# AGE ASSESSMENT FROM CRANIAL SUTURE CLOSURE

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AGE ASSESSMENT FROM CRANIAL SUTURE CLOSURE

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## DEDICATION

I would like to dedicate this thesis to my parents, Galen and Karen Millard, for their encouragement and support of my education, and my new husband Ian Helms for his love and time spent online providing comfort and assistance throughout graduate school.

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# ABSTRACT

AGE ASSESSMENT FROM CRANIAL SUTURE CLOSURE

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Cranial suture closure is a controversial method of age assessment which can be useful in forensic cases with a cranium and no sexable postcrania, which amount to 45% of the cases submitted to the FDB (Shirley 2011). The goals of this study are to determine if significant sex or ancestry differences exist in the rate of cranial suture closure, to test the rates of intra-observer and inter-observer error associated with cranial suture closure as a method of age assessment, and to compare the age distribution of a sample from the Pima County Office of the Medical Examiner derived from cranial suture closure to the known age distribution of a separate sample from the same location published by Anderson (2008). A modern, representative sample of individuals from the William M. Bass Donated Skeletal Collection, Forensic Anthropology Data Bank, Pima County Office of the Medical Examiner, and the Texas State Donated Skeletal

Collection are used for the statistical analyses, which include independent samples t-tests and analysis of covariance. The results indicate that sex and ancestry differences are not significant for this sample. Rates of intra-observer error are high for individual suture locations, however rates for the vault and lateral-anterior systems are only 10% and 20%, respectively. The results of the PCOME test suggest a tendency of cranial suture closure to overage. These findings indicate a need for improvement of this method, which may begin with basic definitions as well as the application of more robust statistical methods.

# CHAPTER I

## INTRODUCTION

Age estimation is an integral part of the biological profile employed by forensic anthropologists in order to assist in achieving an identification of an unknown deceased individual. The biological profile consists of sex, age, ancestry, and stature estimations, which can be compared to missing persons reports. Even if a tentative identification is not made, this profile narrows the search and limits the amount of DNA testing necessary for a positive identification, saving resources for law enforcement agencies.

Age estimates can be achieved in several ways, including macroscopic examination of dental development and eruption, epiphyseal union of long bones, degeneration of pelvic articular surfaces, sternal rib ends, and cranial sutures, as well as microscopic examination of bone in histological analysis (Buikstra and Ubelaker 1994, Komar and Buikstra 2008). Due to the progressive development of bones, aging of skeletons under the age of 25 can be more easily accomplished utilizing the order of epiphyseal fusion in the long bones (Anderson et al. 2010). Between infancy and 17 to 20 years of age, dental eruption is also a reliable indicator of age (Brooks 1955). The closure of the spheno-occipital suture usually occurs between 20 and 25 years of age, and fusion of the medial clavicle usually occurs between the ages of 25 and 28 (Brooks 1955). Aging of unidentified skeletons past the late 20's becomes more difficult, a problem for which methods using degeneration of the pelvis, rib ends, and cranial suture closure were developed. Post-maturation, the adult skeleton is constantly degenerating. These degenerative changes are not as easily or as well documented as developmental changes; they can be influenced by factors including habitual activities and the health of an individual in addition to their age (Anderson et al. 2010). It follows that age estimates for adults are often very broad. In addition, macroscopic methods for adult age assessment typically do not provide error rates. The 1993 ruling in *Daubert vs. Merrell Dow Pharmaceuticals* requires that forensic experts substantiate their assertions with scientifically tested methods and, in particular, probability assessments (Dirkmaat 2008).

Analysis of the pubic symphysis and auricular surface of the pelvis is considered the most reliable macroscopic individual methods of aging for adults (Buikstra and Ubelaker 1994, Komar and Buikstra 2008). The pubic symphysis is the more widely accepted method; however the auricular surface is often better preserved in forensic and archaeological contexts (Lovejoy et al. 1985). Degenerative changes in the sternal end of the right fourth rib can be used to estimate age of an adult (Komar and Buikstra 2008). Most reviews of this method are positive, however it was developed and tested on small samples (Komar and Buikstra 2008). These methods separate individuals by both sex and ancestry prior to aging (Işçan et al. 1984, Buikstra and Ubelaker 1994). Finally, cranial suture closure can be utilized to estimate age at death. The idea that cranial bones fuse progressively with age has been in existence since at least the 16$^{th}$ century (White 2000); however, its utilization as a method of age assessment has been quite controversial since the mid 20$^{th}$ century. Today it is still utilized in the absence of other evidence or in conjunction with other methods.

Synostosis, or closure of the sutures, occurs when small tongues of ossified tissue stretch across the sutural gap and link up slowly along the length of the suture until the union is complete (Singer 1953). Cranial sutures generally fuse with increasing age, although there is considerable variability in closure rates and patterns (Masset 1989). This variability leads to the question of the value of cranial suture closure as a method of estimating age at death. In addition, the standard methods established for scoring cranial suture closure are often criticized for subjectivity and a lack of quantitative analysis (Singer 1953, Brooks 1955, Key et al. 1994, Hershkovitz et al. 1997). Several studies in more recent years have promoted the use of cranial suture closure with the condition that appropriate statistical analysis is applied to the data (Johnson 1976, Meindl and Lovejoy 1985, Masset 1989, Nawrocki 1998, Boldsen et al. 2002). These studies are the result of a trend towards improvement in quantitative methods in forensic anthropology, further encouraged by the Supreme Court decision in *Daubert vs. Merrell Dow Pharmaceuticals* (1993) (Grivas and Komar 2008).

The majority of the literature recommends a multifactorial approach to estimating age at death when appropriate (Todd and Lyon 1924, Brooks 1955, Johnson 1976, Meindl and Lovejoy 1985, Buikstra and Ubelaker 1994, Komar and Buikstra 2008). Multifactorial methods make use of as many age indicators as are available. Unfortunately, multifactorial methods are often not possible due to poorly preserved skeletons. In the Southwestern United States, along the border of Mexico with California, New Mexico, and Texas, citizens primarily from Mexico but also other South American countries die while attempting to illegally cross into the United States. In these cases it is not unusual for incomplete skeletons to be recovered due to scavenging and harsh, isolated conditions (Anderson 2008). The Forensic Anthropology Data Bank, created by researchers at the University of Tennessee, is a large database which consists of anthropological data collected from forensic cases by forensic anthropologists and medical examiners around the country. Of the cases submitted to the Forensic Anthropology Data Bank, 45% consist of a skull with no sexable postcranial elements (Shirley 2011). This would indicate that the os coxae are not present, which are the preferred indicator of aging for adults (Buikstra and Ubelaker 1994). The anthropologist often does not have the opportunity to see the remains *in situ* or search the scene for more elements. What information can be gained from an isolated cranium is fundamental to the goal of producing positive identifications for these deceased individuals.

This study will use a modern, diverse sample and robust statistical analysis to improve and strengthen the reliability and applicability of age estimation from cranial suture closure. Significant disagreement exists in the body of cranial suture literature as to whether population specific methods are necessary (i.e., Todd and Lyon 1924, 1925a,b,c, Baker 1984, Meindl and Lovejoy 1985, Nawrocki 1998); however, in recent years forensic anthropology has been moving towards population specific methods. Though cranial suture closure and its relationship to age at death has been studied since the 16th century, previous studies testing its reliability have included only limited ancestral groups (Bolk 1915, Todd 1924, 1925a,b,c, Brooks 1955, Baker 1984, Meindl and Lovejoy 1985, Key et al. 1994). These samples are often from historic skeletal collections such as the Terry and Todd Collections, which consist of individuals with dates of birth between the 1800's and early 1900's (Anderson et al. 2010). Studies in craniometrics suggest there are problems associated with grouping ancestral groups together for purposes of analysis (Relethford 2004, Spradley et al. 2008). Different ancestral groups have unique population histories which lead to significant craniometric differences in shape and size (Relethford 2004); this can be extrapolated to possibly include varying patterns of suture closure. The sample for this thesis includes only modern skeletal data from individuals of American White, American Black, and Hispanic ancestry, consisting of new and pre-existing data from the William M. Bass Donated Skeletal Collection, Forensic Anthropology Databank (FDB), the Pima County Office of the Medical Examiner (PCOME), and the Texas State Donated Skeletal Collection. American White, American Black, and Hispanic groups are currently the largest in the United States (U.S. Census Bureau). These samples will be utilized to test for significant ancestral and sex differences, test rates of intra-observer and inter-observer error, and to test age distributions derived from the Meindl and Lovejoy (1985) method of cranial suture closure with an age distribution for a similar sample published by Anderson (2008).

In the Chapter 2, a literature review spanning the last four centuries of research on the correlation between age and degree of cranial suture closure is provided. Chapter 3 details the sample composition for this study, as well as the methodology used for scoring and the statistical methods selected for analyses. The results of these analyses are reported in Chapter 4 and a discussion of the results is found in Chapter 5, with a conclusion in Chapter 6.

# CHAPTER II

## LITERATURE REVIEW

### Introduction

Cranial sutures have long been acknowledged to have a relationship with age in humans. Since the 16th century this method of age assessment has been studied in various populations with several methods introduced to produce the most accurate results (Masset 1989). In more recent decades, many studies discussing the lack of accuracy and reliability of the various methods have been published (Singer 1953, Brooks 1955, Key et al. 1994, Hershkovitz et al. 1997). However, in most cases, the use of cranial suture closure is still recommended as part of the biological profile, if only in conjunction with other methods of aging (Todd and Lyon 1924, Johnson 1976, Meindl and Lovejoy 1985, Masset 1989, Boldsen et al. 2002). Examination of cranial sutures can be a useful and noninvasive technique in age estimation. In addition, crania are durable in forensic and archaeological contexts and are often the single element recovered (Masset 1989, Boldsen et al. 2002). However, due to recent studies, the use of cranial sutures as an individual method of aging are generally not considered reliable (Singer 1953, Brooks 1955, Key et al. 1994, Hershkovitz et al. 1997).

## Age Assessment from Cranial Sutures

The process of suture obliteration, or synostosis, occurs when small tongues of ossified tissue stretch across the sutural gap and link up slowly along the length of the suture until the union is complete (Singer 1953). Cranial sutures are generally acknowledged to fuse with increasing age, although there is considerable variability in closure rates and patterns (Buikstra and Ubelaker 1994). Suture closure generally commences in the sagittal suture at approximately 22 years of age, followed by the coronal and lambdoid sutures, with complete union around 47 years of age (Johnson 1976). Examples of younger individuals with complete suture obliteration and older individuals with partial or no closure are often reported as outliers in cranial suture studies (Bolk 1915, Todd and Lyon 1924, 1925 a,b,c). According to Rogers and Allard, the partial obliteration of sutures in older adults occurs in about 3.5% of the population (2004). This variability is what some authors suggest devalues cranial suture closure as a method of accurately assessing age at death (Singer 1953, Brooks 1955, Hershkovitz et al. 1997, Sahni 2005). Various methods have been published utilizing various combinations of endocranial, ectocranial, and palatal sutures (Todd and Lyon 1924, 1925a,b,c, Baker 1984, Meindl and Lovejoy 1985, Nawrocki 1998). There tends to be a higher error rate in the use of ectocranial sutures, probably as a result of the fact that ectocranial sutures close gradually while endocranial sutures tend to be either completely open or completely closed (Key et al. 1994). Sutures have also been found to close earlier on the endocranial surface (Sahni 2005). Buikstra and Ubelaker's *Standards for Data Collection* suggests a composite method of assessing cranial suture closure based on the methods developed by Todd and Lyon (1924, 1925a,b,c), Baker (1984), Meindl and Lovejoy (1985), and Mann and colleagues (1987) in order to increase accuracy (1994). Ten ectocranial, four palatal, and three endocranial suture locations are scored between "0" (open) and "3" (complete obliteration). The one centimeter area of the suture location is scored for the ectocranial sutures, particular segments of the endocranial sutures are scored, and the full length of the palatine sutures are scored. Based on these observations, the individual is assigned to the young adult (20-34 years), middle adult (35-49 years), or old adult (50+) category (Buikstra and Ubelaker 1994).

## History of Cranial Suture Research

In the early years of cranial suture research, from the 16th century to the beginning of the 18th century, studies and results were widely varied. Vesalius and his student Fallopius first noted the obliteration of sutures with age (Montagu 1938). During the 1800's research was conducted on other aspects of cranial change with respect to aging, such as changes in skull diameter and thickening of the cranial bone. Pommerol studied normal and pathological synostosis in different ancestral groups, but was limited to such a small sample that his work was not considered particularly useful (Pommerol 1869). Welcker established four age classes for crania, and noted that while impressed with the value of cranial suture closure as a method of aging, his findings were often contradictory. He also noticed great individual variation up to the age of seven years, which is again noted by Bolk in 1915 (Welcker 1862). Sauvage studied cranial suture closure in a sample of 126 adult crania, and found that the process of obliteration begins endocranially, usually at age 45, and that ectocranial sutures are rarely obliterated (Sauvage 1870). Topinard wrote that he did not hold cranial suture closure in high esteem for aging (Topinard 1885).

