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Visual and Geometric Analysis of Maxillary Sinus Region Variability for Identification of Unknown Decedents

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VISUAL AND GEOMETRIC ANALYSIS OF MAXILLARY SINUS REGION VARIABILITY

FOR IDENTIFICATION OF UNKNOWN DECEDENTS

By

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Abstract

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Positive identification of unknown individuals is highly important in the medicolegal field. Comparison of antemortem and postmortem radiographs is a popular and successful method of making a positive identification, but these methods are often extremely limited due to a lack of antemortem records. A positive identification method utilizing a type of radiograph that is more common in the antemortem record would be very useful for forensic anthropologists and other medicolegal professionals and could increase the likelihood of the individual in question being identified. Panoramic dental radiographs are commonly included in the standard dental exam and provide a clear view of the maxillary sinus region. Visual analysis of the maxillary sinus region of panoramic radiographs was performed by creating an online radiographic matching survey using sets of two radiographs from seven individuals and individual radiographs from seven other individuals. A total of 47 undergraduate and graduate students participated in the online survey. The results from this survey were used to calculate percentages correct for different variables and perform one-way ANOVA and chi-square analyses on the data using Statistical Package for the Social Sciences (SPSS). A preliminary geometric morphometrics analysis was also performed on the maxillary sinus outline shape using Shape 1.3. Results from both the visual and geometric analysis of maxillary sinus shape indicate that elements of the maxillary sinus area could be used as a relatively accurate method for positively identifying unknown individuals.

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INTRODUCTION

The ability to make a positive identification of unknown human remains is one of the most important parts of a medicolegal investigation for both judicial and ethical reasons. Identification of an unknown individual is important both for criminal and insurance purposes, as well as for family reconciliation and return of the remains to loved ones for burial (Ciaffi et al. 2011). In many cases, the identity of the deceased is known or at least suspected due to having identification cards or personal effects associated with their remains (Holobinko 2012). In these instances, a positive identification from a body could come from relatives or friends of the deceased individual who make an identification based on viewing the body or personal effects. However, identification using these methods is not always accurate and can lead to misidentification in some cases. In addition, remains involved in a mass disaster event such as an explosion or plane crash may be commingled in such a way that prevents identification by relatives or personal effects (Blau and Briggs 2011). When the remains of the individual in question have been damaged or already undergone significant decomposition, other methods need to be used to make a positive identification (Silva 2011).

In the last century, researchers have made great strides in developing methods to make positive identifications of human remains, including fingerprinting, dental analysis, genetic testing, and radiograph comparison (Kahana and Hiss 1997). These methods rely on the observation that humans have unique observable features that remain relatively unchanged over time and can be used to identify the individual after death. Some positive identification methods, like genetic testing and fingerprint analysis, rely on data sources that are known to change very little over time. These methods can be used to make a positive identification with nearly 100%

accuracy, making them very useful in a forensic setting (Leo et al. 2013). Others, like dental analysis and radiograph comparison, deal with data sources that can be both changeable and unpredictable (Sweet 2010). These methods are affected by growth and development in childhood, as well as injuries, infections, and trauma sustained to the individual. However, these life events can also be considered identifiers that are unique to the individual, and a positive identification can still be made with high accuracy using these methods. These methods are generally favored when possible because of the prohibitive time and expense needed to obtain results from DNA testing (Leo et al. 2013). The use of these methods in a forensic setting has led to the identification and return of hundreds of remains that would otherwise go unidentified and provided closure for countless family members of these victims.

Positive Identification Using Radiographs

Comparing antemortem and postmortem radiographs is one of the main techniques used to make a positive identification in a death investigation (Kahana and Hiss 1997). Radiographs are a common source of both antemortem and postmortem information due to their relatively low cost and widespread use in diagnosis of skeletal and dental issues. Since skeletal structures are nearly always visible in radiographs, any available antemortem radiographs can potentially be used to make a positive identification (Jablonski and Shum 1989). The shape and contour of the skeletal structures visible in an antemortem radiograph, as well as any evidence of healed or healing trauma, skeletal deformities, and pathological conditions can be compared to those on a postmortem radiograph of an unknown individual to make a presumptive identification. Comparison of antemortem and postmortem radiographs is considered to be a valid and reliable identification method in forensic anthropology; however, reliable identification methods are not yet available for many radiograph types (Jablonski and Shum 1989; Ruder et al. 2012).

Radiographs in general are used in a variety of medical, dental, and security settings to provide information about regions of the body that cannot be readily seen. This can include skin, muscle tissue, and fat in the case of medical and dental radiographs, or clothing and metal (e.g., trailers and railway cars) in the case of security images (Vogel 2007). The first recorded use of radiographs in a legal case was in 1896 in Montreal, Canada, less than one year after their discovery, when radiographs were used to determine that a bullet was still present in the victim's leg in an attempted murder case, leading to the conviction of the perpetrator (Brogden 1995). Gradually, radiographs in general and, more recently, comparison of antemortem and postmortem radiographs, have become commonly used in various death investigation fields.

Recently, there has been a move toward a more "digital forensics," with radiographic examinations of remains by radiologists and forensic pathologists via CT scan or MRI after death (i.e., virtual autopsy) instead of doing a traditional autopsy on fully fleshed remains (Thali et al. 2007; Verhoff et al. 2007; Verhoff et al. 2008; Filograna et al. 2010). In the case of medical or dental records, any one individual may have had several radiographs taken for a variety of diagnostic purposes, and it is estimated that seven out of every 10 people in the United States have had either a medical or a dental radiograph taken in a given year (US EPA 2006). This means that many people in the United States have a wealth of radiographic information that could potentially be used to identify them after death, if needed. However, the likelihood that all of the individuals in a given population will all have one of the same radiograph is very low, which has necessitated the development of a variety of different identification methods using different types of radiographs.

Comparative radiography has been used in forensic death investigations for many years, both for sex and ancestry assessment and positive identification (Leo et al. 2013). These methods have an advantage over other methods of positive identification because they are cheaper than DNA tests, and they can be done on remains that have long since decomposed or have been exposed to violent events such as a plane crash (Riebeiro 2000).

History of Forensic Application of Radiograph Comparison

The first recorded use of radiographs in forensic investigations was in 1921, when Schuller (1921) published an article on the use of chest radiographs in positive identification. Just six years later in 1927, a man who had been previously treated for sinus ailments was murdered and his identity confirmed by a comparison of the antemortem and postmortem radiographs of his nasal accessory and mastoid sinuses (Elliot 1953:682). Radiographs taken of soldiers prior to deployment have been used to identify the remains of soldiers who were previously listed as “missing.” Chest radiographs and, in recent years, dental radiographs, have been used by forensic anthropologists to compare against postmortem radiographs taken from remains whose identity is suspected (Bunch and Fielding 2005; Bruce-Chwatt 2010). Bitewing dental radiographs, commonly used for caries detection by dental professionals, are often used along with dental charts to make identifications based on the dentition of the individual (Andersen and Wenzel 1995; Sakoda et al. 2000; Cattaneo et al. 2006).

A morphological approach to radiograph comparison has historically been deemed the best way to determine whether the radiographs in question belong to the same individual (Kuehn et al. 2002). The shape and trabecular bone pattern of a single clavicle as seen on antemortem and postmortem radiographs was used to make a positive identification of an unknown individual (Sanders et al. 1972). Comparison of antemortem and postmortem radiographs was used to establish the identity of 30 out of the 50 cases that required a positive identification from the St. Louis Office of the Medical Examiner from April 1978 to July 1979 (Murphy et al. 1980).

Radiographs of the chest and spine have been previously used to identify the remains of a man that was found in the East River in Manhattan, New York, after other methods were unsuccessful (Mundorff et al. 2006). In this case, the individual in question displayed a distinctive morphology of the spinous processes that could be seen on both the antemortem and postmortem radiographs.

Identification by radiograph and CT comparison has also been used in several modern mass disaster events, including the Mt. Erebus aircraft crash in 1979, the 2004 Boxing Day tsunami, and the Australian bushfires in 2009, among others (Alexander and Foote 1998; Beck 2011; Cordner et al. 2011). In the case of the Mt. Erebus aircraft disaster, the remains of 11 people that were not able to be identified through other means were identified through antemortem-postmortem radiograph comparison (Alexander and Foote 1998). In the Boxing Day tsunami, dental radiographs were taken of the deceased and compared with dental records from the missing individuals to make identifications (Beck 2011). In the Australian bushfire disaster, radiograph and CT comparison was used alongside other identification techniques to aid in the identification of those whose remains were badly burned in the blaze (Cordner et al. 2011). In each of these disasters, radiograph comparison methods contributed greatly to the identification and subsequent return of the deceased individuals to their families.

The Frontal Sinus

In recent years, positive identification from radiograph comparison of the frontal sinus shape has become extremely common. Over 100 years ago, Turner (1901) studied the frontal sinuses of 578 crania and observed that no two individuals in his study had the same frontal sinus shape, even in the case of identical twins. Despite this knowledge, it was not until the mid-1980s that researchers began to intensively study how comparison of the frontal sinuses could be used in forensic death investigations. Yoshino et al. (1987) concluded from a small study that frontal sinus area is highly variable from person to person and could potentially be unique to an individual as suggested by case studies in the forensic sciences. Since then, there has been an intense focus on the use of radiograph comparison of the frontal sinuses as a positive identification method. All of these studies have come to the same conclusion: the shape of the frontal sinuses as seen on a radiograph can be considered unique to an individual and can be used to make a positive identification, with success rates ranging from 95-100% in a controlled environment (Kullman et al. 1990; Quatrehomme et al. 1996; Kirk et al. 2002; Christensen 2003; Christensen 2005).

Other studies have examined the utility of positive identification from the frontal sinuses when the sinuses do not follow a normal presentation in an individual, such as being smaller than expected or only having one lobe (Smith et al. 2010). Additionally, some studies that focus on visual matching of the frontal sinus as a means of identification have concluded that the shape of the frontal sinuses is different enough from individual to individual that even people with no experience in either anthropology or radiology can usually make a correct association between antemortem and postmortem radiographs, which further increases the validity of the method.

