CCA-R3-CD (Tenn. Crim. App. Oct. 21, 2010).

USA v Plaza, Acosta and Rodriguez, Cr. No.98-362-10,11,12 (2002).

American Board of Forensic Anthropology (2008). Retrieved February 12, 2015, from http://www.theabfa.org/diplomates.html

Acharya, A. B., & Taylor, J. A. (2003). Are a minimum number of concordant matches needed to establish identity in forensic odontology? *The Journal of forensic odonto-stomatology*, *21*(1), 6-13.

Adams, Bradley J. (2003a). The Diversity of Adult Dental Patterns in the United States and the Implications for Personal Identification. *Journal of Forensic Sciences, 48*(3), 497-503.

Adams, Bradley J. (2003b). Establishing Personal Identification Based on Specific Patterns of Missing, Filled and Unrestored Teeth. *Journal of Forensic Sciences, 48*(3), 487-496.

Adams, Bradley J., & Maves, Robert C. (2002). Radiographic Identification Using the Clavicle of an Individual Missing from the Vietnam Conflict. *Journal of Forensic Sciences, 48*(2), 369-373.

Angyal, Miklos, & Derczy, Katalin (1998). Personal Identification on the Basis of Antemortem and Postmortem Radiographs. *Journal of Forensic Sciences, 43*(5), 1089-1093.

Anon, Jack B., Rontal, Michael, & Zinreich, S. James (1996). *Anatomy of the Paranasal Sinuses*. New York: Thieme.

Asherson, N. (1965). *Identification by Frontal Sinus Prints: A Forensic Medical Pilot Survey*. London: Lewis and Co.

Atkins, L., & Potsaid, MS (1978). Roentgenographic identification of human remains. *Journal of the American Medical Association, 240*, 2307-2308.

Besana, J. L., & Rogers, T. L. (2010). Personal Identification Using the Frontal Sinus*. *Journal of forensic sciences*, *55*(3), 584-589.

Blaney, S.P.A (1990). Why Paranasal Sinuses? *The Journal of Laryngology and Otology, 104*, 690-693.

Blanton, P.L., & Biggs, L. (1969). Eighteen Hundred Years of Controversy: The Paranasal Sinuses. *American Journal of Anatomy, 124*, 135-148.

Brogdon, BG (1998). Radiological Identification of Individual Remains. In BG Brogdon (Ed.), *Forensic Radiology* (pp. 149-187). New York: CRC Press.

Brogdon, B.G. (2012). Radiological Identification of Individual Remains. In Michael J. Thali, Mark D. Viner and B.G. Brogdon (Eds.), *Forensic Radiology* (pp. 153-176). Boca Raton: CRC Press.Buchner, A. (1985). The identification of human remains. *Int Dent J, 35*, 307-311.

Byers, Steven (2008). *Introduction to Forensic Anthropology* (Third ed.). Boston: Allyn and Bacon.

Cameriere, Roberto, Ferrante, Luigi, Mirtella, Dora, Rollo, Franco Ugo, & Cingolani, Mariano (2005). Frontal sinuses for identification: quality of classification, possible error and potential corrections. *Journal of Forensic Sciences, 50*(4), 770-773.

Cameriere, Roberto, Ferrante, Luigi, Molleson, Theya, & Brown, Barry (2008). Frontal sinus accuracy in identification as measured by false positives in kin groups. *Journal of Forensic Sciences, 53*(6), 1280-1282.

Campobasso, Carlo P., Dell'Erba, Alessandro S., Belviso, Maura, & Di Vella, Giancarlo (2007). Craniofacial Identification by Comparison of Antemortem and Postmortem Radiographs. *American Journal of Forensic Medicine and Pathology, 28*, 182-186.

Cattaneo, Cristina (2007). The Skeletal Remains of a Child, Victim of Organized Crime: The Study of Postmortem Interval, Personal Identification and Cause and Manner of Death. In Megan B. Brickley & Roxana Ferllini (Eds.), *Forensic Anthropology: Case Studies from Europe* (pp. 137-150). Springfield, IL.: Charles C. Thomas.

Cecil, JS. (2005). Ten years of judicial gatekeeping under Daubert. *American Journal of Public Health, 95*, S74-80.

Champod, C. (2009). Identification and individualization. *Wiley Encyclopedia of Forensic Science*, 1508-1511.

Christensen, Angi M. (2004a). The impact of Daubert: Implications for Testimony and Research in Forensic Anthropology (and the Use of Frontal Sinuses in Personal Identification). . *Journal of Forensic Sciences, 49*(3), 427-430.

Christensen, Angi M. (2004b). Assessing the Variation in Individual Frontal Sinus Outlines. *American Journal of Physical Anthropology, 127*(3), 291-296.

Christensen, Angi M. (2005a). Testing the Reliability of Frontal Sinuses in Positive Identification. *Journal of Forensic Sciences, 50*(1), 18-22.

Christensen, Angi M. and Anderson, Bruce E. (2013) Methods of Personal Identification in *Forensic Anthropology: An Introduction.* Edited by Maria Teresa A. Tersigni-Tarrant and Natalie R. Shirley. Boca Raton: CRC Press, 397-420

Christensen, Angi M., & Crowder, Christian M. (2009). Evidentiary Standards for Forensic Anthropology. *Journal of Forensic Sciences, 54*(6), 1211-1216.

Clark, DH (1986). Dental identification problems in the Abu Dhabi air accident. *American Journal of Forensic Medicine and Pathology, 7*, 317-321.

Cole, S. A. (2009). Forensics without uniqueness, conclusions without individualization: the new epistemology of forensic identification. *Law, Probability and Risk*, *8*(3), 233-255.

Cox, Mary, Malcolm, Matthew, & Fairgrieve, Scott I (2009). A New Digital Method for the Objective Comparison of Frontal Sinuses for Identification. *Journal of Forensic Sciences, 54*(4), 761-772.

Cryer, MH (1907). Some variations in the frontal sinuses. *Journal of the American Medical Association, 48*, 284-289.

Culbert, WC, & Law, FM (1927). Identification by comparison of roentgenograms of nasal accessory sinuses and mastoid processes. *Journal of the American Medical Association, 4*, 1634-1636.

Da Silva, Rhonan Ferreira, Prado, Felippe Bevilacqua, Caputo, Isamara Geandra Cavalcanti, Devito, Karina Lopes, Botelho, Tessa DeLuscena, & Daruge, Eduardo Junior (2009). The Forensic Importance of Frontal Sinus Radiographs. *Journal of Forensic and Legal Medicine, 16* (1), 18-23.

Daubert Tracker. (n.d.). Retrieved January 14, 2015, from http://www.dauberttracker.com/

Derrick, S. M., Raxter, M. H., Hipp, J. A., Goel, P., Chan, E. F., Love, J. C., Wiersema, J.M. & Akella, N. S. (2015). Development of a Computer-Assisted Forensic Radiographic Identification Method Using the Lateral Cervical and Lumbar Spine. *Journal of forensic sciences 60*(1), 5-12.

Devriendt, William, Piercecchi-Marti, Marie-Dominique, Adalian, Pascal, Sanvoisin, Alain, Dutour, Olivier, & Leonetti, Georges (2005). Hyperostosis Frontalis Interna: Forensic Issues. *Journal of Forensic Sciences, 50*(1), 143-146.

Dillon, IG, & Gourevitch, IB (1936). Research on the Pneumatization of the Nasal Accessory Sinuses and of the Mastoid Processes and on the Shape and Dimensions of the Sella Turcica in Twins. *American Journal of Roentgenology and Radium Therapy, 35*, 782-785.

Djuric, Marija (2004). Anthropological Data in Individualization of Skeletal Remains from a Forensic Context in Kosovo - A Case History. *Journal of Forensic Sciences, 49*(3), 464-468.

English, W.R., Robinson, S.F., Summitt, J.B., Oesterle, L.J., Brannon, R.B., & Morlang, W.M. (1988). Individuality of human palatal rugae. *Journal of Forensic Sciences, 33*, 718-726.

Evans, KT, Knight, B, & Whitaker, J. P. (1981). *Forensic Radiology*. Oxford: Blackwell Scientific.

Faigman, DL, Kaye, DH, Saks, MJ, & Sanders, J (1997). *Modern scientific evidence: the law and science of expert testimony. Vols. 1 and 2* (Vol. 1 and 2). St Paul, MN: West.

Farke, Andrew A. (2007). Morphology, constraints and scaling of frontal sinuses in the Hartebeest, *Alecelaphus buselaphus* (Mammalia: Artiodactyla, Bovidae. *Journal of Morphology, 268*, 243-253.

Field, Andy (2009). *Discovering statistics using SPSS*: Sage publications.

Fischman, S.L. (1985). The Use of Medical and Dental Radiographs in Identification *Int Dent J, 35*, 301-306.

Foran, D. R., & Berman, G. M. (2014). Commentary on: Modesti LD, Vieira GM, Galvao MF, de Amorim RF. Human identification by oral prosthesis analysis with probability rates Higher than DNA analysis. J Forensic Sci 2014; 59 (3): 825–9. *Journal of forensic sciences*.

Frayer, D.W., & Bridgens, J.G. (1985). Stab Wounds and Personal Identity Determined from Skeletal Remains: A Case from Kansas. *Journal of Forensic Sciences, 30*(1), 232-238.

Gaensslen, RE, Harris, H, & Lee, HC (2008). *Introduction to Forensic Science and Criminalistics.* New York NY: McGraw Hill.

Gardner, T., & Anderson, T. (2012). *Criminal evidence: Principles and cases*. Cengage Learning.

Gatowski, SI, Doblin, SA, Richardson, JT, Ginsburg, GP, Merlino, ML, & Dahir, V (2001). Asking the gatekeepers: a national survey of judges and judging expert evidence in a post-Daubert world. *Law and Human Behaviour, 25*, 433-458.

Glaister, J, & Brash, JC (1937). The medico-legal aspects of the Buck Ruxton case. Edinburgh: E and S. Livingston.

Glancy, Graham D, & Bradford, John MW (2007). The admissibility of expert evidence in Canada. *Journal of the American Academy of Psychiatry and the Law Online, 35*(3), 350-356.

Gordon, Ian RS, & Ross, Francis GM (1977). *Diagnostic Radiology in Paediatrics*. London: Butterworths.

Gregersen, M., Jensen, S., & Knudsen, P.J.T. (1995). The Crash of the Partnair Convair 340/580 in the Skagerrak: Identification of the Deceased. *Aviat Space Environ Med, 66*, 158-163.

Grivas, Christopher R, & Komar, Debra A (2008). Kumho, Daubert, and the Nature of Scientific Inquiry: Implications for Forensic Anthropology. *Journal of Forensic Sciences, 53*(4), 771-776.

Gruspier, Katherine & Rogers, Tracy (2012). Forensic Anthropology. In *Forensic Science in Canada: A Report of Multidisciplinary Discussion.* Edited by Michael S. Pollanen, Matthew J. Bowes, Sherah L. VanLaerhoven and Joanne Wallace. Toronto: Centre for Forensic Science and Medicine, 21-30.

Haglund, WD, & Fligner, CL (1993). Confirmation of Human Identification Using Computerized Tomograph (CT). *Journal of Forensic Sciences, 38*(3), 708-712.

Harris, A.M.P, Wood, R. E., Nortje, C.J., & Thomas, C.J (1987). The frontal sinus: forensic fingerprint? A pilot study. *Journal of Forensic Odontostomatology, 5*, 9-15.

Hempel, CG (1966). *Philosophy of natural science*. Englewood Cliffs: Prentice Hall.

Holobinko, A. (2012). Forensic human identification in the United States and Canada: A review of the law, admissible techniques, and the legal implications of their application in forensic cases. *Forensic Science International*, *222*(1), 394-e1.

Hogge, Jacquelyn P., Messmer, James M., & Doan, Quynh N. (1994). Radiographic Identification of Unknown Human Remains and Interpreter Evidence Level. *Journal of Forensic Sciences, 39*(2), 373-377.

Hunter, John, Roberts, Charlotte, & Martin, Anthony (1996). *Studies in Crime: An Introduction to Forensic Anthropology*. New York: Routledge.

Ingersoll, JM (1906). The function of the accessory cavities of the nose. *Annals of Otology, Rhinology and Laryngology, 15*, 757-770.

Jayaprakash, P. T. (2013). Practical relevance of pattern uniqueness in forensic science. *Forensic Science International*, *231*(1), 403-e1.

Kahana, T., & Hiss, J. (1994). Positive Identification by Means of Trabecular Bone Pattern Comparison. *Journal of Forensic Sciences, 39*(5), 1325-1330.

Kahana, T., & Hiss, J. (1997). Identification of Human Remains: Forensic Radiology. *Journal of Clinical Forensic Medicine, 4*, 7-15.

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

Kassirer, J., & Cecil, J. (2002). Inconsistency in evidentiary standards for medical testimony. *JAMA, 288*(11), 1382-1387.

Kaye, D. H. (2003). Questioning a courtroom proof of the uniqueness of fingerprints. *International Statistical Review*, *71*(3), 521-533.

Kieser, J. A., Bernal, V., Neil Waddell, J., & Raju, S. (2007). The uniqueness of the human anterior dentition: a geometric morphometric analysis. *Journal of forensic sciences*, *52*(3), 671-677.

Kim, Deog-Im, Lee, U, Park, Sang-Ouk, Kwak, Dae-Soon, & Han, Seung-Ho (2012). Identification Using Frontal Sinus by Three-Dimensional Reconstruction from Computed Tomography. *Journal of Forensic Sciences, 58*(1), 5-12.

Kirk, P. L. (1963). The ontogeny of criminalistics. *The Journal of Criminal Law, Criminology, and Police Science*, 235-238.

Kirk, Nigel J., Wood, R. E., & Goldstein, Marc (2002). Skeletal Identification Using the Frontal Sinus Region: A Retrospective Study of 39 Cases. *Journal of Forensic Sciences, 47*(2), 318-323.

Klepinger, Linda L. (1999). Unusual Skeletal Anomalies and Pathologies in Forensic Casework. In Scott I. Fairgrieve (Ed.), *Forensic Osteological Analysis: A Book of Case Studies*. Springfield: Charles C. Thomas.

Kogon, SL and McLean DF. (1996). Long-term validation study of bitewing dental radiographs for forensic identification. *Journal of Forensic Sciences* 41(2):230-232

Komar, Debra (2003). Lession from Srebrenica: The Contributions and Limitations of Physical Anthropology in Identifying Victims of War Crimes. *Journal of Forensic Sciences, 48*(4), 713-716.

Komar, Debra A, & Buikstra, Jane E (2008). *Forensic Anthropology: Contemporary Theory and Practice*. New York Oxford University Press.

Koot, Michael G., Sauer, Norman J., & Fenton, Todd W. (2005). Radiographic Human Identification Using Bones of the Hand: A Validation Study. *Journal of Forensic Sciences, 50*(2), 263-268.

Koppe, Thomas, & Nagai, Hiroshi (1999a). Quantitative Analysis of the Maxillary Sinus in Catarrhine Primates. In Thomas Koppe, Hiroshi Nagai & Kurt W. Alt (Eds.), *The Paranasal Sinuses of Higher Primates: Development, Function and Evolution* (pp. 121-132). Chicago: Quintessence Publishing Co. Inc.

Koppe, Thomas, Yamamoto, T., Tanaka, O., & Nagai, Hiroshi (1994). Investigations on the growth pattern of the maxillary sinus in Japanese Human Fetuses. *Okajimas Folia Anat. Jpn., 71*, 311-318.

Krennmair, G., Ulm, C.W., Lugmayr, H., & Solar, P. (1999). The incidence, location and height of maxillary sinus septa in the endentulous and dentate maxilla. *J Oral Maxillofac Surg, 57*, 667-671.

Krogman, WM, & Iscan, Mehmet Yasar (1986). *The Human Skeleton in Forensic Medicine*. Springfield, IL.: Charles C. Thomas

Kuehn, Carrie M., Taylor, Katherine M., Mann, F.A., Wilson, Anthony J., & Harruff, Richard C. (2002). Validation of Chest X-ray Comparisons for Unknown Decedent Information. *Journal of Forensic Sciences, 47*(4), 725-729.

Kullman, L., Eklund, B., & Grundin, R. (1990). The Value of Frontal Sinus Identification of Unknown Persons *Journal of Forensic Odontostomatology, 8*, 3-10.

Libersa, C., Laude, M., & Libersa, J.C. (1981). The pneumatization of the accessory sinuses of the nasal fossae during growth. *Anat. Clin., 2*, 265-273.

Limson, K.S., & Julian, R. (2004). Computerized recording of the palatal rugae pattern and an evaluation of its application in forensic identification. *Journal of Forensic Odontostomatology, 22*, 1-4.

Lund, V.J. (1988). The maxillary sinuses of higher Primates. *Acta Otolaryngol, 105*, 164-171.

Manitoba Government (n.d.) Retrieved December 14, 2014, from http://www.gov.mb.ca/health/waittime/diagnostic/ctcat.html

Mann, Robert W. (1998). Use of Bone Trabeculae to Establish Positive Identification. *Forensic Science International, 98*, 91-99.

Maresh, Marion M. (1940). Paranasal Sinuses from Birth to Late Adolescence. *American Journal of Diseases in 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*(6), 1765-1772.

Marquez, Samuel (2008). The Paranasal Sinuses: The Last Frontier in Craniofacial Biology. *The Anatomical Record, 261*(291), 1350-1361.

Martel, W., Wicks, JD, & Hendrix, RC (1977). The accuracy of radiologic identification of humans using skeletal landmarks: A contribution to forensic pathology. *Radiology, 124*, 681-684.

Mayer, J (1935). Identification by sinus prints. *Journal of Virginia Medical Monthly* (62), 517-519.

McCartney, Carole (2012). Forensic Identification and Criminal Justice. Routledge: New York

Messmer, JM, & Fierro, MF (1986). Personal identification by radiographic comparison of vascular groove patterns of the calvarium. *American Journal of Forensic Medicine and Pathology, 7*, 159-162.

Moenssens, Andre (2009) Falsifiability Theory. In *Wiley Encyclopedia of Forensic Science.* Edited by Allan Jamison and Andre Moenssens. Chichester, UK: John Wiley and Sons, 1093

Morse, D., Duncan, J., & Stoutamire, J. (Eds.). (1983). *Handbook of Forensic Archaeology and Anthropology*. Tallahassee: Florida State University Foundation Inc.

Moser, RP, & Wagner, G.N. (1990). Nutrient groove of the ilium, a subtle but important forensic radiographic marker in the identification of victims of severe trauma. *Skeletal Radiol, 19*, 15-19.

Mulligan, M.E., McCarthy, M.J., Wippold, F.J., Lichenstein, J.E., & Wagner, G.N. (1988). Radiologic Evaluation of Mass Casualty Victims: Lessons from the Gander, Newfoundland accident. *Radiology, 168*, 229-233.

Murphy, W.A., & Gantner, G.E. (1982). Radiologic Examination of Anatomical Parts and Skeletonized Remains. *Journal of Forensic Sciences, 27*(1), 9-18.

Murphy, W.A., Spruill, FG, & Gantner, G.E. (1980). Radiographic Identification of Unknown Human Remains. *Journal of Forensic Sciences, 25*, 725-735.

Nambiar, P., Naidu, M. D., & Subramaniam, K. (1999). Anatomical variability of the frontal sinuses and their application in forensic identification. *Clinical Anatomy*, *12*(1), 16-19.

NAS Report. *Strengthening forensic science in the United States: A path forward*. (2009). Washington, D.C.: National Academies Press.

National Institute of Standards and Technology. (n.d.). Retrieved December 16, 2014, from http://www.nist.gov/index.htmlNegus, Sir Victor (1957). The function of the paranasal sinuses. *AMA Arch Otolaryngology - Head and Neck Surgery, 66*, 430-442.

Negus, Sir Victor (1958). *The Comparative Anatomy and Physiology of the Nose and Paranasal Sinuses*. Edinburgh: E. and S. Livingstone Ltd.

O'Higgins, Paul, Bastir, M, & Kupczik, K. (2006). Shaping the face. *International Congress Series, 1296*, 55-73.

Ohtani, Maki, Nishida, Naoki, Chiba, Takashi, Fukuda, Masayuki, Miyamoto, Yoji, & Yoshioka, Naofumi (2008). Indication and limitations of using palatal rugae for personal identification in edentulous cases. *Forensic Science International, 176*(2-3), 178-182.

Owsley, D. (1993). Identification of the Fragmentary, Burned Remains of Two US Journalists Seven Years After Their Disappearance in Guatemala. *Journal of Forensic Sciences, 38*(6), 1372-1383.

Page, M., Taylor, J., & Blenkin, M. (2011). Uniqueness in the forensic identification sciences—Fact or fiction? *Forensic science international*, *206*(1), 12-18.

Pankanti, Sharath, Prabhakar, Salil, & Jain, Anil K (2002). On the individuality of fingerprints. *Pattern Analysis and Machine Intelligence, IEEE Transactions on, 24*(8), 1010-1025.

Pfaeffli, Matthias, Vock, Peter, Dirnhofer, Richard, Braun, Marcel, Bolliger, Stephan A., & Thali, Michael J. (2007). Post-mortem radiological CT identification based on classical ante-mortem X-ray examinations. *Forensic Science International, 171*(2-3), 111-117.

Popper, K. (1989). *Conjectures and refutations: the growth of scientific knowledge.* New York: Harper and Row.

Pretty, I. A., Pretty, R. J., Rothwell, B. R., & Sweet, D. (2003). The reliability of digitized radiographs for dental identification: a Web-based study. *Journal of forensic sciences*, *48*(6), 1325-1330.

Pretty, I. A., Barsley, R., Bowers, C. M., Bush, M., Bush, P., Clement, J., & Wright11, F. (2012). Odontology–dentistry's contribution to truth and justice. *Forensic Science: Current Issues, Future Directions*, 179-210.

Prinz, JF (1993). A forensic dental identification system with error tolerant algorithms and a review of the prevalence of errors occuring in dental records. *Med Sci Law, 33*, 4-10.

Quatrehomme, Gerald, Fronty, Pierre, Sapanet, Michel, Grevin, Gilles, Bailet, Paul, & Ollier, Amedee (1996). Identification by frontal sinus pattern in forensic anthropology. *Forensic Science International, 83*, 147-153.

Rae, Todd C., & Koppe, Thomas (2004). Holes in the Head: Evolutionary Interpretations of Paranasal Sinuses in Catarrhines. *Evolutionary Anthropology, 13*, 211-223.

Rae, T. C., & Koppe, T. (2008). Independence of biomechanical forces and craniofacial pneumatization in Cebus. *The Anatomical Record*, *291*(11), 1414-1419.

Reichs, Kathy (1993). Quantified Comparison of Frontal Sinus Patterns by means of Computer Tomography (CT). *Forensic Science International, 61*, 141-168.

Reichs, Kathy, & Dorion, R (1992). The Use of Computed Tomography (CT) Scans in Comparison of Frontal Sinus Configurations. *Canadian Society of Forensic Sciences, 25*(1), 1-16.

Rhine, Stanley, & Sperry, K. (1991). Radiographic comparison by mastoid sinus and arterial pattern. *Journal of Forensic Sciences, 36*, 272-279.

Ribeiro, F (2000). Standardized Measurements of Radiographic Films of the Frontal Sinuses: an Aid to Identifying Unknown Persons. *Ear, Nose and Throat Journal, 79*, 26-33.