In the 1890's, European researchers Ferraz de Macedo and Aranzadi each conducted a study with an extremely large sample. Ferraz de Macedo used a sample of 1000 skulls, which he separated into ten year age categories based on cranial suture closure (Masset 1989). In 1913 Aranzadi used a sample of 2000 skulls of known age and sex for his research. Despite the large sample sizes of these studies, they have gone largely unnoticed in forensic anthropology because they have been overshadowed by the research of Frédéric in Europe and Todd and Lyon in the United States (Masset 1989). Frédéric (1906) was from Strasbourg, and published in a widely circulated German journal. His sample size included only 287 European skulls of known age and sex, and although his method lacked precision, it became the standard in Europe (Masset 1989). Frédéric himself found cranial suture closure to be of little value due to individual variation (Montagu 1938).

In 1908 Zanolli assessed a small sample of 45 Italian crania and found suture obliteration to be an extremely variable process which occurs earlier in males than females. Zanolli also noted that the process of obliteration is more regular in females (Zanolli 1908).

In 1915, Bolk calculated the absolute frequency of premature obliteration in a sample of 1,820 juvenile European skulls. His purpose was to test the frequency of premature suture closure and determine if it was pathological or physiological in nature. The metopic suture is the only suture which closes in childhood; all other sutures usually fuse in adulthood. Therefore, premature suture closure is defined as any of those persisting sutures fusing prior to adulthood. In 19% of the sample, premature obliteration was observed in one or more sutures (Bolk 1915). Bolk attributed this larger than expected finding to the frequent obliteration of the masto-occipital suture. The frequency of partial closure or complete obliteration of the masto-occipital suture was found to be so high that Bolk doubted it should be considered anomalous. The sagittal suture followed the lambdoid in frequency of premature closure. Bolk found that the highest frequency of multiple sutures prematurely closed were the masto-occipital and sagittal, which suggested to him that the premature closure of one lead to an increased tendency for premature closure in the other. Premature closure also occurred along the coronal, squamosal, fronto-sphenoidal, and spheno-parietal sutures, although in extremely rare instances. Bolk noted that in cases in which the metopic suture remained open past the second or third year of life, there was a decreased tendency for fusion in general (1915). Based on his findings, Bolk argued it is unlikely that premature synostosis is pathological in nature. His reasons included the consistent commencement of closure of the sagittal suture at obelion, which would most likely be inconsistent if it were due to a pathological condition. It also seemed unlikely that one isolated suture would close prematurely if a pathological condition were to blame. Bolk also acknowledged crania in his sample which did show symptoms of rickets or syphilis, but indicated that there was no increased tendency among that sample to show premature suture closure. Bolk concluded that premature closure of sutures is likely an atavistic, or ancestral, characteristic since other primates commence suture closure immediately following the completion of skull formation.

Lenhossek, in 1916, studied the crania of 216 subadults from four months of age to 14 years of age. In many of the crania Lenhossek found obliteration of one or more sutures, most frequently the occipito-mastoid (Montagu 1938). These findings are in agreement with Bolk's statement that premature closure is not pathological and actually quite common.

In 1920 Hrdlička found cranial sutures suitable only to divide crania into the following age groups: subadult, adult, or senile. His study utilized the spheno-occipital or basilar suture, long bone epiphyses, dental development, condition of the teeth and alveolar processes, as well as the state of the vault sutures. Hrdlička found the spheno-occipital suture to be the most reliable characteristic, but also stated that the obliteration of sutures could be useful in conjunction with other characteristics (Hrdlička 1920).

Todd and Lyon's research on cranial suture obliteration in the 1920's was the most utilized and reviewed research in age assessment by cranial suture closure in the United States until the 1980's. Rather than age determination, Todd and Lyon were looking for a regular, or modal, pattern of suture closure. In 1924 and 1925, Todd and Lyon published a series of four papers discussing cranial suture closure and its relation to ancestry and sex, although the only populations represented in the study are American Whites and American Blacks. Todd and Lyon began with a sample of 1000 crania from the Hamann-Todd Collection, and rejected any of unknown age or without a complete postcranial skeleton, reducing the sample size to 514. Another 81 crania were excluded on the basis of being anomalous. The anomalies included precocious union of sutures or premature closure, lack of endocranial closure in vault sutures, achondroplasia, or lack of endocranial closure of any cranial sutures (Todd and Lyon 1924). The final sample included males and females between the ages of 18 and 84 years old. The conclusions of the study are based on the male crania since the female samples were much smaller. The researchers chose to follow Frédéric's classification for the degree of suture closure: "0" for open sutures, "1" for one quarter fusion, "2" for up to one half fusion, "3" for three quarters fusion, and "4" for complete fusion. In cases of "lapsed union", or incomplete union of the suture due to a build-up of bone tissue along the edges of the unclosed portion, Todd and Lyon classified the suture as closed (1924). Sutures were first scored for the American White males. Todd and Lyon observed individual variation despite rejecting such a large quantity of "anomalous" crania, but maintained that a definite trend exists in the progress of suture closure in relation to age (1924).

In the three papers published following the Todd and Lyon 1924 publication outlined above, the authors investigated the difference between endocranial and ectocranial suture closure in American White and American Black male crania. A clear orderly age sequence was observed in the process of suture closure. Sex, ancestry, cephalic index and cranial capacity had very little effect on the sequence of closure. However, ectocranial closure was observed to be slower, more erratic, and less complete than endocranial closure. Timing of the sequence was more obvious endocranially. Lapsed union was characteristic of all ectocranial sutures, although not in all individuals. Todd and Lyon selected a second sample of thirty crania to test their findings. They found they were able to estimate age within 20 years of the actual age at death. In their conclusion, they maintain that cranial suture closure should be used in conjunction with other skeletal indicators in estimation of age at death (Todd and Lyon 1924).

The two methods of Frédéric and Todd and Lyon produced very different results, had small sample sizes and major statistical issues which lead to the disrepute of the entire concept of age assessment from cranial suture closure (Masset 1989). Research since the time of Frédéric and Todd and Lyon has only further obscured the issue.

Woo (1949) produced one of the few studies relating ancestry and suture closure. In particular, Woo studied the relationship between frontal curvature and metopism in American Whites, American Blacks, American Indians and Asians (1949). Metopism is a condition in which the metopic suture remains unfused. Traces of metopism were observed most often in the Asian sample, followed by the American Blacks and finally American Whites (Woo 1949). In the American Indian group, Woo did not find metopism in any of the adult skulls. The Asian and American White crania had a very similar percentage of complete metopism, which was rare in the American Black sample. Woo also observed that skulls with complete metopism had a greater frontal curvature than those without, and skulls with traces of metopism generally had greater curvature than those without. Since Woo found ancestral differences in the frontal curvature, he concluded that ancestral differences exist in degree of metopic suture closure (Woo 1949). These findings support the possibility of ancestral differences in the rate or pattern of cranial suture closure in general, although age estimation was not the focus of Woo's study.

In 1953, Singer reported on the unreliability of age estimation from cranial suture closure. The report is largely a critique of the willingness of researchers over the previous 100 years to follow Todd and Lyon's series of reports. Their work was widely accepted until the late 20$^{th}$ century, despite the fact that researchers prior to Todd and Lyon did not have a high opinion of suture closure as an indication of age (Singer 1953). Some of the concerns Singer discussed with Todd and Lyon's research include the manipulation of data, elimination of crania showing irregular suture closure, lack of inclusion of female crania in the sample, and 'smoothing out' of graph curves. Despite these glaring issues, this misleading research was often quoted in court (Singer 1953). Singer concluded that in any individual skull, the age at death cannot be estimated from the degree of closure of the various cranial sutures because there is simply too much variability (1953).

Another report on the unreliability of cranial suture closure as a method of estimating age at death was published by Brooks in 1955. Brooks used a sample of aboriginal California Indian crania from the University of California Museum of Anthropology and American White and American Black crania from Case Western Reserve University to test the reliability of Todd's method of aging by cranial suture closure. Brooks also wished to determine whether or not it was applicable to ancestral groups other than the American White and Blacks on which it was developed, and compare it with Todd's method of aging based on pubic symphysis morphology. The author found that cranial age estimates, even from endocranial sutures which were recommended by Todd and Lyon, correlated poorly to the known ages and should only be used with caution. Cranial suture closure as a method of aging was found to be unreliable, particularly for females. Cranial suture closure ages for females lagged between five and 25 years behind the pubic symphysis ages. For males, cranial suture ages lagged five to eight years behind pubic symphysis ages (Brooks 1955). In agreement with Singer (1953), Brooks concluded that cranial suture closure is an unreliable method for age estimation, and advocated the use of multiple methods of aging when possible (1955). However, Brooks' study uses a prehistoric test sample for which known ages are unavailable. It is important to both develop and test methods for age at death estimation on modern populations.

Johnson studied age assessment in a cemetery sample of 213 crania from Lancashire, United Kingdom using both dental attrition and cranial suture closure (1976). Johnson's focus was on statistical analyses of these methods, in particular least-squares regression and discriminant function analysis. Johnson found that when the crania were divided into groups of older or younger than 35 years for the sagittal suture and older or younger than 40 years for the other sutures, over 50% of the skulls were categorized correctly (1976). The multifactorial method using the combination of dental attrition and cranial suture closure improved age estimation in the majority of skulls as compared with estimations based on a single variable. Crania of individuals under the age of 20 were more easily aged by dental attrition, while individuals past the age of 50 were extremely difficult to age by either method. Since the current United States population on average lives past the age of 50, this result is particularly discouraging. Experience of the assessor was listed as a possible factor in accuracy of age assessments (Johnson 1976). Individual variation was also discussed in that a lack of suture closure should not necessarily be taken as an indication of youth (Johnson 1976).

## Cranial Suture Research 1980-Present

The long period of criticism of existing research in cranial suture closure led the method to be considered a last resort for age at death assessment. Beginning in the 1980's, several new studies were published in attempts to improve it. Part of this momentum is a result of a trend towards improvement in quantitative methods which became a goal of forensic anthropology during the end of the 20$^{th}$ century. This is largely a product of the 1993 Supreme Court decision in *Daubert vs. Merrell Dow Pharmaceuticals*, which led to the development of the *Daubert* criteria. These criteria stress that testable, replicable, reliable, and scientifically valid methods must be used to justify scientific opinions (Dirkmaat et al. 2008). In order for forensic anthropological methods of identification to be acceptable in court, improvements in quantification were necessary. As a result, the more recent research on age assessment from cranial suture closure includes the use of statistical methods such as linear regression, likelihood ratios, or multivariate analysis (Johnson 1976, Masset 1989, Nawrocki 1998).

It has been established that early studies did not use diverse samples (Bolk 1915, Todd and Lyon 1924, 1925a,b,c, Brooks 1955, Baker 1984, Meindl and Lovejoy 1985, Key et al. 1994). In 1984, Baker conducted a study which included American White, American Black, Mexican-American and Asian-American individuals from the Los Angeles County Medical Examiner's Office. This is the first study to include Americans of Hispanic origin; unfortunately, the Mexican-Americans were arbitrarily grouped with the American White sample. The sample also included a larger number of older adult individuals. The sutures were scored as open, partially closed, or closed. Baker found that age ranges developed from cranial suture closure were often very broad, and not particularly helpful. Baker did find variation in the rate of suture closure between the sexes and ancestral groups, and therefore progressively narrower age ranges can be developed for individuals of known sex and ancestry (1984).

In 1985, Meindl and Lovejoy published a new method for estimating age at death based on the degree of cranial suture closure. In Meindl and Lovejoy's study, the ectocranial sutures of a sample of 236 crania from the Hamann-Todd Collection were scored on a scale from "0" to "3". Despite Todd and Lyon's assertion that endocranial suture closure is more reliable, the authors chose to focus on ectocranial sutures based on a need in the forensic community for methods to age older individuals (Meindl and Lovejoy 1985). Meindl and Lovejoy reasoned that the set of sites selected for the purposes of developing a method appropriate for aging forensic cases should contain some sutures which demonstrate a protracted sequence of closure; in other words, they do not close early in life. Seventeen points were selected and the one centimeter length surrounding the suture locations were scored. Each site should also correlate moderately with age within the primary period of its activity, and some information from each suture should be unique (Meindl and Lovejoy 1985). Some sites were of restricted value and therefore rejected. The remaining sites were divided into the vault system and the lateral-anterior system, the latter of which proved the best overall predictor of age (Meindl and Lovejoy 1985). It was also recommended that the lateral-anterior sites would be most valuable for a forensic system of age determination. Composite scores are calculated from the sum of site scores for both the lateral-anterior sutures and the vault sutures. These composite scores correlate to stages which each provide an age range and a mean age.

