A COMPARATIVE EVALUATION OF THE CHEN ET AL. AND SUCHEY-BROOKS PUBIC BONE AGING METHODS ON A NORTH AMERICAN SAMPLE

By

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A THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

MASTERS OF SCIENCE

Forensic Science

2011

ABSTRACT

A COMPARATIVE EVALUATION OF THE CHEN ET AL. AND SUCHEY-BROOKS PUBIC BONE AGING METHODS ON A NORTH AMERICAN SAMPLE

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Accurately assessing age-at-death of adult human skeletons is fundamental in physical anthropology. The most generally accepted methods for estimating age involve analysis of the pubic bones. Two such methods—Chen et al. (2008) and Suchey-Brooks (1990)—were the focus of this study.

The objective of this research was to evaluate the accuracy of the Chen et al. and Suchey-Brooks methods. The Chen et al. method was developed on a sample of Chinese Han males. This research utilized a known collection of modern pubic bones curated at the Forensic Science Center in Phoenix, Arizona. A sample of 296 left male pubic bones of European ancestry, between the ages of 18 and 70, was evaluated.

Results indicated that there are no statistically significant differences between the two methods. On average the revised Chen et al. method slightly over-ages the specimens while the Suchey-Brooks method slightly under-ages. Both methods have an average error of approximately 9 years from individual's actual age.

This research demonstrates that the Suchey-Brooks method is most accurate for aging young adults, while the revised Chen et al. method is most accurate for aging middle adults. Thus, the Chen et al. method is an important contribution to the field of physical anthropology for aging older adult skeletal remains. There are some limitations, such as subjectivity and the intricate scoring system, so the Chen et al. method should be applied cautiously until further research has been done in the United States.

ACKNOWLEDGMENTS

I would like to thank my thesis committee, Dr. Todd Fenton, Dr. Norman Sauer and Dr. Jennifer Cobbina, for their support and guidance during every stage of this thesis project. This study would never have come to fruition without their help. I would like to thank Dr. Laura Fulginiti for permitting me to study the FSC skeletal sample and for participating in data collection. Thank you for being one of my biggest supporters, and as always, I would not be where I am today without you. I would also like to thank Cheryl Anderson and Jesus Villa for their assistance and Dr. Kristen Hartnett for providing me with information on the FSC sample. I need to thank Paul Curran at CSTAT for his statistical assistance; I would still be floundering in a sea of numbers and data were not for his help.

A very special thank you goes to my family for all of your tireless encouragement and support throughout my academic career. You have helped to make me the person that I am, and I would not have made it through without you. I would also like to thank Andrew Missel for his constant words of encouragement, loving support, and statistical guidance. You helped me push myself farther than I thought possible. And finally, thank you to all of my friends and fellow graduate students for pointing me in the right direction and putting a smile on my face.

Finally, this research could not have been done without financial help from the National Institute of Justice and the Forensic Science Foundation, as well as Michigan State University's Graduate School and Forensic Science Masters Program.

DISCLAIMER

This project was supported by Award No. 2008-DN-BX-K216 awarded by the National Institute of Justice, Office of Justice Programs, U.S. Department of Justice. The opinions, findings, and conclusions or recommendations expressed in this thesis are those of the author and do not necessarily reflect those of the Department of Justice.

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INTRODUCTION

Accurately assessing the age-at-death of adult human skeletal remains is one of the most fundamental aspects of creating a biological profile. A biological profile comprises the demographic characteristics of an individual including sex, age-at-death, ancestry, and living stature (Stewart, 1979; Byers, 2008). Establishing age-at-death, presented in the form of an age range, can assist forensic or medicolegal authorities in properly identifying an unknown decedent (Komar and Buikstra, 2008). It is equally valuable for bioarchaeologists when deducing past conditions of health, disease, and demography (Lovejoy et al., 1985a). However, estimating age-at-death is often challenging. "The estimation of age-at-death of adult skeletal material is," according to Buckberry and Chamberlain (2002:231), "one of the more difficult tasks undertaken by physical anthropologists." The challenge arises due to the variability of genetic and environmental factors which influence skeletal remodeling and degeneration throughout an individual's life (Mulhern and Jones, 2005; Buckberry and Chamberlain, 2002).