Riepert, T., Ulmcke, D., Schweden, F., & Nafe, B. (2001). Identification of unknown dead bodies by X-ray image comparison of the skull using the X-ray simulation program FoXSIS. *Forensic science international*, *117*(1), 89-98.

Rogers, Spencer (1987). *Personal Identification from Human Remains*. Springfield, IL.: Charles C. Thomas.

Rogers, Tracy L., & Allard, Travis T. (2004). Expert Testimony and Positive Identification of Human Remains Through Cranial Suture Patterns. *Journal of Forensic Sciences, 49*(2), 203-207.

Ross, Ann H., & Kimmerle, Erin H. (2009). Contribution of Quantitative Methods to Forensic Anthropology: A New Era. In Soren Blau & Douglas H. Ubelaker (Eds.), *Handbook of Forensic Anthropology and Archaeology* (pp. 479-489). Walnut Creek, California: Left Coast Press Inc.

Rossie, James B. (2006). Ontogeny and Homology of the Paranasal Sinuses in Platyrrhini (Mammalia: Primates). *Journal of Morphology, 267*, 1-40.

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 on two cases. *Journal of Forensic Sciences, 38*, 997-1007.

Saks, M. J. (2010). Forensic identification: from a faith-based “Science” to a scientific science. *Forensic science international*, *201*(1), 14-17.

Saks, M. J., & Faigman, D. L. (2008). Failed forensics: How forensic science lost its way and how it might yet find it. *Annual Review of Law and Social Science*, *4*, 149-171.

Saks, M. J., & Koehler, J. J. (2008). Individualization Fallacy in Forensic Science Evidence, The. *Vand. L. Rev.*, *61*, 199.

Sauer, Norman J., Brantley, RE, & Barondess, DA (1988). The effect of ageing on the comparability of antemortem and postmortem radiographs. *Journal of Forensic Sciences, 33*, 1223-1230.

Saxena, S., Sharma, P., & Gupta, N. (2010). Experimental studies of forensic odontology to aid in the identification process. *Journal of forensic dental sciences*, *2*(2), 69.

Schuller, A. (1943). A Note on the Identification of Skulls by X-ray Pictures of the Frontal Sinuses. *Medical Journal of Australia, 25*, 554-556.

Schuller-Gotzburg, P., & Suchanek, J. (2007). Forensic Odontologists Successfully Identify Tsunami Victims in Phuket, Thailand. *Forensic Science International, 171*, 204-207.

Singleton, AC (1951). The Roentgenological Identification of Victims of the 'Noronic' Disaster. *American Journal of Roentgenology and Radium Therapy, 66*, 375-384.

Skinner, Mark (1988). Method and theory in deciding identity of skeletonized human remains. *Canadian Society of Forensic Sciences, 21*(3), 114-134.

Slobogin, C. (2003). The structure of expertise in criminal cases. *Seton Hall Law Review 34*, 105-121.

Smith, Deborah R., Limbird, Keith G., & Hoffman, J. Michael (2002). Identification of Human Skeletal Remains by Comparison of Bony Details of the Cranium Using Computerized Tomographic (CT) Scans. *Journal of Forensic Sciences, 47*(5), 937-939.

Smith, V. A., Christensen, A. M., & Myers, S. W. (2010). The Reliability of Visually Comparing Small Frontal Sinuses. Journal of forensic sciences, 55(6), 1413-1415.

Steadman, Dawnie Wolfe (2013). The places we will go: paths forward in forensic anthropology. In Ubelaker, Douglas H. (Ed) *Forensic Science: Current Issues, Future Directions*, Wiley-Blackwell Hoboken, 131-159

Stewart, T.D. (1979). *Essentials of Forensic Anthropology*. Springfield: Charles C. Thomas.

Stoney, D. A. (1991). What made us ever think we could individualize using statistics? *Journal of the Forensic Science Society*, *31*(2), 197-199.

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.

Swingler, SM (2005). *The Attraction to New Techniques: Using Magnetic Resonance Imaging to Evaluate the Morphology of the Frontal Sinuses of Monozygotic Twins.* University of Alberta, Edmonton.

Szolar, D., Preidler, K., Ranner, G., Braun, H., Kugler, C., Wolf, G., et al. (1994). The sphenoid sinus during childhood: establishment of normal development standards by MRI. *Surg Radiol Anat, 16*, 193-198.

Takahashi, Ryo (1983). The Formation of the Human Paranasal Sinuses. *Acta Oto Laryngologica Supplement, 408*, 1-28.

Tang, Jian-Pin, Hu, De-Yi, Jiang, Feng-Hui, & Yu, Xiao-Jun (2009). Assessing forensic applications of the frontal sinus in a Chinese Han population. *Forensic Science International, 183*(1-3), 104.e101-104.e103.

Tatlisumak, Ertugrul, Yilmaz Ovali, Gulgun, Aslan, Asim, Asirdizer, Mahmut, Zeyfeoglu, Yildiray, & Tarhan, Serdar (2007). Identification of unknown bodies by using CT images of frontal sinus. *Forensic Science International, 166*(1), 42-48.

Telmon, N., Allery, J-P., Scolan, V., & Rouge, D. (2001). A Case Report Demonstrating the Value of Chest X-rays in Comparative Identification. *Journal of Clinical Forensic Medicine, 8*, 77-80.

Tsunenari, Shigeyuki, Uchimura, Youko, Yonemitsu, Kosei, & Oshior, Seisho (1982). Unusual Personal Identification with Characteristic Features in Chest Roentgenograms. *American Journal of Forensic Medicine and Pathology, 3*(4), 357-360.

Tuthill, H., & George, G. (2002). *Individualization: Principles and procedures in criminalistics*. Lightning Powder Company.

Ubelaker, DH (1984). Chapter 29: Positive Identification from Radiographic Comparison of Frontal Sinus Patterns. In Ted A. Rathbun & Jane E. Buikstra (Eds.), *Human Identification: Case Studies in Forensic Anthropology* (pp. 399-411). Springfield, IL.: Charles C. Thomas.

Ubelaker, DH (1990). Postive identification of American Indian skeletal remains from radiographic comparison. *Journal of Forensic Sciences, 35*, 466-472.

van Alyea, O.E. (1939). Ethmoid labyrinth. *Arch. Otolaryngol., 29*, 881-902.

van Alyea, O.E. (1941). Sphenoid sinus. *Arch. Otolaryngol., 34*, 225-253.

Van der Stelt, P., Webber, R., & Ruttimann, U (1986). Forensic identification of trabecular patterns from dental radiographs. *J Dent Res, 65*, 176.

Varga, M, & Takacs, P. (1991). Radiographic personal identification with characteristic features of the hip joint. *American Journal of Forensic Medicine and Pathology, 12*, 328-331.

Watamaniuk, L., & Rogers, T. (2010). Positive Personal Identification of Human Remains Based on Thoracic VertebralMargin Morphology. *Journal of forensic sciences*, *55*(5), 1162-1170.

Wieglein, Andrew (1999). Development of the Paranasal Sinuses in Humans. In Hiroshi Nagai and Kurt W. Alt Thomas Koppe (Ed.), *The Paranasal Sinuses of Higher Primates: Development, Function and Evolution* (pp. 35-50). Chicago: Quintessence Publishing Co. Inc.

Wood, R. E., Tai, CCE, Bleinkinsop, B., & Johnston, D. (1994). Digitized slice interpostion in forensic dental radiographic identification: An in vitro study. *American Journal of Forensic Medicine and Pathology, 15*, 70-78.

Yoshino, Mineo, Miyasaka, Sachio, Sato, H., & Seta, S. (1987). System of Frontal Sinus Patterns by Radiography. It's Application to Identification of Unknown Skeletal Remains. *Forensic Science International, 34*, 289-299.

Zollikofer, Christoph P.E., Ponce de Leon, Marcia S., Schmitz, Ralf W., & Stringer, Christopher B. (2008). New Insights into Mid-Late Pleistocene Fossil Hominin Paranasal Sinus Morphology. *The Anatomical Record, 291*, 1506-1516.

Zollikofer, Christoph P.E., & Weissman, John D. (2008). A morphogenetic model of cranial pneumatization based on the invasive tissue hypothesis. *The Anatomical Record, 291*(1446-1454).

Zugibe, Frederick T., Taylor, James, Weg, Noah, DiBennerdo, Robert, Costello, James T., & DeForest, Peter (1985). Metropolitan Forensic Anthropology Team (MFAT) Case Studies in Identification: 3. Identification of John J. Sullivan, the Missing Journalist. *Journal of Forensic Sciences, 30*(1), 221-231.

Appendix I 3D data

This appendix presents the results of a pilot study to explore the three dimensional variation in the frontal sinuses. Using Materialise MIMICS™ bone in the CT images was thresholded using the default bone setting between 220-3071 Hounsfield units. A second mask was applied to capture the frontal sinuses using a setting of between -1024 and -135 Hounsfield units. Since this mask captured all the air and much of the soft tissue of the skull it was cropped to encompass the frontal sinus region using the sagittal, axial and coronal viewers. This mask was then edited in 3D to remove the excess before final editing using the axial viewer. Once the mask was satisfactory it was rendered in 3D using "Calculate 3D from mask" function. From the Export menu the 3D renderings of the frontal sinuses were saved as binary .STL files. Once this process had been carried out for all individuals it was repeated blindly a second time. This permitted comparisons to be made between the same individual (different renderings) for intraobserver error.

Ten trials were conducted. Microsoft Excel was used to create nine random groups of ten individuals and one group of 11 individuals. One individual was selected from each group to compare all others to. In the nine trials containing ten individuals, the comparison individual (nominal data) was also represented in the sample with the second frontal sinus rendering. Rapidform XOV3™ 64 was opened. The first frontal sinus rendering of the comparison individual was imported as nominal data and the second file was imported as scan data. The two frontal sinuses were aligned using the auto align and then aligned again using best fit align with a sampling ratio of 100%. Once aligned a whole deviation function was performed with a tolerance of 0.3 to look at the variation and a report was generated. This process was repeated comparing the nominal data to the other frontal sinus renderings. A primary series of ten trials was conducted to compare an 'unknown' individual with 10 others (which may or may not have included a second rendering of the same individual). Rapidform™ is engineering software utilized in this investigation because of its ability to compare STL scan data. STL files are one format for three-dimensional models and are typically utilised by CAD programs. This file type was one of the available formats for export provided by Materialise MIMICS™.

Table I.1 shows the average out of tolerance %, standard deviation and variance values for renders from same skull and those from different skulls; Tables I.2 to I.11 represent the results of the ten trials. The tolerance value represents the amount of deviation from the target. The Rapidform™ default tolerance level of 0.3 mm was used to assess differences in size or shape between the two frontal sinuses. Out of tolerance % is the percent that the second STL (or unknown) differs from the target. In this application being "in tolerance" can be considered the same as morphologically similar; this can be extrapolated to draw conclusions regarding how similar two STLs (or frontal sinuses) are to each other.

Table I.1: Average statistic values for same skull and different skull comparisons

Average statistics	Same skull comparisons	Different skull comparisons
Out of tolerance %	16.24	83.72
Standard deviation	0.31	1.29
Variance	0.16	1.68

Table I.2: Trial one

02271101 (1)	Out of Tolerance %	Standard Deviation	Variance
02271101 (2)	12.375	0.1658	0.0275
8281236	82.9978	1.6292	2.6544
9031128	84.9613	1.5839	2.5087
9090928	85.3711	1.4993	2.2479
10221221	90.618	1.9884	3.9536
10221224	88.3806	1.9574	3.8312
10221306	86.6729	1.9021	3.618
10221308	88.4223	2.1526	4.6336
11181140	77.6799	1.9623	3.8505
12978117	92.3815	1.7268	2.9819

Table I.3: Trial two

10221308 (1)	Out of Tolerance %	Standard Deviation	Variance
8291450	86.6146	1.2691	1.6105
9011340	88.2621	1.4752	2.1763
10221225	90.0126	1.5268	2.331
10221308 (2)	58.6308	0.3629	0.1317
10231230	85.4657	1.4555	2.0142
11031228	86.6964	1.4666	2.1508
11031258b	85.2136	1.4612	2.135
11181225	86.2069	1.322	1.7476
11181227	86.4662	1.1926	1.4223
12798107	79.5227	1.1527	1.3286

Table I.4: Trial three

10221246 (1)	Out of Tolerance %	Standard Deviation	Variance
02271101b	85.8853	1.5157	2.2974
02271101e	87.3514	1.4682	2.1526
02271146a	83.9822	1.3554	1.8372
8291450	85.4909	1.4195	2.0149
9090926	88.4429	1.4544	2.1154
10221225	87.7231	1.5941	2.541
10221246 (2)	15.5889	0.4776	0.228
11031231	89.1618	1.4596	2.1305
12897101	85.4913	1.4086	1.9841
8291410	89.5453	1.368	1.8713

Table I.5: Trial Four

12897111 (1)	Out of Tolerance %	Standard Deviation	Variance
02271101c	77.1122	1.1888	1.4132
02271101d	87.9262	1.5497	2.4017
02271145c	90.0311	1.417	2.008
02271146a	84.6488	1.3107	1.7179
8291441	93.7336	1.6071	2.5827
8291457	83.1558	1.3639	1.8602
11181214	86.6056	1.6368	2.679
11251046	86.6295	1.2739	1.6228
12897111 (2)	18.3358	0.273	0.0745
12987104	76.5495	1.2018	1.4443

Table I.6: Trial five

11181129 (1)	**Out of Tolerance %**	**Standard Deviation**	**Variance**
02271223f	79.9689	0.9971	0.9941
8291401	85.6757	1.171	1.3712
8291452	92.8857	1.0129	1.026
10221223	74.5562	1.041	1.0837
10221313	89.5585	0.8913	0.7944
10231251	90.2387	1.1992	1.4382
11031258b	92.9446	1.073	1.1512
11181129 (2)	17.1712	0.1895	0.0359
11181145	91.0725	1.0356	1.0725
12987104	72.8016	1.0353	1.0719

Table I.7: Trial six

8291433 (1)	**Out of Tolerance %**	**Standard Deviation**	**Variance**
8291433 (2)	19.925	0.5799	0.3363
8281218	90.2853	1.1236	1.4729
9101255	90.1718	1.288	1.6589
10221240	86.633	1.2875	1.6577
10221307	87.111	1.1105	1.2332
10221312	89.47	1.2534	1.5711
11031232	84.3279	1.2854	1.6523
11181202	84.9362	1.0433	1.0885
12798106	87.7776	1.4745	2.1741
12978116	83.4311	1.2337	1.5221

Table I.8: Trial seven

10231230 (1)	Out of Tolerance %	Standard Deviation	Variance
8291430	87.3574	1.1364	1.02913
10221246	81.3073	0.9469	0.8966
10231230 (2)	41.9784	0.2707	0.0733
11031255	86.8033	0.9281	0.8614
11181129	81.1496	1.0434	1.0888
11181142	90.8817	1.067	1.1384
11181214	75.5076	0.9903	0.9808
11181227	83.5866	1.0465	1.0951
12798106	77.6693	0.9598	0.9213
11031225	76.9972	0.877	0.7692

Table I.9: Trial eight

9051201 (1)	Out of Tolerance %	Standard Deviation	Variance
02271145b	89.2773	1.4876	2.213
02271223f	77.2346	1.1527	1.3288
8151058	89.0383	1.3561	1.8391
8291401	85.7807	1.3171	1.7349
8291452	91.373	1.4184	2.012
9051201 (2)	13.3576	0.4541	0.2062
10221225	87.3448	1.5404	2.373
10221307	90.3796	1.2681	1.6082
12897105	90.2974	1.5042	2.2627
12897116	74.2215	1.0439	1.0897

Table I.10: Trial nine

9090927	Out of Tolerance %	Standard Deviation	Variance
02271101e	86.6056	1.5329	2.3499
02271129c	87.6992	1.502	2.2559
02271145c	86.0577	1.5295	2.3394
02271146c	83.3631	1.4914	2.2243
8291502	89.7915	1.4545	2.1154
9031128	81.8872	1.3679	1.8712
9090927	4.253	0.2078	0.432
9090928	86.8242	1.1921	1.421
10221242	86.5515	1.6354	2.6745
11251047	91.3978	1.4698	2.1605

Table I.11: Trial ten

02271128	Out of Tolerance %	Standard Deviation	Variance
02271129	89.9968	1.4443	2.086
8281228	91.9511	1.7418	3.0542
8291405	90.4934	1.6751	2.806
10221223	91.2292	1.4852	2.2058
11031258b	89.2124	1.4748	2.1751
12879103	84.4717	1.3394	1.7939
12978104	84.8459	1.3356	1.7837
12897116	73.427	1.181	1.3947
9090930	92.6596	1.3505	1.8238
11181201	80.2191	1.2763	1.6288

Of particular note is that whenever the matching target render of the frontal sinus was present in the sample, it showed the lowest out-of-tolerance statistics. In fact, there is no overlap in the values between the same skull comparisons and the different skull comparisons. Table I.1 clearly illustrates that the averages of all three statistics are considerably lower between the same skull comparisons than the different skull comparisons, which is consistent with the assumption that two separate renderings of the same individual's frontal sinuses will be more similar to each other than renderings of frontal sinuses from two different individuals.

Figures I.1 and I.2 illustrate the whole deviation output when comparing two STLs of individual 10221308. The whole deviation output (Figure I.1) shows the differences between the two STLs using colour: similarities are illustrated with green (+0.3 to -0.3 mm) while extreme positive dissimilarities are indicated by red (exceeding +1 mm) and extreme negative dissimilarities are indicated by blue (exceeding -1 mm). Figure I.2 is a histogram representing the variation. The single spike illustrates that difference between the two STLs is limited to a particular region, which corresponds to the blue area in the inferior region of the frontal sinuses seen in Figure I.1.

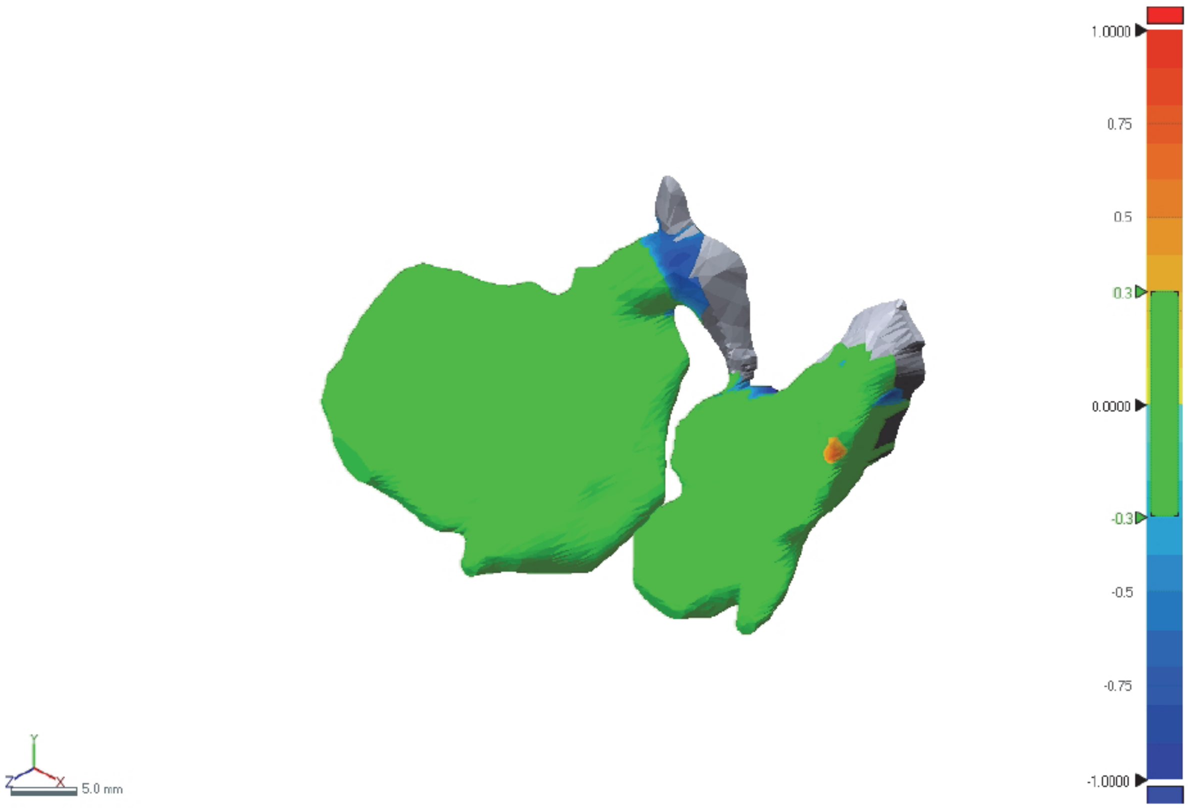


Figure I.1: Trial 2 whole deviation same skull comparison of individual 10221308 illustrating very similar morphology. The deviation is found predominantly in the interior portion.

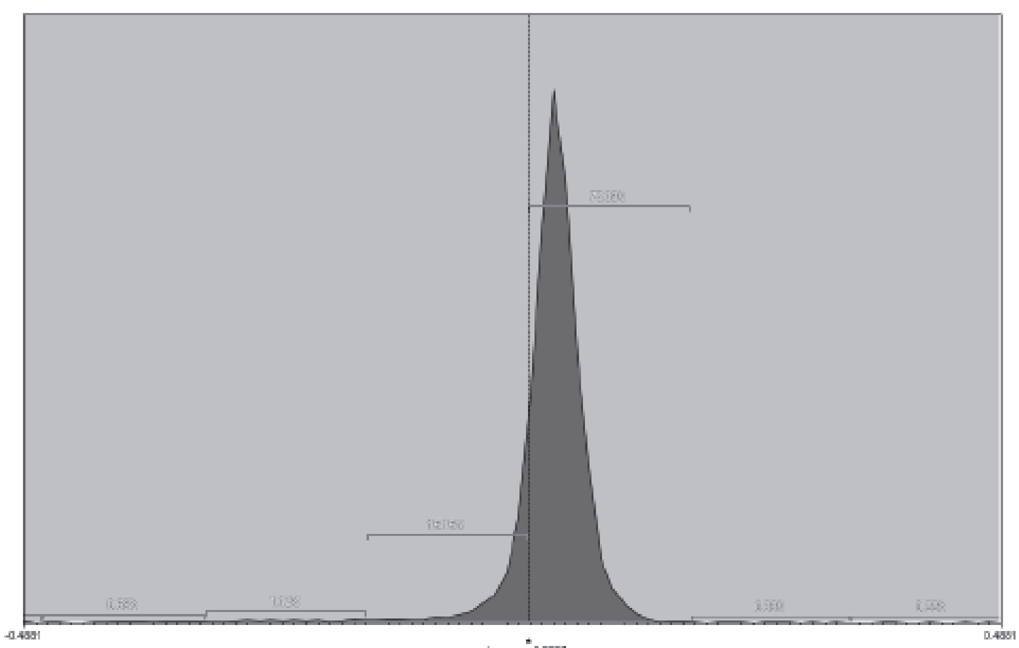


Figure I.2: Graph of whole deviation same skull comparison of individual 10221308.

In most of the trials the same skull comparisons yielded a percent out of tolerance under twenty percent, but in one instance the percent out of tolerance is higher than this at 41.98% (Figures I.3 to I.5). It is important to note that the only way an out of tolerance of 0% would be achieved is if the same scan is compared to itself.