The results of the study indicated that the lateral-anterior system provided the best estimate for a skull of unknown age, and was more useful in the older age range. The lateral-anterior system had another advantage over the traditional vault system; the mean deviations obtained in ectocranial scoring were half of those obtained with the vault system (Meindl and Lovejoy 1985). Remembering that the only ancestral groups included in this study were American White and American Black, Meindl and Lovejoy concluded that there were no ancestral or sexual biases in aging by cranial suture closure, despite previous reports (Woo 1949, Brooks 1955). The authors advocated the use of as many criteria as possible when attempting to assess the age of an unknown individual, and urged caution when using cranial suture closure (Meindl and Lovejoy 1985).

In 1989, Masset researched the different kinds of systematic errors which could have an effect on results of age assessment by cranial suture closure. His reference population was the Lisbon collection of 849 crania of known age from the 19th century. Masset discussed sexual difference as the first major source of error. Whether sexual dimorphism has an effect on cranial suture closure is debated, and Masset found that the only significant difference was in the middle-aged category (Masset 1989). In previous studies which denied any difference, Masset asserted they did not have a large enough group of females between the ages of 30 and 49, and that the differences can be observed in all cranial collections large enough. If sexual differences were not noted, there was a tendency to underestimate the age of every female skull which was incompletely fused (Masset 1989).

The composition by age of the reference population was the second underlying cause for error listed (Masset 1989). For example, between two groups of crania, if one group is composed of only skulls between 20 and 40, and another is composed of only skulls over 50, the age at which there is a complete lack of synostosis will be very different (Masset 1989). These discrepancies lead to differences between authors' results, and as seen with Frédéric and Todd and Lyon, differences in analysis between countries. In order to avoid this source of error, Masset suggested the combination of several populations for statistical study in order to create several populations identical in sex and occurrence of synostosis, differing only in distribution of age at death (Masset 1989).

If anthropologists attribute every cranium the age corresponding to its degree of synostosis, the errors are often more in one direction than the other. Masset calls the tendency of uncompensated errors committed in the outer age categories to accumulate in the middle-aged categories the "attraction of the middle" (1989). This was the third source of error. To avoid it, Masset suggests that instead of attributing an estimated age to the subject, a set of probabilities be created relating the subject to each of the different age categories; in other words, he suggests the creation of a probability profile (Masset 1989).

In order to investigate the value of cranial suture closure as an indicator of age, Key and colleagues (1994) tested three age estimation techniques from ectocranial and/or endocranial sutures on a sample of known age from a cemetery in Spitalfields, London. The three techniques were those developed by Acsádi and Nemeskéri (1970), Perizonius (1984), and Meindl and Lovejoy (1985). The sample included 183 skulls, from a total sample of 387. Only those skulls complete enough to provide a full set of cranial suture data were used. The Acsádi and Nemeskéri method utilizes endocranial sutures, and can be used to distinguish young and middle-aged individuals but does not provide information for crania over the age of 50 years (Acsádi and Nemeskéri 1970). In this study, the authors found an overall poor relationship between the mean closure scores and the known age. This lack of success was attributed to individual variation for which there was no obvious explanation (Key et al. 1994). Since endocranial suture closure occurs at a younger age, it is completed relatively early in the overall lifespan. Therefore, the Acsádi and Nemeskéri (1970) method only reflected age in younger individuals. Meindl and Lovejoy (1985) suggested that their technique is particularly accurate in the older age ranges. The mean ages produced by the Meindl and Lovejoy method on the Spitalfields sample were considerably different from the known ages of the sample. Key and colleagues (1994) found that this particular sample showed more delayed suture closure. This difference suggested care should be taken when applying a method which has been developed with one reference sample on a different sample (Key et al. 1994). Males and females in this sample also showed significant correlation between sex and degree of cranial suture closure. Males tended to exhibit more advanced closure than females, particularly at the coronal and sagittal sutures (Key et al. 1994). The Perizonius (1984) system utilizes both ectocranial and endocranial sutures, and suggests that older and younger individuals (with 50 years as the median point) should be assessed using different endocranial and ectocranial sutural sites according to their approximate age group (Key et al. 1994). In this case, the Perizonius (1984) system failed to recognize half of the young skulls in that category, and there was a lack of correspondence between the older skulls and the scoring system used for them (Key et al. 1994).

Key and colleagues (1994) found the methods of both Meindl and Lovejoy and Perizonius to be subject to such complicating factors as sexual dimorphism. Additionally, all three studies agreed that ectocranial sutures were more susceptible than endocranial sutures to interpopulation variation. Key and colleagues hypothesized a major problem with the tested techniques to be their reliance on mean closure scores rather than assessment of individual suture closure sites. Using individual suture closure sites, the anthropologist can choose not to assess the age of a skull which clearly does not fit with the reference population from which the particular method was developed (Key et al. 1994). The authors acknowledged a large amount of individual variation in suture closure patterns, and suggested further testing on varied populations and primate species to determine the geographical, temporal and ethnic associations, and also the function of cranial sutures in order to further understand the association between age and synostosis (Key et al. 1994). While the authors made it clear that the categories in this study were subjective and non-measurable quantities used as class identifiers, Key and colleagues' study continued the trend towards the use of statistical methods in age assessment through cranial suture closure by providing error estimates and significance tests for each of the methods.

Hershkovitz and colleagues (1997) studied the sagittal suture in 3,636 skulls from the Hamann-Todd and Terry Collections to determine if there was a significant correlation between age and degree of suture closure. The authors suggested a possible relationship between pathological stressors and suture closure, particularly tuberculosis and hyperostosis frontalis interna (1997). This study was a direct response to Meindl and Lovejoy's (1985) suggestion for a large scale blind test of suture status in age assessment (Hershkovitz et al. 1997). Overall, it was a critique of aging by cranial suture closure which stated that the standardized methods are based on two arbitrary assumptions: 1) that the degree of suture closure is a normal progressive process, and 2) that different ontogenic processes operate in different segments of the same suture. There is no factual basis for either of these assumptions and their application is subjective (Hershkovitz et al. 1997). In Hershkovitz and colleagues' study, the conditions of suture closure were defined metrically and separated into five categories instead of the usual four. The results showed a similar frequency distribution of suture categories in males of all age groups after 35 years, which does not lend the method to the forensics arena. Females demonstrated a different and more expected pattern, in which the frequency of skulls with open sutures steadily decreased with age while the frequency of skulls with closed sutures steadily increased. In all cohorts, until the age of 65, significantly more females had open sutures (Hershkovitz et al. 1997). These results suggest that cranial suture closure is sexually biased. Ancestral differences were examined based on the commonality of the "double Y" type suture, or the complete closure of the sagittal suture while the lambdoid and coronal sutures remain completely open. This pattern was more common in American Black males than American White males, but there was little difference among female groups. No association was found between the two pathological stressors and cranial suture closure. Hershkovitz and colleagues (1997) suggested that in light of these results, cranial suture closure patterns may be genetically predetermined. It was well established by this point in the research that they are sexually biased, and more studies have found ancestral differences. Hershkovitz and colleagues cite another study by Kanisius and Luke (1994) in which ancestral biases were found to be significant between Europeans and Australian Aborigines, and research which reports austosomal dominant and recessive patterns of premature suture closure patterns (1997). The authors suggested that if genetic predisposition is a factor, biological adaptation may also be an influence (Hershkovitz et al. 1997). In summary, Hershkovitz and colleagues did find sex and ancestral biases, possibly as a result of genetic differences (1997).

Nawrocki (1998) performed one of the most recent and applicable studies on cranial suture closure, though with a relatively small sample. Nawrocki examined ectocranial, endocranial, and palatine sutures in a sample of 100 crania from the Terry Collection. Two individuals from each ancestry and sex category were chosen for each half decade, and no crania were removed from the sample barring damage. Nawrocki followed Meindl and Lovejoy's method of scoring for 16 ectocranial, seven endocranial, and four palatine sutures. A second sample consisting of 61 White individuals was obtained from medical dissection rooms in order to test the first sample's results (Nawrocki 1998). Nawrocki found a moderately strong correlation between the score and age of the Terry sample crania. A least scores linear regression equation was then constructed to predict age for an unknown case, which ranged between 25.3 and 82.8 years (an improvement on Meindl and Lovejoy's range of 30.5 to 56.2 years) (Nawrocki 1998). Nawrocki then created an equation to test the effects of ancestry and sex on suture closure rates, finding a correlation between suture closure and sex, but not ancestry. However, Nawrocki did observe an interaction between ancestry and sex (1998). The author suggested that discrepancies between the reference population and a second population resulted from sampling error and secular trends (Nawrocki 1998). Nawrocki emphasized the importance of the reference sample, proper statistical methods, and sources of error.

In 2005, Nawrocki and Zambrano reported at the American Association of Physical Anthropology meetings that based on the results of an analysis of variance, there are significant differences in the rate and/or pattern of suture closure between the sexes and among ancestral groups. Nawrocki and Zambrano's study utilized European- and African-American individuals from the Terry Collection and a modern forensic sample of only European-Americans.

Sahni and colleagues (2005) investigated age assessment from cranial suture closure in a modern sample of individuals from Northwestern India. 538 males and 127 females over the age of eighteen for a total of 665 individuals composed the sample. Sutures were recorded only as “open” or “closed”. Up to fifty percent closure was categorized as open. Sutures were divided up into segments as opposed to using the traditional suture locations for scoring. Sahni and coworkers found that obliteration begins earlier in males than in females, begins earlier on the endocranial surface, and that commencement and obliteration is so erratic it is not useful for estimating age. Since previous research showed that long bone epiphyses fuse earlier in Indians than in western Caucasians, the authors expected the same pattern in cranial sutures as well. This was not the case (Sahni et al. 2005).

In 2007, in an effort to reduce the subjectivity and quantify age estimations from cranial suture closure, Kirk utilized laser technology to measure the amount of light reflected off of a suture joint. The sample consisted of 196 Black male crania from the Hamann-Todd Collection, and the standard suture scores were collected as well as Meindl and Lovejoy’s (1985) landmarks. A general trend of decreasing measurements with increasing age was observed (Kirk 2007).

In 2008, Cray Jr. and colleagues studied the modal progression of ectocranial suture closure in primates, including *Homo sapiens*, *Pan troglodytes*, and *Gorilla gorilla*. It was hypothesized that based on the phylogenetic relationships, all three species would have similar patterns of closure. The results of the study showed that while all three showed a similar lateral-anterior closure pattern, *G. gorilla* had a unique closure pattern from *H. sapiens* and *P. troglodytes*, whose patterns both followed strong posterior to anterior gradients (Cray Jr. et al. 2008).

# Conclusion

Forensic anthropology continues to be an evolving field of study, not simply an application of standard methods (Komar and Buikstra 2008). The current methods of age assessment from cranial suture closure have been developed from historic skeletal reference samples including largely American White, American Black, and European White individuals (Spradley 2008). With the development of any anthropological technique, it is recommended to use a reference sample which is representative of the population on which the technique will be used. According to the U.S. Census Bureau, the White, Hispanic, and Black populations are currently the first, second, and third largest in the country. Particularly in the United States, with the large number of unidentified border crossers in Southwestern medical examiner's offices, it is important to improve cranial suture closure techniques and include individuals referred to as Hispanic in the sample. While it is understood that population-specific studies should be conducted where possible, for the purposes of this paper Hispanics will be defined as Spanish-speaking peoples who may originate from a variety of countries.

Often the samples used in previous studies were not particularly large due to limited availability of skeletal populations for research. Some early samples included one to two thousand individuals, and yet included only historic European Whites (Masset 1989). More recent samples attempt to make use of more modern data, which has limited the sample size to one or two hundred. In addition, significant disagreement exists as to the value of age assessment from cranial suture closure. This disagreement is partially due to the various sample compositions and statistical methods used in different studies, but the method is also often criticized for its subjectivity, lack of quantification, and lack of accuracy. It is agreed that sutures generally fuse with increasing age, and that certain patterns of fusion exist. It is also agreed that significant individual variation in pattern and rate of closure exist. Reliability studies conducted in the mid-20$^{th}$ century found existing methods to be lacking in accuracy and applicability to populations other than the reference sample. However, beginning in the late 1970's and 1980's, new methods of statistical analysis applied to cranial suture closure were found to somewhat improve this method of age estimation. Following the 1993 ruling in *Daubert vs. Merrell Dow Pharmaceuticals*, researchers in the various fields of forensic science have even more motivation to increase quantification of existing methods and use methods of statistical analyses which provide error estimates. Not only does the use of more robust statistical methods increase the accuracy of our techniques for age assessment, but they help age assessment conform to the *Daubert* criteria (Komar and Buikstra 2008). Consistently, researchers have promoted the use of a combination of several skeletal traits for age estimation; however, in archaeological and forensic contexts, multiple skeletal elements are often not available for analysis.