Despite these challenges, there are many techniques and methods available to forensic anthropologists and bioarchaeologists to facilitate estimation of age-at-death. The variety can complicate the decision of which technique should be used and which is likely to be the most accurate (Baccino et al., 1999). The most accepted and widely used methods for age assessment rely on changes of osseous and dental elements (Byers, 2008; Hens et al. 2008). Methods for estimating age from the skeleton can be divided into two phases: modeling changes and remodeling changes. Modeling changes are based on the growth and development of the bones (and dentition) and are applicable to subadults.

After the skeleton has finished maturing, bone continues to remodel throughout adulthood (Byers, 2008).

The most frequently used and well accepted techniques for assessment of age in adults involve an analysis of the pubic bones (Meindl et al., 1985; Meindl and Lovejoy, 1989; Djurić et al., 2007). The reliability of the pubic bones for age estimation is primarily based on two factors. First, numerous studies have demonstrated that the pubic bones advance through observable changes into adulthood after other skeletal elements have ceased their developmental changes (McKern and Stewart, 1957; Meindl and Lovejoy, 1989). The second factor is that the age-related changes of the pubic bone, and the pubic symphyseal face, are distinctive and clearly perceptible (Meindl et al., 1985).

Some of the most distinct age-related changes of the pubic bones are visible on the pubic symphyseal face. The symphyseal face in young individuals is billowy and is described as having marked ridges and furrows. With age the ridges and furrows begin to diminish and eventually the symphyseal face will appear flat or concave (Todd, 1920). The ventral (anterior) and dorsal (posterior) margins of the symphyseal face also proceed through distinct stages of bone deposition and degradation. Features such as the dorsal plateau and the ventral bevel appear later in life, and when both margins are fully developed, a rim will be visible around the circumference of the symphyseal face. The texture and consistency of the bone are also features that transform with age; in young individuals the bone is dense and heavy, but with age it begins to degrade resulting in visible porosity (Todd, 1920; McKern and Stewart, 1957; Meindl et al., 1985).

These changes have been distinctly correlated with age ranges and can be utilized to estimate the age of an unknown individual. Numerous methods for age assessment via the pubic bones are available, including the Chen, Zhang, and Tao (2008) (subsequently referred to as Chen et al.) and Suchey-Brooks (1990) methods. Developed in 2008, the Chen et al. method focuses on nine morphological features of the male pubic bone for the Chinese Han population. Chen and colleagues analyzed 262 pairs of pubic bones from which they deduced four statistical equations for male age estimation. In addition to developing a method for age-at-death estimation using morphological changes, the aim of the Chen et al. study was to improve upon current pubic bone aging methods such as Suchey-Brooks (1990).

Chen and colleagues (2008) state that with the use of their statistical formulae, evaluating males only, and subdividing each feature, age-at-death can be quantitatively estimated with a high degree of accuracy and reliability. In fact, their study notes that in China this method can accurately age males within one year, and that an average of 98% of the variance in age can be explained by their 9 features. Based upon these impressive claims I wanted to evaluate the Chen et al. method to determine if its utility is as great in the United States as it is in China.

BACKGROUND

Assessment of Age at Death

In both forensic and paleodemographic contexts, age is one of the essential biological parameters which facilitates the identification of human skeletal remains. Although numerous methods exist for estimating age at death, adult age estimation can be one of the more difficult elements of the biological profile (İşcan, 1989; Buckberry and Chamberlain, 2002; Osborne et al., 2004; Mulhern and Jones, 2005). More than any other aspect of the biological profile, as Dr. William Maples notes, "the accuracy of age-estimation techniques are very much at the mercy of the individual applying them…[T]here is always a certain amount of deviation between results obtained in the reference laboratory and the application of aging techniques by individuals in the field" (İşcan, 1989:13).

The techniques and processes for assessing age for juvenile and adult skeletal remains are distinct, and the latter is often more challenging. An estimation of age for young individuals is based primarily upon the predictable sequence of bone growth and development which is fairly constant across populations (İşcan, 1989). For adults, the estimation of age is more difficult since aging patterns are less obvious and an accumulation of years allows for greater internal differences to develop among the various skeletal age indicators (İşcan, 1989; Ubelaker, 2008). For example, "a skeleton may present a relatively youthful-appearing pubic symphysis and sternal end of the fourth rib and yet show premature arthritic development and extensive tooth loss" (Ubelaker, 2008:40). Despite these challenges, the pubic bone demonstrates significant age-related changes, which is why it is considered a reliable skeletal region for assessing age at death in both archaeological and forensic investigations (Scheuer and Black, 2000).