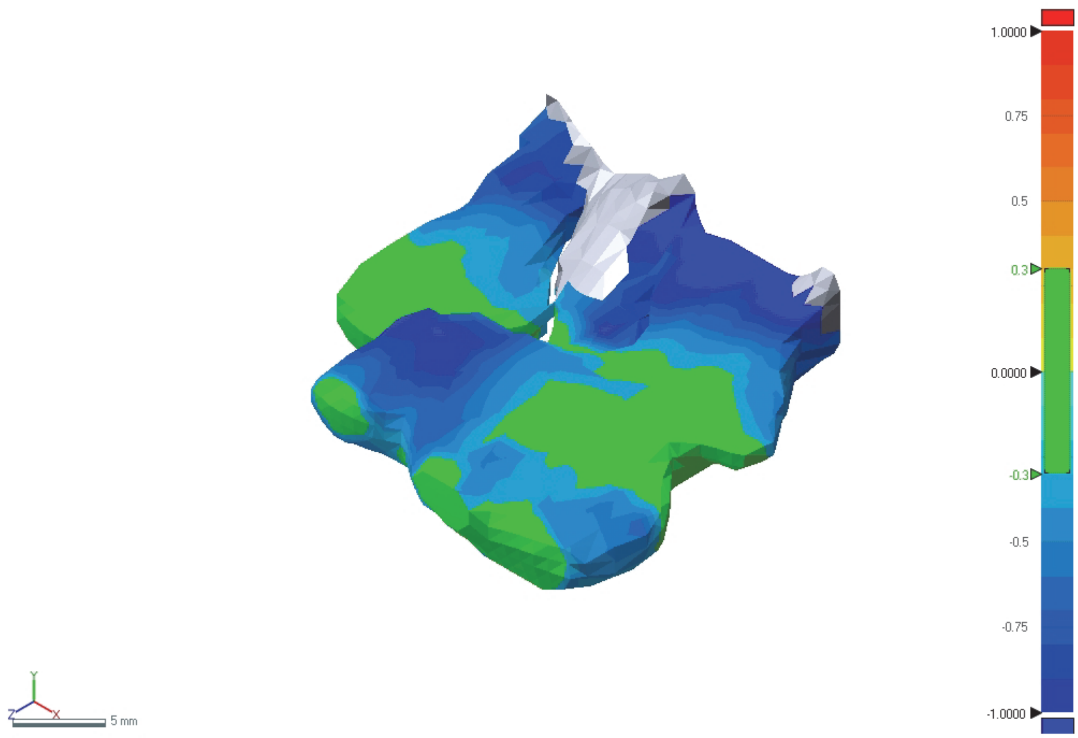


Figure I.3: Same skull comparison showing the whole deviation for individual 10231230 illustrating moderately similar morphology. Deviation is also found in the interior portion.

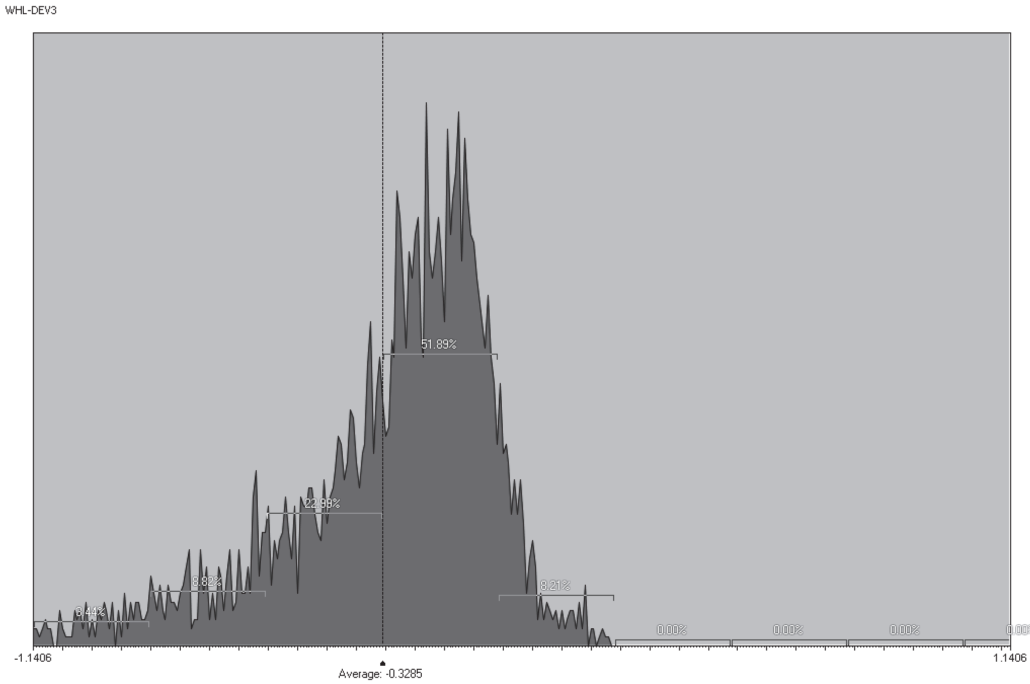


Figure I.4: Graph of whole deviation for individual 10231230

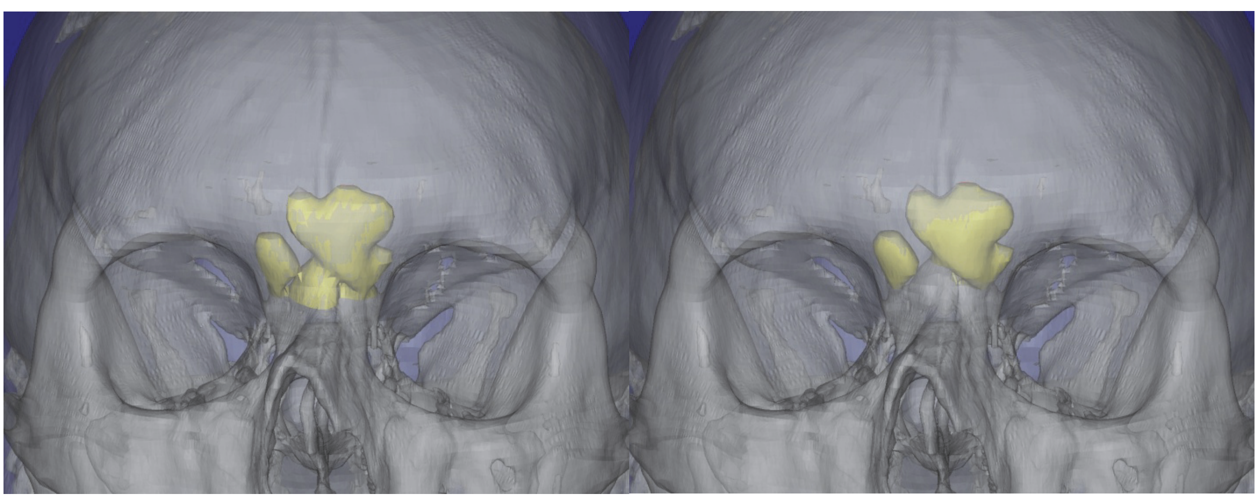


Figure I.5: Individual 10231230 showing difference in 3D rendering

Figures I.3 and I.5 clearly show that most of the deviation in this instance is coming from the inferior portion of the frontal sinuses. Figure I.4 illustrates that there is some deviation in the mid portion of the frontal sinuses. A same skull comparison of individual 9090927 (Figures I.6 and I.7) shows variation confined to the inferior portion of the frontal sinuses even though the percent out of tolerance in this comparison is low (4.253%). Due to difficulties in determining where the ethmoid air cells end and the frontal air cells begin the standard procedure has been to apply an arbitrary line connecting the superior portions of the eye orbits to serve as the most inferior portion of the sinuses (Christensen, 2004b). While this practice increases standardisation and reduces the challenge of determining the inferior portion of the frontal sinuses, it also excludes the morphology at the most inferior portions and because of the desire to capture all of the morphological variation in the frontal sinuses it was decided not to employ it here. Additionally, individuals with very small sinuses that do not extend above the superior borders of the orbits would be excluded and falsely categorised as not possessing frontal sinuses.

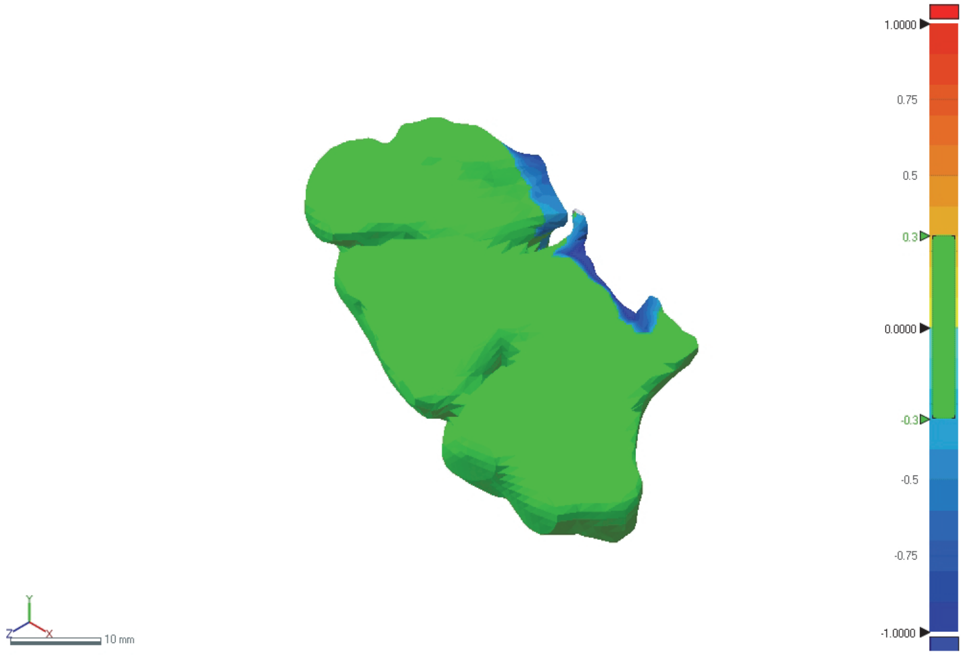


Figure I.6: Same skull comparison showing whole deviation for individual 9090927. The deviation is found predominantly in the interior portion.

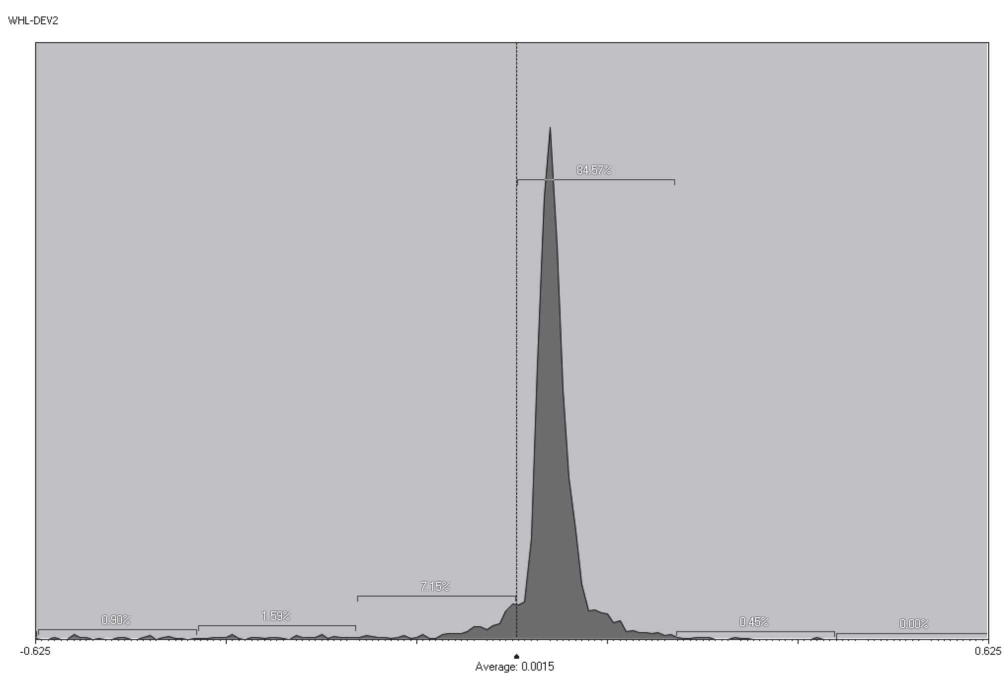


Figure I.7: Histogram of whole deviation for individual 9090927

Two individuals (12897111 and 02271145c) with large sinuses (volumes are 8.874 cm^3 and 19.115 cm^3 respectively) were compared. In this case, the whole deviation analysis produced a 90% out of tolerance value. Although the overall shape of these sinuses is similar in many regards when looked at in the frontal view, the whole deviation image shows specific regions with the most variation. In this comparison case it can be seen that the most variation, illustrated by red and blue, is not confined to a particular area of the sinuses, but appears spread throughout (Figures I.8 and I.9).

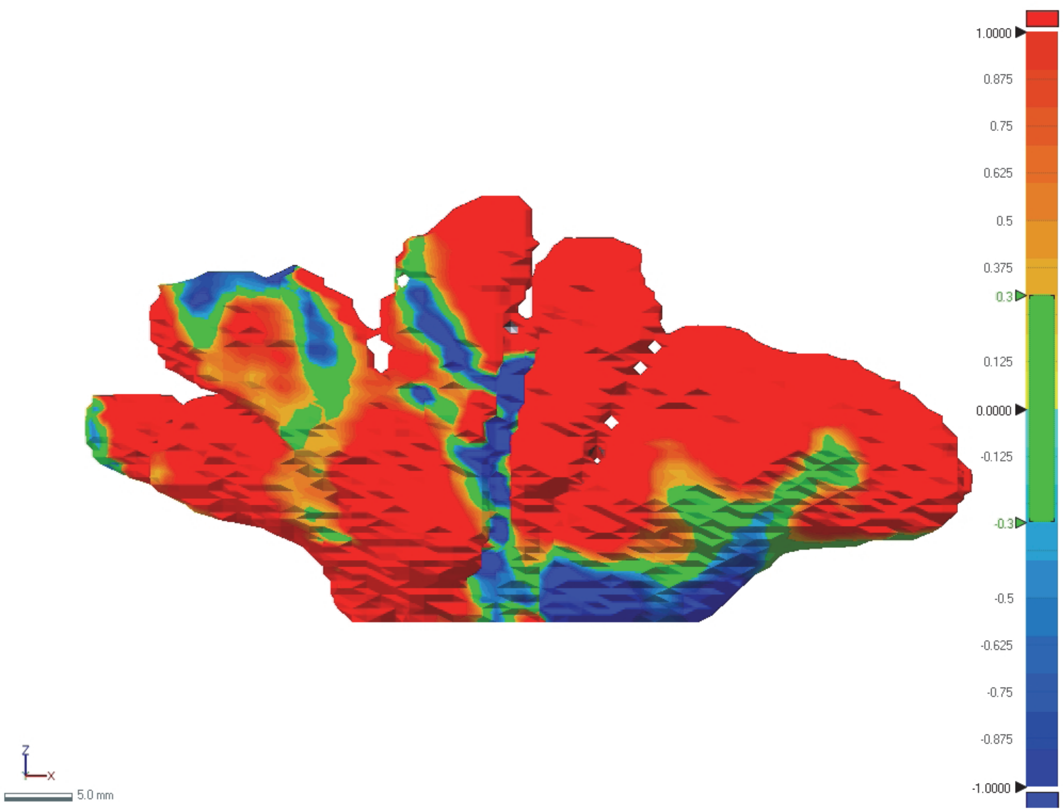


Figure I.8: Comparison of 12897111 and 02271145c. Deviation found throughout.

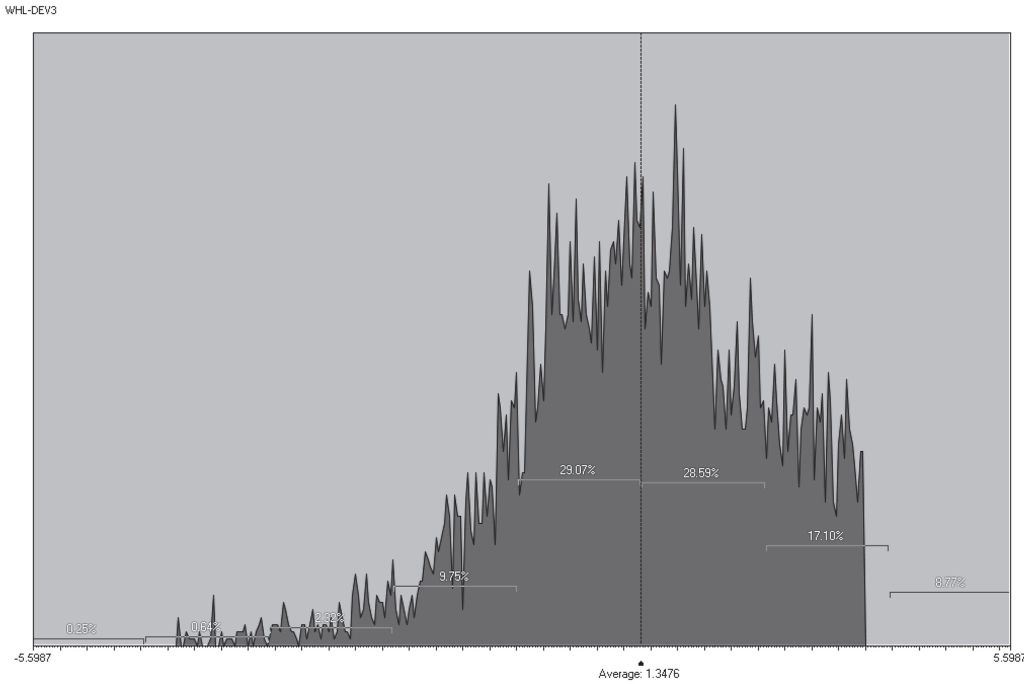


Figure I.9: Histogram of whole deviation for comparison of 12897111 and 02271145c

Comparison of another two individuals (02271128 and 9090930) showed an out of tolerance at 92.6596%. As with two other previous examples variation between the frontal sinuses of these two individuals appears to be spread throughout the frontal sinuses, and not particularly concentrated on any regions. Figure I.10 shows the 3D rendering of Individual 02271128 and Figure I.11 illustrates 3D rendering of individual 9090930. Figure I.12 shows the comparison between individuals 02271128 and 9090930 and Figure I.13 presents the histogram illustrating with the many spikes spread throughout that deviation is not limited to a certain region.

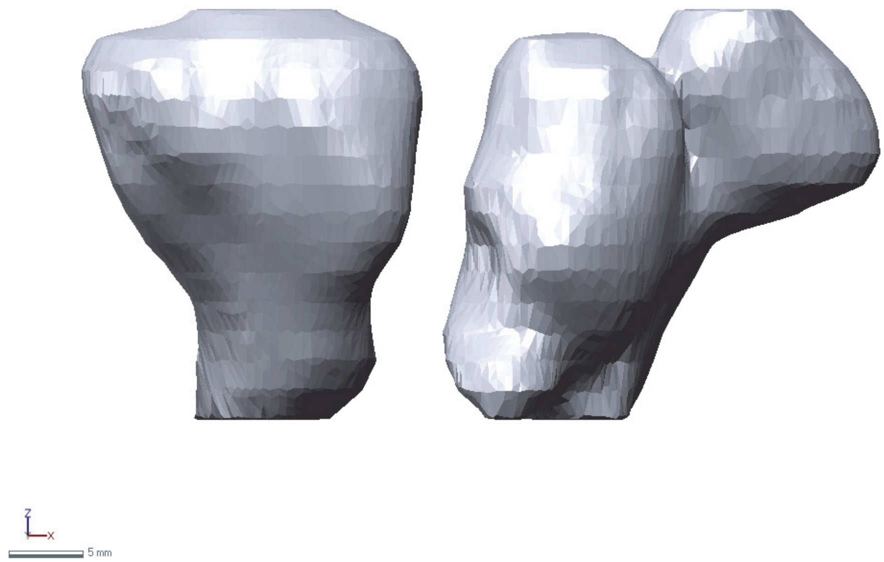


Figure I.10: 3D rendering of Individual 02271128

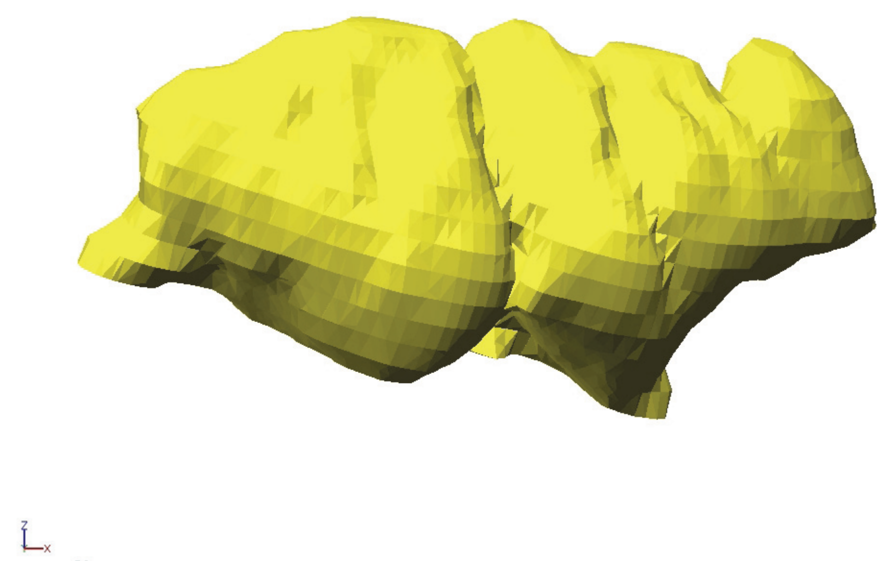


Figure I.11: 3D rendering of Individual 9090930

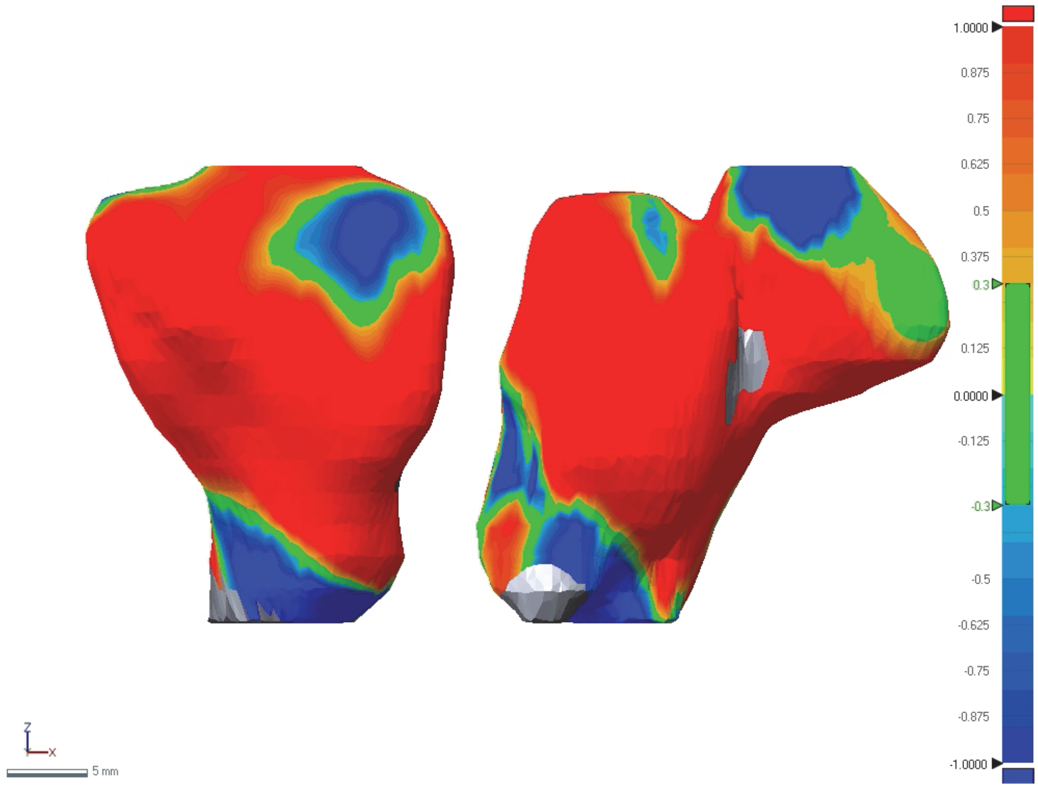


Figure I.12: Comparison of 02271128 and 9090930; 92.6596 % out of tolerance. Deviation present throughout.