This thesis will take into account the body of literature on cranial suture closure and attempt to provide a refined consensus on the value of the method, namely by testing the method for ancestral and sex differences on a sample more representative of the current United States population as identified by the U.S. Census Bureau. In addition, intra-observer and inter-observer error tests will provide a quantitative assessment of the effectiveness of the method. Finally, the method will be tested on a sample from the

PCOME and the resulting age distribution will be compared to one published by Anderson (2008) for the PCOME spanning 2001 through 2007.

# CHAPTER III

## MATERIALS & METHODS

### Materials

Samples

The samples for this study are taken from the William M. Bass Donated Skeletal Collection at The University of Tennessee in Knoxville, the Forensic Anthropology Data Bank (FDB), the Pima County Office of the Medical Examiner in Tucson, Arizona (PCOME), and the Texas State Donated Skeletal Collection. The William M. Bass Donated Skeletal Collection sample consists of 112 crania, 25 of which are American Black, five are Hispanic, and 82 are American White. 38 individuals are female and 74 are male (Table 1). 120 crania from this collection were originally examined, however only individuals with a specific known age (i.e., not “30’s”) and a single identified ancestral category are included in the analysis. Data was collected from some crania with two or more self-reported ancestral groups, and these were not included in the analyses as the purpose is to identify ancestral differences in rate of suture closure.

Two hundred and thirty-six individuals with a known age, single ancestral category and a full set of ectocranial suture scores from the FDB are included, 132 of which are female and 141 are male. Sixty-three of the individuals are American Black, 193 are American White, and 17 are Hispanic (Table 1). In both the William M. Bass and FDB samples, only the American White, American Black and Hispanic individuals are included in the analysis since they compose the largest ancestral groups within the United States as well as the William M. Bass Donated Skeletal Collection and the FDB. The PCOME sample consists of 80 crania, the majority of which are unidentified and therefore do not have a known age or ancestry; however, ancestry is presumed to be Hispanic based on the context in which the remains are found. The fatalities from the PCOME included in this sample are usually found in the desert south of Tucson, Arizona and north of the U.S. and Mexico border, an area which is known to be used for trafficking undocumented border crossers (Anderson 2008). Two of these individuals have been identified at the time of this writing, a 13 year old Hispanic female and a 27-28 year old Hispanic male. For the purposes of the analysis in this study, the positively identified male's age is set at 27. The adult male is included with the William M. Bass and FDB samples. Any individuals under the age of 18 were not included in the combined sample, as more reliable methods exist for aging immature remains.

The samples discussed above compose the combined dataset used in the analysis of covariance to determine whether ancestral differences exist in the progression of cranial suture closure relative to age. This dataset has a total sample size of 350, a mean age of 46.43 years, 145 females and 205 males. Seventy-seven of these individuals are American Black, 252 are American White, and 21 are Hispanic. The minimum age is 18 and the maximum is 99. The distribution of the combined sample including the William M. Bass Donated Skeletal Collection, FDB, and PCOME by age and ancestry can be seen in Table 1. Age distributions of the combined sample by sex and ancestry can be seen in Figures 1-5.

**Table 1: Distribution of the combined sample including crania from the William M. Bass Donated Skeletal Collection, the FDB, and the PCOME by age and ancestry.**

| Age Category | White Female | White Male | Black Female | Black Male | Hispanic Male | Hispanic Female | Total Females | Total Males |
|---|---|---|---|---|---|---|---|---|
| 18-29 | 33 | 21 | 10 | 11 | 8 | 2 | 46 | 40 |
| 30-39 | 24 | 25 | 7 | 8 | 3 | 3 | 34 | 36 |
| 40-49 | 9 | 21 | 2 | 13 | 3 | 0 | 11 | 37 |
| 50-59 | 12 | 29 | 3 | 8 | 0 | 1 | 16 | 37 |
| 60-69 | 13 | 19 | 2 | 1 | 0 | 0 | 15 | 20 |
| 70+ | 21 | 25 | 3 | 9 | 1 | 0 | 24 | 35 |
| Total | 112 | 140 | 27 | 50 | 15 | 6 | 145 | 205 |

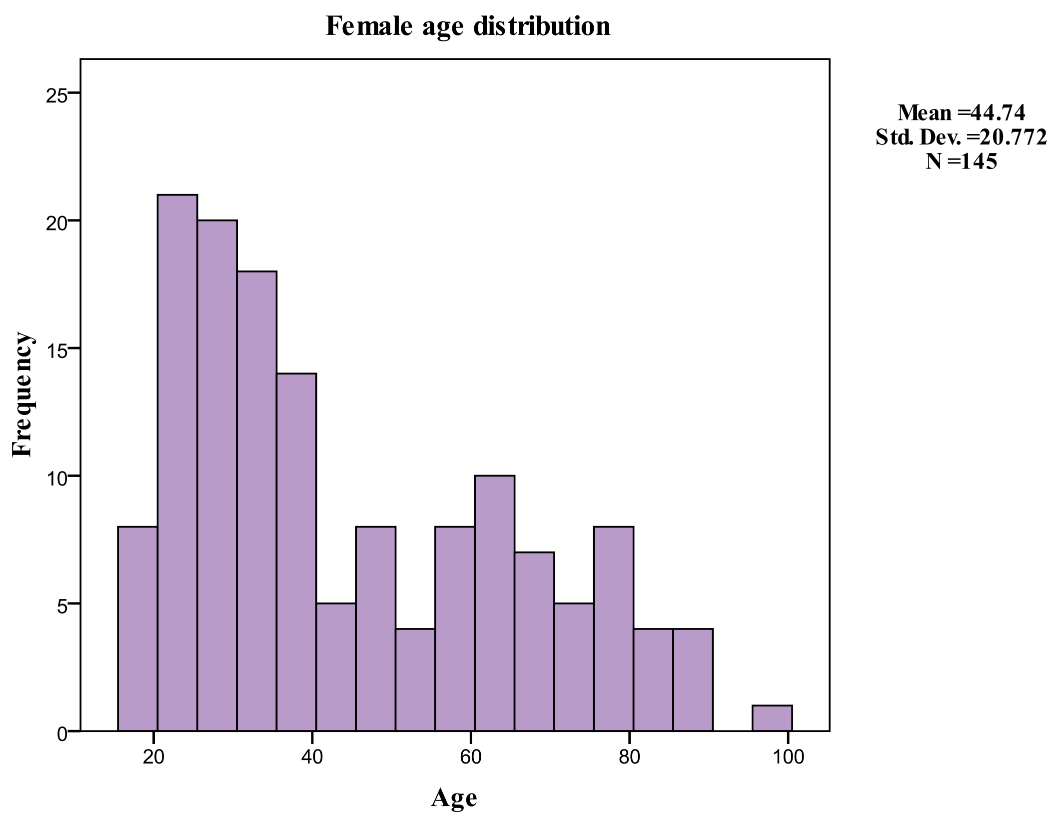


**Figure 1: Female age distribution of the combined sample including crania from the William M. Bass Donated Skeletal Collection, the FDB, and the PCOME.**

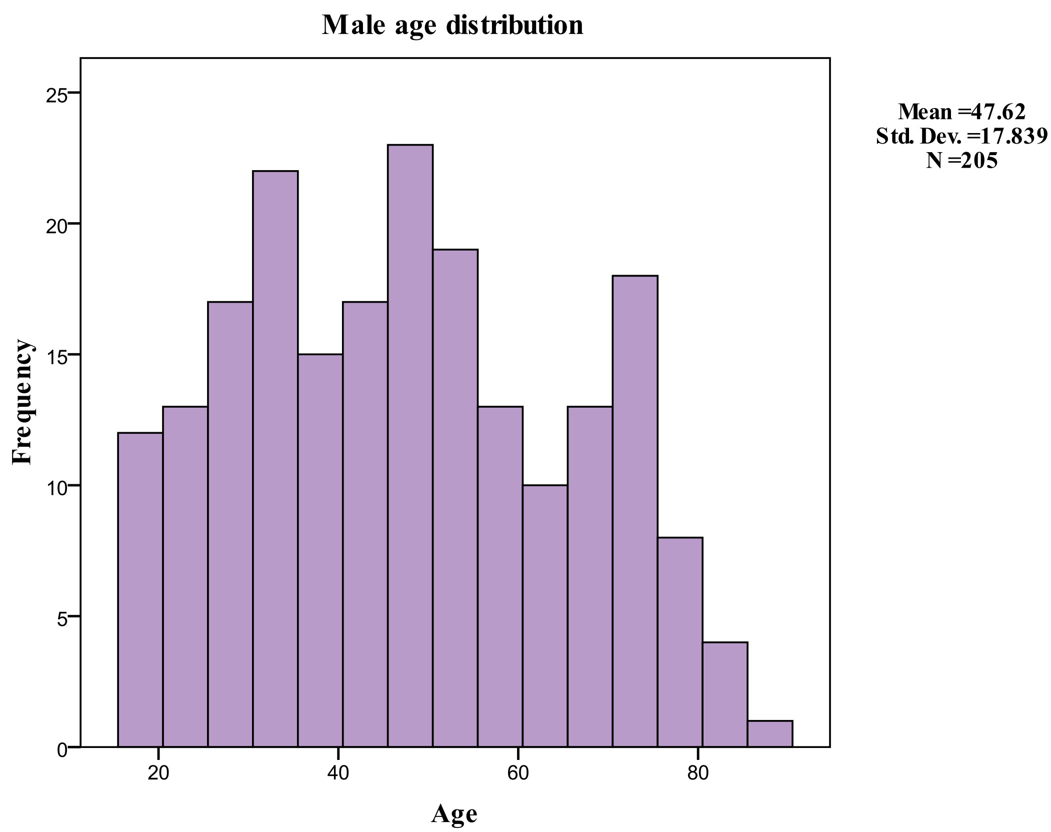


**Figure 2: Male age distribution of the combined sample including crania from the William M. Bass Donated Skeletal Collection, the FDB, and the PCOME.**

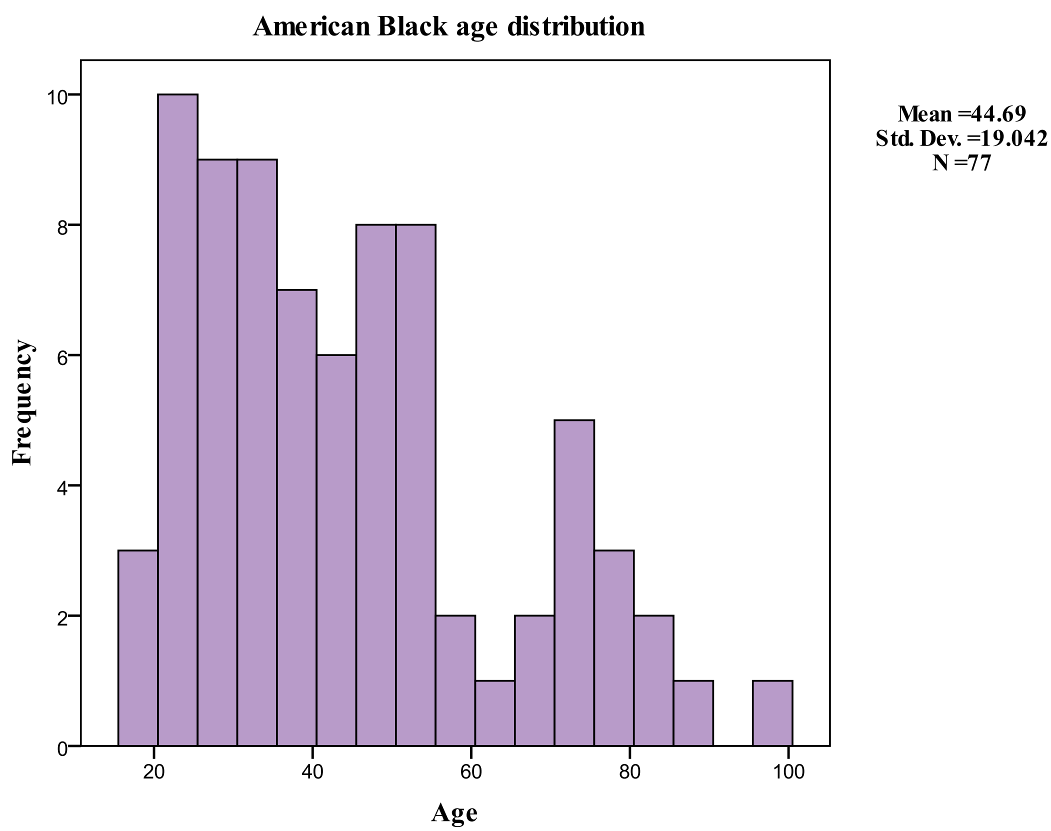


**Figure 3: American Black age distribution of the combined sample including crania from the William M. Bass Donated Skeletal Collection, the FDB, and the PCOME.**