However, in order to successfully use the frontal sinuses to make a positive identification, the unidentified individual needs to have had a full or partial craniofacial radiograph before death, something that is not common in the antemortem records of most individuals (Pfaeffli et al. 2007). It is estimated that radiographs of the head and neck region only account for about 5% of all radiographs taken, which limits the use of identification methods that incorporate these types of radiographs (Brogdon 1998). In addition, congenital absence of the frontal sinus is relatively common, with an incidence as high as 14-16% in some populations (Tang et al. 2009;

Leo et al. 2013). Finally, the frontal sinuses are often involved in the standard calvarium autopsy cut, which can reduce the ability to use frontal sinus comparison methods even when antemortem records are available. Although this method is extremely successful when the right conditions are met, there is a need for a method of positive identification from radiographs that is more broadly applicable to the general population.

Issues with Radiograph Comparison Methods

In general, positive identification methods using antemortem and postmortem radiograph comparison suffer from two problems. As previously described, the first is a lack of antemortem data for comparison with postmortem data from unknown individuals. Not every individual will have the necessary antemortem records needed to make a positive identification, and many of the current methods (i.e. frontal sinus and chest radiographs) rely on antemortem data that only a few people in a given population will have.

To combat this issue, studies in recent years have focused on creating identification methods from as many different types of antemortem medical records as possible, including radiographs, CT images, and MRI scans. Reichs (1993) used CT images of the cranium to quantify the frontal sinus patterns as seen on a horizontal plane for use in positive identification and concluded that a positive identification can be made from this view when using a standardized scoring system. Several other studies have attempted to use measurements and structural observations from CT images of the frontal sinus to create coded formulas that assess similarity (Riepert et al. 2001; Tatlisumak et al. 2007; Uthman et al. 2010). Other studies by Teke et al. (2007) and Uthman et al. (2011) have used CT imaging of the maxillary sinuses to assess the sex of an individual, with overall percentages of 69.3% and 73.9% respectively. Another study used CT images of the maxillary sinuses to assess both the ancestry and sex of an individual and found a 90% correct ancestry prediction and a 79% sex prediction (Fernandes 2004). Other studies have looked at the potential for determining the sex of an individual from the size and shape of the frontal sinuses on radiographs, but concluded that it provided a percentage correct that was only slightly higher than what would be expected by chance (Goyal et al. 2013). Another study has used visual comparison of both the frontal and maxillary sinuses from CT scans to make preliminary positive identifications (Ruder et al. 2012).

After death, the maxilla often remains intact even in cases of extreme taphonomic changes to the skeleton (Lerno 1983). This indicates that methods of positive identification using structures of the maxilla could be widely applicable in a forensic setting. Dental identification from antemortem records is the most obvious identification method from the maxilla and maxillary dentition due to its high success rate, but dental identification from skeletonized remains is sometimes not possible. This can be due to a lack of antemortem dental records, since some individuals do not have access to adequate dental care for financial or geographic reasons, although this number is decreasing over time.

Although these methods are considered successful at positively identifying individuals, all of these methods suffer from a lack of consistently available antemortem records for postmortem comparison. Despite the immense success of frontal sinus identification methods, few people in a given population will have the antemortem frontal face radiograph needed to do a postmortem comparison of the frontal sinuses. Similarly, chest radiograph identification and many of the CT identification methods have the same problem of a lack of antemortem data for comparison, although this is changing with the increased use of CT scans after head injuries (Ruder et al. 2012). If a method of identification from radiograph comparison could be reliably done using a more common radiograph, it could greatly influence the number of unknown human remains that could be positively identified.

The second issue is that visual methods of radiograph comparison generally lack the scientific rigor needed in order to be used as evidence in court (Cattaneo 2007). Evidence from criminal cases that is submitted in court in most states must adhere to the Daubert standards of evidence admission, which stress the need for testable, reliable, and replicable methods to be used for justifying conclusions from the evidence at hand (*Daubert v. Merrell Dow Pharmaceuticals* 2003; Ousley et al. 2005). These standards are a modification of Rule 702 of the Federal Rules of Evidence on evidence admissibility in court, which was developed as a movement away from expert opinions on evidence to a more scientific way of evaluating evidence using the scientific method. Both the Daubert decision and Rule 702 provide guidelines for anthropologists on how to weigh evidence that may be largely anthropological and of a diverse nature, since most research studies in anthropology do not hold to the standards of Daubert or the Federal Rules of Evidence. Research in forensic anthropology attempts to either test existing methods in order to be in compliance with Daubert standards or publish a new method for further testing and analysis in order to comply with Daubert in the future. Because most methods of visually comparing antemortem and postmortem radiographs are based more on expert opinion than on scientifically gathered data, their use in a criminal case may be called into question.

The Maxillary Sinuses

The maxillary sinuses are bilateral air spaces located in the maxilla that can be of various shapes and sizes (Teke et al. 2007; Mihailovic et al. 2009). They have thin walls, and can sometimes extend into the zygomatic processes and zygomatic bone (Teke et al. 2007).

Volumetric analysis of the maxillary sinuses indicates that their size is not dependent on age (after 20 years old), sex, or bilateral comparison (Emirzeoglu et al. 2007; Kirmeier et al. 2011). The sinus anatomy of at least some individuals as seen on radiographs or CT scans appears to be extremely varied, although the extent of this variability among individuals is not known (Basak et al. 2000; Kantarci et al. 2004). Areas of particular interest in the sinus include the sinus floor, medial border, and lateral border, with the sinus floor appearing to show the most variability between individuals (Sharan and Madjar 2006). Because of their proximity to the dentition, the floor of the maxillary sinus can sometimes involve the root apex of one or more teeth, particularly the second or third molars, which can have a significant impact on the overall sinus shape. This usually presents itself as recesses or hillocks in the sinus that can be observed using panoramic radiography or CT scans. Involvement of the root apex is thought to occur in at least 50% of adult cases and varies depending on the root shape and sinus floor extension.

It is unclear whether the maxillary sinuses serve a functional purpose or are merely a byproduct of the shape of the nasomaxillary complex (Enlow 1990). If the latter is correct, then the sinus shape itself could be governed by factors other than function (Butaric et al. 2010). However, other studies have suggested that maxillary sinus size is larger in individuals in cold-adapted climates, leading to the belief that the maxillary sinuses serve some purpose in facilitating thermogenesis (Churchill et al. 2004). Whatever their purpose, the maxillary sinuses are present on nearly every individual, with no published reports of congenital absence of the sinuses. This differs greatly from the frontal sinuses, which has a reported congenital absence incidence of 10-16% in the general population (Christiansen 2003; Tang et al. 2009; Leo et al. 2013).

The maxillary sinuses are not present in most individuals until around the age of five, and the sinus area undergoes changes in shape and volume until the ages of 18-20 due to the development of the permanent dentition (Melson 1967; Teke et al. 2007; Park et al. 2010). This is similar to the development pattern seen from the frontal sinuses (Spaeth et al. 1997; Fatu et al. 2006). Other incidents, such as maxillary sinus surgery, tooth extraction or antemortem tooth loss (in the case of root apex involvement), and dental implants where a maxillary bone graft is necessary can impact the shape of the maxillary sinus in adulthood (Teke et al. 2007; Mihailovic et al. 2009). Panoramic radiographs and, rarely, CT imaging are often used to examine how tooth extraction or implants will affect the maxillary sinus, since exposure of the sinus to infection or trauma can cause serious complications (Sharan and Madjar 2006).

Postmortem tooth loss is an especially common hindrance to dental identification, since the ligaments that hold the tooth root into the alveolar process decay after death, causing the teeth to potentially become loose and fall out (McKeown and Bennett 1995; Oliveira et al. 2000; Duric et al. 2004). In some cases, up to 57% of individuals have been reported as having some degree of postmortem tooth loss, either from the decomposition process or poor recovery of the remains (Oliveira et al. 2000).

In addition, methods of identification from antemortem records rely on having a presumptive identification of the individual in question, since it is impractical to compare postmortem records against medical or dental records from hundreds of potential individuals. In cases where the identity of the individual in question is presumed and dental identification either cannot be done or yields inconclusive results, another method of positive identification using dental radiographs would be extremely useful.

Panoramic Radiography

Panoramic dental radiographs are two-dimensional images that provide a global view of the dentition, the entire mandible, and most of the maxilla (Mihailovic et al. 2009). They are one of the most commonly used radiographs for oral surgery and dental implants, and are gradually becoming standard in dental practices for general imaging purposes across the United States, since the bitewing radiographs traditionally used for dental diagnostic purposes only show a few teeth and the surrounding tooth root area (Pasler 1993; Mihailovic et al. 2009). Panoramic radiographs provide dental practitioners with a better overall view of the dentition and surrounding areas, allowing them to make a more unified and detailed diagnosis and provide a better standard of care to the patient.

The basic equipment needed to take a panoramic radiograph consists of a horizontal rotating arm that holds a source of x-rays and a moving film mechanism that is arranged on the side opposing the x-ray source arm (Rai and Kaur 2013). The subject's head is positioned between the x-ray source and the film, and the arms of the machine rotate around the head of the subject. The subject's head is stabilized to prevent movement, usually by having the subject bite down on a small piece of plastic that attaches to the front of the machine. If this method is used for stabilization, it also provides standardization for distance and positioning of panoramic radiographs. However, the equipment used to take panoramic radiographs can also be used to take radiographs of other views of the dentition and surrounding structures. This is usually done to examine the cephalometric view for assessing the side profile of a patient or to make a diagnosis of temporomandibular joint issues, although these uses are not as common (Rai and Kaur 2013).

While it may be possible to observe identifying features in these radiographs as well, it is important to keep in mind that head positioning may not be standardized in these cases. The midline of panoramic radiographs is almost always blurred due to the additive principles of this form of radiography (Pasler 1993). This means that in the maxillary region, the nasal cavity and central incisors are often too distorted to consistently observe in a panoramic radiograph. However, the maxillary sinus region and most of the dentition can still be readily seen.

The United States Army was the first to implement panoramic radiographs into dental exams after they were found to show overall dental health before active-duty deployment more clearly than the previous bitewing radiographs (Chaffin et al. 2004). Soon after, dental practices across the United States also began to adopt panoramic radiographs into the standard dental exam because of the increased diagnostic ability they provide. Not only are panoramic radiographs relatively common within the antemortem record, with approximately 80% of college-aged individuals having had at least one taken (Collins 2013), but they also usually provide a clear view of the maxillary sinus cavities and surrounding regions. Thus, a method of positive identification that utilizes panoramic radiographs to compare the maxillary sinuses would be very useful in a forensic setting.