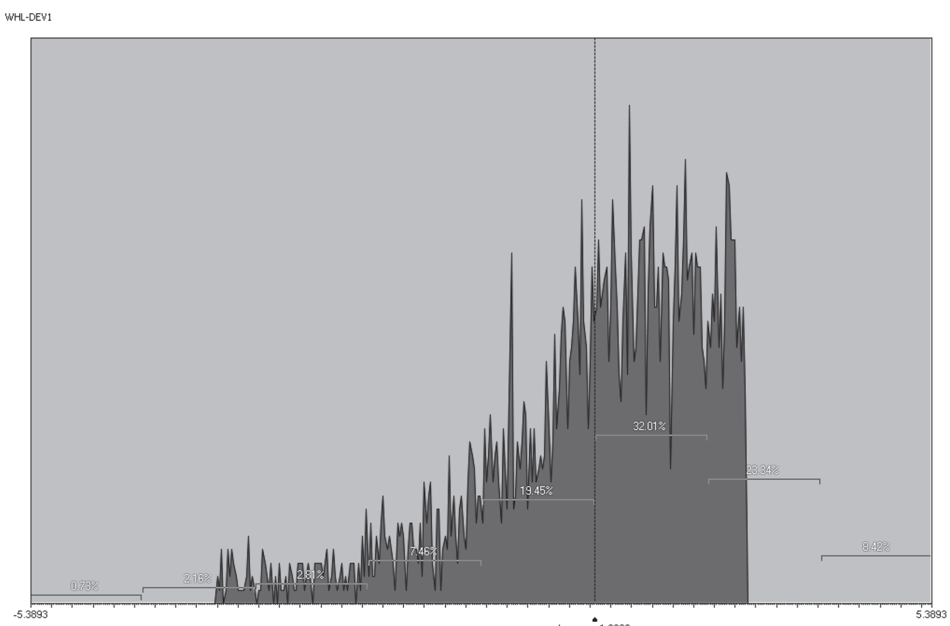


Figure I.13: Histogram of whole deviation for comparison of individuals 02271128 and 9090930

One interesting comparison is that between individuals 11181129 and 12987104. This comparison produced an out-of-tolerance of 72.8016%, which is below the average out-of-tolerance of 83.72% for different skull comparisons (Table I.1). Figure I.14 and Figure I.15 depict the 3D renderings of individuals 11181129 and 12987104 respectively. Figure I.16 shows the comparison between individuals 02271128 and 9090930 and Figure I.17 presents the histogram illustrating with the many spikes spread throughout that deviation is not limited to a certain region.

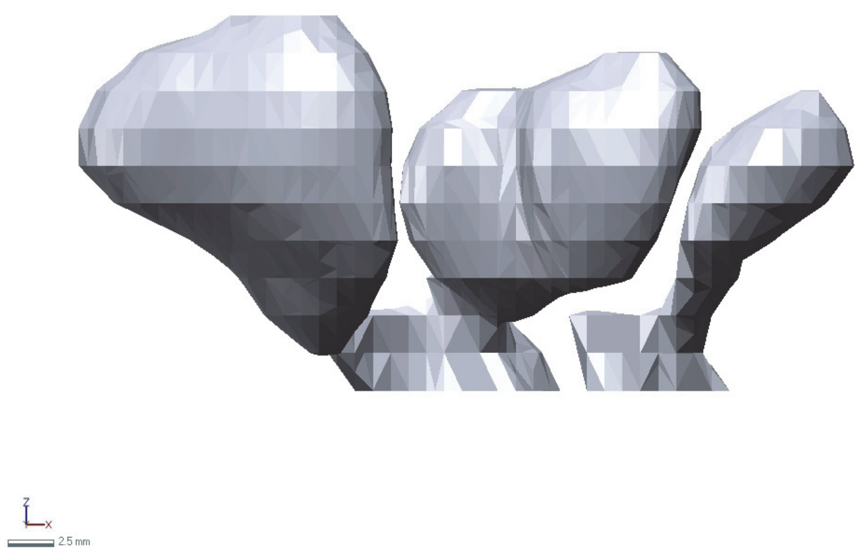


Figure I.14: 3D rendering of individual 11181129

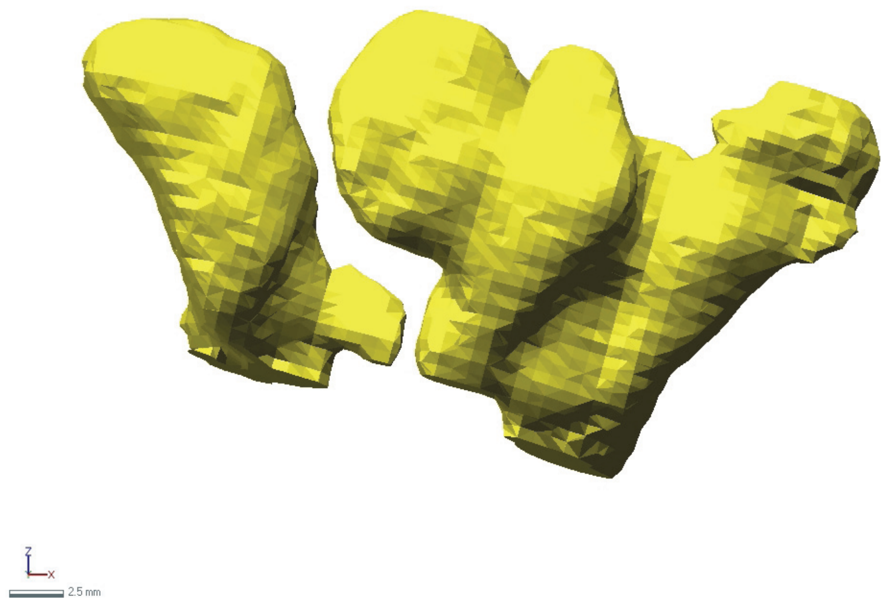


Figure I.15: 3D rendering of individual 12987104

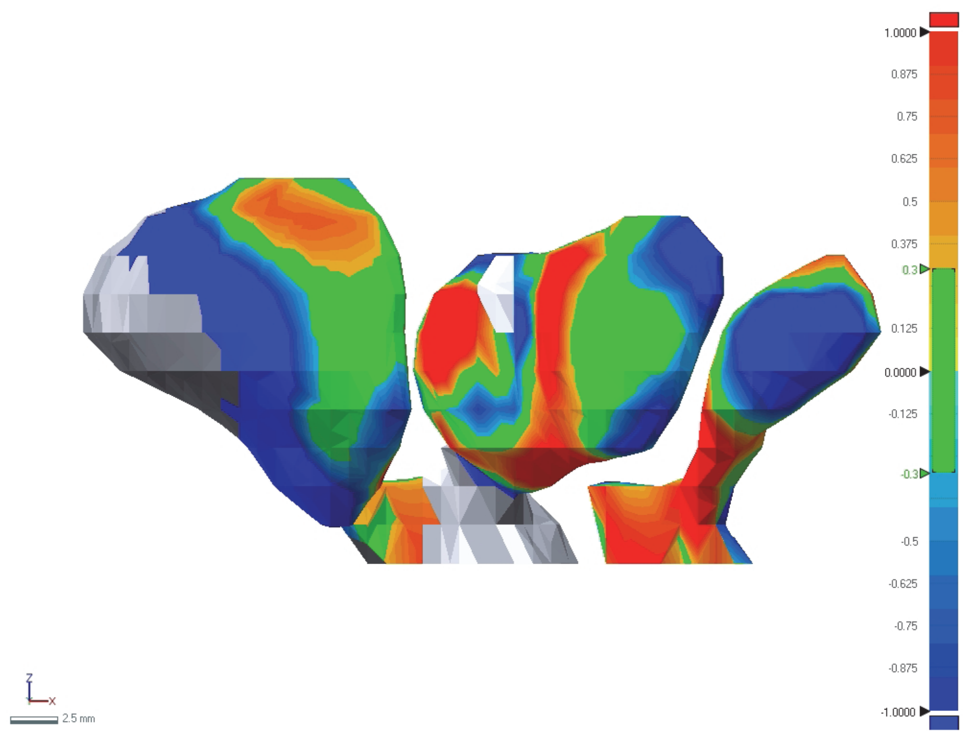


Figure I.16: Comparison of individuals 11181129 and 12987104; 72.8016% out of tolerance. Deviation present throughout.

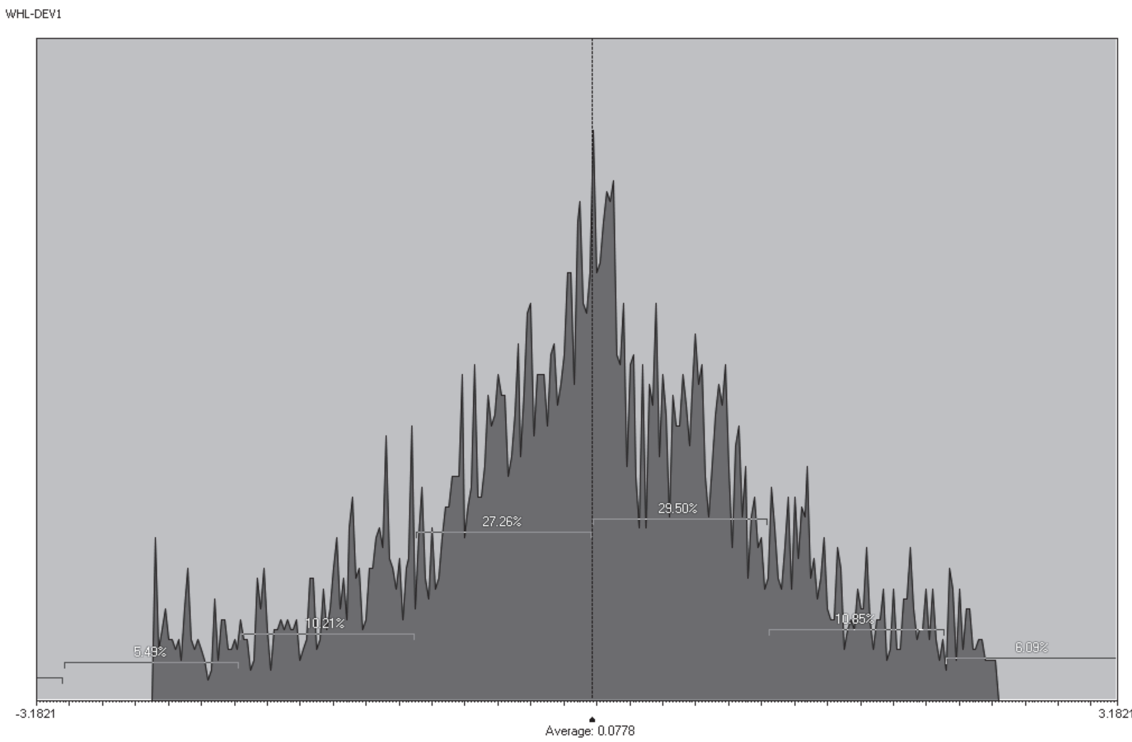


Figure I.17: Histogram of whole deviation comparison of individuals 11181129 and 12987104

This pilot study illustrates the promise of a three-dimensional approach to quantification of variation and uniqueness in the frontal sinuses. Preliminary analysis of the different skull comparisons illustrates that variation is a function of both size and shape in all three dimensions, rather than being confined to specific regions of frontal sinus anatomy viewable on two dimensional images. These findings highlight an important limitation of current forensic anthropological methods to establish identity based on frontal sinus variation. Further methodological development needs to be carried out to improve the alignment procedure for the three-dimensional technique, including testing the use of specific landmarks, and standardise the rendering of the most inferior portion of the frontal sinuses to eliminate errors in capturing this region. With further work it is expected that the frontal sinus variation can be quantified more accurately using three dimensional variation to inform forensic anthropological methods intended to document individuality and form a basis for positive identification.

Appendix II Raw Data

Ribeiro (2000) measurement data

First measurements (1), second measurements (2)

	A (1)	B (1)	C (1)	D (1)	X (1)	A (2)	B (2)	C (2)	D (2)	X (2)
02271101 b	47.04	13.42	9.95	24.37		47.12	16.76	22.82	8.26	
02271101 c	55.43	9.63	15.69	32.57		55.6	9.65	15.06	32.41	
02271101 d	62.98	30.75	15.71	19.63		63.02	31.17	15.81	19.55	
02271101 e	59.69	18.16	22.34	21.99		59.84	18.46	23.01	21.7	
02271101 f	48.01	29.83	11.97	9.12		47.99	29.37	11.44	8.98	
02271101 g	50.38	12.6	24.08	15.57		50.63	12.47	23.91	14.59	
2271101	89.44	24.41	30.22	42.35		89.46	24.35	31.92	43.81	
2271128	58.12	36.55	10.73	12.2		58.05	36.67	10.28	12.01	
2271129	68.05	16.73	40.53	14.25		67.85	16.7	41.1	14.68	
02271129 b	58.25	18.5	11.14	31.18		58.51	18.26	10.87	31.42	
02271129 c	57.49	7.37	22.92	30.39		57.66	7.35	21.59	30.36	
02271129 d	58.38	33.29	6.35	23.1		58.59	33.35	6.54	23.1	
02271129 e	71.21	12.28	16.82	46.3		71.26	12.41	16.87	46.04	
02271129 f	37.44	27.24	3.82	7.69		37.28	27.5	3.87	7.11	
02271145 a	55.48	13.51	25.12	18.17		55.32	13.37	25.79	17.83	
02271145 b	58.43	21.08	16.79	22.18		58.23	20.72	17.29	23.18	
02271145 c	77.52	10.03	27.36	45.23		77.47	9.64	28.04	45.09	
02271145 d	52.07	10.49	10.21	32.4		52.16	10.09	10.56	32.48	
02271146 a	50.1	12.67	19.54	19.18		49.91	12.01	20.21	18.97	
02271146 b	52.92	20.58	6.65	26.36		52.84	20.39	6.83	26.59	
02271146 c					21.83					21.69
2271222	49.73	26.29	1.23	23.55		49.65	25.89	1.05	23.89	
02271223 b	70.17	6.21	39.79	29.78		70.03	6.68	40.03	28.06	
02271223 c	46.36	20.46	11.1	15.26		46.47	20.2	11.14	15.53	
02271223 d	65.61	14.39	22.48	31.31		65.48	14.19	21.98	31.69	
02271223 e	67.26	26.06	10.64	32.89		67.25	25.68	10.83	33.56	
02271223 f	25.71	21.84	2.25	2.17		25.67	22.57	2.01	1.43	
2271223	85.36	33.55	36.46	19.22		85.09	34.18	37.54	18.22	
8151058	58.88	12.31	27.43	21.56		58.81	12.38	27.52	20.48	
8281218	61.54	9.11	26.37	28.96		61.39	8.68	26.52	28.88	
8281222	56.5	21.54	11.35	25.41		56.39	21.74	11.27	25.22	
8281228	53.1	30.21	10.22	14.09		52.86	29.58	10.19	14.16	

8281230	63.04	24.29	33.73	5.93		62.89	24.31	33.66	5.93	
8281235	54.71	19.08	17.51	20.58		54.76	19.02	17.13	20.14	
8281236	12.08	0	4.72	7.22		12.69	0	4.74	7.65	
8291401	34.47	10.3	11.37	13.2		34.6	10.33	11.39	13.19	
8291405	87.64	9.85	49.54	37.73		87.74	10.5	49	37.67	
8291406	61.55	21.26	14.35	28.08		62.04	21.37	14.43	28.42	
8291410	78.97	22.67	50.38	10.05		78.43	21.84	50.02	9.4	
8291430	72.43	20.85	31.04	24.42		72.69	20.79	30.65	24.18	
8291433	59.7	17.8	29.89	14.19		59.85	18.36	28.89	13.99	
8291439	63.79	13.34	22.83	29.47		63.82	13.26	22.02	29.26	
8291440	56.92	11.89	23.04	24.69		57.23	11.94	22.65	25.04	
8291441	61.98	23.5	17.58	24.52		62.09	23.05	16.83	24.3	
8291443	36.47	20.78	2.5	13.63		36.36	20.48	3	12.93	
8291450	49.74	17.87	22.38	13.35		49.96	17.82	22.05	12.58	
8291452	61.05	22.7	27.56	11.45		61.01	23.3	27.56	11.87	
8291457	48.57	19.84	19.07	11.83		48.88	20.19	18.62	10.59	
8291502	55.75	14.25	12.68	30.43		55.84	14.11	13.05	30.26	
9011339	53.47	18.18	11.56	26		53.27	13.02	16.6	24.28	
9011340	46.31	9.55	16.64	20.65		46.23	9.9	16.91	20.05	
9021236	52.43	33.38	12.17	8.06		52.27	33.26	11.89	8.53	
9031128	31.31	0	5.07	26.34		31.36	0	5.72	25.69	
9051201	56.25	28.15	17.93	10.87		56.21	27.24	18.84	11.37	
9051203	49.69	20.69	16.72	13.85		49.77	19.22	16.78	14.77	
9090926	51.02	23.93	9.02	18.7		50.96	23.4	9.37	19.28	
9090927	55.62	7.13	31.22	19.23		55.56	7.25	31.06	18.52	
9090928	49.34	15.3	17.82	18.89		49.23	14.61	16.74	18.36	
9090930	64.28	12.39	24.31	30.66		64.09	12.51	23.05	30.1	
90921211					19.63					19.65
9101255	65.54	12.22	26.15	30.13		65.41	11.26	26.76	30.26	
10221221	35.68	11.75	11.6	12.74		34.97	11.65	10.81	12.49	
10221223	33.39	19.29	3.8	10.54		33.38	18.82	4.19	10.89	
10221224	48.25	37.28	4.95	6.49		48.08	36.36	5.07	6.91	
10221225	54.1	19.58	12.42	23.36		54.07	19.6	12.72	23.12	
10221240	42.55	11.12	21	11.92		42.59	10.87	20.63	11.95	
10221242	75.8	46.09	18.11	16.8		76.12	45.97	18.42	17.31	
10221246	51.07	6.6	18.61	27.41		51.07	6.43	18.56	26.89	
10221248	64.95	9.95	26.66	30.63		65.08	9.52	27.1	30.98	
10221252 a	49.91	19.11	17.94	13.57		49.98	18.95	18.03	14.38	
10221252 b	58.84	12.02	10.3	40.53		58.86	11.19	10.33	40.06	
10221306	38.29	29.16	8.02	2.09		38.01	28.3	8.78	2.06	
10221307	54.48	31.33	11.7	13.18		54.32	31.29	11.66	13.16	
10221308	44.43	21.55	11.16	12.74		44.16	21.35	11.45	12.12	
10221310	64.56	17.65	12.88	36.61		64.72	18.18	12.59	36.08	
10221311	34.87	9.45	13.05	12.79		35.09	9.73	12.78	12.7	
10221312	54.72	24.74	14.14	16.95		54.91	24.7	14.38	17.16	

10221313	56.62	8.13	34.79	14.58		56.84	8.02	34.75	15.1	
10231228	64.58	13.07	22.55	30.12		64.42	13.24	22.43	30.35	
10231229	59.67	18.66	26.2	15.41		59.59	18.63	26.3	15.56	
10231230	27.66	14.83	3.34	9.95		27.59	14.45	3.53	9.94	
10231251	55.37	28.98	17.81	9.28		55.27	28.35	18.32	9.23	
11031225	64.24	15.74	15.75	34.14		63.96	15.11	15.75	34.73	
11031227	57.29	13.59	34.15	10.47		57.23	12.87	34.09	11.34	
11031228	45.22	8.66	16.62	20.4		45.1	8.16	16.57	20.75	
11031230	58.04	16.82	21.2	22.31		57.79	16.37	21.23	22.42	
11031231	60.49	26.7	29.18	6.77		60.85	26.57	28.95	6.96	
11031232	59.84	18.84	27.76	15.69		59.74	18.78	27.04	16.11	
11031243	58.53	31.17	18.61	10.3		58.45	31.29	18.22	10.21	
11031255	64.38	8.48	24.08	33.91		64.2	8.82	24.2	34.15	
11031258	55.28	17.1	12.17	27.2		55.19	17.51	12.11	26.63	
11031258 b	43.67	18.65	5.03	20.65		43.73	10.99	11.76	20.91	
11181133	82.55	36.99	23.82	29.86		82.47	37.15	23.34	30.52	
11181129	42.79	15.32	12.17	15.55		42.75	15.37	12.2	15.4	
11181140	5.81	0	3.74	2.15		5.8	0	3.56	2.07	
11181142	59.55	16.43	9.03	35.81		59.5	16.3	9.11	36.04	
11181143	58.19	8.33	26.46	25.34		58.35	8.52	26.34	25.74	
11181145	40.75	8.15	14.81	18.04		40.68	8.31	14.66	17.97	
11181146	76.49	11.62	36.25	33.63		76.5	11.99	36.27	34.19	
11181201	51.45	8.21	27.32	16.91		51.31	8.38	27.65	16.54	
11181202	35.14	27.64	6.81	1.89		35.67	27.11	6.48	2.61	
11181203	66.91	26.2	15.62	29.36		66.97	26.39	15.92	28.61	
11181204	51.77	21.12	8.98	23.33		51.74	21.91	8.77	22.76	
11181214	44.28	6.01	15.9	22.46		44.26	6.31	15.58	22.62	
11181218	39.83	20.23	7.58	12.32		39.72	19.41	8.48	12.15	
11181225	43.5	16.44	16.16	11.07		43.48	16.4	16.27	11.2	
11181226	68.45	40.05	17.8	14.87		68.69	39.55	17.76	14.55	
11181227	42.2	30.18	6.25	6.27		42.26	30	6.39	6.29	
11251046	70.79	6.85	38.09	29.2		70.85	7.19	37.1	29.15	
11251047	81.97	18.73	30.97	40.14		81.55	18.95	31.31	40.16	
12789100					25.55					26.08
12789102	51.76	40.19	7.03	5.22		51.73	30.63	17.05	5.32	
12789120	67.66	17.03	24.51	29.76		67.54	16.94	24.54	30.03	
12798106	69.88	20.02	10.43	44.24		69.91	20.08	10.44	44.1	
12798107	50.82	6.51	27.77	17.84		50.68	6.67	27.79	17.67	
12798112	28.26	26.81	1.54	0						27.56
12798118	63.62	12.77	27.68	25.45		63.81	12.79	27.56	25.45	
12879103	30.92	12.48	8.86	10.13		30.95	12.55	8.76	10.2	
12879113	60.13	19.5	28.48	13.64		60.13	19.31	29.15	13.43	
12879119	48.53	17.74	2.65	28.83		48.64	17.87	2.27	29.06	
12897101	44.03	18.89	13.65	12.04		44.12	19.04	13.68	12.23	
12897105	63.02	16.46	19.58	29.63		63.12	16.8	19.57	29.72	