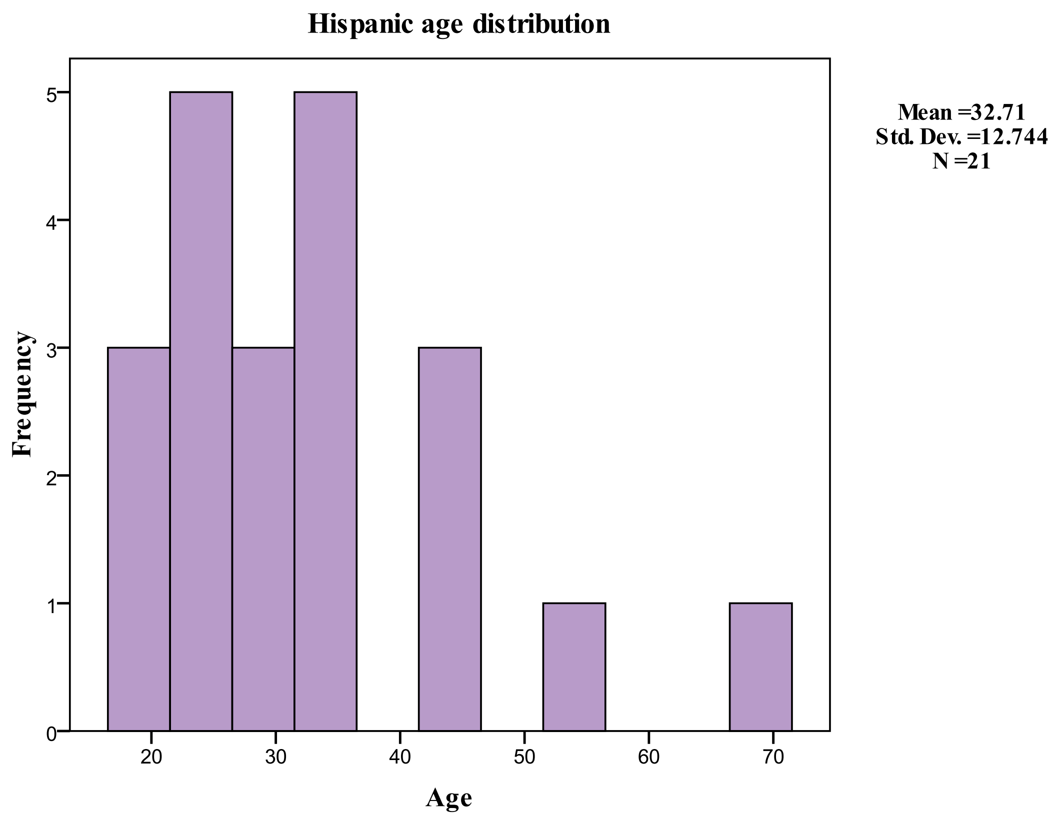


**Figure 4: Hispanic age distribution of the combined sample including crania from the William M. Bass Donated Skeletal Collection, the FDB, and the PCOME.**

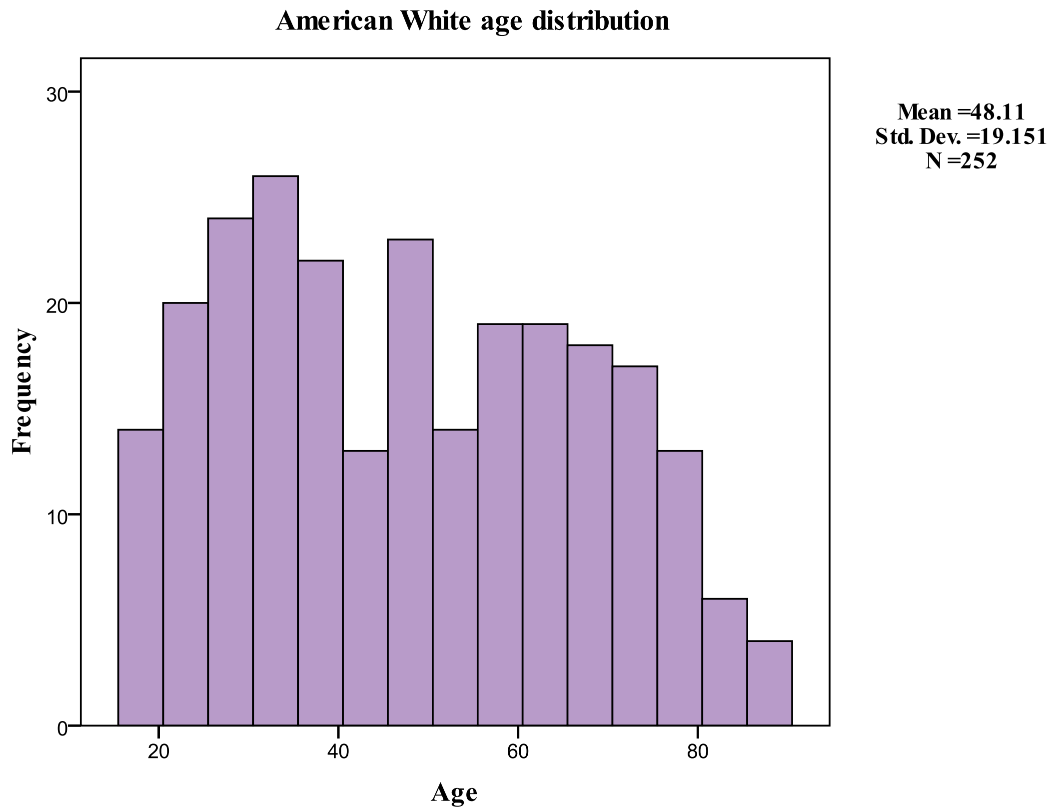


**Figure 5: American White age distribution of the combined sample including crania from the William M. Bass Donated Skeletal Collection, the FDB, and the PCOME.**

The Texas State Donated Skeletal Collection sample consists of ten individuals of known age and self-reported ancestry, between the ages of 32 and 87. The sample is equally distributed between males and females, however these individuals are all of American White ancestry with only one Hispanic individual (Table 2). This sample is not included with the William M. Bass Donated Skeletal Collection, FDB, and PCOME samples for the analysis of covariance, and is only used for the intra-observer and inter-observer error tests.

**Table 2: Texas State University summary statistics**

| Sample | Mean Age | Min Age | Max Age | Female | Male | American Black | American White | Hispanic |
|---|---|---|---|---|---|---|---|---|
| Texas State | 63.10 | 32 | 87 | 5 | 5 | 0 | 9 | 1 |

## Methods

### Data Collection

All crania in this study were scored using the method outlined by Meindl and Lovejoy (1985). The ten ectocranial sites scored are listed and defined in Table 3.

**Table 3: Ectocranial suture observation sites (Meindl and Lovejoy 1985)**

| | |
|---|---|
| ***(1) Midlambdoid*** | Midpoint of each half of the lambdoid suture (in "pars intermedia" of the lambdoid suture) |
| ***(2) Lambda*** | At lambda (in "pars lambdica" of sagittal and "pars lambdica" of lambdoid sutures) |
| ***(3) Obelion*** | At obelion (in "pars obelica" of the sagittal suture) |
| ***(4) Anterior Sagittal*** | Point on the sagittal suture at the juncture of the anterior one-third and posterior two-thirds of its length (usually near the juncture of the "pars bregmatica" and "pars verticis" of the sagittal suture) |
| ***(5) Bregma*** | At bregma (at "pars bregmatica" of the coronal and "pars bregmatica" of the sagittal sutures) |
| ***(6) Midcoronal*** | Midpoint of each half of the coronal suture (in "pars complicata" of the coronal suture) |
| ***(7) Pterion*** | At pterion, the region of the upper portion of the greater wing of the sphenoid, usually the point at which the parietosphenoid suture meets the frontal bone |
| ***(8) Sphenofrontal*** | Midpoint of the sphenofrontal suture |
| ***(9) Inferior Sphenotemporal*** | Point of the sphenotemporal suture lying at its intersection with a line connecting both articular tubercles of the temporomandibular joint |
| ***(10) Superior Sphenotemporal*** | Point on the sphenotemporal suture lying 2 cm below its juncture with the parietal bone |

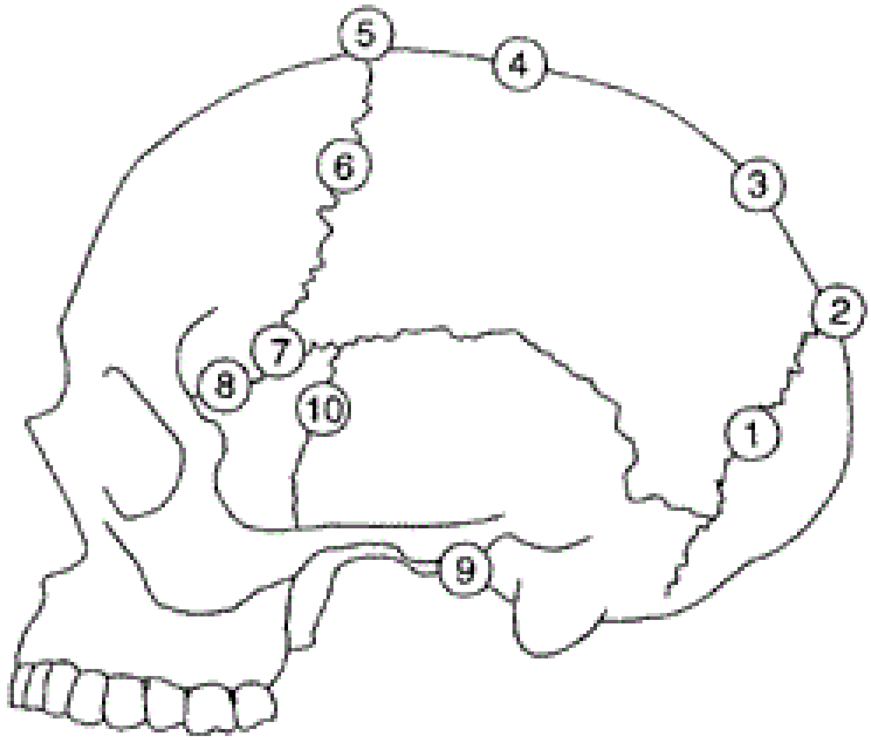


**Figure 6: Location of sites to be used to record ectocranial suture closure. Drawing by P. Walker (after Mann et al. 1987; Meindl and Lovejoy 1985: 59; Todd and Lyon 1924, 1925a-c).**

Figure 6 shows a lateral view of the cranial vault with the numbered locations of the ectocranial suture sites scored with this method. The names of the locations with corresponding numbers are provided in Table 3. A photo of the inferior sphenotemporal location (#9 in Figure 6) used in this study is provided in Figure 7 as the definition in Meindl and Lovejoy (1985) is unclear. The definition of this location references the "articular tubercles of the temporomandibular joint" (Table 3), which do not exist on the human skull. A single articular eminence forms the anterior portion of the temporomandibular articular surface (White 2000), which is suspected to be what Meindl and Lovejoy (1985) refer to as the two articular tubercles. This location is found at the point of intersection between the sphenotemporal suture and a perpendicular line drawn across the articular eminence of the temporomandibular articular surface.

**Figure 7: Inferior sphenotemporal suture location.**

The data sheet provided by *Standards for Data Collection from Human Skeletal Remains* was used for data collection in this study (Buikstra and Ubelaker 1994). All sutures were scored on the left side barring damage, in which case it was noted on the data sheet which sutures were scored on the right side.

Only the one centimeter area surrounding the suture observation site was scored, between "0" and "3". A score of "0" indicates a completely open suture, "1" indicates the suture is less than 50% closed but includes even a single tongue of bone reaching across the suture, "2" indicates greater than 50% closure, and "3" indicates complete obliteration of the suture (Meindl and Lovejoy 1985). Examples of these stages are provided for both the vault and lateral-anterior systems in Figures 8 and 9. In some circumstances, the suture location was difficult to score due to variation. For example, when scoring bregma, if the sagittal portion was completely fused and the coronal portion was completely open, the suture location was scored a “1”. In cases where endocranial fusion can be seen from the ectocranial surface, but the ectocranial suture is open, the suture location is also scored a “1”.