There is some previous research on radiographic or CT examination of the maxillary sinuses, but these studies generally either focus on sex identification from sinus volume (Teke et al. 2007; Amin and Hassan 2012) or ancestry classification from sinus shape and volume (Fernandes 2004). Currently, only two previous studies have examined the possibility of a positive identification method from the maxillary sinuses using panoramic radiographs. Soler (2011) performed a validity study using two panoramic radiographs each from ten skulls, for a total of 20 radiographs, and used these radiographs to create an online radiograph matching survey in which participants were shown two radiographs and asked to record whether or not they matched. The results from this survey indicated that radiographs could be successfully matched 84% of the time. Collins (2013) further tested this study by replicating Soler's methods, but using 15 skulls for a total of 30 radiographs. The radiographs were put into a PowerPoint slideshow after collection and a class of 29 undergraduate and graduate students was asked to record whether the radiographs were a match to one another. This obtained a correct matching rate of 82.4%, similar to the results from Soler (2011). Both of these pilot studies obtained a much higher correct matching rate than the rate of 50% that would have been expected had the radiographs shown no visual similarities to one another and been selected by the participants at random. These preliminary studies indicate that the maxillary sinus area of panoramic radiographs could potentially be used to make a positive identification. In addition, Brogdon (2011) adds further weight to these pilot studies by independently suggesting that features visible in panoramic radiographs, such as the dental arches and paranasal sinuses, could provide clues as to the identification of a person. However, this statement needs further testing before it can be implemented by forensic professionals, and the lack of information about the maxillary sinuses hinders this process somewhat.

Although panoramic radiographs are also used by forensic odontologists to make a dental identification, the benefit of having a second identification method utilizing panoramic radiographs is twofold. One benefit is that some individuals have had no dental work performed on their teeth, and some individuals are edentulous. In these cases, dental identification can either provide a very broad generalization about who the individual might be or provide no information at all. A second benefit is that dental records do not always match up with the available radiographs because of past dental work that was not documented. In these cases, having a method of identification that utilizes panoramic radiographs would not just be a secondary identification method; it could be used as an identification method in its own right.

Radiograph Comparison Techniques

Several different techniques for visual and metric assessment of various structures visible in radiographs have been proposed. The most obvious of these is a visual comparison of the postmortem radiograph to the antemortem radiograph in question (Schuller 1921; Elliot 1953; Christensen 2003). This can be done by either a direct visual comparison where the forensic professional compares the radiographs side-by-side, an overlay method where the radiographs are overlaid either physically or in a photo editing program and compared, or a tracing method where the outline of the area being studied is traced and the tracing compared to either another tracing or the second radiograph (Besana and Rogers 2010). These methods have the benefit of being relatively fast and easy to perform, with no specialized equipment needed. However, methods of visual comparison often lack the scientific rigor necessary to be in compliance with the Daubert standards for evidence because visual comparison of skeletal structures relies on the personal experience of just one person, and some experts argue that radiograph visual comparison methods should be used in conjunction with more quantitative assessments of shape similarity (Riepert et al. 2001; Christensen 2003).

Some studies have used a method of coding the shape of the outline being studied as a way to assess variability (e.g. Reichs 1993; Besana and Rogers 2010). This method is more closely related to quantitative assessment methods than visual assessment methods, but it does not capture the nature of the variability present. Instead, it merely assesses that variability is present in some form and is different than that of any others in the sample. While this is a method that can be used relatively easily, it cannot provide the same level of information that other quantitative methods can. Additionally, many of the variable regions that are normally coded for have been found to be dependent on one another and cannot be used in a combined probability analysis (Besana and Rogers 2010).

Quantitative assessments of shape similarity from radiographic images fall into two basic categories, one involving ratio data and one involving geometric shape data. Collecting ratio data from radiographs or other images usually involves taking several measurements on the image in question and comparing the resulting values against the values obtained from other similar images (Cox et al. 2009; da Silva et al. 2009). Ratio methods have the benefit of accounting for size differences between images, since measurement ratios remain the same when an image is enlarged or decreases in size. This is a fairly simplistic method for quantitatively assessing shape similarity, and since the only equipment necessary for this analysis is a pair of sliding calipers, it is also readily accessible for most forensic practitioners. However, methods such as these often lack reproducibility because there are no standardized measurement points, which put ratio methods into contention with the Daubert evidence admission standards. Ratio methods also fail to take the actual shape of the area being measured into account, which eliminates a major source of potentially useful information from the analysis altogether (Slice 2005). Because of this, other methods of quantitative shape assessment are usually preferable to ratio methods.

Geometric Morphometrics

Techniques from geometric morphometrics can be used to analyze the shape of either a three-dimensional or two-dimensional object. In the context of geometric morphometrics, shape is defined as "the geometric properties of an object that are invariant to location, scale, and orientation" (Slice 2005:3). This is especially helpful when size differences between the study units could affect the outcome of the study, such as grouping cranial shape of skeletal populations by ancestry or sex.

Data collection in geometric morphometrics involves taking coordinate points at certain positions along the object being analyzed. These points can either be standard points such as the Howells (1973) landmarks for cranial measurement that are frequently used in research in physical anthropology, or they can change depending on the object being studied. Coordinate points can be taken in several ways, with two of the most common ways being either with a 3D digitizer or 3D scanner or using computer software to place data points on the outline of a 2D object. In the case of two-dimensional shapes, elliptic Fourier approximation is normally used to examine the characterization of closed contours (Kuhl and Giardina 1982).

Elliptical Fourier analysis is especially useful for analysis of 2D shapes because the resulting descriptors are not only invariant with dilation, translation, rotation, and starting point of the contour, but also keep all of the information about the shape of the contour intact during the process (Kuhl and Giardina 1982). This makes it ideal for gathering geometric data from photographs and radiographs, among other things. To obtain Fourier coefficients, the contour of the object being studied is first chain coded, which is a process that approximates a continuous contour using a sequence of piecewise linear fits consisting of standardized line segments. The code then repeats on successive transversals of the contour. The chain code can be made increasingly more complex if needed, which results in increasing higher harmonic content in the Fourier analysis itself and makes the analysis more accurate. All of these properties make chain coding useful for elliptical Fourier analysis. However, it is important to note that chain coding is not the only method of obtaining the shape of a contour; any piecewise linear representation of a contour can also be used in elliptical Fourier analysis.

Elliptical Fourier analysis itself is a general procedure that fits a closed curve to an ordered set of data points in a two-dimensional plane (Kuhl and Giardina 1982; Ferson et al. 1985). It does this by using decomposition of a curve into a sum of harmonically related ellipses, which together can be used to classify shape outlines of objects (Kuhl and Giardina 1982). The first harmonic locus is oval-shaped and is used to determine orientation of the shape outlines in question. Subsequent harmonics are used to account for rotation of the shape outline and normalize the shape classifications by size. Translation of the shapes is ignored in this procedure. If enough harmonics are used in the analysis, the harmonics will approximate the outline shape of the object. When dealing with continuous, unquantified contours, the Fourier descriptors make it possible to obtain unique, separate classifications of shapes as long as enough harmonics are used in the series. This means that Fourier descriptors can be a good resource for template matching. However, depending on the sampling interval, the contours will generally be encoded differently for each orientation on the sampling grid, and some outline information may be lost from the contour. This can be of varying importance depending on the application of the data. Statistical analyses can tease out the effects of these issues from the results of the elliptical Fourier analysis if necessary.

The success and accuracy of elliptical Fourier analysis and chain coding of the outlines in question relies heavily on being able to separate the outline of an object from the rest of the image. In some cases, such as photographs that have been taken specifically for use in a geometric shape analysis, this can often be done in the analysis program itself or with a supplemental program such as tpsDig, which digitizes the outline of an object with x, y-coordinates (Rohlf 1997). In other cases, such as radiographs and general photographs, the outline of the desired area cannot be picked up by the analysis software and must be separated manually. This can be done by tracing the outline in photo editing software or tracing over the top of the image using tracing paper and uploading the outline into the analysis program. Both automatic and manual outline tracing have potential issues. When using a program that automatically determines the outline of an object, there is the potential for software error or error in the outline from shading or other visible issues with the image. If the outline needs to be manually traced, human error is introduced because the process of outlining the contour of a shape can be subjective. These issues can affect the results of the elliptical Fourier analysis to varying degrees, but not enough to discount or discontinue its use in anthropological and biological research.

Because data analyzed using geometric morphometrics looks at only the geometric shape of the unit in question and not size or orientation, methods in geometric morphometrics have been widely applied in anthropology and biology. Researchers have found ways to incorporate geometric morphometrics into a wide array of research questions, including analysis of 3D data coordinates taken from a skull, shape analysis of photographs of leaves from a particular species, shape analysis of salmon morphology as correlated with genetics, and analysis of sinus shape from radiographs (Hard et al. 1999; Christensen 2003; Prossinger 2004; Christensen 2005; Yoshioka et al.2004; Yoshioka et al. 2006). In particular, Christensen (2003; 2005) has used the geometric morphometrics method of elliptical Fourier analysis to analyze the shape of the frontal sinuses as seen from anterior-posterior cranial radiographs of 584 skulls and conclude that frontal sinus shape is probably unique to an individual. This was an important advancement within the forensic sciences, since it quantitatively confirmed what forensic professionals had been saying based on visual observation for almost 100 years.

A possible issue with using geometric shape analysis of radiographs to make a positive identification is that some aspects of the radiograph that could also potentially be used to make an identification, such as density and margins of other visible portions of the radiograph, will not be apparent from a shape analysis of just the sinus region (Kanchan 2010). Depending on their location, these aspects can also interfere with the analysis of the sinus shape itself, especially since a tracing method must be used in order to obtain the sinus outline for shape analysis. Using both a visual and a geometric method of analysis is a way to account for this, since human participants can pick up on subtle visual similarities and differences between radiographs in a way that a geometric shape analysis cannot. Similarly, a geometric shape analysis can provide information on how the shape of an object is mathematically similar to or different from another object, something that the average human observer cannot readily do. Because of this, methods of radiograph comparison for positive identification should include both visual and geometric analysis methods.