There are numerous explanations for the irregularity of adult aging, the most significant being human variation. Human aging is progressive and universal but age-related processes are highly variable (Schmitt et al., 2002). Rates of skeletal remodeling are directly affected by both genetic and non-genetic processes and are inconsistent between and among individuals and populations. Skeletal remodeling can be influenced by multiple factors including diet, health, cultural practices, living environment, and trauma, and since the majority of adult skeletal aging methods rely on evaluation of remodeling changes, adult age estimation can be complicated for physical anthropologists (İşcan, 1989; Buckberry and Chamberlain, 2002; Schmitt et al., 2002; Mulhern and Jones, 2005; Falys et al., 2006; Hens et al., 2008). As a result, methods designed to estimate age at death for human skeletal remains are continually being developed and revised (Schmitt et al., 2002).

Accuracy for Adult Age at Death Estimation Methods

Within the field of forensic anthropology, accuracy is a relative term since each morphoscopic age-at-death estimation technique has unique measures of accuracy and precision (Buikstra and Komar, 2008). For example, each phase of the Suchey-Brooks (1990) pubic symphyseal surface aging method (discussed in the following chapter) has a mean, standard deviation, and 95% age range, which is not the same as two standard deviations due to the non-normal distribution of the sample (Klepinger, 2006; Buikstra and Komar, 2008). Unfortunately, as Schmitt (2004) and Klepinger (2006) note, even this large 95% range underestimates the extent of variability. One study, however, states that the Suchey-Brooks (1990) method accurately assigns 72.0% of females and 89.74% of males into the correct phase in a Balkan sample (Djurić et al. 2007).

For the medial surface of the right fourth rib, İşcan and Loth (1984; 1985) provide a mean, standard deviation, standard error, 95% confidence interval and an age range to assess accuracy. However, as Klepinger (2006) emphasizes, the small sample sizes for these studies result in misleading confidence intervals. When the İşcan and Loth (1984; 1985) studies were tested for inter-observer error, Krogman and İşcan (1986) note that accuracy is within one age phase (which has mean accuracies between 4 and 20 years from actual age at death).

For the auricular surface method, originally developed by Lovejoy et al (1985a), the eight modal age stages are distributed in non-overlapping groups of 5 to 10 years. Thus, Lovejoy et al. (1985a) were confident that age could be accurately estimated within 5 to 10 years. These age ranges were deemed to be too narrow by Buckberry and Chamberlain (2002) who revised the Lovejoy et al (1985a) method. Buckberry and Chamberlain (2002) present a mean, standard deviation, median age, and age range for each stage as measures of accuracy. A test of Buckberry and Chamberlain's (2002) method, using inaccuracy and bias as the measures of accuracy, find that the original Lovejoy et al. (1985a) method is on average 8 years more accurate than the revised method for individuals aged 20 to 49; but for individuals 50 to 69 years, the revised method is almost 7.5 years more accurate than Lovejoy et al. (1985a) (Mulhern and Jones, 2005).

As these examples demonstrate, there is not a standard age, age range, or confidence interval which identifies an age-at-death estimation as "accurate." Each method employs different means for measuring accuracy, as well as different values for what is considered "accurate." While Lovejoy et al. (1985a) consider a range of 5 to 10 years to be an accurate estimation of age at death, Suchey-Brooks (1990) consider 58 years to be an accurate range (Suchey-Brooks Phase V for Females can range between 25 to 83 years). Therefore, accuracy, in forensic anthropology, is contextually related to individual methods.

The Pubic Bones and the Pubic Symphysis Joint

The pubic bone (or pubis) is one of three elements that, when mature, form the large irregular-shaped bone of the hip—the *os coxa*. Before maturity, each of the paired *os coxa*e is composed of three bones (ilium, ischium, and pubis) and several epiphyses (Figure 1) (McKern and Stewart, 1957). Around the time of puberty these three elements begin to unite and fuse at the acetabulum (Scheuer and Black, 2000).