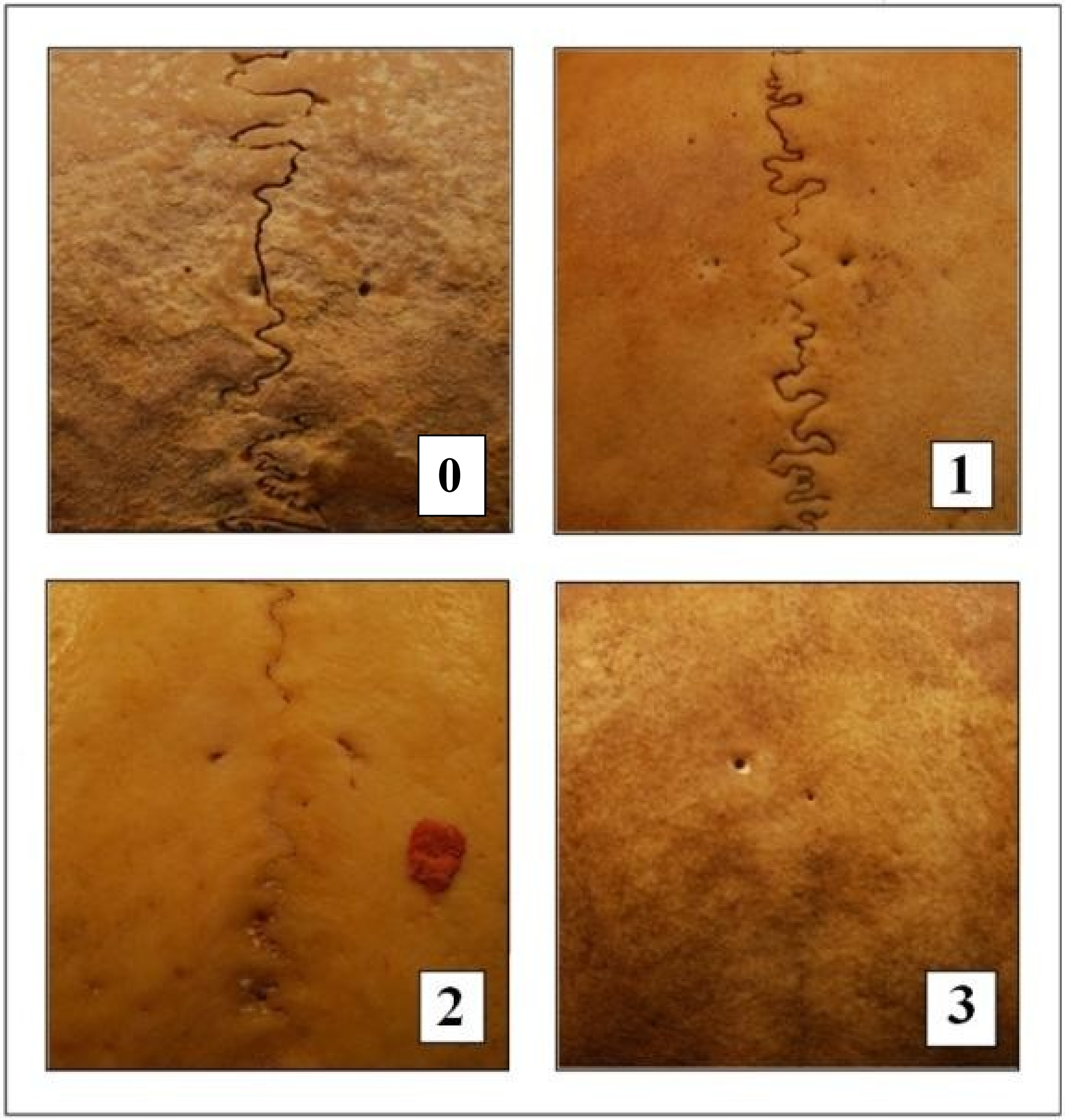


**Figure 8: Vault suture closure stages. Illustration of degrees of closure for sagittal suture at obelion. Texas State Donated Skeletal Collection.**

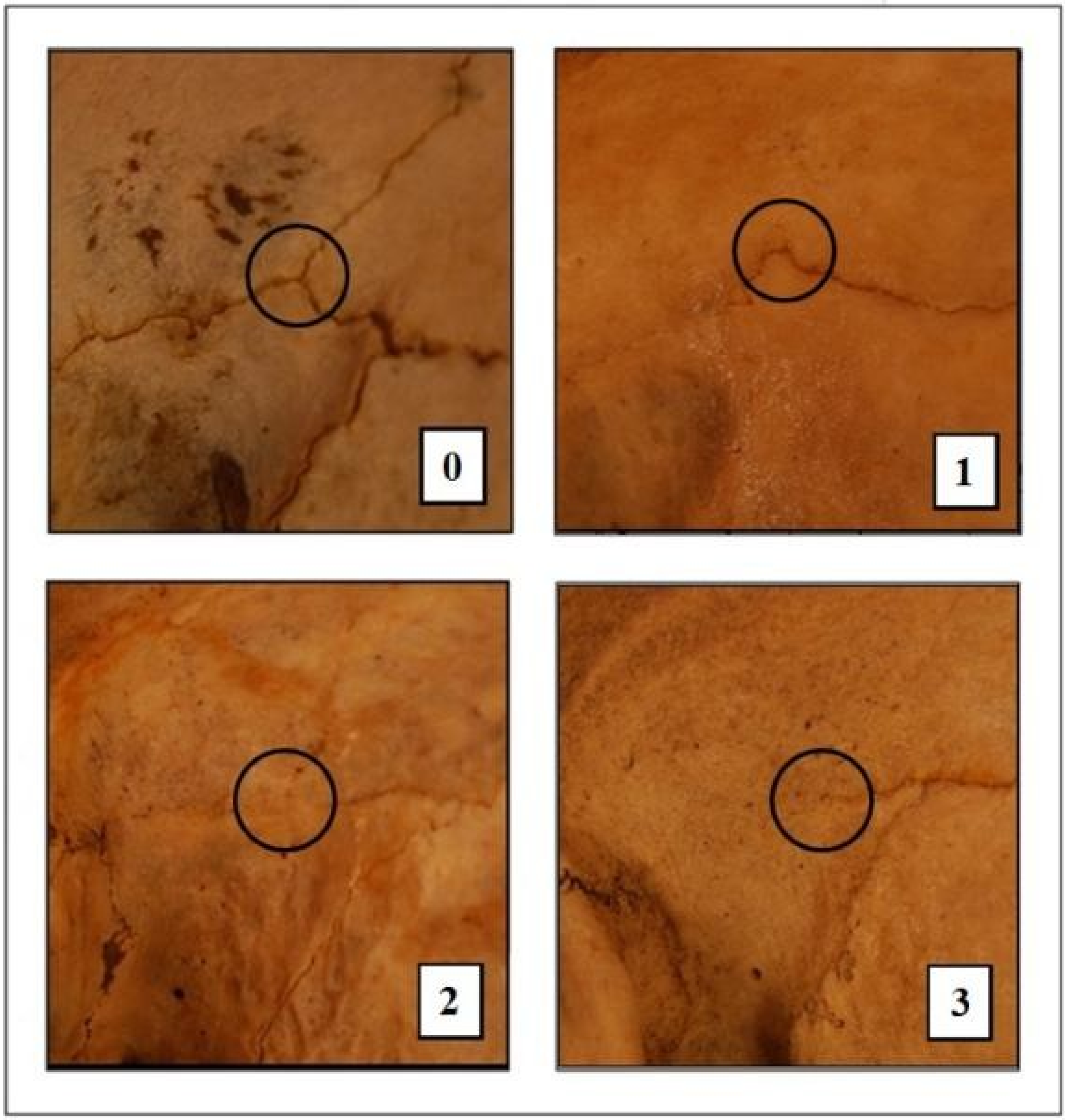


**Figure 9: Lateral-Anterior suture closure stages. Illustration of degrees of closure for pterion. Texas State Donated Skeletal Collection.**

Sites were not scored if they were obscured by dirt or tissue. Next, the scores were added together to create two composite scores, one for the vault system and one for the lateral-anterior System. The vault system includes the first seven sutures, and the lateral-anterior System includes the last five (midcoronal and pterion are included in both systems) (Table 3). These two scores correspond to age ranges and mean ages from Meindl and Lovejoy (1985).

The Forensic Anthropology Data Bank sample is used in this study to round out the age and ancestral biases in the William M. Bass Donated Skeletal Collection sample. All of the samples were combined to first test for significant ancestral differences using an ANCOVA run in SAS/STAT® Version 9.1.2. These William M. Bass and FDB samples were used to test the accuracy of the Meindl and Lovejoy (1985) method of aging by cranial sutures. The PCOME sample is assumed to be mostly Southwestern Hispanic, based on context of the remains when discovered. This sample is used to compare the age ranges calculated with cranial suture closure to the distribution of ages for undocumented border crossers reported by Dr. Bruce Anderson in 2008. The sample from Texas State University provided the data for both inter-observer and intra-observer error tests.

Intra-observer Error

The sample of ten crania from the Forensic Anthropology Center at Texas State (FACTS) was scored twice by the author, approximately two weeks apart, in order to provide data for an intra-observer error test. Precision and accuracy were both considerations in this test. Precision is the percentage of cases for which trial one and trial two evaluations conflict. Accuracy is evaluated by comparing the assessment of each cranium to the recorded ages of the identified individuals (Rogers 2005). Accuracy basically tests how often the method correctly ages, while precision tests how often one observer comes to the same conclusion. First precision was calculated for each suture site by comparing the author's scores from trial one and trial two (Table 4). The accuracy rates for the vault and lateral-anterior systems was calculated by first determining whether or not the age ranges provided by the score for each donation actually encompassed the known age of the individual. The number of correct evaluations for each system was added to find an overall accuracy rate for both the vault and lateral-anterior systems. The results can be seen in Tables 4 and 5.

Inter-observer Error

In order to test inter-observer error rates using the ectocranial suture closure method, a first year graduate student from Texas State's forensic anthropology program scored six of the same donations scored by the author. The student was instructed to read through the section on scoring cranial suture closure in *Standards* (Buikstra and Ubelaker 1994) and to follow those instructions for scoring the ten ectocranial and four palatine suture locations. These instructions include the definitions for the suture locations from Meindl and Lovejoy (1985), as well as photographic examples of vault sutures scored "0" through "3". Independent samples t-tests were performed on each of the suture sites scored as well as the summed suture score for both the vault and lateral-anterior systems.

ANCOVA

Next, analyses of covariance were performed using the general linear model (PROC GLM) in SAS/STAT® Software Version 9.1.2 to test for significant ancestral and sex differences in both the vault and the lateral-anterior suture systems. The Type III Sum of Squares, which analyzes the effect of each variable after controlling for the effects of all other variables in the model, ia relied on to determine significance. In the case of significant biases resulting from ancestry or sex, the samples should be separated for further testing of the method.

PCOME Test

Sixty-two individuals from the original 80 are included in this analysis, as the remaining 18 did not have a full set of ectocranial suture scores due to damage. The composite score for each individual was used to find the correct stage for both the vault and the lateral-anterior, which correlates to an age range and a mean age. Anderson (2008) reported a mean age of undocumented border crosser fatalities over a five year period (2001-2006) as 30.5 years. Therefore, the vault and lateral-anterior mean ages were averaged for each individual. These mean ages were then grouped in ten year age groups according to those reported in Anderson's (2008) article, and the percentage of each age group compared between the PCOME sample and the numbers reported in Anderson (2008).

# CHAPTER IV

## RESULTS

### Intra-observer Error

The average intra-observer error for all suture sites was 40.3%. The individual intra-observer error rate for each site is listed below in Table 4. The accepted level of intra-observer error is 10% (Rogers 2005). For overall stage, one result of the ten crania for the two vault trials was different, giving a 10% error rate. Two results of the ten crania for the two lateral-anterior trials were different, giving a 20% error rate.

**Table 4: Intra-observer error rates for individual suture sites**

| | |
|---|---|
| Midlambdoid | 30% |
| Lambda | 40% |
| Obelion | 10% |
| Anterior Sagittal | 60% |
| Bregma | 60% |
| Midcoronal | 70% |
| Pterion | 40% |
| Sphenofrontal | 30% |
| Inferior Sphenotemporal | 50% |
| Superior Sphenotemporal | 30% |
| Incisive | 30% |
| Anterior Median Palatine | 40% |
| Posterior Median Palatine | 40% |
| Transverse Palatine | 60% |
| Spheno-occipital | 25% |

The accuracy rates for the ten scored crania for each trial can be found in Table 5. Both the vault and lateral-anterior systems performed poorly in terms of correctly scoring the individual into the proper stage which would encompass the individual's known age. In trial 2, the lateral-anterior system performed marginally better.