Research Predictions

This research uses both visual and geometric analysis of the maxillary sinuses to examine whether positive identification from the maxillary sinuses could be possible in a forensic setting. Panoramic radiographs were chosen as the means for analysis of the maxillary sinuses because they are common in the antemortem dental records and, unlike bitewing dental radiographs or anterior-posterior cranial radiographs, they provide a clear view of the sinus area. Three hypotheses are proposed for investigation in this research. Based on previous panoramic radiograph visual matching research that suggests an 82-84% matching rate success, it is predicted that the visual matching data obtained from this research will produce results that are greater than would be expected by chance. A null hypothesis of this prediction is that the radiograph matching success rate obtained from this research will not be greater than what would be expected by chance.

Previous research has indicated that education level is positively correlated with success at visually comparing radiographs. Therefore, it is predicted that success rates for visual comparison of the maxillary sinus area in panoramic radiographs will be significantly different for undergraduate students than for graduate students. A null hypothesis of this prediction is that radiograph matching success rates will not show significant differences between undergraduate and graduate students.

Finally, geometric shape analysis has been used in frontal sinus shape research to mathematically assess individuality of sinus shape with great success. Because of this, it is predicted that the shape of the maxillary sinuses from different panoramic radiographs of the same individual will show measurable similarities to one another and measurable differences from the maxillary sinuses of every other individual, similar to what has been found in previous studies using other craniofacial sinuses (e.g., Christensen 2003; Christensen 2005). A null hypothesis for this prediction is that no significant differences will be present between the maxillary sinus shapes of the individuals in the data.

CHAPTER TWO:

MATERIALS AND METHODS

The process for collecting panoramic dental radiographs is as follows. Since panoramic dental radiographs are often taken at least a year apart, using panoramic radiographs from living people simulates the reality of not having a recent radiograph comparison in an actual forensic investigation. It also accounts for the potential variation involved in using multiple different x-ray machines, since it is unlikely that a forensic investigator will be able to take a postmortem radiograph using the exact same machine that took the antemortem radiograph.

It is also not known how much change the maxillary sinuses undergo during the lifetime of the individual. Several studies have concluded that the frontal sinuses undergo significant remodeling during the childhood years, but become fixed around 18-20 years of age (Quatrehomme et al. 1996:151). There is some evidence to suggest that the maxillary sinus region changes greatly during the childhood years due to the development and eruption of adult teeth, which is a reasonable assumption (Melson 1967). Because of this, the decision was made to not include individuals under the age of 18 in this study to reduce potential error in the results. However, this could possibly be addressed in a separate research study.

It was necessary to file a research proposal with the Institutional Review Board of the University of Montana for approval before this study began. The proposal was approved under expedited review, cited as presenting no more than minimal risk to participants. The identification number for this research is IRB 70-13.

The first step of this study was to collect two panoramic radiographs each from a number of participants. Participants for this were recruited from the northern California and western Montana regions by advertisement fliers and by word-of-mouth. Participants were selected based on having at least one, preferably two, panoramic radiographs and being 18 years of age or older.

The participants were required to sign a consent form before the radiographs were taken into possession, and the age and sex of each participant at the time of collection was recorded, along with the year that each radiograph was taken. All radiographs used in this study were taken prior to the start of this study for dental diagnostic purposes only; no radiographs were taken for the purposes of this research. Participants were not provided any compensation for participating, and all participant identities were kept confidential.

A total of 14 people participated in this phase of the study, seven who had two panoramic radiographs and seven who had one panoramic radiograph, for a total of 21 usable panoramic radiographs. The age of the participants when the earliest radiograph was taken ranged from 14 years to 85 years, and those who had more than one panoramic radiograph had a time gap of one to five years between when the radiographs were taken. If needed, the radiographs were converted to a digital format by scanning them to an image file using an HP all-in-one photo printer. The digital radiograph files were then stored in a secure folder for later use.

Radiograph Comparison Survey

The radiographs gathered from the participants were first used to create an online survey to determine whether the maxillary sinus areas of an individual from the first panoramic radiograph are similar enough to be matched to the maxillary sinus areas from the second radiograph. To test this, the teeth were cropped out of all of the panoramic radiograph as much as possible using Windows Live Photo Gallery 4 to avoid the issue of observers also using the dentition in making the identification (Figures 1 and 2). In cases where the apex of the root of a tooth was involved in the sinus area, the root apex was left in the field of view so as not to interfere with the sinus area. An online survey was created using SurveyGizmo, and the cropped radiographs were used to create two sets of seven different matching scenarios. The first matching scenario involved showing an antemortem cropped radiograph from an individual as a comparison, then showing four possible radiographs from the participant to choose from: the second radiograph from that individual, and three other radiographs from other individuals chosen at random. The participants were asked to select the corresponding letter (A, B, C, or D) of the radiograph that they believed was the match for the antemortem radiograph in question. This was repeated until all seven pairs of matching radiographs were represented in the survey.

The survey also contained seven different matching scenarios involving only two radiographs for a simple yes/no answer to the question. This was done to compare the results with the two pilot studies that have been done previously in order to examine the correlation between the results and assess whether the results from the more complicated matching exercise could be repeatable elsewhere. The non-matching radiographs for each of the survey scenarios were chosen at random from the available pool of radiographs. In addition, the survey also collected basic information from the survey participant, including academic standing (freshman, sophomore, junior, senior, graduate, faculty), field of study (Social Sciences, Natural Sciences, Humanities, other), years of radiograph comparison experience, and previous completion of an osteology class. Participants were also asked to record the screen size of the device they took the survey on to see if the percentage correct increased with a larger screen size (more radiographs visible at once in the lineup portion of the survey). Participants for the survey were recruited by word of mouth from a pool of graduate students and advanced undergraduate students at the University of Montana campus.

Microsoft Excel and SPSS were used to perform analyses on the data from the radiograph matching survey. SPSS was used to provide counts for all survey respondents based on the demographic questions in the survey. Microsoft Excel was used to calculate overall percentages correct for both radiograph survey conditions and percentages correct for several different variables provided by the demographic questions. Percentages correct were calculated for the field of study variable, with the humanities, natural science and all responses of "other" being combined into one condition because of the small sample size of each of these groups ($n \leq 8$).

SPSS was used to perform a one-way ANOVA for both of the radiograph scenarios and all of the demographic questions. ANOVA is a way to test the equality of three or more means at one time by using variances. This analysis assumes that the populations that the samples are from are approximately normally distributed, the samples are independent, and the variances between the samples are equal. If significant differences between the means are present, then the results of the ANOVA will be statistically significant at the 0.05 level.

A one-way ANOVA was performed on the academic standing variable. A one-way ANOVA was performed on the field of study variable. A one-way ANOVA was also computed for the osteology/no osteology variable. A one-way ANOVA was computed for the radiograph experience variable. A one-way ANOVA was also performed for the screen size variable.

SPSS was used to perform chi-square tests for both of the radiograph scenarios and all demographic questions. Chi-square tests are a method for testing the association between row and column variables by measuring the divergence from the value expected under the null hypothesis of no association. In the case of the radiograph comparison and field of study variables, the distribution of participants across the different demographic variables was heavily weighted toward one or more possible answers. This was accounted for by either not performing a chi-square test on the data in the case of the radiograph comparison experience variable or by combining the natural sciences, humanities, and “other” options in the field of study variable to create one larger group for comparison with social sciences. Combination of responses was also necessary for the academic standing variable, since most of the participants fell into the graduate or senior group. In this case, the freshman, sophomore, junior, senior, and “other” participants were combined into a single “undergraduate” group for comparison with the graduate group. This makes the results of the survey more meaningful, since two larger groups are being compared against one another instead of one large group against several small groups.

Geometric Morphometric Analysis

Shape 1.3 (Iwata and Ukai 2002) was used to perform an elliptical Fourier analysis and a principal components analysis on the sinus shapes visible in the radiographs because it allows for the capture of outline data from images. However, in order to obtain the outline shape using Shape 1.3, the area around the outline must be relatively distinct from the outline itself. Since radiographs often contain too many different outlines and shading variations to fall into this category, Shape 1.3 is unable to extract outline data from radiographs directly. A tracing method must be used to isolate the shape in question in these cases.

To isolate the shape of the maxillary sinuses for use in Shape 1.3, a cropped radiograph image was uploaded into Adobe Illustrator, and the sinus shapes were manually traced onto a separate layer at high magnification using the pencil function. The resulting shape was filled in, and the original radiograph image was removed to create a filled-in outline of the sinuses. This process was repeated for all available radiographs.

This resulted in 42 sinus shape images files, saved individually. Shape 1.3 operates on the assumption that all images to be analyzed as a group are together in one file. Corel

PaintShop Pro v. 16.1.0.48 was used to merge the individual sinus outline files into one file by cropping and resizing the image area to be used, copying the image, and then pasting the image as a new selection onto an expanded canvas. This process was repeated for all sinus outline files, which resulted in one image file with every sinus outline represented. The merged image was then saved as a full-color bitmap image (.bmp) for use in Shape 1.3.

Shape 1.3 is a suite of four main interconnected shape analysis programs: ChainCoder, CHC2NEF, PrinComp, and PrinPrint. These programs are available to the general public and are relatively user-friendly, which makes them ideal for analyzing shape data (Iwata and Ukai 2002). All four of these programs were used to analyze the sinus outline shapes obtained from the previous steps and obtain elliptical Fourier descriptors and principal components scores from the outline data.

ChainCoder was used to obtain chain codes from the uploaded sinus shape outlines. This is the first step in obtaining elliptical Fourier descriptors (EFDs) for further analysis. In ChainCoder, the merged image containing all of the sinus outlines was uploaded, and all areas of the image were selected for analysis. The image was converted to gray scale, and image binarize was set to 127. The ero dil filter was set to 4 in order to reduce noise in the images and clarify the outline images. Chain codes for each of the sinus outlines were then obtained by running the ChainCoder program, and the resulting chain codes were saved to a file for uploading into CHC2NEF.

The second program in the Shape 1.3 suite, CHC2NEF, calculates the normalized EFDs from the chain codes produced in the previous step. The chain code file for the sinus outlines was uploaded into CHC2NEF to obtain EFDs for the sinus outlines. The maximum harmonics used in the analysis was set to 25 due to the complexity of some of the sinus shapes, and the first harmonic ellipse was used to normalize the EFDs based on the size and alignment of the major axis of the ellipse. After normalization had been completed, the resulting outlines were rotated 180 degrees if necessary in order to orient them roughly to the same position. The resulting EFDs were saved to a file for uploading into PrinComp.