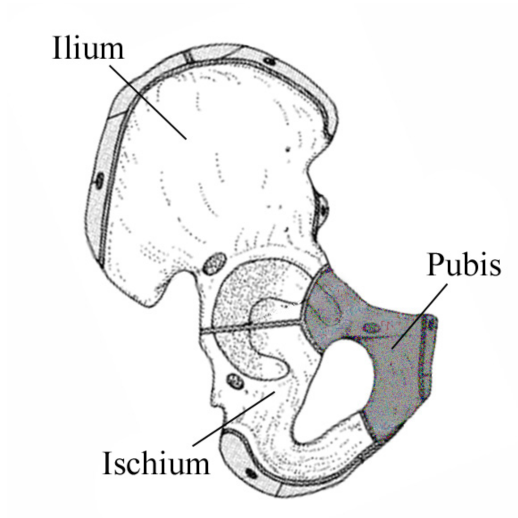


Figure 1: The *os coxa*. The shaded region is the pubic bone (Modified from Scheuer and Black, 2004).

The pubic bone, according to Scheuer and Black (2000), forms the anterior lower portion of the *os coxa* and is composed of a body, a superior ramus which fuses with the illium, and an inferior ramus which fuses with the ischium. The left and right pubic bones converge, although separated by symphyseal cartilage, at the midsagittal plane to form the pubic symphysis joint (Figure 2) (Krogman and İşcan, 1986). This is a slightly moveable (amphiarthoris) joint with a fibrocartilaginous disk between the two bones (Suchey and Katz, 1998). The joint surface of each pubic bone, the symphyseal surface, undergoes systematic and observable changes over the course of a lifetime (Todd, 1920; McKern and Stewart, 1957). The symphyseal surface in young individuals has alternating horizontal ridges and depressions, but with age, the ridges and depressions begin to diminish and eventually the surface appears flat or concave (Todd, 1920).

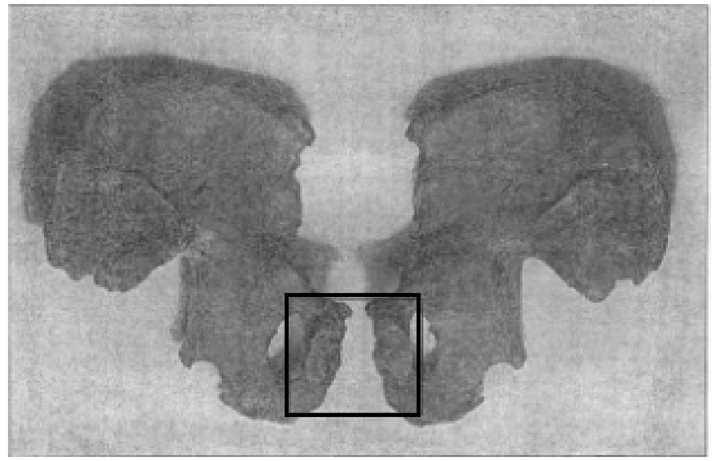


Figure 2: Pubic symphyseal surfaces (Todd, 1920)

Historical Research on the Pubic Bone

Morphological changes in the pubic bone throughout life, and their relationship to skeletal age, have been recognized for centuries (Todd, 1920; McKern and Stewart, 1957). Beginning in 1761, according to Todd (1920), the anatomist Dr. William Hunter was the first to observe the similarities between the pubic symphysis and the joints between each vertebra; both being fibrocatilaginous symphyses. Dr. Hunter was followed by Swiss anatomist Christoph Aeby, who in 1858, described the symphyseal face of the pubis “as a more or less irregular convex surface bounded by an oval outline” (Todd, 1920:294). In 1872, German physician and anatomist Friedrich Henle recognized that with age, the symphyseal face experienced variation in texture and dimensions, and in 1889, anatomist John Cleland described changes in the pubic bone which he attributed to differences between males and females. These differences were later attributed to age-related modifications rather than sex (Todd, 1920). Although these early scientists recognized that the pubic bone underwent gross morphological changes, they did not associate specific changes with particular age stages (McKern and Stewart, 1957).

The First Method to Evaluate the Relationship between Age and the Pubic Bone

The first systematic study and formal method for evaluating age-related morphological changes of the pubic bone was conducted by T. Wingate Todd in 1920 (Suchey, Wisely and Katz, 1986; Meindl and Lovejoy, 1989). Todd notes that certain bones associated with joints, especially amphiarthroses such as the pubic symphysis, change with age. Based upon these changes, Todd began to study the pubic symphysis as a region for age estimation (Todd, 1920). Prior to this time researchers felt there was a distinct lack of data from which an accurate skeletal age estimate could be made. In particular, there were no reliable criteria to estimate age for individuals between 25 and 55 years old (Todd, 1920).