12897109	48.52	7.64	30.66	10.96		48.67	7.66	30.69	11
12897111	66.32	15.58	34.82	19.67		66.45	15.73	34.62	19.59
12897114	32.64	12.39	1.11	19.55		33.75	12.19	2.05	19.22
12897116	39.37	15.25	0.97	24.09		39.43	15.34	0.93	23.94
12987104	36.15	27.08	4.61	4.62		36.09	26.9	4.22	5
12987108	16.84	0	2.8	13.86		41.12	29.13	1.35	2.87
12987117	50.12	11.78	9.71	29.51		50.13	11.89	9.4	29.21

Reichs and Dorion (1992) scoring data

Individual	Original slice	Known slice	Unknown slice
2271101 b	43200124220012	43200124220012	43200124220000
2271101 c	43200124320012	43200124320012	43200122000000
2271101 d	41321444430022	41321444430022	41321444430022
2271101 e	42252004520012	42252004520012	42252004520012
2271101 f	42300004000022	42300004000022	44321004000022
2271101 g	41300004110044	41300004220044	41300004220044
2271101	41244224420014	41243224421113	41144224420014
2271128	41211004120012	41211004120012	42211004120012
2271129	43300004430024	43300004430024	43321004430024
2271129 b	43200004000000	43200004000000	43200234000000
2271129 c	43242004001112	44242004001112	44242004000013
2271129 d	43200004000000	43200004000000	43200004000000
2271129 e	43243004520015	43243004520015	42200004520015
2271129 f	43300004000023	43300004000023	43300004002122
2271145	41321004330022	41321004232100	41321003000000
2271145 b	41212004420000	41211004421100	41131004421100
2271145 c	41247234520012	42247234520012	42212124520000
2271145 d	44200004000012	44200004000012	43231004000012
2271146 a	42311004110000	42311004110000	41311004110000
2271146 b	44200452000000	44200452000000	43243124421114
2271222	44211004000012	44211004000012	44211004001100
2271223 b	42322004320000	42322004320000	42321224320022
2271223 c	42200004420012	43200004420012	42200004000012
2271223 d	42244004220044	42243004220044	43244004220044
2271223 e	42200124420044	42200124420044	42200124420045
2271223	41223124130045	41223124130045	41200124130045
8151058	42321004320000	42321004320000	42321004320000
8281218	41300004110044	41300004110044	41300004122144
8281222	42211004000012	42211004000012	43211004000012
8281228	41322444000022	41322444000022	41122444000022
8281230	42311224000022	42311224000022	42342224000022
8281235	41100224230024	41100224230024	41100224230025
18291401	41200314220000	42200314220000	42200004220000
8291405	42345224132113	41343224132113	41377224330045
8291406	42342314330063	42342314330063	42322314000063
8291410	42342124000023	42343124002122	42343124530023
8291430	41343004320013	41343004320013	41344004320013
8291433	42300003000022	41311004000022	41300004000022
8291439	42321004220045	42321004220045	42321004220046
8291440	41200003000000	41200003000000	41200004000000

8291441	42311004000023	42300124000023	42300124000023
8291443	40000124000012	40000124000012	40011004000012
8291450	41211004000022	41111004000022	41342004000022
8291452	41221004110044	41200004110044	42200124120012
8291457	42300004230000	42300004230000	41300004330000
8291502	43212004420013	43212004420013	42212004420013
9011339	43212004000013	43212004000013	42211004000013
9011340	41200004130000	41200004130000	41200004110000
9021234	43212004220044	43212004220044	43211004220044
9021236	41121004000012	41121004000012	41121004000012
9031128	41300004110000	41300004110000	41300004110000
9051201	42300004330000	41300004330000	41300004330000
9051203	41100124000022	41100124000022	41100124000022
9090927	42300234430022	42300234430022	41363004430022
9090928	42200004420012	42211004420012	42200004420012
9090930	41242004220013	41242004220013	41242004220013
9101255	41242004320000	41242004320000	41242004320000
10221221	40000004000012	40000004000012	44200004000012
10221223	30000003000000	30000003000000	40000003000000
10221224	41300444220000	41300444220000	41311224120000
10221225	41300003000012	41311003000012	41300444230044
10221240	41122122000000	41122122000000	41221124430023
10221242	43211004520013	43211004520013	41200454520013
10221246	41100004320044	41100004320044	41100004320044
10221248	41131004320044	41131004320044	42231004520012
10221252 a	42300124000000	42300123000000	43300004320000
10221252 b	44212004000012	44211004000012	44211004000012
10221306	40022004000022	40022004000022	45321004000022
10221307	41221124430022	41221124430022	41221124430022
10221308	42300124000022	42300124000022	42300004000022
1022310	42243003000012	42242003000012	42311004320045
10221311	42200002000000	42200002000000	41100224220000
10221312	41121004130023	41221004130023	41121004130023
10221313	41300004530023	41300004530023	41300004530023
10231228	41246004320044	41247004320044	41274004320044
10231229	44300224000000	43300224000000	42300004000000
10231230	45200004000000	45200004000000	45200003000000
10231251	41100004420012	41100004320012	41100004320012
11031225	42200124220045	42200124220045	42200124220045
11031227	41342004000022	41300004000022	41200004000022
11031228	41300224420000	41300224420000	41321004420000
11031230	41211004420013	41211004420013	41211004320013
11031231	43323004000023	43322004000023	43322004002122
11031232	42200004120044	42200004120044	41200124320012
11031243	41311004220044	41111004220044	41200124220022

11031255	42211004420013	42211004420013	41211004421112
11031258	41242004320012	41221004320012	42321004320013
11031258 b	43211004000012	43211004000012	43211004000012
11181129	43211123000000	43211123000000	43211123000000
11181133	41242124320013	41243124320013	41243004320013
11181140	10000001000000	10000001000000	20000001000000
11181142	41200134320000	43200134320012	41200134000000
11181143	41200004520013	41200004420013	41200004000012
11181145	41100004320012	41100004320012	41100004320012
11181146	41300224430024	41300224430024	41121224330023
11181201	42300004130022	42300004130022	42331004130022
11181202	40000003000000	40000003000000	40000003000000
11181203	41200444320045	41200444320045	41200444320045
11181204	41200004420000	42200004420000	41200004000012
11181214	44211004000012	44200004000012	44200004000012
11181218	41300233000000	42300233000000	42300223000000
11181225	42321004230000	42321004230000	42322004230000
11181226	42300314330045	42300314330045	41300314330045
11181227	41300003000000	41300003000000	41300002000000
11251046	42321004130023	42321004130023	42321004230000
11251047	41245224321112	41245224421112	41244224421112
12789102	42322124000022	42322124000022	42322124000022
12789120	41311004220045	41211004220045	41211004220045
12798106	43245004000014	43214004000014	43214004000014
12798107	42331454330022	42331454330022	42363124330022
12798118	41111004220044	41111004220044	41311004120000
12879103	41200124320000	41100124320000	41200124320000
12879113	42300004530023	42300004530023	42300004000023
12879119	45200004000013	45200004000013	45211003000000
12897101	41200002000000	41200002000000	41100002000000
12897105	41300004421112	41300004421112	41100004324144
12897109	41300004000000	41300004000000	41300004000000
12897111	42321224430022	42321224430022	42321224000022
12897114	44200003000000	44200003000000	43200223000000
12978116	40000004000012	40000004000012	40011004000012
12987104	43211004000013	43211004000013	44211004000013
12987108	40000003000012	40000003000012	40011003000012
12987117	42211004320012	42200004320012	42211004230000

Cox et al. (2009) outline measurements

Degs/indivs	3	6	9	12	15	18	21	24
02271101 b	19.6426	21.9367	23.2987	25.0265	26.3707	27.1626	27.3913	27.3729
02271101 c	22.5407	21.1188	21.0103	20.6982	20.2814	19.9822	19.8945	19.7815
02271101 d	22.2854	26.6126	27.1295	27.3868	27.0518	21.4953	21.7747	22.2554
02271101 e	27.3357	28.2088	28.1457	27.639	27.0705	26.6396	26.8055	26.4809
02271101 g	19.9782	21.2706	23.0038	23.8466	24.8097	26.3577	25.6637	24.5097
2271101	43.8718	45.457	46.0214	45.3718	44.2283	40.9443	39.9382	35.77
02271129 b	22.1548	20.3482	13.0888	12.6633	12.4867	14.9991	17.3762	18.3654
02271129 c	24.284	24.9592	25.5104	25.7014	25.4874	25.2184	24.939	24.4453
02271129 d	20.8911	22.2254	23.4816	24.679	25.2139	25.6058	25.6989	25.7005
02271129 e	36.4398	36.6557	36.698	36.7192	36.9091	37.2003	37.4661	37.772
02271129 f	17.1017	17.1731	17.683	18.4949	19.2237	19.6311	20.002	20.2303
2271129	23.683	31.4021	33.8264	34.8997	35.481	35.3451	35.2396	35.5318
02271145a	24.5872	24.7988	24.6306	27.8624	27.6966	26.6313	25.8176	25.3936
02271145b	21.3495	25.5211	29.0678	29.5873	29.2158	29.4204	29.2685	28.7587
02271145 c	41.7989	39.4947	35.8868	33.4319	34.5903	34.7548	32.5433	33.814
02271145 d	18.1576	19.5096	22.2175	24.8508	25.5795	24.5276	22.4482	21.872
02271146a	20.7657	22.1387	23.0459	23.488	23.3975	23.4224	23.2421	23.3248
02271146b	19.3194	20.9601	23.3737	25.5178	25.3142	25.4256	25.9404	25.9633
2271222	25.635	26.791	27.5678	27.9683	28.1113	28.2035	28.189	29.0771
02271223b	34.2046	35.2766	35.5158	35.1232	34.944	34.5034	33.3816	22.0213
02271223c	16.289	17.6602	19.0991	19.7122	20.0055	20.0274	20.0017	19.988
02271223d	28.4936	32.1535	33.9279	34.4531	34.4178	33.948	33.1478	30.2977
02271223e	26.4786	28.0486	28.6993	29.9059	31.7847	32.3865	32.9928	33.1972
02271223f	2.7238	2.5761	2.4992	2.4234	2.3221	2.2579	2.2	2.1491
2271223	41.3242	50.666	52.6414	53.4949	53.8139	53.9289	53.4954	53.1794
8151058	21.6476	34.6186	37.2513	37.9365	36.8885	34.1657	32.128	31.9199
8281218	22.2833	25.8576	29.2544	30.9695	31.5794	31.9173	31.2446	30.3981
8281222	21.4295	23.4272	24.9142	25.8971	26.361	26.6252	26.4824	26.4375
8281228	18.6999	19.2885	20.6331	26.6852	29.9059	31.432	32.5212	33.1626
8281230	24.646	27.0122	29.3671	33.4964	32.9595	31.7658	30.88	27.114
8281236	4.8072	4.4902	4.2533	4.071	3.8532	3.6798	3.4929	3.2536
8291401	17.8551	18.0069	17.8889	17.9438	17.4741	16.8799	16.3826	15.878
8291405	42.0261	44.6843	46.3233	47.5305	48.5641	48.868	48.806	48.2501
8291406	27.9779	31.1955	32.4205	33.4537	33.3051	32.7793	33.4692	33.6186
8291410	33.5923	32.6373	31.5815	30.2279	31.6548	33.083	33.883	34.1549
8291430	22.4301	29.1463	35.4057	36.6678	37.4249	35.5156	33.1236	32.5697
8291433	19.6769	22.4137	26.2488	30.556	34.6897	35.0219	32.7739	29.3065
8291439	20.8861	21.3079	21.9126	22.3464	22.5241	24.3997	26.4815	27.6125
8291440	22.34	24.8947	29.0402	30.2561	31.2054	31.8259	32.3605	32.5965
8291441	23.5624	24.1604	24.9469	25.9848	27.3997	29.1765	30.3634	31.0423
8291443	12.4138	11.9118	11.6014	10.8676	9.4558	6.8188	6.3013	5.9064
8291450	22.0558	24.4821	24.819	25.3961	25.194	24.7792	24.346	24.8946
8291452	20.868	24.547	28.2128	29.207	29.089	27.3417	26.7061	25.5918
8291502	14.8952	15.9829	17.1281	24.2215	25.0245	25.5877	25.6308	25.322
9011339	23.8904	24.6835	25.355	25.1978	24.3895	23.4514	21.9328	20.8288
9011340	18.0084	19.1578	21.2167	22.2299	22.7924	22.6615	21.8872	19.1617

Degs/indivs	27	30	33	36	39	42	45	48
02271101 b	26.2373	24.9684	24.0525	22.5166	21.4455	20.4474	15.9453	16.2912
02271101 c	19.7234	19.6484	19.7036	19.9981	20.0434	19.8982	19.8153	19.4294
02271101 d	22.8692	23.6697	24.2904	24.838	25.3652	25.4914	25.4157	25.1394
02271101 e	25.1533	24.7145	24.4873	23.2589	22.0189	20.8981	20.8235	20.9404
02271101 g	24.236	23.8848	22.1178	19.2196	19.4149	19.3019	18.5224	17.5645
2271101	35.4738	34.9809	34.2464	33.6749	33.0839	32.366	31.4477	30.6749
02271129 b	19.191	19.5401	20.022	20.0588	19.9761	19.8382	19.367	18.9474
02271129 c	23.7093	22.9242	21.3961	17.5467	17.7853	18.4317	18.9008	19.242
02271129 d	25.3808	24.9359	24.4215	24.1338	23.4454	20.1969	18.8784	17.7679
02271129 e	37.524	33.53	33.5891	33.2602	32.9314	32.4649	31.3835	28.4087
02271129 f	20.4701	20.7646	21.379	21.863	22.0193	21.8586	20.6987	14.6623
2271129	35.9195	35.4598	34.4376	28.0489	26.9253	25.727	21.6709	21.8022
02271145a	25.3934	23.3907	21.0591	19.0384	16.4188	17.3092	18.2806	18.3843
02271145b	27.9315	27.2139	26.7512	25.9594	25.7293	25.0464	24.2635	23.6066
02271145 c	34.7187	34.4872	33.7947	33.1553	32.8246	30.9437	27.3192	27.0986
02271145 d	22.2895	22.5857	22.2183	21.7522	21.5202	20.9782	19.3565	13.29
02271146a	23.3238	23.316	23.298	23.1061	22.8301	22.2828	21.9113	21.7134
02271146b	26.407	26.4313	26.4654	26.4326	26.0243	25.3298	14.9694	15.2166
2271222	25.7256	19.6997	19.8763	20.1975	20.4294	20.342	20.3604	20.158
02271223b	21.0808	20.406	19.8693	19.6255	19.2522	18.6109	18.2572	18.0942
02271223c	20.0094	19.9618	19.7801	19.2267	18.828	18.6187	18.1323	17.5648
02271223d	30.9836	31.2964	31.2334	30.3824	28.3458	23.8708	22.8401	22.5084
02271223e	32.6339	31.6722	30.9524	30.0645	29.7887	29.7937	29.9431	26.0585
02271223f	2.0909	2.0375	1.9892	1.9466	1.9546	1.903	1.8778	1.8805
2271223	53.5761	53.4794	52.2691	52.5388	51.6357	46.0359	43.4003	40.0483
8151058	30.7117	28.9262	24.7606	23.8715	23.3457	23.4744	23.396	23.0196
8281218	28.683	27.8063	27.6668	27.9314	27.3694	26.524	23.3017	22.9664
8281222	26.2061	25.8411	25.4254	24.8973	24.4911	23.8336	23.1043	22.579
8281228	33.4836	33.0064	31.9775	30.3607	29.4671	28.6987	27.0125	24.1547
8281230	25.4041	25.6035	25.8238	25.9063	25.0287	24.4733	24.3167	23.5296
8281236	3.0675	2.8463	2.6867	2.4886	2.3359	2.2235	2.1017	2.0026
8291401	15.2609	14.88	14.7176	14.7175	14.4489	14.1087	13.9217	13.7725
8291405	46.6129	42.9975	41.5581	41.7462	41.5702	41.2243	39.5904	37.4242
8291406	33.4124	33.4007	32.5403	30.6136	29.8571	29.5675	29.143	28.0357
8291410	33.8791	33.2896	32.4688	33.0663	33.2819	33.081	32.3951	32.0554
8291430	32.3778	32.1398	31.2164	25.7697	23.9063	23.5938	24.1907	24.6855
8291433	28.6262	27.9353	25.862	24.6691	24.3522	23.833	22.9109	21.8665
8291439	27.3089	26.8531	26.518	26.1781	26.0351	25.7697	24.7015	23.344
8291440	32.6457	32.0963	29.1219	26.726	24.9735	24.8239	25.7866	26.4275
8291441	31.5082	31.8843	32.079	32.0858	32.0241	31.6145	31.0575	30.4685
8291443	5.9268	6.3593	7.1597	7.764	8.2227	9.0129	9.6634	9.8727
8291450	25.4631	25.9273	26.3182	26.6583	26.9825	27.1465	26.9114	25.8912
8291452	23.3007	23.0209	23.4195	23.4517	23.2856	23.3155	23.3256	23.3155
8291502	23.7391	23.4568	22.3761	21.1756	20.43	20.4721	20.4424	20.5969
9011339	19.2968	17.3275	16.2444	16.4767	17.0018	17.4568	17.7831	18.0529
9011340	18.1851	17.863	17.711	17.5684	17.3822	17.2433	17.0873	16.5179

Degs/indivs	51	54	57	60	63	66	69	72
02271101 b	17.0078	17.5833	17.6964	17.3734	17.1772	16.9487	16.598	16.5813
02271101 c	18.7451	18.2694	17.5378	16.9701	16.4922	15.91	14.8452	10.6316
02271101 d	24.737	24.5904	25.026	24.7395	10.443	10.4287	11.134	12.613
02271101 e	20.9828	20.4897	19.8245	19.0554	18.9359	19.2367	19.7638	19.665
02271101 g	16.6168	13.3876	12.9537	12.8127	12.9142	13.0095	13.3273	13.7087
2271101	29.9807	22.0627	21.7955	21.3611	20.957	20.7193	21.1638	21.9746
02271129 b	18.6934	18.4785	18.1589	17.5855	17.0994	16.6936	16.4057	16.1921
02271129 c	19.4087	19.2689	18.8658	18.4971	18.4076	18.8528	19.2068	19.1874
02271129 d	15.767	16.1374	17.2381	17.6795	18.2692	18.8421	19.3042	19.9311
02271129 e	28.288	29.576	30.3466	30.8334	31.2557	31.5821	31.9679	31.9985
02271129 f	14.1381	13.7524	13.5677	13.461	13.416	13.3428	13.2177	13.021
2271129	21.9457	22.093	22.1564	22.4829	23.1591	23.7693	24.1201	24.7426
02271145a	18.5809	18.3896	18.1575	18.1	18.2951	18.5893	18.7858	19.0347
02271145b	23.3005	22.4096	15.5886	16.1381	16.944	17.8696	18.627	19.5579
02271145 c	26.904	26.2083	25.3657	21.816	23.2325	25.0355	26.658	27.5472
02271145 d	14.0433	13.8504	13.696	13.4814	13.6114	13.9089	15.4119	17.9161
02271146a	21.3839	21.1889	21.2761	21.1544	21.0444	21.1595	21.3833	21.2781
02271146b	16.0272	16.924	17.4187	17.6058	17.5127	17.4468	17.511	17.4784
2271222	19.3613	18.138	17.1835	17.1626	17.3351	17.6143	18.0022	18.2937
02271223b	18.0736	18.1019	18.2345	18.4188	18.5052	18.1965	17.8767	17.6074
02271223c	16.9109	16.2324	15.7185	15.2327	11.1359	10.523	10.2916	10.5897
02271223d	22.4608	22.5229	22.5579	21.1056	16.7675	16.8407	17.1629	17.4502
02271223e	25.588	24.7196	24.0457	23.8162	23.5714	21.8854	22.4954	23.5067
02271223f	1.8427	1.8356	1.8526	1.8303	1.8561	1.873	1.9077	1.9059
2271223	41.4703	42.2373	43.0232	43.0586	42.2986	41.4318	40.6363	33.2224
8151058	22.6107	22.0842	20.5403	19.0142	18.8369	19.0836	19.1535	19.3363
8281218	24.7935	25.7527	25.8955	25.3118	24.772	24.2345	23.7944	23.4444
8281222	20.3403	18.6495	16.7987	18.2519	19.3619	19.7324	19.5129	19.0179
8281228	22.1539	20.6411	16.7835	16.454	16.5008	16.3392	15.9387	15.7605
8281230	23.0098	22.7528	21.7243	20.434	19.3376	17.1559	17.7896	18.7408
8281236	1.9093	1.8367	1.7692	1.7194	1.6736	1.6323	1.5957	1.5944
8291401	13.8291	13.7259	13.2879	12.8544	12.4615	11.9261	10.6206	8.8865
8291405	38.5183	37.8358	36.8914	35.7973	34.7018	34.218	33.8279	33.7425
8291406	26.5063	25.0243	23.5486	21.4058	20.5379	21.2135	21.0845	20.7708
8291410	30.3946	29.5653	30.4423	31.3547	31.5002	30.886	30.3476	29.7745
8291430	24.9957	24.8731	24.2121	23.5686	22.9698	22.7274	23.0218	22.097
8291433	20.8291	19.9315	19.4581	19.2218	19.2764	19.3834	19.3949	19.0203
8291439	22.0857	20.9507	19.9385	18.1873	18.8831	19.1522	18.9211	18.2111
8291440	26.668	26.0636	25.7379	25.84	25.8758	26.0934	25.9403	25.3908
8291441	29.7641	29.4121	29.497	29.4622	28.8871	28.1173	26.9726	23.3778
8291443	10.1498	10.4981	10.7974	10.9719	11.2237	11.779	12.0694	12.3018
8291450	24.5008	23.0921	21.8329	20.8639	20.284	20.2053	20.3772	20.2338
8291452	23.1556	22.76	22.2138	20.2219	20.1854	21.1119	21.8838	22.7278
8291502	20.0836	19.3632	18.5164	17.4682	15.7457	15.2249	15.0374	15.5725
9011339	18.4095	18.5374	18.3582	17.9403	17.5538	16.9494	15.2701	13.6842
9011340	15.9597	15.3373	14.6815	14.3873	13.9248	13.4806	13.3425	12.8444