**Table 5: Accuracy rates for the vault and lateral-anterior systems**

| | Vault | Lateral-anterior |
|---|---|---|
| Trial 1 | 50% | 50% |
| Trial 2 | 40% | 30% |

## Inter-observer Error

Of all of the suture sites, only the sphenofrontal and the palatine sutures produced significant levels of inter-observer error (Table 6). The p-values are shown in bold.

**Table 6: Inter-observer error rates for all suture sites**

| | Levene's test for equality of variances | | t-test for Equality of Means | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | 95% Confidence Interval of the Difference | |
| | F | Sig. | t | df | **Sig. (2-tailed)** | Mean Difference | Std. Error Difference | Lower | Upper |
| Midlambdoid | .000 | 1.000 | .000 | 10 | **1.000** | .000 | .298 | -.664 | .664 |
| Lambda | 7.656 | ,020 | -.349 | 10 | **.734** | -.167 | .477 | -1.230 | .897 |
| Obelion | .000 | 1.000 | .000 | 10 | **1.000** | .000 | .471 | -1.050 | 1.050 |
| Anterior Sagittal | .328 | .580 | -.447 | 10 | **.664** | -.167 | .373 | -.997 | .664 |
| Bregma | .225 | .646 | -1.103 | 10 | **.296** | -.500 | .453 | -1.510 | .510 |
| Midcoronal | 1.712 | .220 | .953 | 10 | **.363** | .333 | .350 | -.446 | 1.112 |
| Pterion | .094 | .765 | -.877 | 10 | **.401** | -.333 | .380 | -1.180 | .513 |
| Sphenofrontal | .328 | .580 | 2.236 | 10 | **.049** | .833 | .373 | .003 | 1.664 |
| Inferior Sphenotemporal | .625 | .448 | -.542 | 10 | **.599** | -.167 | .307 | -.851 | .518 |
| Superior Sphenotemporal | .625 | .448 | -.542 | 10 | **.599** | -.167 | .307 | -.851 | .518 |
| Incisive | . | . | -2.236 | 10 | **.049** | -.500 | .224 | -.998 | -.002 |
| Anterior | 1.712 | .220 | -3.814 | 10 | **.003** | -1.333 | .350 | -2.112 | -.554 |

| Table 6, continued | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Posterior | 1.607 | .234 | -1.861 | 10 | **.092** | -.500 | .269 | -1.099 | .099 |
| Transverse | 1.712 | .220 | -2.860 | 10 | **.017** | -1.000 | .350 | -1.779 | -.221 |
| Vault Sum | .078 | .786 | -.479 | 10 | **.642** | -.833 | 1.740 | -4.710 | 3.044 |
| Lateral-anterior Sum | 1.951 | .193 | .504 | 10 | **.625** | .500 | .992 | -1.709 | 2.709 |

## ANCOVA

The results of the analysis of covariance show that ancestry, sex, and the interaction between ancestry and sex are not significant for either the vault or the lateral-anterior system at the 0.05 level (Tables 7 and 8).

**Table 7: Vault ANCOVA results**

| Dependent Variable | Source | DF | Type III SS | Mean Square | F value | Pr>F |
|---|---|---|---|---|---|---|
| Score | Ancestry | 2 | 185.4818364 | 92.7409182 | 2.72 | **0.0676** |
| | Sex | 1 | 89.7706190 | 89.7706190 | 2.63 | **0.1059** |
| | Ancestry*Sex | 2 | 15.2101037 | 7.6050519 | 0.22 | **0.8005** |

**Table 8: Lateral-Anterior ANCOVA results**

| Dependent Variable | Source | DF | Type III SS | Mean Square | F value | Pr>F |
|---|---|---|---|---|---|---|
| Score | Ancestry | 2 | 29.59734743 | 14.79867371 | 0.81 | **0.4459** |
| | Sex | 1 | 28.74800165 | 28.74800165 | 1.57 | **0.2107** |
| | Ancestry*Sex | 2 | 18.09803424 | 9.04901712 | 0.50 | **0.6100** |

These results indicate the samples may not need to be separated by ancestry or sex for future testing of the method.

## PCOME TEST

The results of the comparison between the PCOME age distribution of border crosser fatalities and one calculated from cranial suture closure can be found below in Table 9. The age distribution reported by Anderson (2008) indicates that the majority of border crosser fatalities are between 21 and 40 years of age, with a mean of 30.5 years. The age distribution calculated from the PCOME sample in this study shows the majority of fatalities between 31 and 50, with an average of 42.76 years, suggesting a tendency of cranial suture closure to overage in this sample.

**Table 9: Comparison of actual age distribution of border crosser fatalities and an age distribution of border crosser fatalities calculated with cranial suture closure**

| | <21 | 21-30 | 31-40 | 41-50 | >51 | Mean Age |
|---|---|---|---|---|---|---|
| Anderson (2008) | 18.3% | 37.2% | 26.6% | 13.21% | 4.7% | 30.5 years |
| Millard | 0% | 0% | 27.4% | 62.9% | 9.7% | 42.76 years |

# CHAPTER V

## DISCUSSION

### Methodology

While cranial suture closure is regarded as one of the simplest methods of age assessment in forensic anthropology, it is also considered one of the most useless. In part, this is due to confusion over the definitions and an inability to narrow the resulting age range. In particular, the definition of the inferior sphenotemporal suture location proved problematic for this researcher. For cranial suture closure to be a productive method of age assessment, the definitions must be clear. The suture locations should not only be clearly defined, but images should be provided of each location. Part of the subjectivity inherent in the method is due to the problem of defining what is scored as a "0" and what is scored as a "3". In particular, the images in this thesis illustrating the difference between the major sutures of the vault system and the sutures of the lateral-anterior system should be helpful in terms of clarification. In the experience of this observer, the sutures of the vault are much easier to score as they are larger and more complex. One can easily see the tongues of ossified tissue linking up. The lateral-anterior suture locations tend to have smaller, straighter sutures which are not as obvious in their closure. The difference between a "1" and a "2" is often quite difficult to establish. In this same vein, instances of closure which are somewhat unusual were run into during this study and the observer had to create a set of rules to follow in order to maintain consistency in scoring. These instances are not discussed in any other cranial suture literature. For example, in Chapter 3 it is mentioned that the author observed some suture locations where endocranial closure could be viewed from the ectocranial surface, and the ectocranial suture itself was completely open. In other instances, a suture location which is an intersection of two sutures would exhibit complete closure for one suture and the other suture would be open or only partially closed. For example, at lambda, the sagittal could be completely fused but the lambdoid suture is not. How should these instances be scored? These unusual cases are not mentioned in the literature. In this case, both of those types of events were scored as a "1" for partial closure. This may not be the best method, but it is at least consistent. These difficulties inherent in the method must contribute to the lack of positive results over the years, as opposed to the general inexperience of the observer. With clarification on these points, this method could be straightforward enough for beginning forensic anthropologists. For cranial suture closure to be an applicable method of age assessment, it needs to be completely redone in terms of methodology and provide visual examples of all of these situations, as well as all of the suture locations.

The Hispanic data in this study are lacking. Only six percent of the sample combining individuals from the FDB and the William M. Bass Donated Skeletal Collection were Hispanic. The PCOME sample is presumed to be entirely Hispanic, and yet only two of 80 individuals were positively identified at the time of the study and therefore useful for the analysis of covariance. There are limited locations with skeletal collections including modern Hispanics, and the FDB is the only database with modern

Hispanic data. Part of the difficulty is that "Hispanic" is such a broad term. The U.S. Census Bureau recognizes all individuals from Spanish-speaking countries to be Hispanic, including those from South America, Central America, Spain, Puerto Rico, and several Caribbean countries. A category for individuals who are "Mixed" is also provided under this umbrella-term. It is worth noting that the data from the U.S. Census Bureau is all based on self-reported racial, ethnic, or ancestral categories. In any case, very few individuals today are purely of one ancestral category.

The analysis of covariance was not significant for ancestry (Tables 8 and 9), and yet it is possible that with a larger, more equally distributed sample (in terms of ancestry) ancestry may be significant. Again, this is based on samples with mostly self-reported ancestry. In the future, more individuals from the PCOME sample will be positively identified and the ANCOVA may be redone with a larger Hispanic component to the sample.

In order for the age ranges provided by this method to be useful to law enforcement, they need to be narrowed; transition analysis is a method with the capability to do this. Transition analysis is a rigorous method of statistical analysis developed by paleodemographers for estimating age at death which provides likelihood ratios along with associated confidence intervals (Komar and Buikstra 2008). This method determines the mean age at transition for each phase of fusion (Rios et al. 2008). It was developed in order to deal with several issues in age estimation, including the issue of "age mimicry" discussed by Masset (1989), the inability to accurately estimate ages for skeletons approximately 50 years and older, and the problem of attempting to estimate the age of an individual skeleton or a small sample of skeletons (Boldsen et al. 2002).

Transition analysis is applicable for small samples, including individual skeletons, and can be used for any skeletal trait that can be arranged into an invariant series of senescent stages. Boldsen and colleagues (2002) focused the method on age estimation of adults, as there are more limitations for age estimation of adult skeletons than for juveniles. Their sample included 186 skeletons from the Terry Collection. The skeletal traits they observed included the pubic symphysis, the iliac portion of the sacroiliac joint, and ectocranial sutures. The authors chose to include cranial sutures despite their questionable value, since isolated crania are often found in archaeological and forensic work. The correlation coefficient for cranial sutures in this study was 0.66, 0.82 for the iliac portion of the sacroiliac joint, 0.86 for the pubic symphysis, and 0.88 for all three of the trait complexes combined. The results of the study show that age ranges for older skeletons are broader than those for young skeletons; however, transition analysis both provides a likely age range and error estimate, which negates the need for open-ended terminal intervals (i.e. 50+ years) (Boldsen et al. 2002).

## Intra-observer Error

In this study, higher than acceptable levels of intra-observer error were found for all suture sites scored, including the ectocranial vault and lateral-anterior systems as well as the palatine and sphenooccipital sutures. Obelion had the lowest, and only acceptable, level of 10% error. Obelion is historically noted to be the first point of fusion on the sagittal suture, which also fuses earlier than the others (Johnson 1976). The low error rate at obelion may result from the fact that it is often completely obliterated, which makes it very simple to score. Obelion was followed by the sphenooccipital at 25%, and midlambdoid, sphenofrontal, superior sphenotemporal, and incisive at 30%. These results are discouraging; however, when the suture scores for these ten donations were combined and assigned to their corresponding stage, the error rates for the vault and lateral-anterior were 10% and 20%, respectively. While still high, this indicates that 80-90% of the donations were scored into a stage which correctly represented their known age. Overall, the intra-observer error of the vault system is within the accepted level. It is possible that a more experienced observer as well as a larger sample size would produce better results for the lateral-anterior system. The vault system may have performed more accurately because the sutures included in this system are much easier to see and score on the traditional "0"-"3" scale (Figures 9 and 10). This is reflected in the fact that the Meindl and Lovejoy (1985) publication and *Standards* (Buikstra and Ubelaker 1994) only provide examples of vault sutures scored "0" through "3". The sutures of the lateral-anterior system are smaller and do not seem to fuse in the same manner as those of the vault. The intra-observer error rates indicate that while individual suture sites have a high likelihood of being scored differently by the same observer, the overall categorization based on these scores is still likely to be the same.

<u>Inter-observer Error</u>

In contrast, only five suture locations, four of which are on the palate, show significant levels of inter-observer error. This suggests that inter-observer error, and therefore subjectivity, is perhaps less of an issue than previously thought. A larger inter-observer error study should be performed in order to confirm or disprove these results, as only six crania were used in this study. It is acknowledged by the author that the introduction of the FDB sample is possibly a large source of error, since many anthropologists contribute to the FDB. It is not possible to score these forensic cases oneself to minimize the error; the benefits of including this large and diverse sample of modern individuals is thought to outweigh the risks of introducing error in this case. It is the only database in which to find modern, identified Hispanic remains with standard anthropological data. The FDB sample allowed this study to avoid the usual biases in ancestry and age. It would have been preferable for the author to score the entire sample, however this was not possible due to financial and time constraints, as well as a lack of availability for this type of sample.

Previous studies do not explicitly test intra-observer or inter-observer error rates for the Meindl and Lovejoy method of cranial suture scoring. Meindl and Lovejoy (1985) do state that the lateral-anterior system performs more accurately than the vault, but this study found the accuracy of both systems to be poor when broken down to the suture sites. Again, the vault was actually found to perform better in this study.

## ANCOVA

Results of the analysis of covariance showed that there is no significant effect of sex, ancestry, or interaction between sex and ancestry on the rate of cranial suture closure in either the vault or lateral-anterior systems in the three largest groups of the current United States population. Ancestry was the closest to significance with a probability of 0.067 in the vault sutures. These results suggest that separate methods of aging by cranial suture closure may not be necessary for the modern American population.