In light of the need for aging data, Todd and his colleagues began amassing a skeletal collection with the most accurate antemortem records that could be obtained at the time. The collection, in 1920, (later to become the Hamann-Todd Osteological Collection) consisted of 650 male and female skeletons of European and African ancestry. For this first systematic study, 306 males of European ancestry were used to assess age changes of the pubic bone. Todd notes that there was a problem with obtaining accurate ages at death since civil and hospital records were not dutifully maintained; he also observes that individuals tended to provide their ages in round numbers which produced distinct increases in the numbers of individuals within certain age categories (Todd, 1920). Thus, it is possible that many individuals in the sample had age estimates "which are more than a couple of years off" (Suchey, Wiseley, and Katz, 1986:36). Todd also distinguishes between two different types of skeletal aging: normal developmental progression and morphological changes induced by external factors such as disease (Todd, 1920).

Based upon his investigations, Todd developed a ten-phase system which describes changes of the male pubic bone for individuals between the ages of 18 and 50 years (Figure 3) (Todd, 1920). He concludes that the pubic bone is best for aging individuals between 20 and 40 years old and that the technique should not be used in isolation. He suggests using the pubic bone in conjunction with other aging methods when the whole skeleton is available (Todd, 1920). Todd's publication "Age changes in the pubic bone. I. The white male pubis," is heavily illustrated with photographs which serve as a guide for identification. The photographs are useful visual references which demonstrate human variation and provide examples of young skeletons, to which many scientists at that time did not typically have access (Todd, 1920).

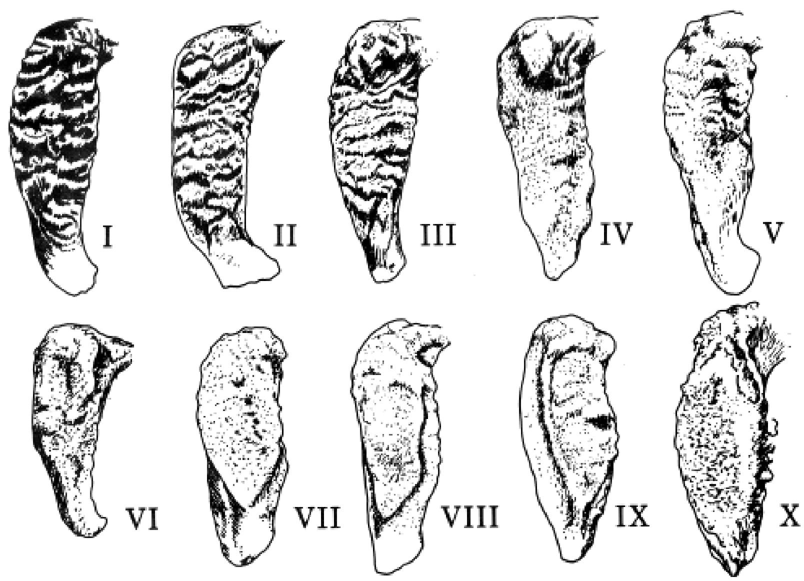


Figure 3: Todd's ten pubic symphysis phases (Suchey, Wisely, and Katz, 1986)

Revisions of the Todd Method

Numerous studies have reviewed or improved upon the Todd method for pubic bone age estimation. The first to evaluate this method was Kazuro Hanihara who conducted a study in 1952 in which Japanese pubic bones were aged using Todd's ten-phase system (Hanihara and Suzuki, 1978). Hanihara concludes that there is little difference between Caucasian and Japanese individuals when the Todd method is applied. However, if Caucasian standards are used, Japanese individuals tend to present as three years older than their actual age (Hanihara and Suzuki, 1978).

The first validation and systematic study of Todd's pubic aging method was conducted by Sheilagh T. Brooks in 1955 (Suchey, Wiseley, and Katz, 1986). Two samples were used for this study. The first was the University of California Museum of Anthropology (UCMA) series which consisted of approximately 400 archaeological individuals. The second was the Western Reserve University (WRU) series which was the original sample upon which Todd based his aging method (Brooks, 1955). Brooks notes that the Todd system has three general categories: Phases I-III are post-adolescent, Phases IV-VI show the build up of the symphyseal outline, and Phases VII-X demonstrate quiescence and breakdown of the symphyseal face. Based upon her statistical analyses, Brooks states that Todd's Phases V-VIII should be shifted three years younger to accommodate for the method's prevalence to over-age individuals. With these slight modifications, she states that the pubic bone could be made into one of the more reliable adult age indicators (Brooks, 1955).