Degs/indivs	75	78	81	84	87	90	93	96
02271101 b	16.4094	16.3963	16.3362	16.3999	16.3375	16.0417	14.9644	13.2714
02271101 c	12.7139	14.5058	15.6476	17.7984	19.4019	20.2134	20.7452	20.9985
02271101 d	14.0047	14.9419	15.4682	15.9105	16.5015	17.1914	17.7648	19.0485
02271101 e	18.7174	17.3769	16.5713	17.1542	18.9224	19.2745	19.3641	19.5755
02271101 g	13.9813	13.9886	13.9989	13.9021	13.4747	12.5771	12.0384	11.3438
2271101	22.5634	22.795	23.1529	23.0849	21.9154	23.0392	28.8392	30.9449
02271129 b	16.195	16.1461	16.2348	22.6827	24.0798	28.0571	29.1976	29.6348
02271129 c	18.9584	18.6446	18.4715	18.0868	17.0575	16.7816	18.0798	18.5992
02271129 d	20.4729	21.1024	21.7903	22.3705	23.0803	23.7802	24.2535	25.0126
02271129 e	31.1033	29.4845	28.4482	27.9854	27.2069	20.044	21.607	24.3744
02271129 f	12.8158	12.8109	12.8309	12.7437	12.4989	12.1444	11.9191	11.675
2271129	27.3239	29.5827	27.817	22.7176	19.339	14.6495	30.6548	31.2171
02271145a	19.2102	19.3697	19.8056	19.7298	19.6498	19.3966	19.1401	18.3161
02271145b	19.6707	19.6803	19.4876	19.3508	19.2749	19.167	19.1938	18.8661
02271145 c	28.0096	26.1098	24.836	28.7395	32.0944	33.643	33.9806	34.189
02271145 d	19.1921	21.9062	20.6413	20.3832	20.3552	20.2131	20.2398	20.2683
02271146a	21.1641	20.9546	20.812	20.5586	20.4739	20.3379	19.8847	19.3796
02271146b	17.2928	17.2233	17.1915	17.7197	18.8383	20.1858	21.2224	21.2632
2271222	18.7409	19.2416	19.6531	20.3022	20.8757	21.5629	22.0501	22.3378
02271223b	17.408	17.386	17.3604	17.6417	18.0313	18.2723	18.2332	23.4322
02271223c	11.5343	13.1853	13.9066	14.4667	14.9181	14.9913	15.1523	15.1227
02271223d	17.9087	18.2762	19.0713	20.2347	21.0493	21.5338	22.2687	22.7473
02271223e	24.6434	25.3615	25.3972	25.4897	25.5712	26.1709	31.121	33.3473
02271223f	1.9093	1.918	1.932	1.9826	2.0052	2.0037	2.0385	2.0809
2271223	31.2211	32.2202	32.7584	33.2186	33.9266	33.4555	31.9773	30.8396
8151058	19.6337	20.109	22.1116	24.5443	25.3377	25.688	24.698	23.1863
8281218	23.1575	22.7915	22.3442	20.8529	19.2886	18.4511	22.9854	24.4881
8281222	18.721	18.4924	18.3138	18.5195	19.0353	19.8603	20.4133	21.1543
8281228	16.2747	17.3448	17.9832	18.4357	18.4732	18.5047	18.3598	18.4357
8281230	19.6367	19.4511	19.3861	19.1929	20.1008	20.4194	20.3896	20.183
8281236	1.5673	1.5457	1.5333	1.5242	1.4933	1.4681	1.4705	1.4763
8291401	8.627	9.005	9.4768	9.9291	10.4797	11.0981	11.3516	11.4774
8291405	33.8031	34.8198	34.9761	35.0767	34.9271	34.0553	33.3582	32.5
8291406	20.0506	19.573	19.2236	18.4701	18.7007	18.9093	19.1671	19.2457
8291410	29.3136	28.9553	26.3913	25.3867	25.9182	26.2436	26.0983	25.0279
8291430	21.0089	20.5016	20.1902	19.8077	18.182	17.8621	21.7501	22.3175
8291433	18.0501	17.2895	16.6538	15.1407	13.0317	10.5691	9.5251	10.0996
8291439	16.8389	16.9692	16.9715	16.1247	15.2719	14.5228	14.9359	16.6324
8291440	24.932	24.4386	24.0122	23.7238	23.3838	22.9839	21.48	20.0281
8291441	20.6549	21.1359	22.3935	22.9084	23.0338	23.0584	23.1448	23.2399
8291443	12.744	13.1526	13.14	12.9364	12.6054	12.1477	10.452	9.6618
8291450	20.1466	20.5179	20.6521	20.5081	20.2602	20.0657	19.8709	19.507
8291452	23.7307	24.4077	24.5416	24.6654	24.686	22.3886	18.6022	16.8862
8291502	15.9605	15.9983	15.9744	16.0426	17.8365	20.9327	21.5626	21.7124
9011339	11.9781	11.321	15.3834	17.8235	18.9424	19.8611	20.2368	20.4225
9011340	11.7914	10.6913	8.7481	9.6738	10.7958	13.0585	14.6598	15.3754

Degs/indivs	99	102	105	108	111	114	117	120
02271101 b	12.0711	11.8122	11.8746	12.8415	14.0445	14.5661	14.8409	15.0311
02271101 c	21.0581	20.9285	20.677	20.5631	20.3982	19.9469	19.2192	18.6174
02271101 d	19.51	19.1405	18.2544	17.2706	16.4209	15.8209	15.2423	14.7295
02271101 e	19.7089	19.831	19.6374	20.1443	21.2656	22.7722	24.1928	24.8872
02271101 g	10.7681	9.5093	8.5307	8.1667	11.3952	13.7748	14.9408	15.8582
2271101	32.0805	32.3004	32.2046	32.175	30.8522	28.6394	29.2003	30.1385
02271129 b	29.8404	30.1267	30.5118	30.9801	31.4825	31.927	32.3893	31.8472
02271129 c	18.7326	18.9197	18.8971	18.5843	17.8377	17.2586	16.9862	16.9047
02271129 d	25.9277	26.3245	26.6659	26.7817	26.7149	27.1671	28.9042	30.0028
02271129 e	25.284	25.4615	25.5141	25.2174	24.6722	24.6382	24.3762	24.1514
02271129 f	11.5103	11.4828	11.5255	11.705	12.0227	12.3897	12.5936	12.1409
2271129	31.4355	30.4685	27.2346	25.5258	24.905	24.4871	24.2998	24.5079
02271145a	15.7545	13.4862	12.5489	12.152	11.7905	11.496	11.285	11.1554
02271145b	18.4996	19.6009	20.0266	20.3284	20.7087	20.6321	20.5036	20.8325
02271145 c	33.7692	32.9922	33.4858	33.9997	33.7796	33.5863	33.1982	32.154
02271145 d	20.0528	19.6071	19.739	20.5278	22.4482	22.7515	22.5478	22.0701
02271146a	19.022	18.6095	19.5068	20.721	21.9084	22.379	22.6436	22.7567
02271146b	21.3677	21.2898	21.1789	20.4603	19.9001	19.2918	17.8197	14.7558
2271222	22.4912	22.7177	22.8659	23.1556	23.4464	23.5342	23.6282	23.5541
02271223b	24.1958	24.6316	25.0843	25.3329	25.1681	24.4211	23.9234	23.6416
02271223c	15.2264	15.2793	15.373	15.4771	15.6698	16.0083	16.7821	19.1415
02271223d	22.643	21.9466	21.5003	22.7803	24.1615	24.76	25.1082	25.4697
02271223e	33.8534	34.0058	33.769	32.5874	31.2378	29.9402	29.1797	28.4602
02271223f	2.094	2.1491	2.2106	2.2478	2.321	2.3702	2.4678	2.5445
2271223	29.5083	26.1721	33.681	34.6385	35.9294	38.1035	39.2761	40.4072
8151058	19.9103	18.3999	17.7852	17.4522	17.2862	17.334	17.4045	17.5523
8281218	24.5888	24.0648	24.1415	24.2148	24.6581	25.2238	25.4321	25.3118
8281222	21.8372	22.7223	22.998	23.2256	23.4565	23.3129	23.2606	23.3004
8281228	18.4494	18.5142	18.2711	17.4839	16.6559	14.6621	13.4547	16.1231
8281230	19.5004	18.2713	18.2618	18.192	17.7148	16.2749	15.2502	13.9551
8281236	1.4896	1.5036	1.5208	1.5487	1.5508	1.5884	1.6309	1.6778
8291401	11.5998	11.7937	11.942	12.1336	12.3588	12.6319	12.9382	13.2268
8291405	31.1394	29.078	27.5833	27.5629	27.5643	27.5368	28.1377	29.0367
8291406	19.2998	19.255	19.2652	19.233	18.9345	18.5177	18.2944	17.9114
8291410	27.3994	29.4151	30.5394	33.6533	33.9994	34.4755	36.7432	36.4442
8291430	21.5075	20.9906	20.8216	25.2123	27.7723	28.7829	29.6312	29.8178
8291433	11.1043	11.421	11.6249	11.8758	12.1814	12.73	14.1656	16.6492
8291439	17.5983	18.2341	18.4029	18.6364	18.6916	18.6	18.1808	17.61
8291440	19.6692	19.6784	19.6692	19.7309	19.8854	19.9201	19.4615	18.5341
8291441	23.1243	22.8356	23.2426	25.6447	26.3742	26.8761	27.57	28.2424
8291443	9.0552	8.8641	8.9277	9.6473	13.3816	14.7448	15.1253	15.4235
8291450	19.1434	11.1942	13.4561	14.5351	15.6346	16.1699	16.576	16.9764
8291452	15.8585	16.3148	17.2601	17.964	18.5108	18.7661	19.1202	19.8747
8291502	21.6837	21.2221	20.1795	19.2332	18.435	17.8557	17.3016	16.9027
9011339	20.608	20.9618	21.132	21.19	20.8954	21.0834	21.1734	20.5208
9011340	15.4789	15.5859	15.8266	16.0332	16.2252	16.0805	15.7123	15.615

Degs/indivs	123	126	129	132	135	138	141	144
02271101 b	15.1025	15.2178	15.376	15.4463	15.5563	15.7733	18.2529	21.0676
02271101 c	18.1401	18.2019	19.9846	21.1429	21.8236	22.0339	22.1827	22.2212
02271101 d	14.0319	13.4646	13.2535	26.8079	28.4353	28.629	28.4777	28.0461
02271101 e	25.0834	24.9269	24.8023	25.1021	25.6496	26.1778	25.9273	25.6981
02271101 g	17.763	18.4563	18.9203	18.6781	18.8493	19.4978	20.1371	20.44
2271101	30.9021	31.6573	31.8566	32.5403	34.706	35.3935	35.4228	35.4352
02271129 b	31.1071	30.0175	27.9113	27.5171	28.2586	29.0213	28.6415	32.3836
02271129 c	17.067	17.4509	17.9194	22.9322	24.6542	26.3081	28.0901	28.6463
02271129 d	30.5314	30.918	31.8418	32.6946	33.0113	33.47	33.8694	34.2592
02271129 e	24.473	25.953	27.9553	30.6707	32.5136	33.1233	33.2641	33.1133
02271129 f	11.6083	11.12	10.5942	9.5915	8.8269	8.2572	7.7075	7.4133
2271129	24.1576	22.5163	19.9765	27.1707	29.4013	30.7326	31.9454	34.2004
02271145a	14.9357	16.8102	18.1405	18.9836	19.716	20.5028	21.5881	22.6243
02271145b	21.1077	21.4184	21.5631	21.7655	22.0812	22.2273	22.3807	22.532
02271145 c	30.4431	29.5222	31.5821	33.5035	35.8117	37.397	37.1413	36.4107
02271145 d	21.6251	21.9135	23.5679	24.863	26.1354	26.4985	26.6074	26.7073
02271146a	22.979	23.4416	24.2348	25.078	25.3839	25.5323	25.3728	24.7073
02271146b	15.0067	16.0086	16.9709	16.8054	16.3935	19.2364	21.9855	22.0375
2271222	23.7789	24.0147	24.3161	24.7241	25.8881	28.0458	29.8303	31.2469
02271223b	24.1656	25.7827	28.8991	29.7666	30.2414	31.548	32.8074	34.033
02271223c	20.0827	20.9482	21.6298	22.2324	22.3987	22.7585	23.0177	22.5128
02271223d	25.3843	25.8306	26.4743	27.5007	28.0969	28.6345	29.6172	29.8687
02271223e	27.8514	27.519	27.2629	27.0244	28.401	30.5637	31.7899	32.1355
02271223f	2.6286	2.7194	2.8362	2.871	2.9347	2.962	2.9528	2.9965
2271223	40.5865	40.1254	37.8149	34.428	32.5279	31.4358	30.1291	28.9481
8151058	17.6614	17.6758	17.5582	16.7154	15.7861	14.5846	14.8719	15.2479
8281218	24.893	23.2729	25.5775	27.9311	31.0254	31.7464	32.9829	33.7916
8281222	23.8523	24.4708	24.9569	25.0394	24.8655	24.7154	26.0267	47.1851
8281228	17.0667	17.6322	18.2	19.0115	20.2293	21.1422	22.1182	23.0825
8281230	7.589	6.4388	13.3435	13.8641	14.2546	14.8078	15.1997	15.6782
8281236	1.7288	1.7641	1.8381	1.9167	2.0166	2.1215	2.2683	2.3878
8291401	13.6058	13.813	13.8291	13.7168	13.8658	14.0529	14.3071	14.4098
8291405	30.2128	30.5791	31.3066	31.6445	31.2525	34.2738	35.1185	36.1868
8291406	17.4042	16.7963	16.514	18.5242	19.9744	23.1709	24.8066	26.2443
8291410	35.5955	35.3206	34.5636	32.7592	30.482	34.0999	33.6624	40.3531
8291430	29.0682	28.4463	27.9519	28.0466	29.0582	30.9467	33.1002	34.3036
8291433	18.212	18.9407	19.7974	20.5556	20.9491	21.0245	21.1127	21.2598
8291439	17.2634	18.6627	19.4147	20.1682	20.6969	21.6394	27.4276	28.9814
8291440	17.765	17.2	20.2165	21.2204	22.2761	23.1747	24.361	25.4508
8291441	29.0963	30.0126	31.0308	31.9263	31.4504	29.9584	28.6227	28.6626
8291443	15.7441	16.1085	16.4279	16.7144	17.1208	17.3403	17.0615	17.097
8291450	17.2793	17.5528	18.0603	19.8637	21.4392	22.2118	23.0114	23.6834
8291452	20.6113	20.9739	21.2956	21.7133	22.7362	25.887	27.4332	27.9652
8291502	16.7362	21.2947	22.3036	23.3164	24.0049	23.9539	23.9241	23.7068
9011339	19.832	18.6068	18.1614	23.7844	24.3837	25.0153	25.5784	25.5447
9011340	15.4549	15.1699	14.8349	14.708	14.6557	14.6769	15.1324	16.1368

Degs/indivs	147	150	153	156	159	162	165	168
02271101 b	22.4001	23.2857	24.0644	25.1578	25.7066	25.9159	25.6149	24.8281
02271101 c	22.393	23.0877	24.2058	24.7937	31.7143	33.6651	35.1313	35.7374
02271101 d	27.6919	27.5202	27.2524	26.7415	26.0553	25.4083	25.1262	24.8209
02271101 e	26.363	27.662	29.3648	30.3564	30.6666	30.9564	32.3137	32.3616
02271101 g	20.976	23.4088	24.6705	24.8806	25.0794	25.2462	24.8217	23.2751
2271101	35.6606	35.9403	39.3748	43.4645	46.4009	46.6685	45.9456	45.0327
02271129 b	34.2354	35.0689	35.9211	36.5193	36.7301	36.796	36.3159	35.7833
02271129 c	29.2068	29.7602	30.0488	30.8479	32.1042	32.9777	33.3983	33.169
02271129 d	34.5374	34.9336	35.3634	35.5956	35.7648	35.502	35.0345	34.2214
02271129 e	32.425	31.7707	31.0318	33.9248	34.7696	35.4524	35.7467	35.7006
02271129 f	15.0038	15.8015	16.337	17.0027	17.7649	18.468	19.177	19.4343
2271129	34.8012	35.1344	35.6916	36.0202	35.7943	35.4369	34.8097	34.0139
02271145a	23.9051	25.3631	26.73	27.9927	28.6555	29.0202	28.9824	28.5042
02271145b	22.5838	22.8117	26.2971	28.3959	29.0878	29.7544	30.2202	29.8424
02271145 c	34.9382	35.9141	39.702	41.7184	42.6206	43.2887	43.8927	44.5287
02271145 d	26.8473	27.0128	27.2743	27.5598	28.025	28.4176	28.3398	27.7389
02271146a	24.0968	23.5081	23.2045	26.8369	27.5843	28.1487	28.0464	27.4139
02271146b	21.2978	20.3621	23.9098	25.2244	25.6675	25.7727	25.5147	24.5395
2271222	31.6934	31.9575	32.0187	31.7295	31.5285	30.8814	29.7395	27.9683
02271223b	35.3672	35.6223	35.5891	35.2973	34.7457	34.5238	34.3341	34.3833
02271223c	22.4964	25.7014	26.382	27.3442	27.6559	27.7916	27.5485	27.1582
02271223d	29.3312	28.4823	29.1206	30.0959	30.9576	31.5359	31.978	32.2911
02271223e	34.2285	35.4595	36.6167	37.5891	37.9382	37.9326	37.5153	35.1991
02271223f	3.0039	3.0197	3.0437	3.0758	3.0746	3.0527	3.0084	2.9721
2271223	28.5535	28.4242	30.7554	32.6007	33.6003	33.7839	34.3258	34.1586
8151058	15.7694	16.4436	17.2182	18.3259	19.5169	20.3697	21.0553	20.8496
8281218	34.0746	34.2876	33.733	32.1142	29.0508	29.6764	31.3655	31.65
8281222	46.1329	44.1661	41.9475	40.553	38.9953	37.5901	37.4103	38.1613
8281228	24.2936	24.8465	25.0304	24.8518	24.6151	24.0537	23.3243	22.1655
8281230	16.165	17.5964	24.7058	27.8893	28.4089	28.967	29.3116	29.3553
8281236	2.5667	2.7059	2.9275	3.1461	3.4393	3.7256	3.9988	4.2409
8291401	14.5753	14.934	15.4906	16.4956	17.1453	17.5795	17.3113	16.9369
8291405	37.3719	38.0884	38.5737	39.3502	41.2399	41.0964	41.744	41.466
8291406	27.852	28.8727	29.5119	29.9903	30.1721	30.3387	30.1978	29.745
8291410	45.7013	47.675	48.6816	48.6502	47.9852	47.5992	47.5141	47.1904
8291430	35.0674	35.7319	36.0671	36.209	36.451	36.7727	36.8209	35.8181
8291433	21.4644	21.9297	23.3088	24.7524	25.4986	26.0807	26.2944	24.8813
8291439	30.4836	30.9983	31.0702	30.6242	29.9074	28.5312	26.0602	24.0185
8291440	26.0103	26.4709	26.8898	28.0412	28.0349	27.8914	26.3888	24.4985
8291441	29.582	30.6922	31.9557	33.2312	34.1291	34.606	34.7046	34.3321
8291443	17.1457	16.6735	16.4463	16.8332	17.7661	18.8849	19.4611	18.9894
8291450	23.6347	23.0545	21.73	21.5046	25.2389	26.0028	25.9987	25.4501
8291452	28.1923	27.9841	26.7893	24.4975	25.2568	28.7347	31.747	32.0806
8291502	23.5906	27.623	29.6138	30.0722	31.0782	31.8466	31.9789	31.1503
9011339	25.3616	24.8473	24.5375	24.9175	27.6223	28.2089	28.4003	28.3432
9011340	17.672	19.9035	22.1134	23.0921	23.9924	24.4691	24.8669	24.5084

Degs/indivs	171	174	177
02271101 b	23.2844	21.9367	19.9172
02271101 c	35.6353	33.7188	27.6419
02271101 d	24.3031	23.2024	22.012
02271101 e	31.3456	28.9068	27.3988
02271101 g	21.5062	19.8257	19.424
2271101	44.8578	44.2208	42.0598
02271129 b	35.0416	33.8616	22.8612
02271129 c	32.4602	31.4107	24.8553
02271129 d	32.7878	30.2893	21.6924
02271129 e	35.1539	33.9788	34.3048
02271129 f	19.147	18.6319	17.974
2271129	31.8371	25.1	23.2425
02271145a	27.6528	26.2744	25.491
02271145b	25.4494	22.0055	20.5342
02271145 c	44.2369	41.4601	41.7304
02271145 d	26.7181	24.3884	18.1576
02271146a	26.0735	23.4826	21.2988
02271146b	22.5908	20.4546	18.5857
2271222	26.5078	26	25.1796
02271223b	34.3834	33.7484	32.4161
02271223c	25.9131	23.544	16.7062
02271223d	32.1154	30.8016	28.7496
02271223e	32.0157	27.8678	25.6572
02271223f	2.9439	2.924	2.9128
2271223	33.0571	32.0623	33.0341
8151058	20.0735	19.0336	18.4423
8281218	30.9657	23.4122	21.5424
8281222	38.9874	40.1043	40.3976
8281228	21.0345	19.9718	19.3802
8281230	25.3254	23.6968	23.0225
8281236	4.3959	4.5355	4.7592
8291401	15.9342	15.4249	16.2339
8291405	40.3174	39.9582	42.6891
8291406	29.1463	27.7779	26.043
8291410	45.7406	43.1639	36.3935
8291430	26.9465	25.2077	21.6004
8291433	23.4362	21.7499	19.8748
8291439	22.7055	21.7041	20.9981
8291440	25.3122	24.6509	22.4013
8291441	33.3237	31.591	29.4584
8291443	17.8564	16.406	14.7906
8291450	24.2012	22.37	21.2277
8291452	31.7665	29.3934	20.9274
8291502	29.7504	16.884	15.3145
9011339	28.6772	28.3298	27.3196
9011340	23.0963	20.6975	18.3797