PrinComp, the third program in the Shape 1.3 suite, is designed to calculate principal components from the normalized EFDs obtained in CHC2NEF. The file containing the EFDs was uploaded into PrinComp, and "principal components analysis" was selected from the "analysis" drop-down menu. The resulting principal components were saved to a text document using the "Make Report" button. From there, the scores of the principal components were calculated by selecting the "calculate prin score" from the "analysis" drop-down menu and selecting the normalized EFD file. The resulting scores were displayed as a text document and saved for further analysis.

PrinPrint, the final program in Shape 1.3, is used in conjunction with PrinComp in order to visualize the shape variation explained by each principal component. This was done on the sinus outline data by selecting the "reconstruct contour" option from the "analysis" window on PrinComp and selecting the first five principal components to be reconstructed on the reconstruct contours dialog option. Selecting a save file name for principal component contours will automatically open PrinPrint to display the resulting contours. Since PrinPrint does not give the option of saving the contour reconstructions, the contours were saved by taking a screenshot of the program window.

Shape 1.3 was used to perform a principal components analysis on the combined sinus outline data. This analysis assumes that there are no subgroups within the data set and uses the pooled variance/covariance matrix. The resulting eigenvectors from the matrix are the principal components, which represent a factor that is causing variation in the data. From these, the first three principal components were chosen for further analysis because they represent a large portion of the total variation in the data set. The first three principal components were plotted against one another using SPSS, and Microsoft Word was used to add ovals around the points representing the sinus outlines from the same side of the body (R or L) from the same individual (0001, 0002, 0003, 0004, 0005, 0006, 0007) in order to examine how well the sinus shapes from the same individual cluster together.

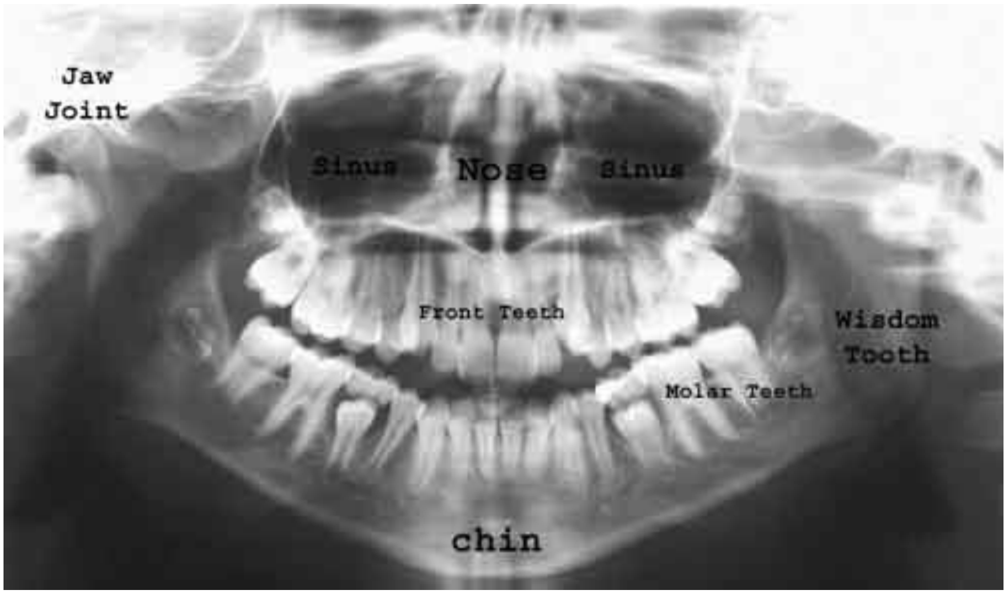

Figure 1. Example of a panoramic radiograph with basic visible anatomy labeled

Figure 2. Panoramic radiograph from Figure 1 that has been cropped to remove the dentition and labeled to show the relevant visible anatomy.

CHAPTER THREE

RESULTS

Table 1 provides the distribution of all survey respondents based on each of the demographic variables. Table 2 provides the overall percentage correct for the radiograph matching scenario as a whole, as well as the percentages correct for the academic standing, osteology vs. no osteology, and field of study demographic variables. Table 2 also contains the results from one-way ANOVA tests between conditions within the demographic variables. Table 3 provides the overall percentage correct for the radiograph lineup scenario as a whole, as well as the percentages correct for the academic standing, osteology vs. no osteology, and field of study demographic variables. The results from one-way ANOVA tests between conditions within the demographic variables are also shown in Table 3.

Table 4 provides the results of chi-squared tests for each radiograph match in the radiograph matching scenario vs. each of the demographic variables. Table 5 represents the results of chi-squared tests for each radiograph set in the radiograph lineup scenario vs. each of the demographic variables.

Table 6 gives the first ten principal components, the associated eigenvalues, and the percent variance after the principal components analysis was run. These ten principal components represent almost all of the variance within the entire data set. Figure 3 represents the plot of principal components 1 and 2 for the combined sinus outline data set. Figure 4 represents the plot of principal components 2 and 3 for the combined sinus outline data set. Figure 5 represents the plot of principal components 1 and 3 for the combined sinus outline data set.

Table 1. Distribution of survey participants (n = 47) for each demographic variable

Distribution of survey participants

Comparison	Categories	Counts
Academic Standing		
	Freshman	3
	Sophomore	7
	Junior	5
	Senior	14
	Graduate	12
	Other	6
Field of Study		
	Social Sci	33
	Humanities	4
	Natural Sci	2
	Other	8
Completed Osteology		
	Yes	17
	No	30
Years X-ray Comparison		
	0	44
	1-2years	2
	3-5years	1
Device Screen Size		
	10" or less	5
	10.1"-12"	3
	12.1-14"	12
	14.1-16"	9
	16.1-18"	12
	18.1-20"	3
	20.1+	3

Table 2. Radiograph matching percentages and one-way ANOVA test results for each of the demographic variables.

Results of one-way ANOVA tests , radiograph matching			
Populations Compared		% Correct	Significance
Overall		**84.19**	
Undergrad vs. Grad			0.195
	Undergrad	82.86	
	Grad	88.1	
Osteolgy vs. No Osteo			0.519
	Osteo	85.71	
	No Osteo	83.33	
Field of Study			0.466
	Social Sci	83.55	
	All Others	85.71	
X-ray Compare Exp.			0.583
Screen Size			0.003

Table 3. Radiograph lineup percentages correct and one-way ANOVA test results for each of the demographic variables

Results of one-way ANOVA tests, radiograph lineup			
Populations Compared		% Correct	Significance
Overall		**80.85**	
Undergrad vs. Grad			0.086
	Undergrad	78.57	
	Grad	87.5	
Osteology vs. No Osteo			0.071
	Osteo	86.27	
	No Osteo	77.77	
Field of Study			0.365
	Social Sci	79.79	
	All Others	83.33	
X-ray Compare Exp.			0.962
Screen Size			0.627

Table 4. Chi-squared test results for the radiograph matching scenario and each demographic variable.

Results of chi-squared tests, radiograph matching

Testing	X-ray Pair	χ2	Significance
Academic Standing			
	X-ray 2	6.777	0.238
	X-ray 3	3.089	0.686
	X-ray 4	1.655	0.894
	X-ray 5	3.956	0.556
	X-ray 6	8.583	0.127
	X-ray 7	6.981	0.222
Field of Study			
	X-ray 2	1.218	0.749
	X-ray 3	1.855	0.603
	X-ray 4	0.74	0.864
	X-ray 5	4.946	0.176
	X-ray 6	0.433	0.933
	X-ray 7	0.743	0.861
Osteology			
	X-ray 2	0.634	0.426
	X-ray 3	0.236	0.627
	X-ray 4	0.211	0.646
	X-ray 5	0.002	0.966
	X-ray 6	0.579	0.447
	X-ray 7	0.254	0.614

Table 5. Chi-squared test results for the radiograph lineup scenario and each demographic variable.

Results of chi-squared tests, radiograph lineup			
Testing	X-ray Set	χ2	Significance
Academic Standing			
	X-ray 1	2.408	0.79
	X-ray 2	11.409	0.044
	X-ray 4	2.021	0.846
	X-ray 5	8.318	0.14
	X-ray 6	3.579	0.611
	X-ray 7	6.644	0.249
Field of Study			
	X-ray 1	0.433	0.933
	X-ray 2	2.342	0.504
	X-ray 4	5.742	0.125
	X-ray 5	2.341	0.505
	X-ray 6	1.168	0.761
	X-ray 7	2.879	0.411
Osteology			
	X-ray 1	0.579	0.447
	X-ray 2	3.363	0.067
	X-ray 4	0.002	0.966
	X-ray 5	0.236	0.627
	X-ray 6	1.334	0.248
	X-ray 7	0.209	0.647

Table 6. Eigenvalues and percent of variance for principal components analysis of the combined sinus outlines data set

PC	Eigenvalue	% Variance
1	0.0378	54.27
2	0.012	17.24
3	0.0064	9.54
4	0.0036	5.16
5	0.0023	3.31
6	0.0017	2.45
7	0.0014	2.04
8	0.00062	0.88
9	0.00059	0.85
10	0.0005	0.72