Nawrocki (1998) is the most recent study to find an effect of ancestry or sex on the rate of cranial suture closure. Specifically, he found the interaction between sex and ancestry had a significant effect. This difference may be accounted for by a comparison of Nawrocki's sample and the sample in this study, as well as a comparison of methodology. His sample consisted of 100 American Black and White males and females from the Terry Collection. The Terry Collection mostly consists of individuals with birth dates falling between 1850 and 1900 (Ousley and Jantz 1998). The sample for this study focuses on modern skeletal remains of individuals from the three major ancestral groups currently in the United States. In addition, the mean age for his sample falls around 53-55 years, while the mean age for the sample in this study is approximately ten years younger. Another divergence between these two studies which may account for differing results is the combination of the palatine sutures with the endocranial and ectocranial by Nawrocki (1998), while endocranial suture data was not collected for this thesis. The author did collect data from the palatine sutures; however the statistical analyses focused on the ectocranial sutures. Inter-observer error rates are provided for the palatine sutures, but the ANCOVA only includes ectocranial suture data.

## PCOME Test

The comparison of the mean ages found in a sample of individuals from the PCOME with Meindl and Lovejoy's (1985) method of age assessment by cranial suture closure to the prior age distribution reported by Anderson (2008) results in an older age distribution with a mean age approximately 12 years older. Anderson (2008) reports the highest percentage of border crosser fatalities to be in the 21-30 year range, while the majority of those scored using Meindl and Lovejoy's (1985) method fell in the 41-50 year range. This suggests a tendency to overage using this method, which may again be a reflection of Masset's (1989) "age mimicry", in which the results of the test sample will mimic the age distribution of the reference sample. It also may be a phenomenon particular to this sample. Conducting a similar test on the sample from the William M. Bass Donated Skeletal Collection may clarify this point.

# CHAPTER VI

## CONCLUSION

The results in this study were largely unsurprising. However, several important pieces of information can be gained. The intra-observer and inter-observer error tests were enlightening in that they provide quantitative estimates of error; previously cranial suture closure has been considered disreputable without providing error rates. While the intra-observer error rates for individual suture sites are high in some cases, the overall error rates for the vault and lateral-anterior systems (10% and 20%, respectively) were not exceptionally high. Inter-observer error was not found to be statistically significant for any ectocranial suture location. The ANCOVA found no significant sex or ancestral differences in the modern sample of American Black, American White, and Hispanic individuals. These results suggest that it may not be necessary to know the sex and ancestry of human remains prior to scoring the cranial sutures. While these results are not definitive, they are an improvement in that they were tested on a modern and representative sample. This will be beneficial in cases with an isolated or fragmentary cranium. The PCOME test suggests the tendency of Meindl and Lovejoy's (1985) method to overage. This should highlight the importance of properly distributed reference samples and the need to develop a method to derive narrow, closed age estimates.

There are several steps which need to be taken in future research if anthropologists wish to truly improve age assessment from cranial suture closure. First, photographic examples should be taken to document both the individual suture locations and unusual instances of suture closure. The Meindl and Lovejoy (1985) publication does not provide basic photographic examples of closure, only definitions. *Standards* (Buikstra and Ubelaker 1994) improved on this slightly by providing photographic examples of a major vault suture. This study provides examples of both the major vault sutures as well as an example of a lateral-anterior suture location. Still, the addition of photographic examples of each location and any unusual instances of closure will both lessen subjectivity of the method and make the process of scoring less frustrating.

Secondly, the Meindl and Lovejoy (1985) method should be tested on the William M. Bass Donated Skeletal Collection and FDB samples to attempt to see if it overages on those samples as well. This will explain whether the results of the PCOME test are isolated to that sample, and help to determine if the method needs to be completely re-done with a reference sample with a more normal age distribution.

Future positive identifications made for individuals in the PCOME sample of 80 may also provide an opportunity to add these individuals into the large sample including the William M. Bass Donated Skeletal Collection and the FDB, and conduct another analysis of covariance. Since ancestry was nearing significance, the addition of these individuals may alter the results.

In addition, this research may be improved by the use of transition analysis in an attempt to narrow the final age ranges derived from the collection of cranial suture closure data. Transition analysis is a method of statistical analysis which calculates likelihood estimates of age at death along with confidence intervals which will define clearer age categories and provide error estimates.  This key improvement will not only make the use of ectocranial suture closure as a method of age assessment more convenient and reliable, but it will strengthen the method in terms of satisfying the *Daubert* criteria and the rules of evidence, a prominent goal in forensic anthropology today.

## REFERENCES


2009. SAS/STAT. 9.1.2 ed. Cary, NC: SAS Institute, Inc.

Acsádi GY and Nemeskéri J. 1970. History of human life span and mortality. Budapest: Akadémiai Kiadó.

Anderson BE. 2008. Identifying the dead: Methods utilized by the Pima County (Arizona) Office of the Medical Examiner for undocumented border crossers. JFS 53:8-15.

Anderson MF, Anderson DT, and Wescott DJ. 2010. Estimation of adult skeletal age-at-death using the sugeno fuzzy integral. AJPA 142:30-41.

Baker, RK. 1984. Relationship of cranial suture closure and age analyzed in a multi-racial sample of males and females. Thesis. California State University, Fullerton.

Birkby WH, Fenton TW, and Anderson BE. 2008. Identifying southwest Hispanics using nonmetric traits and the cultural profile. JFS 53:29-33.

Boldsen JL, Milner GR, Konigsberg LW, and Wood JW. 2002. Transition analysis: a new method for estimating age from skeletons. In: Hoppa RD and Vaupel JW (eds.) Paleodemography: Age distributions from skeletal samples. Cambridge, UK: Cambridge University Press. pp. 73-106.

Bolk L. 1915. On the premature obliteration of sutures in the human skull. AJPA 17:495-523.

Brooks ST. 1955. Skeletal age at death: Reliability of cranial and pubic age indicators. AJPA 13:567-597.

Buikstra JE and Ubelaker DH. 1994. Standards for data collection from human skeletal remains. Fayetteville, Arkansas: Arkansas Archaeological Survey Report Number 44.

Cray Jr. J, Meindl RS, Sherwood CC, and Lovejoy CO. 2008. Ectocranial suture closure in *Pan troglodytes* and *Gorilla gorilla*: pattern and phylogeny. AJPA 136:394-399.

Dirkmaat DC, Cabo LL, Ousley SD, and Symes SA. 2008. New perspectives in forensic anthropology. AJPA 137(S47):33-52.

Fulginiti LC. 2008. Fatal footsteps: Murder of undocumented border crossers in Maricopa County, Arizona. JFS 53:41-45.

Grivas CR and Komar DA. 2008. Kumho, Daubert, and the nature of scientific inquiry: Implications for forensic anthropology. JFS 53:771-776.

Hershkovitz I, Latimer B, Dutour O, Lyman J, Wish-Baratz S, Rothschild C, and Rothschild BM. 1997. Why do we fail in aging the skull from the sagittal skull? AJPA 103:393-399.

Hinkes MJ. 2008. Migrant deaths along the California-Mexico border: An anthropological perspective. JFS 53:16-20.

Hrdlička A. 1920. Anthropometry. Philadephia: Wistar Institute of Anatomy and Biology.

Işcan MY, Loth SR, and Wright RK. 1984. Age estimation from the rib by phase analysis: white males. JFS 29:1094-1104.

Johnson JS. 1976. Comparison of age estimation using discriminant function analysis with some other age estimations of unknown skulls. Journal of Anatomy 121: 475-484.

Kanisius PH and Luke DA. 1994. Is the complexity of the human sagittal suture related to the size of the temporal muscle? International Journal of Anthropology 9:265-272.

Key CA, Aiello LC, and Molleson T. 1994. Cranial suture closure and its implications for age estimation. International Journal of Osteoarchaeology 4:193-207.

Kirk JD. 2007. Cranial suture closure: a quantitative method for age estimation using laser instrumentation. Thesis. Wichita State University.

Komar DA and Buikstra JE. 2008. Forensic anthropology: contemporary theory and practice. New York: Oxford University Press.

Lovejoy CO, Meindl RS, Pryzbeck TR, and Mensforth RP. 1985. Chronological metamorphosis of the auricular surface of the ilium: A new method for the determination of adult skeletal age at death. AJPA 68:15-28.

Masset C. 1989. Age estimation on the basis of cranial sutures. In: Işcan MY (ed.). Age Markers in the Human Skeleton. Springfield, IL: CC Thomas. pp. 71-103.

Meindl RS and Lovejoy CO. 1985. Ectocranial suture closure: a revised method for the determination of skeletal age at death based on the lateral-anterior sutures. AJPA 68:57-66.

Montagu MFA. 1938. Aging of the Skull. AJPA 23:355-375.

Nawrocki S. 1998. Regression formulae for estimating age at death from cranial suture closure. In: Reichs K (ed.). Forensic Osteology: Advances in Identification of Human Remains (2nd ed.). Springfield, IL: CC Thomas. pp. 276-292.

Ousley SD and Jantz RL. 1998. The forensic data bank: Documenting skeletal trends in the United States. In: Reichs K (ed.). Forensic Osteology: Advances in Identification of Human Remains (2nd ed.). Springfield, IL: CC Thomas. pp. 441-458.

Perizonius WRK. 1984. Closing and non-closing sutures in 256 crania of known age and sex from Amsterdam (AD 1883-1909). Journal of Human Evolution 13:201-216.

Pommerol F. 1869. Sur la synostose des os du crane. Paris, 1-118.

Relethford JH. 2004. Boas and beyond: migration and craniometric variation. American Journal of Human Biology 16:379-386.

Rios L, Weisensee K, and Rissech C. 2008. Sacral fusion as an aid in age estimation. Forensic Science International 180(111.e1-111.e7).

Rogers TL and Allard TT. 2004. Expert testimony and positive identification of human remains through cranial suture patterns. JFS 49:203-207.

Rogers TL. 2005. Determining the sex of human remains through cranial morphology. JFS 50(3):493-500.

Sahni D, Indar J, and Neelam S. 2005. Time of closure of cranial sutures in northwest Indian adults. Forensic Science International 148:199-205.

Sauvage H. 1870. Sur l'état senile du crane. Bull. Soc. Anthrop., Paris, V, Ser. 2, 576-586.

Shirley N, Fatah EEA, Jantz R, and Mahfouz M. 2011. Improving sex estimation from the cranium using 3-dimensional modeling from CT scans. Proceedings: National American Academy of Forensic Sciences, Chicago IL.

Singer R. 1953. Estimation of age from cranial suture closure: a report on its unreliability. Journal of Forensic Medicine 1:52-59.

Spradley MK, Jantz RL, Robinson A, and Peccerelli F. 2008. Demographic change and forensic identification: problems in metric identification of hispanic skeletons. JFS 53:21-28.

SPSS for Windows, Rel. 17.0.0. 2008. Chicago: SPSS Inc.

Steadman DW, Adams BJ, and Konigsberg LW. 2006. Statistical basis for positive identification in forensic anthropology. AJPA 131:15-26.

Todd TW and Lyon DW. 1924. Endocranial suture closure, its progress and age relationship: Part I adult males of the white stock. AJPA 7:325-384.

Todd TW and Lyon DW. 1925a. Cranial suture closure, its progress and age relationship: Part II ectocranial closure in adult males of white stock. AJPA 8:23-45.

Todd TW and Lyon DW. 1925b. Cranial suture closure, its progress and age relationship: Part III endocranial closure in adult males of negro stock. AJPA 8:47-71.

Todd TW and Lyon DW. 1925c. Cranial suture closure, its progress and age relationship: Part IV ectocranial closure in adult males of negro stock. AJPA 8:149-168.

Topinard P. 1885. Êléments d'anthropologie générale. Paris, 253-284, 644-646.

U.S. Census Bureau; 2005-2009 American Community Survey 5-Year Estimates; generated by Alexandra Millard; using American FactFinder; <http://factfinder.census.gov>; 30 January 2011.

Welcker H. 1862. Untersuchungen über wachsthum und bau des menschlichen schädels. Leipzig, xvi-148.

White TD. 2000. Human Osteology (2nd ed.). San Diego, California: Academic Press.

Woo J. 1949. Racial and sexual differences in the frontal curvature and its relation to metopism. AJPA 7:215-226.

Zambrano CJ and Nawrocki SP. 2005. A test of Meindl & Lovejoy's method of adult age at death from cranial suture closure. Proceedings: American Association of Physical Anthropology, Milwaukee WI.

Zanolli V. 1908. Studio sulla obiterazione deele suture craniche. Atti. Soc. Rom. Antrop., XIV, 13-44.

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