Degs/indivs	3	6	9	12	15	18	21	24
9021234	21.7439	22.4223	23.0153	24.2867	25.6569	27.1219	28.2115	28.9348
9021236	20.8895	22.0104	25.0203	26.0332	27.4263	27.8557	27.7952	27.4477
9031128	15.6731	15.5628	20.8637	23.7975	25.0141	25.8181	21.8742	21.7132
9051203	25.2306	25.7441	25.7787	25.473	25.4689	26.0509	26.2452	26.2257
9090926	19.6974	21.0311	22.9117	24.5763	25.1552	25.679	25.8779	25.9887
9090927	26.197	27.6581	28.7403	29.2869	29.4846	29.4617	29.2922	29.0675
9090928	20.5643	20.5403	19.9904	19.9639	20.6037	20.9828	20.7526	20.2751
9090930	25.6333	27.0174	27.6829	27.411	26.3802	25.0071	24.9125	25.5075
9101255	25.9495	32.1237	33.8714	34.3081	34.3534	33.3523	31.4358	29.94
10221221	12.3262	12.8001	13.9393	15.4807	15.8194	15.8878	15.8843	15.9503
10221223	6.9691	7.2232	7.399	7.5673	7.663	7.6888	7.756	7.8965
10221224	21.7637	22.4318	23.3023	24.7978	24.3737	24.2859	24.1665	23.7348
10221225	22.4021	22.2223	22.3747	23.0483	23.2981	23.2275	22.6055	21.0648
10221240	20.1079	21.1663	21.7655	22.2828	22.5602	22.5181	22.3365	22.0501
10221246	20.7071	21.6956	23.3237	24.4154	24.9166	25.005	24.9236	24.6834
10221248	28.7486	34.0011	36.7885	37.9062	38.0229	37.4066	34.1137	32.3628
10221252a	21.4342	21.262	21.1021	21.0346	21.1274	20.9113	20.6016	20.2915
10221252b	23.119	23.5585	23.9509	24.3607	24.3191	24.2759	23.9685	23.4884
10221306	12.9668	13.8321	14.7448	15.4977	16.1586	16.7081	17.3781	17.8343
10221310	24.3303	25.7251	29.3861	30.3243	30.4624	29.8327	29.0081	27.6673
10221311	16.1116	17.2642	18.2641	18.8737	18.8636	15.2661	14.6907	14.5823
10221312	25.2147	26.3472	27.6708	28.6741	28.9194	28.7353	28.065	27.2723
10221313	26.4245	27.0594	27.7786	28.2621	28.4504	28.281	28.0907	27.7744
10231228	21.385	26.8034	30.3166	31.7854	32.9561	33.9521	34.2198	33.7035
11031225	17.7052	19.2868	21.7814	24.4219	25.7233	26.1644	26.2005	26.0992
11031227	23.6732	26.3016	32.6409	33.1439	33.2436	32.8702	31.8876	27.3346
11031228	19.5803	19.9553	20.4299	20.6769	20.8498	21.3973	21.8287	21.9508
11031231	21.5088	30.535	32.6961	33.383	33.3461	34.1047	33.4548	32.662
11031232	22.8495	24.995	26.2564	26.1831	25.7915	25.4564	25.1225	24.0177
11031243	25.4928	26.369	27.1048	27.4815	27.3743	27.1	26.2568	26.1807
11031255	21.0608	25.7739	27.2499	27.7428	27.3731	26.8807	30.3714	30.4109
11031258	19.0593	19.5814	25.3512	27.0071	27.9148	28.1765	28.2889	27.9351
11181129	16.4943	17.4673	20.4147	22.2771	23.3583	23.6819	23.5274	23.2293
11181133	38.1378	36.3981	36.8323	38.1939	38.5865	38.4318	38.1827	37.8376
11181142	34.4214	39.1649	40.1772	40.6452	41.0805	41.3666	41.1894	40.3982
11181143	21.7636	25.3406	31.0193	31.9843	32.1893	31.7177	31.1253	30.3046
11181145	15.2582	15.8159	17.126	18.6529	19.6007	20.0639	20.2223	20.2986
11181146	23.262	34.3253	35.3089	36.4951	37.477	37.9586	37.9665	37.3422
11181201	21.5626	23.6363	25.8059	26.8309	27.3336	27.1895	26.636	25.8182
11181202	7.0105	7.6232	8.2848	9.0413	9.6348	10.3342	11.0613	11.72
11181203	27.2459	28.5786	28.7066	28.6232	28.2845	28.0213	27.5091	26.0477
11181204	19.7183	21.4884	22.6236	23.5565	24.2447	23.935	23.8231	23.9404
11181214	16.5746	17.2997	18.1706	18.6721	18.8201	18.6812	18.3352	17.5694
11181218	17.5078	18.6198	19.5417	20.0927	20.2713	20.3237	19.9012	19.5541
11181226	31.7986	31.8437	32.0608	31.4238	30.8757	30.3693	29.3335	27.8339
11251046	22.4646	30.2799	35.7588	35.4353	34.1979	31.7865	28.7652	28.1042

Degs/indivs	27	30	33	36	39	42	45	48
9021234	28.84	28.1464	22.9229	22.4247	22.1637	21.9338	20.766	19.1024
9021236	26.9819	26.2018	24.9742	24.57	23.323	21.9182	20.736	16.3066
9031128	21.0125	20.6322	20.8016	20.9299	21.4082	20.7417	17.7451	18.0575
9051203	26.0361	25.5733	25.1809	24.583	23.3832	22.1973	21.0463	19.9547
9090926	26.2502	26.5059	26.6645	26.2538	25.3396	24.1392	22.9519	21.7968
9090927	28.8278	28.3886	27.6533	25.4553	20.705	20.3251	19.9663	19.772
9090928	18.8405	18.2365	18.2724	18.5916	18.8335	18.6824	18.4691	18.3066
9090930	26.2153	26.8543	27.8579	27.8922	27.5137	26.9853	26.1962	24.9171
9101255	29.4985	29.5241	29.5824	29.3324	28.322	27.1353	25.4175	26.8646
10221221	17.6783	18.4124	20.1106	19.5707	21.092	16.2122	15.7723	15.7333
10221223	8.0593	8.3732	8.6832	9.0336	9.3565	9.9243	11.5065	12.152
10221224	23.2736	22.8372	20.279	20.1082	20.3499	19.8556	11.6329	12.6854
10221225	17.6873	16.8078	16.3734	16.147	15.9745	15.2662	14.4462	13.5057
10221240	21.8598	20.9249	19.2008	14.4598	13.8014	12.923	11.1065	11.3859
10221246	24.4673	24.2568	23.92	23.5566	23.1911	22.9268	22.8944	22.3571
10221248	30.1477	29.0153	23.3326	21.6272	20.7419	20.1662	19.8949	19.718
10221252a	19.8829	19.7033	19.5183	19.3272	18.1156	16.8447	15.7491	14.6969
10221252b	22.9218	22.3148	21.5326	20.9545	19.8221	16.4699	16.6516	17.654
10221306	18.3899	18.6124	18.8767	18.6054	18.1721	17.7253	17.3131	17.1676
10221310	27.1157	27.162	27.0735	25.9733	24.5486	23.1631	21.5604	20.0588
10221311	14.5405	14.5786	14.6568	14.8583	15.0948	15.2036	14.8841	14.4565
10221312	25.4799	21.8961	22.0632	22.3208	21.9848	21.4597	20.6686	19.2452
10221313	27.2275	26.4954	25.8119	25.3034	24.9376	24.5	23.9807	22.6715
10231228	34.493	35.145	34.9119	34.4066	33.3048	31.7361	29.6938	28.1821
11031225	25.9605	25.8364	26.2914	27.7683	24.4357	20.8482	20.9065	20.8451
11031227	27.8277	27.8477	26.4772	21.5968	22.2732	22.9241	23.4123	22.9218
11031228	21.0448	19.7424	19.036	18.2784	17.463	16.9726	16.6221	15.9599
11031231	32.3967	32.9821	33.3648	33.039	31.0248	29.1628	28.2825	25.0171
11031232	23.0545	22.106	20.6579	20.0313	19.6657	18.8989	17.9598	16.9191
11031243	26.0316	25.7077	25.5024	25.2156	24.417	23.034	21.9552	21.0521
11031255	29.7287	29.3097	29.5722	30.2061	31.2359	31.7245	29.5374	23.0594
11031258	27.1649	25.531	24.0093	23.9028	24.3232	25.0798	25.1618	25.1168
11181129	22.5127	22.0906	21.4148	20.654	19.9596	19.5417	19.0884	18.3237
11181133	37.5976	35.2499	32.5392	32.7349	32.95	32.8778	32.7681	33.0012
11181142	39.5421	37.014	33.7239	27.5593	27.128	26.9186	27.4508	28.5829
11181143	29.5126	25.457	25.0411	23.8593	22.7186	21.4646	17.3133	17.1045
11181145	20.1899	20.0243	19.6257	19.1867	18.5252	17.6445	16.6423	16.1044
11181146	36.3413	35.7742	35.1508	34.6246	32.5081	30.1448	30.045	29.3829
11181201	24.67	23.348	21.2944	18.7957	18.3946	18.4254	18.6151	18.8552
11181202	11.9501	12.1774	12.2582	12.3109	12.3815	12.3731	12.1282	11.9168
11181203	24.9349	23.6176	22.9617	22.9604	22.9723	22.7911	22.5009	21.9726
11181204	23.7066	23.4753	23.0127	22.1863	21.6659	21.4451	20.4241	11.4318
11181214	16.6353	14.7558	13.2718	12.5534	12.348	12.5878	13.209	13.6901
11181218	19.1662	19.0232	18.8354	18.551	17.8891	16.9804	16.0225	14.6039
11181226	27.5031	28.0019	28.7366	28.8263	28.7412	28.4458	27.513	26.598
11251046	25.1625	25.5846	27.5183	28.5135	27.8512	27.1835	26.1778	24.4608

Degs/indivs	51	54	57	60	63	66	69	72
9021234	15.7503	14.951	14.4254	13.7906	13.461	13.9762	14.8363	15.684
9021236	15.4473	14.081	13.3184	12.7728	12.3628	12.0588	11.6685	11.4015
9031128	18.5452	18.3819	17.8507	14.9528	14.9774	14.8621	14.8639	14.7752
9051203	19.2644	18.8455	18.6673	18.6413	18.6278	17.958	16.805	16.1591
9090926	19.6608	19.8548	20.1126	20.1756	20.4268	20.3493	19.1716	18.5416
9090927	19.3	18.0949	17.4909	17.2963	17.2899	17.4916	17.8359	17.9329
9090928	17.9701	17.4533	17.0892	16.7734	16.6741	16.7836	16.8697	16.7697
9090930	24.1534	23.863	23.9029	23.9356	23.6322	23.2743	23.0023	22.9115
9101255	27.7032	27.6968	27.0761	26.4238	25.7964	25.2662	24.8996	24.1076
10221221	15.5391	14.9399	14.3982	14.0057	15.45	15.2761	14.8019	14.5291
10221223	11.9526	11.6718	11.5571	11.3061	11.1295	10.9977	10.8958	10.9252
10221224	12.5797	12.2879	12.2793	12.3646	12.759	12.7319	9.0299	8.8253
10221225	12.6287	11.7439	11.1076	10.4894	9.4804	8.66	8.1842	7.8332
10221240	12.1251	12.7166	13.3811	13.9578	14.4005	14.7823	15.1058	15.3745
10221246	21.6113	20.8155	20.3028	20.1063	20.1753	20.2994	20.4167	20.1871
10221248	19.5943	18.824	15.9426	16.0533	16.3066	16.6566	16.795	16.9599
10221252a	12.5415	12.906	13.3161	13.7996	13.9878	14.1753	14.3824	14.5181
10221252b	18.957	20.2033	21.4842	22.0072	22.5609	22.9961	23.4421	23.9657
10221306	17.1193	17.0325	16.8014	16.319	15.4919	14.7929	14.1424	13.5791
10221310	18.2726	18.2732	17.9028	16.6713	15.4649	16.1853	19.3415	21.0583
10221311	13.9615	13.5625	13.152	12.8363	12.5854	12.2742	11.7523	10.6762
10221312	17.94	15.2748	14.4242	14.1271	13.9202	13.7493	13.5019	13.1483
10221313	21.0795	19.6454	18.273	18.3534	18.4853	18.5501	18.5477	18.5293
10231228	27.9263	28.1618	27.6441	26.8979	26.2827	25.8168	25.0818	23.0324
11031225	20.7824	20.8362	20.7041	20.0848	19.4706	18.3507	17.6495	17.236
11031227	22.1823	20.2248	20.0216	20.0117	20.1422	20.3831	20.8161	21.2037
11031228	15.2763	14.2065	12.492	13.452	14.5003	15.3797	16.2673	16.9421
11031231	25.6461	26.1938	26.5024	26.2479	25.3747	24.1712	23.8932	23.681
11031232	12.173	12.6389	13.2698	14.5353	15.7587	16.6632	17.7395	18.3677
11031243	20.2442	19.6405	19.0332	18.5527	18.0287	17.4575	16.2656	15.2095
11031255	21.7461	19.8104	20.3449	20.9347	21.0007	21.0469	21.1524	21.1322
11031258	24.4355	23.1402	22.0966	21.1585	19.0232	17.6842	16.6081	15.318
11181129	17.6354	16.9546	16.1903	14.8852	12.8798	7.9895	8.3276	8.5368
11181133	32.3689	32.0785	31.4803	30.3703	28.9108	23.2756	21.428	19.3364
11181142	29.4683	30.057	30.109	29.2507	28.2639	27.3561	26.25	25.6289
11181143	17.4533	19.6814	21.6269	22.7613	23.218	23.7105	23.915	23.7466
11181145	15.6441	15.2194	15.0154	14.771	14.6345	14.3181	14.0802	13.8157
11181146	27.267	25.6782	26.0468	25.8902	25.066	24.2401	24.1793	24.6781
11181201	19.0958	19.2824	19.2466	18.7144	17.8303	16.8259	9.6089	10.5628
11181202	11.7237	11.6604	11.54	11.5231	11.4658	11.4858	11.4112	11.1398
11181203	21.0255	19.5191	16.4239	15.9159	16.0763	16.281	15.988	15.2432
11181204	12.3743	14.4947	16.7606	18.168	18.9698	19.4678	19.8531	19.8179
11181214	14.037	14.3726	14.7488	14.8268	14.8033	14.7077	14.7294	14.3021
11181218	9.591	9.5785	9.4424	9.3035	9.0486	8.7861	8.5159	8.328
11181226	26.107	24.6605	19.7415	19.6176	19.0565	18.1345	17.1085	13.1824
11251046	23.819	23.3355	22.5238	18.9493	18.6243	18.3813	20.4992	21.3037

Degs/indivs	75	78	81	84	87	90	93	96
9021234	16.4997	17.2414	17.9624	18.0353	17.9625	17.9374	17.8165	17.6424
9021236	11.0614	10.3697	9.7185	9.3262	9.1808	9.2778	16.3526	16.9654
9031128	14.5995	14.48	14.342	13.9472	12.9585	12.0668	11.4419	10.902
9051203	15.673	15.3851	15.1035	14.7724	13.9866	12.9271	11.9032	11.3632
9090926	18.3437	19.6121	20.8975	22.4763	22.859	23.1696	23.5017	23.9451
9090927	18.1454	18.6076	18.7949	18.8784	19.0069	19.4986	20.0454	20.2302
9090928	16.5671	16.4219	16.2069	16.0447	15.873	15.5873	14.6081	13.3986
9090930	22.7682	22.4841	22.2714	22.0656	21.6526	21.359	21.0704	20.5204
9101255	22.2863	16.6549	19.3336	23.5885	26.6241	27.1818	27.5425	27.71
10221221	14.2705	14.0385	13.5861	12.5613	12.5947	12.5494	12.5106	12.5054
10221223	10.955	11.0457	11.1034	11.1858	11.3941	11.6959	12.0306	12.144
10221224	8.6437	8.4866	8.3622	8.1672	8.048	7.815	7.4273	7.0539
10221225	7.6195	7.4818	7.4606	7.5423	7.7398	8.0907	8.4192	8.5903
10221240	15.6031	15.9826	16.3178	16.4331	16.3281	15.6696	14.5296	12.6336
10221246	19.6836	18.6162	17.5274	17.5915	20.8285	21.1763	21.1582	21.1958
10221248	17.299	17.5455	17.6151	17.6091	17.5944	17.2259	16.7313	15.5293
10221252a	14.4753	14.2513	13.9814	13.8854	13.7847	13.6796	13.5685	13.3212
10221252b	24.6277	25.0177	25.7723	25.5343	25.3153	25.165	24.9118	24.1446
10221306	12.6833	11.1598	6.9344	7.4604	10.3593	13.0805	14.0268	14.3469
10221310	22.1883	23.1073	23.9504	24.6673	25.3863	25.8765	24.7416	23.0805
10221311	9.3045	8.2007	8.3365	9.2467	14.0221	15.5353	15.7973	16.0429
10221312	12.7328	12.0433	11.2577	10.4589	9.3375	7.173	4.4634	2.6791
10221313	18.6291	18.5614	18.4311	18.3076	18.4428	19.7326	21.1836	21.9047
10231228	22.6725	21.3962	21.5931	23.1872	25.2842	27.7266	28.3987	28.6303
11031225	16.9232	16.5462	15.748	15.1788	14.6564	14.0117	13.0718	12.2867
11031227	21.6489	21.8089	21.7888	22.0711	22.4128	22.8726	23.3338	22.8725
11031228	17.4638	17.2875	16.7309	15.3902	14.0216	12.0269	11.8335	13.9969
11031231	23.5365	23.3158	22.8692	22.1181	21.2869	20.2209	18.3204	13.5539
11031232	19.37	20.7223	21.9304	22.9171	23.0924	23.1682	23.2535	23.2435
11031243	14.5777	13.9475	13.5389	13.2282	13.172	13.1542	12.7889	11.9028
11031255	21.1135	20.8416	20.7653	20.5045	20.0105	18.9344	26.1959	26.7711
11031258	15.7645	16.9232	17.7593	18.1376	18.5634	19.1437	19.7784	19.8615
11181129	8.8509	9.2201	9.2187	9.3277	9.4193	9.4064	9.5051	9.5885
11181133	18.9451	19.6295	21.3513	23.3684	24.4388	25.0323	24.8868	24.9041
11181142	25.5233	24.9952	24.6826	24.3734	24.207	23.9729	23.0638	22.6851
11181143	23.4557	23.164	22.6672	20.7351	21.6982	24.2229	24.5198	24.6826
11181145	13.5444	13.4316	13.2487	13.0612	12.6622	12.3483	12.2183	12.8647
11181146	25.6662	26.1198	26.2839	26.7662	26.903	26.6182	26.5728	26.4374
11181201	11.8117	13.8485	15.8617	16.7545	17.5996	17.652	17.6756	17.5948
11181202	10.8611	10.5839	10.379	10.1264	9.9036	9.7495	9.6021	9.4995
11181203	14.5028	13.8328	12.9615	12.9341	14.9439	15.41	15.7347	15.9827
11181204	19.6158	19.5119	19.3705	19.7519	20.6527	22.0247	22.6147	22.9417
11181214	13.9119	13.1443	9.2814	11.12	12.5526	14.0102	15.0158	15.4085
11181218	8.0934	7.8033	7.298	7.0303	6.9318	6.8513	6.9318	16.145
11181226	13.3963	14.0167	14.7369	15.7336	16.5968	17.1622	17.4414	17.768
11251046	21.5066	21.5017	21.4282	20.8876	21.0613	21.8805	22.2353	17.2848

Degs/indivs	99	102	105	108	111	114	117	120
9021234	17.5696	17.289	16.7006	16.501	16.5476	16.6587	16.8618	16.9344
9021236	16.9166	16.4781	16.5764	17.5778	17.9049	17.8155	17.7737	17.9279
9031128	10.3358	9.8955	9.5941	9.6873	12.3737	12.9563	13.5436	14.0128
9051203	11.2169	11.3695	12.0772	13.1716	13.7578	14.1122	14.4028	14.8737
9090926	24.5869	25.3509	26.0245	26.2487	25.3634	25.7295	25.0896	25.3058
9090927	20.2184	20.0926	19.1642	18.1129	16.8828	15.8435	16.5942	17.5537
9090928	11.6789	13.0346	14.3962	16.17	17.2024	18.2219	19.6887	20.5032
9090930	19.7448	21.0292	22.2288	23.0123	23.1697	23.3227	22.897	22.4631
9101255	27.7394	26.7988	26.6288	27.5531	28.5859	29.5156	30.5721	31.0127
10221221	12.5337	12.6287	12.9015	16.1451	16.356	16.5589	16.6677	15.4891
10221223	12.2947	12.3486	12.4352	12.6036	12.6962	12.9048	13.0627	13.2851
10221224	6.7926	6.5359	6.2525	6.0309	5.9535	6.0323	6.1465	6.4164
10221225	8.7906	8.9181	9.0782	9.2764	9.5017	9.6513	17.4046	18.1028
10221240	5.4905	5.5086	5.6515	6.1734	6.8199	7.4159	8.0283	9.0826
10221246	21.296	21.5018	21.7768	21.8724	21.7305	21.4822	21.3773	20.8024
10221248	14.5375	14.0323	14.0256	14.7988	15.6861	16.4	16.9485	17.3636
10221252a	13.0205	12.6125	12.3756	12.1498	11.9706	11.7534	11.5679	11.2974
10221252b	23.7228	23.3649	22.8207	22.3958	24.246	25.5278	27.2845	28.1354
10221306	14.4728	14.4903	14.4251	14.429	14.4958	14.5804	14.6514	14.4959
10221310	22.7114	22.8095	22.9822	23.1637	23.1494	22.5668	22.2831	22.4022
10221311	16.2458	16.4633	16.6734	16.8718	16.9926	16.6463	16.3212	16.0677
10221312	12.7148	13.7823	14.6965	15.7892	16.5845	17.5105	20.0153	20.8762
10221313	23.1199	24.3718	25.4964	24.736	24.0105	23.4495	22.6742	22.5502
10231228	28.7763	28.5866	27.2731	25.3294	23.0912	22.9782	23.4209	24.1095
11031225	11.8674	11.5162	17.5706	18.0669	18.401	17.7537	16.8036	16.5727
11031227	22.0414	21.0616	20.5003	20.1731	19.9597	19.7214	19.0423	16.046
11031228	15.0716	16.0833	16.5049	16.7161	16.8923	17.0747	17.3211	17.4265
11031231	13.2733	13.6418	14.4283	15.0377	15.3102	15.6504	15.8011	15.8297
11031232	23.079	21.4282	17.3617	16.4467	16.2421	16.2538	16.5278	16.9421
11031243	10.9887	10.3146	10.3376	13.5454	14.3217	14.7585	15.21	15.6293
11031255	27.0772	27.4008	27.6846	27.691	26.887	26.0808	29.1038	30.4082
11031258	19.8272	19.1195	17.7581	16.8185	18.442	20.4234	21.2928	22.0481
11181129	9.7412	9.9281	10.3615	11.0224	11.877	12.2764	12.63	12.9406
11181133	24.08	23.7653	27.0422	27.7348	28.0758	28.4956	28.9907	28.9236
11181142	22.3685	21.957	21.2592	20.4752	19.4718	18.5838	19.5002	20.3803
11181143	24.7876	24.5631	24.1389	23.9536	24.0607	24.003	23.6572	23.4352
11181145	13.7032	14.5459	14.9825	15.1745	15.1902	15.2008	15.1427	15.2367
11181146	26.2839	25.9409	24.9846	24.8608	26.221	26.9764	27.6538	28.3716
11181201	17.4122	16.8776	14.581	16.5779	17.7755	19.3444	19.9742	20.3848
11181202	9.4226	9.2893	9.2846	9.3002	9.284	9.286	9.3215	9.3558
11181203	16.2229	16.4387	16.5779	16.5285	16.3146	20.5992	22.0728	23.0648
11181204	23.1985	23.5662	23.86	24.2301	24.1346	22.9359	22.3086	22.2658
11181214	15.5979	15.6677	15.7802	15.9345	16.2352	16.6129	17.0389	17.439
11181218	16.837	17.5107	18.1428	19.3642	20.1395	20.6229	20.7464	20.6875
11181226	18.3189	18.8348	18.9888	19.1951	19.2949	19.3389	18.9815	18.1883
11251046	15.2938	22.0383	22.9287	23.4868	24.0057	23.7436	23.3134	22.8587