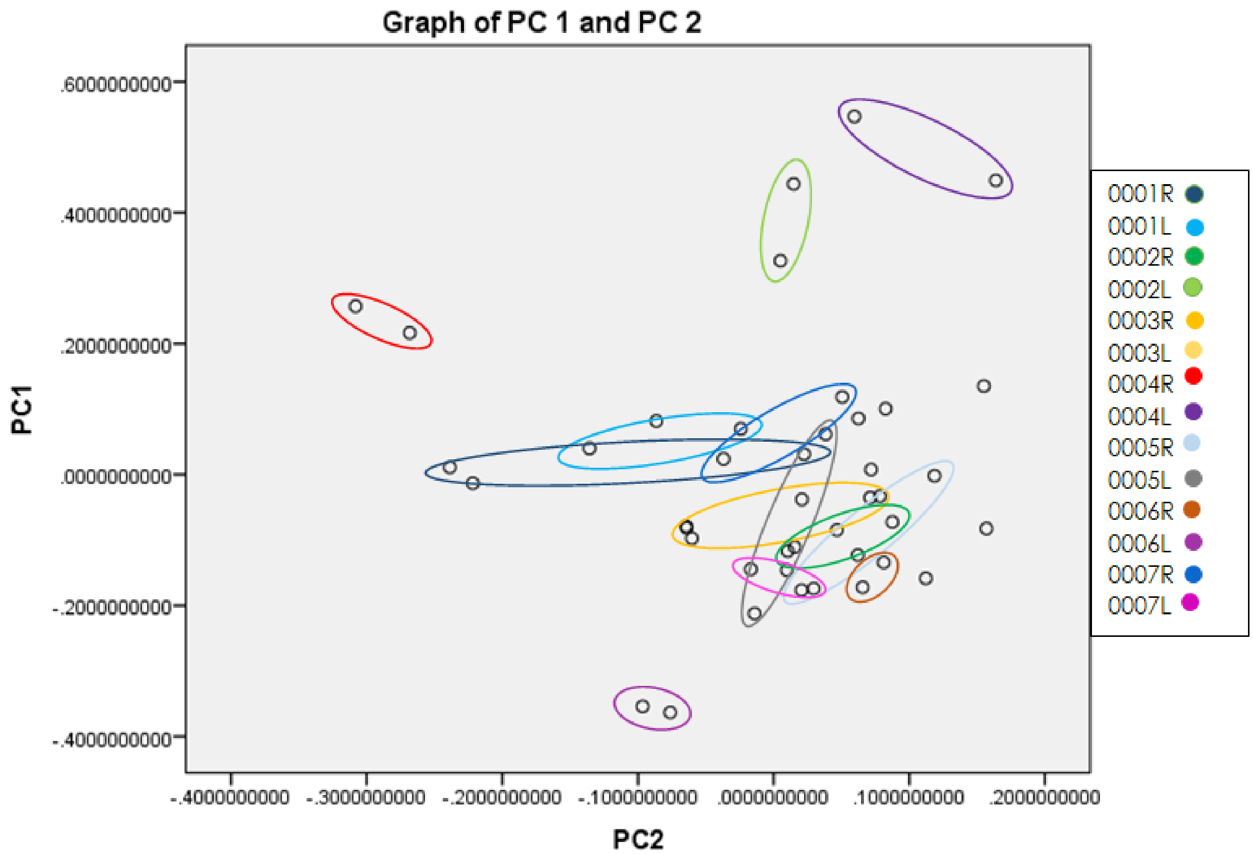

Figure 3. Plot of principal components 1 and 2 for the combined sinus outline data, with points representing each sinus outline (two per radiograph) and colored ovals showing the grouping between the sinus outlines from the participants that provided two radiographs, separated by left (L) and right (R) sinus outlines.

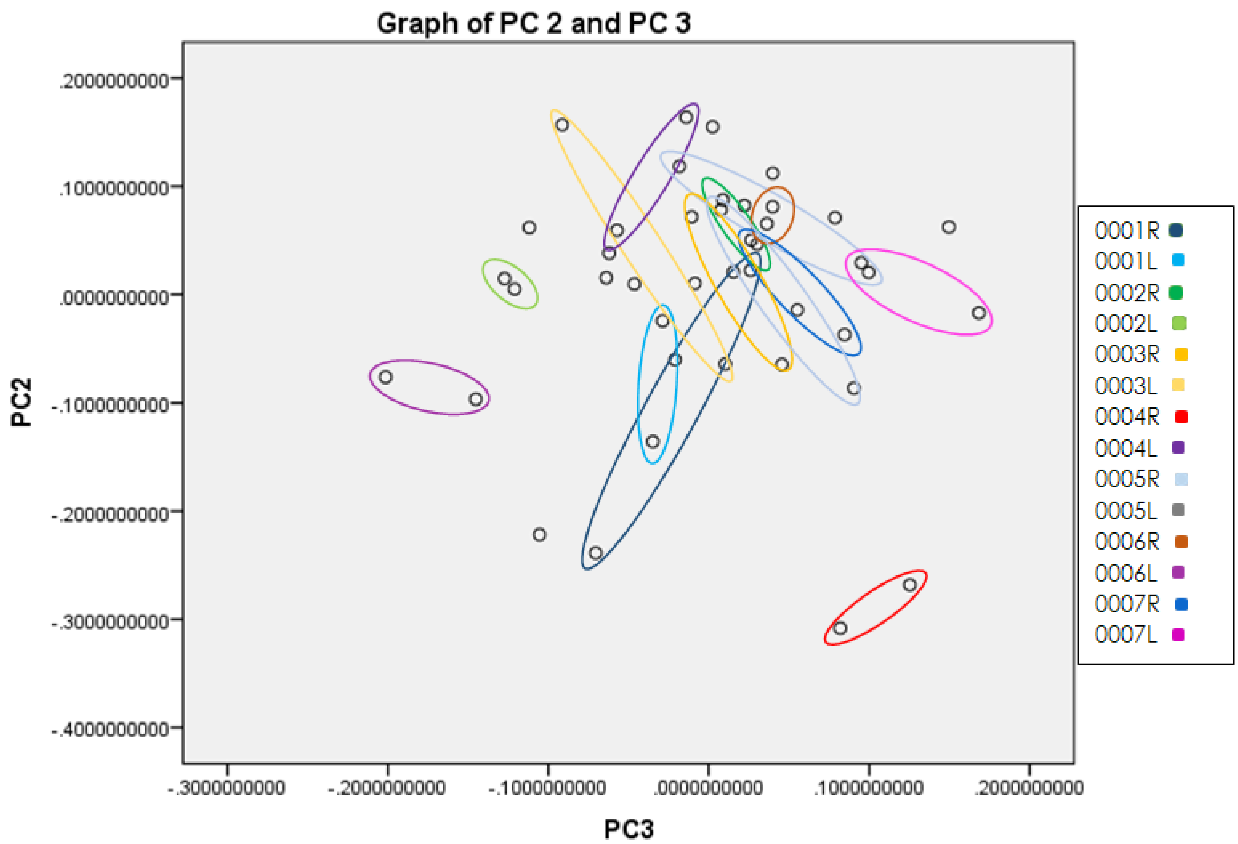

Figure 4. Plot of principal components 2 and 3 for the combined sinus outline data, with points representing each sinus outline (two per radiograph) and colored ovals showing the grouping between the sinus outlines from the participants that provided two radiographs, separated by left (L) and right (R) sinus outlines.

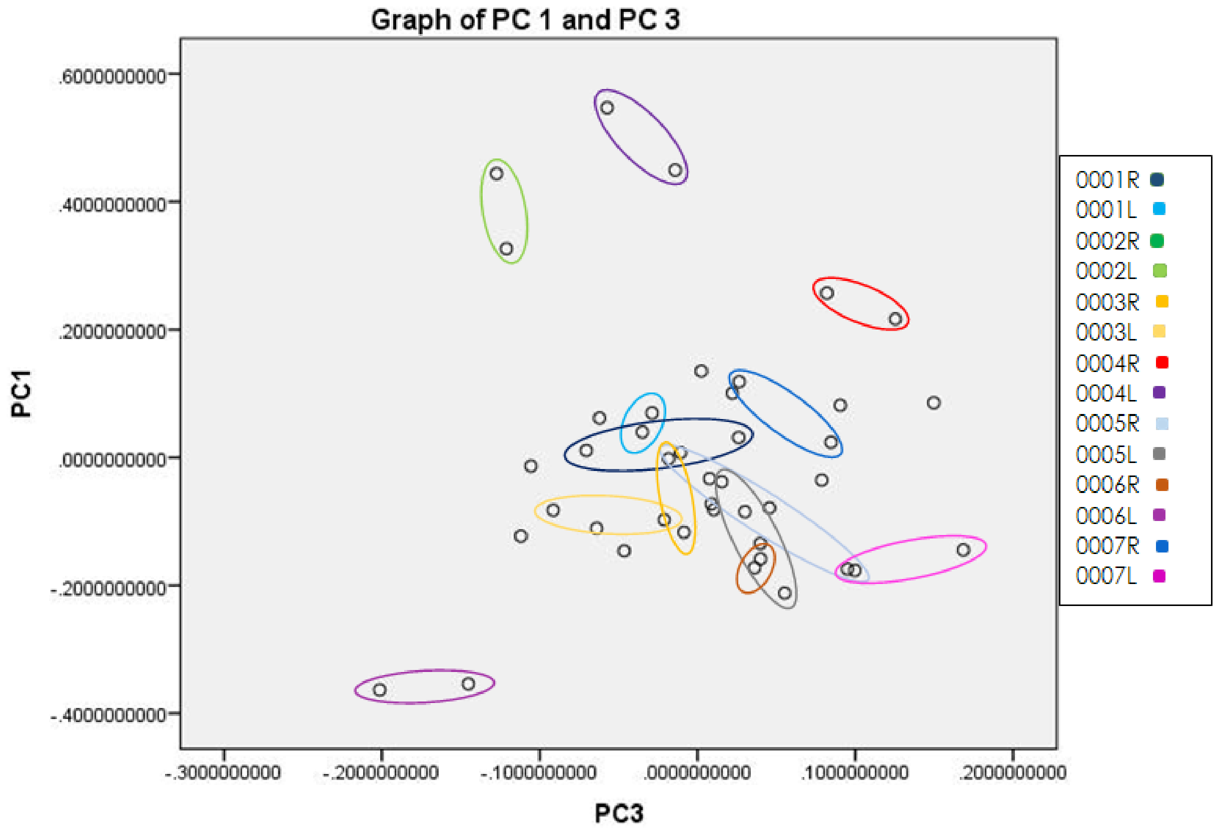

Figure 5. Plot of principal components 1 and 3 for the combined sinus outline data, with points representing each sinus outline (two per radiograph) and colored ovals showing the grouping between the sinus outlines from the participants that provided two radiographs, separated by left (L) and right (R) sinus outlines.

CHAPTER FOUR

DISCUSSION

Distribution of participants across the different demographic variables was relatively good, with only the radiograph comparison and field of study variables showing a large weighting of participants, toward zero years of experience and social sciences respectively.

The overall correct percentage for the radiograph matching scenario in the survey was calculated to be 84.19%, which indicates that a high level of individualization can be seen in the maxillary sinus region of panoramic radiographs (Table 2). If the maxillary sinus regions of two panoramic radiographs showed no distinct differences from one another, the expected correct matching percentage would be about the same as picking the correct radiograph by chance, or around 50%. The overall correct matching percentage from the radiograph matching scenario is also consistent with the correct matching percentages found by Soler (2011) and Collins (2013), Although this study uses radiographs from living people, the results from this research appear to be similar in efficacy to the results from the two previous pilot studies, which used radiographs from living people instead of radiographs taken from skulls in a skeletal collection. This also suggests that the results from the radiograph lineup scenario in the survey can be considered valid, since they were obtained using the same conditions as the radiograph matching scenario.