Focusing particular attention on the pubic symphyseal face, McKern and Stewart (1957) were the next group to amend the Todd system. The pubic symphyseal face is ideal because its modifications and epiphyseal-like additions of bone continue into later adulthood, while most other elements of the skeleton have quiesced (Meindl and Lovejoy, 1989; McKern and Stewart, 1957). In their 1957 study, McKern and Stewart note that Todd's method only addresses typical phases, with "typical" indicating regular progression through each phase rather than considering symphyseal variation. To ameliorate this problem they developed a new system which accounted for all variation. They chose a formula which evaluates three components, each with individual chronological age sequences: the dorsal plateau, ventral rampart and the symphyseal rim. Each component includes five subdivisions that are scored independently (Figure 4) (McKern and Stewart, 1957). A score of 0-5 is assigned for each of the three components and the sum of those three scores is used to derive the estimated age of the individual (Suchey, Wiseley, and Katz, 1986).

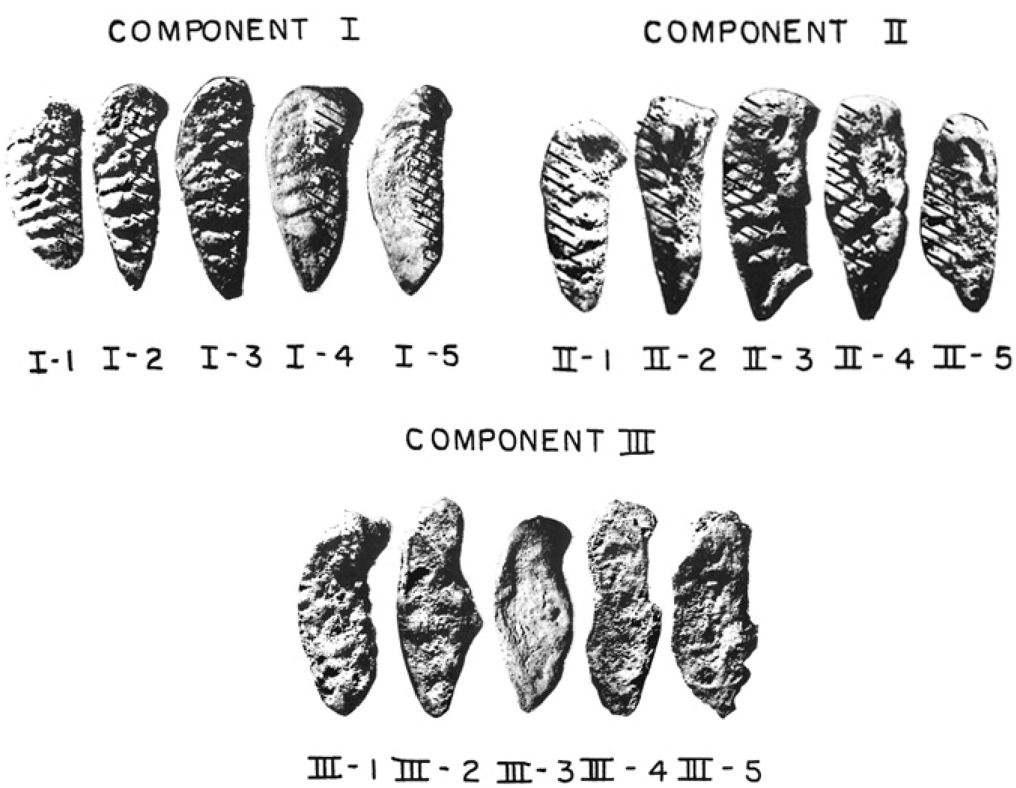


Figure 4: McKern and Stewart pubic symphyseal components (1957)

McKern and Stewart (1957) describe the age-related changes of the symphyseal face as follows: The dorsal plateau begins on the dorsal demi-face and gradually fills in until it becomes flat. The ventral rampart is more variable and may remain incomplete leaving a hiatus. The ventral rampart begins as a beveling (flattening) of the ventral demi-face and then the rampart begins to form as extensions of either the superior or inferior surfaces. The symphyseal rim is the final stage of maturation. At the same time the rim is completing, the bone texture begins to change from a granular to a more fine-grained and dense bone. With increased age, the rim begins to breakdown and becomes smooth.