Degs/indivs	123	126	129	132	135	138	141	144
9021234	16.6834	15.0585	13.7406	13.5809	20.766	22.0715	23.6178	24.5498
9021236	18.1791	18.3133	21.6583	23.5696	24.8794	26.1043	27.06	27.4021
9031128	14.3903	14.4175	14.5667	14.9205	15.3544	15.7069	15.9367	16.254
9051203	15.5711	16.2601	16.9843	17.7777	18.6173	19.5398	20.7784	21.7616
9090926	24.4565	19.8895	19.9355	20.6741	22.3451	24.5028	25.3666	25.5408
9090927	18.0083	18.541	19.0083	19.5523	20.0397	20.2519	20.5188	21.1813
9090928	21.0916	21.9405	22.6497	23.2306	22.9375	22.5222	27.3702	29.2192
9090930	22.5654	23.3331	25.5108	26.3826	27.2081	27.8835	28.5651	34.4541
9101255	31.2498	31.6024	31.384	30.4926	28.4684	27.3236	26.9406	28.9755
10221221	15.0915	12.2504	12.4654	12.9307	18.4522	16.6692	16.7382	17.3353
10221223	13.6024	13.9033	14.3252	14.7176	15.0123	15.2137	15.2533	14.8824
10221224	6.7246	7.1364	8.1276	13.1573	14.2703	15.5485	16.9381	18.5804
10221225	18.3914	17.9913	17.3864	16.8989	16.4917	16.5462	16.744	18.7058
10221240	9.9476	10.3602	10.8227	11.4915	12.2172	12.9759	13.1882	13.2555
10221246	20.0675	20.2399	21.847	22.925	23.9616	25.1633	26.3733	27.3015
10221248	17.8058	18.4567	19.2267	20.2473	23.2243	24.1909	24.3739	24.8313
10221252a	11.0948	24.4657	25.7454	26.6829	27.7179	28.5829	29.2239	29.5533
10221252b	29.0408	29.8786	30.9819	31.8371	32.1604	32.7767	33.5688	34.0924
10221306	14.3148	14.1405	13.858	13.5985	13.3611	13.0089	12.7419	12.183
10221310	22.7146	22.2457	22.177	25.7247	28.6646	29.4065	29.9859	30.7403
10221311	15.8025	15.6061	15.4585	15.2449	15.0965	15.0963	15.3294	15.7353
10221312	21.2739	21.2189	22.493	24.215	24.7987	25.268	25.7376	25.6206
10221313	22.1555	21.2664	20.7834	22.1122	22.7156	23.1193	23.2529	23.5663
10231228	25.5175	28.2889	29.7354	31.0399	31.5688	32.1432	32.6029	33.0334
11031225	16.8528	17.016	17.2263	17.3332	20.0514	22.1159	23.6022	24.4816
11031227	14.1549	13.3129	12.6562	12.6892	14.1083	15.6529	16.8093	17.9803
11031228	17.3912	17.7899	19.1051	20.0983	20.9337	21.558	21.8568	22.3069
11031231	15.8394	15.7489	15.6399	15.2613	15.1887	18.1462	19.8041	20.9496
11031232	17.3847	18.1442	18.8221	19.0887	23.2053	25.14	26.7345	27.2676
11031243	16.1449	16.6586	17.0086	16.9007	23.5055	24.741	25.4272	29.6441
11031255	31.0425	31.0327	31.6456	32.3827	32.0503	31.023	35.9949	37.3721
11031258	22.7696	23.1848	23.1429	22.8122	22.47	23.2427	27.2614	27.61
11181129	13.3669	13.8535	14.429	14.9173	15.1401	15.0402	14.8884	14.7772
11181133	34.1433	35.7395	35.8158	34.5284	33.1487	36.2457	37.9244	38.764
11181142	20.9003	21.2344	21.1389	21.145	21.2607	21.3377	21.6174	21.9152
11181143	23.0431	22.4057	21.6451	22.6665	25.2756	25.7273	26.1132	26.9494
11181145	15.3301	15.5062	15.9604	16.8753	18.0393	19.2893	20.176	20.9552
11181146	28.7984	29.0513	28.7387	28.154	27.1223	27.3368	32.0308	33.6156
11181201	20.9563	21.3521	21.9598	22.141	22.2736	22.8423	23.5874	23.8639
11181202	9.4258	9.4938	9.5557	9.5594	9.3054	8.9913	8.7724	8.547
11181203	23.9625	24.3008	24.4363	24.5926	25.5896	26.57	26.592	29.2095
11181204	22.3006	21.682	21.1996	23.096	24.2186	25.6071	27.0733	28.4953
11181214	17.998	18.1253	18.2339	18.7386	19.5817	20.3646	20.7417	21.6492
11181218	20.8938	21.1272	21.3613	21.4522	21.5483	21.3249	21.0826	20.899
11181226	17.6641	19.2422	21.4426	22.3083	22.635	22.549	25.8112	29.6674
11251046	22.7585	23.0099	23.819	25.2449	27.0066	28.0112	28.8683	29.0209

Degs/indivs	147	150	153	156	159	162	165	168
9021234	24.8969	26.0727	27.3797	27.8213	28.166	28.7709	28.9914	28.7703
9021236	27.7127	27.8304	27.904	27.8829	27.6938	27.341	26.6505	25.7034
9031128	16.8402	17.2628	17.1541	17.1971	17.0779	17.006	16.7981	16.6521
9051203	22.0714	22.3162	22.3976	22.4395	22.8702	23.8349	24.4935	24.791
9090926	25.4503	25.085	24.7729	25.1044	27.415	27.7142	27.5598	26.6469
9090927	21.9856	23.3266	24.6299	25.05	25.1892	25.7061	26.2778	26.6935
9090928	30.4541	30.7643	30.7339	30.1506	29.3878	29.126	29.3791	29.497
9090930	35.8255	36.0906	36.4551	36.7276	36.6743	36.7224	37.1412	37.7128
9101255	30.3149	30.7351	31.1387	31.7744	32.3766	32.6354	32.5747	32.1082
10221221	18.5605	19.0044	18.9215	18.664	18.2406	17.7789	17.277	16.2572
10221223	14.6603	14.2391	13.9011	13.4599	12.8673	12.0308	10.693	9.6805
10221224	20.2417	22.0221	22.7973	23.4553	23.9018	24.2996	24.5682	24.7635
10221225	23.3938	23.8941	24.4997	24.3829	24.2508	25.4713	31.2029	32.02
10221240	13.3811	13.6052	13.8485	13.9128	13.9808	15.7293	18.5059	20.2951
10221246	27.3999	27.8078	28.0743	28.5239	28.4621	28.3309	27.7542	27.1165
10221248	25.1957	25.5969	26.296	26.8359	27.4806	27.7641	28.1769	28.4696
10221252a	30.2165	30.3726	30.2794	30.291	30.2085	29.837	29.0553	27.5895
10221252b	34.6762	35.1153	35.4928	36.1233	36.5949	36.7788	36.6254	36.168
10221306	11.046	10.3675	10.4235	10.9449	11.5743	12.09	12.2474	12.242
10221310	31.3343	31.2992	30.7472	32.4772	34.9086	36.1683	36.5842	36.2479
10221311	16.215	16.5317	16.8789	17.3526	17.4867	17.5466	17.2744	16.9114
10221312	25.5729	25.4106	25.5031	25.7117	25.6961	25.8836	26.5465	27.3072
10221313	23.8707	23.3627	22.7564	26.4067	28.4912	29.3456	29.8808	29.7689
10231228	32.9448	33.2361	33.7196	33.7796	33.5452	33.3682	33.2086	29.4342
11031225	24.51	24.5124	24.1517	23.8212	23.5747	23.3158	23.2251	22.5082
11031227	19.314	20.5494	21.4208	21.7722	22.295	22.526	23.2668	23.6661
11031228	23.0713	24.1343	24.7685	25.3196	25.7173	25.6395	25.3383	24.6273
11031231	21.7982	25.219	26.2687	27.3224	28.323	28.5063	28.5128	28.2407
11031232	27.3373	27.4068	27.5984	28.324	31.3515	33.429	34.5277	34.6493
11031243	30.8078	32.4381	33.4834	34.3501	34.847	35.1247	34.9791	34.0926
11031255	37.7004	38.003	38.1188	38.1837	38.1931	38.3402	37.9861	36.8044
11031258	28.3551	29.1168	30.0271	30.2541	30.3169	30.043	29.3469	28.0243
11181129	14.3978	14.2005	19.4011	20.1329	20.4961	20.7479	20.5667	19.9942
11181133	38.7604	38.5886	39.3232	40.8074	41.1652	41.4396	41.3722	42.593
11181142	22.0309	24.2266	25.4178	26.1971	26.1437	25.7995	25.187	24.4003
11181143	27.8735	28.3316	28.6343	28.1642	27.271	27.1212	27.7107	27.5673
11181145	21.4065	21.6418	21.9794	22.2896	22.6621	22.8753	22.2606	20.7745
11181146	35.6775	40.6653	41.628	41.8914	42.0497	42.2452	41.7476	38.7814
11181201	24.5862	25.5659	26.1333	26.2972	26.2263	25.7459	25.1183	24.4131
11181202	8.224	7.8006	7.4285	7.0047	6.4006	5.9062	5.5229	5.4531
11181203	31.2074	31.5568	31.9625	31.6964	31.4075	31.6664	33.3181	35.4411
11181204	28.9399	29.1416	29.4875	29.8295	29.984	29.7341	29.078	27.8127
11181214	23.4524	24.0035	24.1836	24.2828	24.2999	24.1219	23.7495	23.1871
11181218	20.9237	20.9752	21.1453	21.0867	21.0208	20.8989	20.6092	20.1699
11181226	31.2337	31.8837	32.0559	32.0877	32.6616	33.7477	35.0376	35.6483
11251046	30.7151	31.9173	32.9094	33.6715	34.1466	34.7514	35.4941	36.2403

Degs/indivs	171	174	177
9021234	27.7589	23.7949	22.0359
9021236	24.191	22.3938	20.2907
9031128	16.1967	15.4988	14.8551
9051203	25.4215	25.3348	25.1877
9090926	23.3065	20.7279	19.4403
9090927	26.9583	26.5126	25.2622
9090928	27.9378	25.5182	22.463
9090930	37.2935	30.9623	28.8172
9101255	30.9806	28.0615	26.0572
10221221	14.9639	13.7332	12.7482
10221223	8.8464	8.0833	7.6373
10221224	24.3826	23.4172	21.9854
10221225	32.124	29.1305	24.3049
10221240	20.56	20.5673	19.9212
10221246	25.8982	23.7323	21.0863
10221248	28.4242	27.8819	27.0798
10221252a	25.3084	20.6072	21.3045
10221252b	34.7681	29.2502	24.0412
10221306	12.3165	12.23	12.2281
10221310	34.4179	30.189	25.7363
10221311	16.1052	15.2431	15.5114
10221312	26.2218	25.3174	24.3934
10221313	29.0069	27.8553	26.6347
10231228	26.5257	22.0542	20.7488
11031225	21.3218	20.0005	18.9151
11031227	24.6753	24.3255	24.3486
11031228	23.4163	22.24	20.0003
11031231	27.363	25.243	22.3965
11031232	34.1482	32.7776	22.8495
11031243	32.0428	30.0067	27.0283
11031255	34.6825	32.3363	20.9415
11031258	19.2651	17.1933	15.9654
11181129	18.8472	17.2964	15.8916
11181133	43.2785	44.424	43.9758
11181142	25.3197	27.7272	29.9053
11181143	26.5744	25.0082	23.8625
11181145	18.4742	16.6121	15.2582
11181146	35.9878	34.4076	22.2671
11181201	23.4919	22.107	20.0351
11181202	5.5013	5.7268	6.0658
11181203	37.5536	38.153	35.3261
11181204	20.9279	17.9225	16.5398
11181214	22.4684	21.6612	17.5564
11181218	19.436	18.6198	18.0085
11181226	36.2376	36.6655	36.4325
11251046	35.8333	27.5974	23.6385

Degs/indivs	3	6	9	12	15	18	21	24
11251047	31.6403	39.798	42.1496	43.0999	42.854	42.5584	42.7896	43.3784
12789120	20.7916	27.7186	31.4046	31.8869	32.106	32.4836	32.3477	31.6044
12798106	16.3809	18.4497	30.7342	30.9568	29.9723	27.7962	27.8843	28.0739
12798107	23.112	30.3732	31.4126	30.8739	28.5539	24.6883	20.1477	20.9883
12798118	29.507	33.1214	33.5152	33.169	32.6365	31.9936	30.9745	29.8124
12879103	15.6114	15.356	14.9465	14.4734	14.0339	13.5466	13.1568	12.7805
12879113	21.0974	28.6766	31.7335	31.8292	31.375	30.2929	30.0921	29.5642
12879119	19.7229	20.1667	20.2624	19.9455	17.9502	16.9019	17.4183	17.8396
12897101	20.2286	20.8739	21.2569	21.6986	22.0148	22.1653	21.9346	18.4233
12897105	25.7077	31.0002	33.7428	33.614	31.825	28.5272	27.2468	26.1535
12897109	15.7164	16.6395	25.5082	24.5605	24.0227	23.5073	23.0726	21.1106
12897111	20.7351	26.5346	34.2195	35.0113	34.8165	33.7131	27.0557	25.4545
12897114	13.6413	13.5484	13.493	15.623	16.3125	16.2943	15.6085	15.268
12987108	7.7988	7.8118	7.8666	7.9615	8.082	8.1664	8.3019	8.4602
12987117	20.715	21.4883	21.7657	21.5803	20.4357	20.5338	21.421	22.6834

Degs/indivs	27	30	33	36	39	42	45	48
11251047	43.4682	41.9073	40.8295	38.1985	37.0166	29.9155	26.7006	25.2829
12789120	30.2812	30.0738	29.4829	27.4219	23.1307	20.95	20.6355	20.4999
12798106	28.1056	28.5993	28.8163	28.2471	25.8843	22.4385	24.2367	26.0073
12798107	21.6319	21.714	21.8107	21.5974	21.0442	17.942	17.9898	18.3042
12798118	27.256	25.2821	19.8955	20.2414	20.2961	20.0581	19.6078	18.865
12879103	12.4259	12.0207	11.3445	10.7789	10.2507	9.6912	9.1161	7.9588
12879113	28.5213	28.1545	27.9099	27.4867	26.2364	25.3632	23.9467	24.0148
12879119	18.043	17.7303	16.1406	14.6848	14.5844	14.5876	14.5674	14.4264
12897101	17.7358	17.5987	17.5105	17.2761	17.1545	17.117	17.3901	17.9416
12897105	25.7309	25.3794	25.3275	24.9769	24.9606	24.597	23.7798	22.612
12897109	19.9201	19.3088	18.9694	18.3325	12.8894	12.5803	12.1812	11.6882
12897111	31.7345	32.7616	32.9093	31.509	30.6998	29.8603	28.241	26.9373
12897114	15.1204	15.0798	15.1814	15.3249	15.6131	15.7825	15.864	15.7016
12987108	8.5745	8.7125	8.8675	9.0316	9.1649	9.2829	9.3992	9.4636
12987117	23.6372	24.7139	25.3049	25.4879	25.004	24.052	22.4419	21.5624

Degs/indivs	51	54	57	60	63	66	69	72
11251047	26.5229	27.7396	28.7729	29.6962	30.1528	30.0463	29.6466	29.2815
12789120	20.4197	20.3152	20.2202	19.8442	19.2935	18.5633	18.0371	16.3782
12798106	26.6776	26.4345	27.4072	27.6652	28.1502	27.1071	25.3876	26.2429
12798107	18.3048	18.0261	17.6133	17.3052	17.0442	16.7855	16.6418	16.4967
12798118	16.9327	17.1284	18.2752	18.7032	18.839	18.9778	18.9045	18.5087
12879103	6.9529	6.2054	5.1877	4.3246	3.2095	1.4219	1.5275	1.7276
12879113	23.6364	23.0662	18.9433	19.8237	20.4319	20.9809	22.0746	23.6779
12879119	14.0693	13.6185	13.095	12.1041	6.9506	9.9909	15.1024	16.3444
12897101	18.5151	19.2422	20.0043	20.771	21.4024	21.8405	22.0687	21.6183
12897105	21.5033	17.1152	17.0214	16.4202	15.2047	17.66	18.4563	19.0453
12897109	11.4792	11.3641	11.2179	11.0663	10.9067	10.6959	10.3294	9.8487
12897111	26.9264	24.8023	22.0162	19.6427	20.9528	21.671	23.3537	24.6699
12897114	15.478	15.0552	14.5623	13.9664	13.6116	13.6901	13.9752	14.5801
12987108	9.5017	9.4369	9.3686	8.8412	7.7664	6.1232	6.3274	6.6578
12987117	20.5225	20.1409	15.6932	14.5829	14.2704	13.6901	11.796	12.0276

Degs/indivs	75	78	81	84	87	90	93	96
11251047	28.1056	26.126	24.7133	23.5544	22.5425	21.523	21.935	23.2518
12789120	14.8716	14.4449	13.6064	11.8277	14.6108	15.8027	16.7478	17.1075
12798106	27.213	28.1594	27.2152	34.0302	36.7502	36.499	36.6805	35.298
12798107	16.1999	16.1463	15.1116	13.9234	13.148	12.3616	8.0122	7.0691
12798118	18.0441	17.2749	15.8914	14.6394	13.4881	12.113	8.2693	13.2719
12879103	4.1606	5.356	5.6227	5.7475	6.4856	7.7797	8.49	8.4932
12879113	24.3208	24.2703	24.1461	23.2511	22.2318	21.5836	21.2027	21.032
12879119	17.4031	18.1562	18.8438	19.5778	19.9959	20.0593	20.0411	20.0768
12897101	21.1828	20.8193	20.4313	19.7749	18.3357	12.3784	11.3658	10.8972
12897105	19.4514	19.8736	20.2809	20.6681	21.2434	22.4689	23.0167	22.8158
12897109	9.1385	15.8425	17.7816	18.6585	19.3926	19.8615	20.7016	21.2846
12897111	25.1021	25.4127	26.1315	26.4543	26.3454	26.2543	23.6677	23.1486
12897114	17.1046	22.5796	23.97	24.5051	24.9581	25.2556	24.8089	23.9473
12987108	6.9894	7.2778	7.4851	7.6375	7.7352	7.8342	7.9184	8.0428
12987117	13.7038	14.8016	15.5689	16.1953	16.4693	16.4899	16.4265	16.4508

Degs/indivs	99	102	105	108	111	114	117	120
11251047	23.4876	23.247	23.4761	24.7121	25.5787	26.471	27.3296	28.3001
12789120	17.3993	17.8044	18.2709	19.0412	20.7576	21.2745	20.5831	20.0518
12798106	31.7761	29.0446	27.6148	25.6764	29.2945	31.5946	32.8394	32.6285
12798107	11.9997	14.2152	14.7065	14.8906	15.0509	15.3845	15.6679	15.581
12798118	15.0696	15.9964	16.7005	17.2546	17.8047	18.2002	18.4746	18.629
12879103	8.3944	8.5385	8.7812	8.8869	8.987	9.0115	8.8758	9.0629
12879113	17.8437	18.0717	19.7956	20.704	20.8054	20.5895	19.8341	19.4094
12879119	19.943	19.7245	19.4082	18.816	18.3492	17.9589	17.5379	16.6376
12897101	11.6842	12.3271	12.9685	13.6564	14.0099	14.3754	14.9888	15.4753
12897105	22.4486	21.6949	21.0602	20.443	19.9742	19.5076	19.2571	18.9972
12897109	21.9352	22.379	22.5214	22.0259	21.3783	20.8979	20.2729	19.9652
12897111	24.4363	24.8442	25.0483	25.0926	25.1346	23.7934	22.5985	21.6891
12897114	22.3944	21.2199	20.762	20.2701	19.1106	18.362	17.2557	16.1798
12987108	8.1366	8.1774	8.2445	8.3752	8.5693	8.776	9.1202	9.5557
12987117	16.2591	15.8516	15.4282	15.3596	15.32	15.2426	14.9984	15.1779

Degs/indivs	123	126	129	132	135	138	141	144
11251047	29.2798	30.1886	30.2526	29.6979	28.6366	27.0608	29.4982	30.4095
12789120	19.3885	17.6735	17.2221	20.95	22.5115	24.2166	25.0582	24.3647
12798106	31.7332	31.0013	27.0092	27.2306	27.803	29.2505	30.8801	31.1403
12798107	15.65	15.7898	15.3166	14.5641	13.855	13.1115	12.4006	12.1582
12798118	18.8628	18.9974	18.8667	18.4411	17.9946	22.097	23.155	24.1312
12879103	9.3623	9.7049	10.0474	10.5669	10.7777	11.4001	11.4013	11.617
12879113	18.8722	17.9882	16.5894	19.0301	20.1312	21.2149	21.4129	21.2677
12879119	15.3507	13.4558	10.5345	16.186	17.6342	18.4897	19.1142	19.7635
12897101	16.3248	17.1026	17.917	18.3721	18.9756	19.4988	20.0434	20.6863
12897105	19.1462	19.8558	21.078	21.2048	20.8626	22.2479	24.2244	24.9769
12897109	19.7746	19.5891	19.772	19.5651	19.2511	18.5758	16.4766	16.6206
12897111	20.1304	22.0483	22.9653	23.6227	23.8265	24.1758	24.789	25.8002
12897114	15.1249	14.7679	15.0863	16.0168	17.0111	17.2952	16.949	18.304
12987108	10.0455	10.6847	11.0031	11.1533	11.0987	11.0489	10.9386	10.738
12987117	15.4203	15.6693	15.6527	15.3449	14.9613	14.5267	21.0441	24.1936

Degs/indivs	147	150	153	156	159	162	165	168
11251047	30.5982	30.493	30.2372	29.9961	29.4283	31.5427	31.1405	31.1377
12789120	33.6899	34.3662	34.8724	35.1648	34.8321	34.6172	35.3381	35.9028
12798106	31.9266	31.4557	26.7701	32.1437	33.1585	34.5745	37.4104	39.0399
12798107	12.3493	12.6607	13.3508	13.7544	22.0332	23.0822	23.2046	22.8061
12798118	24.5203	24.7229	24.657	24.391	24.8011	26.8057	28.3153	30.6765
12879103	11.7758	12.2058	13.1503	13.5188	13.5694	13.5164	13.2484	12.7857
12879113	20.9534	21.296	23.0057	23.5115	24.8234	28.1962	28.783	28.7352
12879119	20.188	20.7059	21.0941	21.5598	21.4372	21.0449	27.353	28.1684
12897101	21.0216	20.8838	20.8904	21.288	21.7267	22.3718	22.9897	23.1829
12897105	24.96	24.621	23.7542	23.4832	23.5391	28.4571	30.074	30.3055
12897109	16.5583	16.3035	15.7912	18.7098	20.4793	22.368	23.4221	23.8716
12897111	27.343	28.3437	29.2418	30.4181	31.3098	31.9676	32.3426	32.3328
12897114	19.6297	20.0692	20.3308	20.4003	20.3944	19.7104	18.3787	17.7706
12987108	10.4043	10.1098	9.912	9.848	9.8352	9.7098	9.4837	9.2352
12987117	25.2689	25.6172	26.5873	28.4934	29.2716	29.487	29.5266	28.8554

Degs/indivs	171	174	177
11251047	30.3712	29.2489	29.5857
12789120	35.4433	28.4129	21.0219
12798106	38.3276	36.1994	17.0436
12798107	20.9808	22.4316	22.1361
12798118	31.2646	30.554	27.7655
12879103	12.2474	13.5676	15.1992
12879113	26.9513	24.4374	21.3027
12879119	28.3585	27.8899	26.6898
12897101	22.2938	20.5952	19.1999
12897105	29.7942	27.2175	22.5366
12897109	23.5016	21.7125	15.8964
12897111	32.1938	31.3545	25.5925
12897114	16.9661	15.7349	15.1547
12987108	8.9435	8.679	8.2212
12987117	27.9269	27.6893	23.1169