The overall correct percentage for the radiograph lineup scenario in the survey was calculated to be 80.85%, which also indicates that a high level of individualization can be seen in the maxillary sinus region of panoramic radiographs (Table 3). This further indicates that there are observable similarities between the maxillary sinus regions of panoramic radiographs from the same person, since the overall correct percentage is much higher than the percentage correct of around 25% that would be expected if the radiographs were picked by chance. This also suggests that comparison of the maxillary sinus region of true antemortem and postmortem panoramic radiographs could be used as a reliable positive identification method, since the radiograph from the same individual can be correctly identified even when other options are present.

Graduate vs. Undergraduate

Differences in correct percentages were observed between undergraduate participants and graduate participants in the radiograph matching scenario, with a correct percentage of 82.86% obtained for undergraduate participants (n = 35) and a correct percentage of 88.10% obtained for graduate participants (n = 12) (Table 2). The percentage obtained from the graduate participant sample is higher than the overall correct percentage from the radiograph matching scenario, which indicates that this method could potentially have an even greater matching success rate than what is observed in this study. However, the graduate participant sample is small, which could reduce the validity of the results. A one-way ANOVA of the academic standing variable for the radiograph matching scenario indicates that the differences between undergraduate and graduate percentages correct are not significant at the 0.05 level (p = .195) (Table 2). This is consistent with what was found by Collins (2013), but inconsistent with the generally accepted observation by Sholl and Moody (2001) that success with correctly matching radiographs is positively correlated with education level and years of experience. Future research should further examine this discrepancy by utilizing both a larger sample size and participants with experience in radiograph comparison.

Differences in correct percentages were also observed between undergraduate participants and graduate participants in the radiograph lineup scenario, with a correct percentage of 78.57% obtained for undergraduate participants (n = 35) and a correct percentage of 87.50%

obtained for graduate participants (*n* = 12) (Table 3). In addition to these differences, the graduate percentage correct was much higher than the overall percentage correct, which further indicates that there are observable similarities between the maxillary sinus regions of panoramic radiographs from the same individual. However, a one-way ANOVA of undergraduate versus graduate percentage correct for the radiograph lineup scenario indicates that the differences between undergraduate and graduate percentages correct are not significant at the 0.05 level ($p = .086$) (Table 3). This is also inconsistent with the generally accepted observation that the percentage correct for radiograph comparison increases with education level, but because the percentages correct are approaching significance at the 0.05 level, repeating this study with a larger sample of graduate student participants could reveal a significant difference between the groups.

Field of Study

Slight differences were observed for the radiograph matching scenario between participants from the social sciences and participants from all other fields, with a correct percentage of 83.55% obtained for social sciences participants (*n* = 33) and a correct percentage of 85.71% obtained for all other participants (*n* = 14) (Table 2). A one-way ANOVA of the number correct for the field of study variable indicates that these differences are not significant at the 0.05 level ($p = .466$) (Table 2). This suggests that participants in the social sciences are slightly worse than participants from other fields at differentiating between radiographs from different individuals, but not enough to make a significant difference in the overall results. Because the observed *p*-value is large, a larger sample size would likely not reveal significant differences between the groups.

Slight differences were also observed for the radiograph lineup scenario between participants from the social sciences and participants from all other fields, with a correct percentage of 79.79% obtained for social sciences participants (*n* = 33) and a correct percentage of 83.33% obtained for all other participants (*n* = 14) (Table 3). A one-way ANOVA of the percentage correct for the field of study variable indicates that these differences are not significant at the 0.05 level (*p* = .365) (Table 3). This also suggests that participants from the social sciences are slightly worse than participants from other fields at differentiating between radiographs from different individuals, but not significantly so.

Osteology vs. No Osteology

Slight differences in correct percentages were observed for the radiograph matching scenario between participants who had taken an osteology class and participants who had not taken an osteology class, with a correct percentage of 85.71% obtained for participants who had taken an osteology class (*n* = 17) and a correct percentage of 83.33% obtained for participants who had not taken an osteology class (*n* = 30) (Table 2). However, a one-way ANOVA of the percentage correct for osteology versus no osteology participants indicates that these differences are not significant at the 0.05 level (*p* = .519) (Table 2). This indicates that completion of an osteology class does not significantly affect the correct matching percentage for the radiograph matching scenario.

Differences in correct percentages were observed for the radiograph lineup scenario between participants who had taken an osteology class and participants who had not taken an osteology class, with a correct percentage of 86.27% obtained for participants who had taken an osteology class (*n* = 17) and a correct percentage of 77.77% obtained for participants who had not taken an osteology class (*n* = 30) (Table 3). A one-way ANOVA of the percentage correct for osteology versus no osteology participants indicates that these differences are not significant at the 0.05 level ($p = .071$) (Table 3). This further indicates that completion of an osteology class does not significantly affect the correct matching percentage for the radiograph lineup scenario. However, because this p-value is approaching significance at the 0.05 level, a larger sample size could reveal significant differences between the groups.

Radiograph Comparison Experience

Although radiograph comparison experience was one of the demographic questions in the survey, the overwhelming majority of survey participants indicated that they had no previous radiograph comparison experience (Table 1). Only three participants said that they had radiograph experience, ranging from 1-5 years of experience. A one-way ANOVA indicated that there were no significant differences in the radiograph matching scenario between participants who had previous radiograph comparison experience and those who did not ($p = .583$) (Table 2). A one-way ANOVA also indicated that there were no significant differences in the radiograph lineup scenario between participants in this variable ($p = .962$) (Table 3). However, these results are biased because of the small sample size and should not be taken to mean that radiograph comparison experience is not necessarily correlated with radiograph comparison success rates. Instead, these results indicate that radiographs from the same individual can be correctly matched with a high degree of accuracy by participants with no previous radiograph comparison experience. Future research should utilize participants with more experience in radiograph comparison to examine whether experience level has an effect on the overall percentage correct for both the matching and lineup scenarios.

Screen Size

Because the radiographs in the lineup survey scenario needed to be positioned vertically instead of horizontally due to limitations of the survey program, not all of the radiographs in the lineup scenario could be viewed at the same time on smaller device screens while taking the survey. A one-way ANOVA indicates that screen size has a significant effect in radiograph matching success at the 0.05 level (p = .003) (Table 2). Surprisingly, a one-way ANOVA indicates that screen size does not have a significant effect in radiograph lineup percentage correct at the 0.05 level (p = .627). These results are surprising, since a larger screen size appears to have more of an effect on the radiograph matching scenario than on the radiograph lineup scenario, the opposite of what was predicted. This could be because a larger screen size would also make the radiographs in the matching scenario larger, which could aid in making a correct visual comparison.

However, the survey participants were comprised of undergraduate and graduate students, not trained professionals in a forensic field. The participants were also not given any training on strategies for successfully comparing radiographs before beginning the radiograph comparison scenarios. For these reasons, it could be said that all of the participants were on a level playing field in terms of experience, since the only measurable difference between the participants was years of school beyond a high school education.

Future research should repeat this study using participants who are experts in the fields of forensic pathology, forensic odontology, and forensic anthropology instead of students in these fields to obtain a more realistic figure for percent correctly matched. Future research could also examine how a brief section of training on radiograph comparison strategies at the beginning of the survey affects the overall correct percentage for successfully matching the radiographs. In both of these directives, the impacts of participant sample size and screen size should also be taken into account.

Geometric Shape Analysis

The first two eigenvalues obtained from the data set using a principal components analysis account for approximately 72% of the variance in the data set, and using the first ten eigenvalues accounts for about 96% of the variance (Table 6). Each of the eigenvectors indicates something in the data that is causing variation within the data set, and it appears that the combined sinus outline data set has several factors that heavily influence variation. Since the first principal component is almost always size and the second principal component usually represents a shape variable, these results indicate that there are mainly size differences between the sinus outlines in the data set, although shape appears to also be playing a more minor role. Since both positive and negative eigenvalues are present, the first component likely represents both size and shape (Cadima and Jolliffe 1996). The presence of positive and negative values for the first principal component indicates that a significant portion of the differences between the sinus outlines is accounted for by both the size and shape of the sinus outlines.

The graphs of the first three principal components indicate that some of the sinus outlines from the same individual group relatively well with one another. The graph of principal component one vs. principal component two shows close groupings of the 0002R, 0002L, 0004R, 0006L, 0006R, and 0007L sinus sets, with only the 0001L sinus set showing almost no grouping tendencies (Figure 3). This indicates that some shape similarities are present in the sinuses of radiographs from the same individual. The graph of principal component two vs. principal component three also shows close groupings of the 0002R, 0002L, 0004R, 0006R, and 0006L sinus sets, with only the 0001L and 0003L sinus sets showing very little grouping tendencies (Figure 4). These clusters indicate that some shape similarities are present in the sinus radiographs from the same individual. The graph of principal component one vs. principal component three shows close groupings of the 0001L, 0002L, 0003R, 0003L, 0004R, 0006R, 0006L, 0007R, and 0007L sinus outline sets, with only the 0005R outline showing very little grouping tendencies (Figure 5).

Overall, the graph of principal component one vs. principal component three appears to show the most grouping tendencies, with nearly all sinus outline points showing close or moderate groupings. The points representing the 0002L, 0004R, 0006L, and 0006R sinus outline sets consistently group closely with one another across all three principal components graphs. This could indicate that the antemortem and postmortem sinus outlines from these individuals are very similar in shape and cannot be grouped closely with sinus outlines from any other individual in the group. The small number of sinus outlines compared in this study is a limiting factor, and these results should be taken to be only a preliminary examination of maxillary sinus shape.

The principal components results appear to support the third hypothesis, which predicts that the shape of the maxillary sinuses from different panoramic radiographs of the same individual will show measurable similarities to one another and measurable differences from the maxillary sinuses of every other individual, since sinus shapes from some individuals cluster very tightly together across combinations of the three principal components. However, some individuals did not cluster with one another, and instead appeared to be more similar to the sinus shapes of other individuals in the data set than with one another. This could be due to the fact that some of the radiographs in the data set were taken when the participant was under the age of 18, and some of the participants had undergone orthodontic manipulation of their dentition in between the time that the two radiographs were taken. The influence of this is unknown, but it is possible that the shape of the sinuses is at least slightly affected by either the growth and development process or the performed orthodontic work in these cases.