The McKern and Stewart system is flexible, so that with a slight change in scoring, the age estimation will be within an accurate range (McKern and Stewart, 1957). This study, however, does not incorporate many individuals in older age groups (only 15% of the sample was older than 31 years) and is developed exclusively on military servicemen returned from the Korean War (Meindl and Lovejoy, 1989; Suchey, Wiseley, and Katz, 1986). With increased age the pubic symphysis tends to decelerate its metamorphosis, and this is not well documented (McKern and Stewart, 1957). This is problematic because the method does not provide a complete representation of the changes that occur in older adults. Nonetheless, McKern and Stewart feel that their new method "expresses the true nature of symphyseal variability and does not confine the observer to the narrow limits of typical phases" (1957:88).

A study conducted by Suchey, Wiseley and Katz in 1986 evaluated both the Todd (1920) and McKern-Stewart (1957) methods. Using a modern autopsy sample of 739 males collected from Los Angles County autopsies (first described by Katz and Suchey,

1986) the authors reexamined Todd's phases of pubic development and the McKern-Stewart method. Suchey, Wiseley and Katz (1986) conclude that the Todd method tends to overestimate the ages in the sample by an average of 3 to 4 years, and that the McKern-Stewart method works fairly well for individuals under the age of 25 (standard deviations are all less than 5.0), but when individuals are older than this, the method becomes less useful (standard deviations are between 6.52 and 13.89). These results are to be expected as the McKern-Stewart sample had few individuals over the age of 30 years. Suchey and colleagues suggest that both methods poorly predict ages in older age groups and that the cutoff age for using these methods should be 40 years. Finally they state that modifications are needed for both aging methods before they are applicable to modern, diverse and older populations (Suchey, Wiseley, and Katz, 1986).

In 1978, Hanihara and Suzuki developed yet another method based on the Todd system. Their study assesses age from the pubic symphysis by employing multiple regression analysis and quantification theory model I analysis (defined as a multiple regression analysis with dummy variables) (Igarashi et al., 2005). This study is limited to individuals between the ages of 18 and 38, because after the age of 40, the variability becomes too great for the method to accurately age (Hanihara and Suzuki, 1978). Only 70 pairs of Japanese pubic bones were used to conduct this study and both males and females were combined, even though Hanihara and Suzuki (1978) state that it is desirable to separate males and. They examine seven features for their model: ridges and furrows, pubic tubercle, lower end, dorsal margin, superior ossific nodule, ventral beveling and symphyseal rim. Hanihara and Suzuki describe both multiple regression analysis (MRA) and quantification theory model I (QMI) and state that QMI is more reliable than MRA, especially for individuals younger than 30 years old (confidence ranges for QMI are between -6.51 and 4.89 while for MRA they are between -5.36 and 6.46) . They also note that ages can be calculated using normalized scores (Hanihara and Suzuki, 1978).

A study conducted in 1985 by Meindl and colleagues use blind tests to assess current pubic aging methods for accuracy. The McKern-Stewart, Gilbert-McKern (pubic aging method for females), Hanihara-Suzuki, and Todd systems were examined. Meindl et al. (1985) address the concern of ancestry and sex on the application of pubic aging, since a major critique of aging standards is that they are strictly based on European populations. Statistical analyses show that no race-sex combination produced a significant bias in age determination. The results of this work also demonstrate that a subjective aging application is superior to a typological aging approach. "Archetypal aging," according to Meindl et al., "is less accurate than a more generalized and interpretive method" (1985:33). By this they mean that examining each specimen in accordance with descriptive explanations of the aging pattern is more accurate than matching each specimen to a typological cast. The Todd system, according to the authors, was being used as a typological standard when it was intended to be used in a more subjective manner to describe age changes (Meindl et al., 1985). Meindl and colleagues revise the Todd method and establish five major biological phases: pre-epiphyseal, active epiphyseal, immediate postepiphyseal, maturing/pre-degenerative, and degenerative. Based upon their results, they conclude that their modified Todd system is the most reliable, however all of the methods underestimate the ages of the sample individuals (Meindl et al., 1985).