Issues and Future Research

One potential issue with the results of this research is the use of radiographs from individuals who were under the age of 18 when the radiograph was taken. Although radiographs were not obtained from anyone under the age of 18 at the time the consent form was signed, both to be in accordance with the IRB and avoid using individuals whose sinus structure may still be changing due to normal growth and development, some of the radiographs in this study were taken when the participant was under the age of 18. Since panoramic radiographs are generally taken on a three to five year rotation and the main participant sample for the radiographs was between the ages of 18 and 25, this could not be helped. However, even if the sinus shapes of some of the participants were not yet fixed at the time the radiograph was taken, this would mean that the visual and geometric assessments of positive identification capabilities obtained in this study would be underestimated instead of overestimated. This provides a more conservative assessment of the potential use of the maxillary sinuses for positive identification purposes and suggests that the overall correct percentage of 80.85% obtained from the online survey in this study could be an underestimate. Future research should use panoramic radiographs from individuals who were over 18 years of age at the time the first radiograph was taken in order to address this issue.

A second issue with this research is the small sample size of both individuals with two panoramic radiographs and radiograph matching survey participants. While the number of panoramic radiograph matching questions was intentionally kept small in order to avoid survey participant fatigue, the preliminary geometric morphometrics analysis would have greatly benefitted from a larger radiograph sample size. Future research should utilize panoramic radiographs from more individuals. In the case of the online survey, some of the one-way ANOVA and chi-square analyses approached significance at the 0.05 level. These variables could likely attain significance if more participants had taken the survey. Future visual matching research should utilize a larger sample size of survey participants in order to avoid this issue.

Previous research has shown that participants with more training and experience in their field tend to perform better on visual comparison or matching exercises. In general, participants who took the panoramic radiograph comparison survey did not have prior experience with radiograph comparison, which could influence the results. Because of this, it is likely that the correct matching percentages obtained in this study are artificially low and could be improved if the study was repeated using participants who are both medicolegal professionals and have some training in radiograph comparison. Future research should repeat this study using participants who are experts in the fields of forensic pathology, forensic odontology, and forensic anthropology instead of students in these fields to obtain a more realistic figure for percent correctly matched. Future research could also examine how a brief section of training on radiograph comparison strategies at the beginning of the survey affects the overall correct percentage for successfully matching the radiographs. In both of these directives, the impacts of participant sample size and screen size should also be taken into account.

Both visual and geometric methods of individualization have their benefits and detriments, so both were included and assessed in this research. The results from the visual matching survey indicate that individuals with little to no specialized training can successfully identify the correct postmortem match to an antemortem radiograph about 80% of the time, even when the two radiographs were taken up to five years apart. This indicates that the maxillary sinus region of panoramic radiographs show enough similarities with one another and show enough differences from other radiographs that they can potentially be successfully matched in a forensic setting. The preliminary results from the geometric morphometric analysis of maxillary sinus shape indicate that radiographs from individuals who were over 18 at the time the first radiograph was taken tend to group together in a principal components analysis. This further corroborates the results from the visual matching survey, and indicates that the maxillary sinuses could potentially be used to positively identify individuals in a forensic setting.

Currently, an issue with any research that examines the potential for positive identification in the forensic sciences is that it suppresses the uncertainty inherent in the scientific process in order to arrive at some conclusion (Biedermann et al. 2008). Research into unique personal identifiers such as fingerprints or frontal sinus shape often makes the mistake of assuming that since no exact matches were found among the samples being studied, the area of study is unique to an individual (Page et al. 2011). Using the scientific method, hypotheses can only be disproven, not proven; therefore, it is incorrect to assume that a given region of the body is unique to that individual, since this assumption cannot be proven using the scientific method. In addition, even if it is mathematically possible for something to be unique, it does not necessarily mean that that object is truly unique in practice.

However, error rates for a positive identification method can be estimated, given a large enough sample size. This is often done in research in the forensic sciences, since having a known error rate for a method puts the method in compliance with the Daubert standards of evidence admissibility in court. Researchers in the forensic sciences must be cautious about classifying a feature as being individual and unique to a person, since many of the current literature (including this study) does not utilize a large enough sample size to be able to make this claim (Broeders 2006; Saks 2010). This study uses a "line-up" method of visual identification, which is the first part of the method suggested by Saks (2010) to avoid making a false assumption of individualization, but it cannot utilize the second part because it involves DNA analysis. However, since the identity of the individuals that provided radiographs for this study is known, we can make general assumptions about the utility of the maxillary sinuses for identification purposes from the results of the visual comparison survey. Prior probabilities can also be used to introduce uncertainty to future calculations of individuality, but this was not used in this research due to the small sample size associated with the preliminary geometric shape analysis (Biedermann et al. 2007).

Another issue with using the maxillary sinuses as a means of positive identification is that in general, they are more susceptible to change than the frontal sinuses. While the frontal sinuses are generally only affected infrequently by trauma or disease, the maxillary sinuses can be greatly affected by antemortem tooth loss or implantation, trauma, and infection (Lee et al. 2010). In addition, there is evidence in the results from this research to suggest that orthodontic manipulation of the dentition also causes change in the shape of the maxillary sinuses, since two of the individuals who provided two of their panoramic radiographs for inclusion in this study had orthodontic braces at the time one of the radiographs was taken. The sinus outlines of these individuals showed very little grouping tendencies in the principal components analysis of the elliptical Fourier descriptors (Figures 3, 4, 5), although participants in the visual matching survey were still able to identify the correct postmortem radiograph for these individuals with a high degree of accuracy. Because of this, the medical and dental history of the individual in question is something that should be taken into consideration when deciding whether to use a positive identification method, especially one involving the maxillary sinuses. Future research should examine a larger sample of individuals with these potentially confounding dental issues and determine whether methods of positive identification using the maxillary sinuses are appropriate for use in these cases.

Finally, an issue with using panoramic radiography in a positive identification method is that the technology used to examine the maxillofacial areas in dental situations may change rapidly in the near future. Some dentist offices, especially those in more populated areas, are beginning to adapt a new three-dimensional panoramic radiograph technique that is not compatible with the two-dimensional version used in this research (Syn 2014, personal communication). Along the same vein, some dentist offices in less populated areas have not yet adapted the two-dimensional panoramic radiograph into their practices because of the immense start-up costs associated with the purchase of the necessary equipment. This leads to an issue of differential utility of this method even within what would normally be considered the same geographic area, something that this research was hoping to avoid. However, the differential adaption of panoramic radiography in dental practices could also make it possible to use this method in a forensic setting for longer than would normally be expected. In addition to replicating this research with a larger sample size, future research should examine whether a method of positive identification from the maxillary sinuses could also be used with the new three-dimensional panoramic radiograph technology. Because of the length of time needed to build an adequate sample size of radiographs from living people and the need for the three-dimensional panoramic radiograph to go into relatively common use before enough data can be collected, this research will take some time to complete.

A final way in which accuracy could possibly be improved for maxillary sinus comparison techniques is by developing a protocol for what practitioners would look for when attempting to make a comparison, similar to what is already employed in fingerprint analysis methods. This could involve identifying areas of the maxillary sinus that are particularly variable in a population and are therefore useful for presumptive or positive identification of an individual. The floor of the maxillary sinuses appears to fit this criterion, since this region is highly variable and is influenced by both tooth position and sinus size. Future research should develop and test a matching protocol using specific areas of comparison.

CHAPTER FIVE

CONCLUSION

Overall, the results from the survey indicate that people with little to no experience can correctly select the matching panoramic radiograph based on the maxillary sinus region with a relatively high degree of accuracy. Academic standing, field of study, and previous completion of an osteology class did not have a significant effect on the correct matching percentages obtained from the survey. This deviates from the generally accepted statement that success at radiograph matching is positively correlated with increased education and increased experience. Given the potential impacts of these two future research directives, the correct matching percentages obtained from this survey should be used as a tentative baseline, not an end result for the success rate of this method. Despite the limitations associated with this survey, the percentages obtained from the survey indicate that there is an observable similarity in the maxillary sinus area of two panoramic radiographs from the same individual and noticeable differences from radiographs from other individuals, since the obtained percentages were much higher than would be expected if the radiographs were selected by the participants at random. This is important information to know before doing a more intensive research study, and it can be concluded from these results that the maxillary sinuses from the same individual are relatively stable over time, enough to be successfully compared by people with little to no experience and using radiographs that were taken at different times.

The results from the survey support the first hypothesis, since the correct matching and lineup percentages were significantly greater than the percentages that would have been expected if the radiographs were selected at random by the survey participants (50% and 25% respectively). This confirms that the maxillary sinus area of panoramic radiographs can be individualized to a person with a relatively high degree of accuracy, which indicates that they could potentially be used as a positive identification method. However, the second hypothesis was not supported by the survey data, since significant differences in radiograph matching and lineup success rates were not observed between undergraduate participants and graduate participants. This could be due to the small sample size of graduate student participants, since more undergraduate students than graduate students participated in the survey. This could also be due to the fact that very few of the survey participants had any radiograph comparison experience, and it may be that previous radiograph comparison experience is the main influencing factor in the differences in matching success rates obtained by Sholl and Moody (2001).

When combined with the results from the preliminary geometric morphometrics analysis, these results indicate that the maxillary sinus area as seen in panoramic radiographs can be used as a method of positive identification with relatively high accuracy. This is consistent with results found from visual and geometric analysis of the frontal sinuses and preliminary results based on visual matching of the maxillary sinuses. Academic standing and radiograph comparison experience did not have a significant impact on the visual matching success rates, but these results may have been impacted by small sample sizes, especially in the case of the radiograph comparison experience variable. Future research will examine if the visual comparison success rate can be raised by individuals with radiograph comparison experience in order to conform to Daubert standards of evidence admission in court.

The results from the preliminary geometric morphometric analysis of the shape of the maxillary sinuses also indicates that the maxillary sinuses have properties that could be individualizing, but these results are less conclusive than the results from the visual comparison survey due to the nature of principal components. Future research will expand the sample size of this data set and compare the shapes of the sinus outlines using likelihood ratios to further assess any similarities in maxillary sinus shape between and within individuals.

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