Another study evaluating methods for determining age at death from the pubic symphysis was undertaken by Katz and Suchey in 1986. In particular, the Todd system and the McKern-Stewart system were examined. This study evaluates a sample of 739 documented male pubic bones from Los Angeles county autopsies. The specimens range in age from 14 to 92 years old (Katz and Suchey, 1986). The main purpose of this study is to use a large sample and apply regression analysis to study the performance of aging methods. The sample for this study, as mentioned above, has a wide age distribution and all individuals have known birth and death dates. The individuals were born both in the United States and in foreign countries, and pubic bones outside of normal morphology were removed from the study sample. The ancestry of each individual was determined by a typological approach focusing on appearance, which today is inherently problematic. Katz and Suchey feel that that their sample is representative and is superior to the samples used for the Todd and McKern-Stewart methods (Katz and Suchey, 1986).

Katz and Suchey heavily critique both the Todd and McKern-Stewart methods. They note that the collection used by Todd consisted mostly of males over the age of 40, and that some of the specimens did not have known ages (only three individuals had recorded documents of birth). They state that the original Todd system usually over-ages individuals, so they recommend a modified system with only six phases. The McKern-Stewart sample consisted predominantly of white males in their twenties, all of whom had died in the Korean War. The McKern-Stewart method focuses on three components of the symphyseal face, but Katz and Suchey feel that the system is difficult for inexperienced individuals to use (Katz and Suchey, 1986).

Katz and Suchey conclude that the Todd system tends to over-age individuals by approximately 5 years, and neither the Todd nor the McKern-Stewart system accounts for variability in older individuals. At the time this article was written, it was generally accepted that pubic bone morphology could not accurately be used to determine the age of older individuals. As such, the authors eliminated specimens over the age of 40 for their statistical analyses. The regression analyses improved when individuals over this age were removed, with the standard deviations being reduced by an average of 5 units (Katz and Suchey, 1986). When the statistical data were reviewed, the authors note that the Todd (especially the modified six-phase Todd) system is more accurate than the McKern-Stewart method. They also state that these standards can not be used to assess ages for females because an analysis of females pubic bones demonstrated that females present more variability than males (Katz and Suchey, 1986).

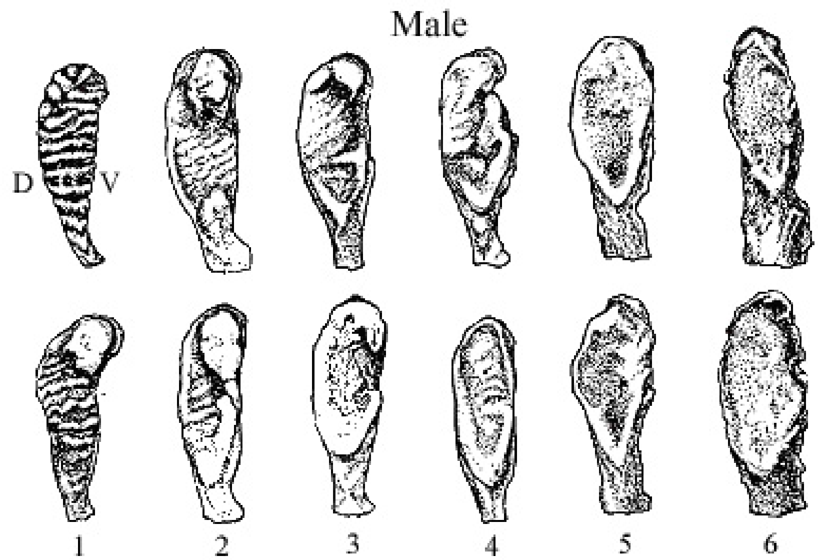
Yet another study was conducted by Sinha and Gupta in 1995 to determine if Indian pubic bones could be accurately aged using Western standards. The sample for this study consisted of 82 pairs of male pubic bones autopsied at Lady Hardinge Medical College and Associated Hospitals. The ages of each individual were recorded and verified via police records and birth certificates; the ages ranged from 12 to 75 years old. Samples were excluded from the study if they were pathological, if they showed signs of fracture, of if there was doubt as to the age of the individual (Sinha and Gupta, 1995). Multiple features of the pubic symphysis were examined for this study: ridges and furrows, dorsal margin, ventral beveling, lower extremity, ossific nodule, upper extremity, ventral rampart, dorsal plateau, and symphyseal rim. Sinha and Gupta examined and documented the formation and completion/disappearance of each trait. The pubic bones were then aged according to the Todd, McKern-Stewart, and Hanihara-Suzuki aging methods (Sinha and Gupta, 1995).

Most studies suggest that Todd's system imprecisely ages individuals, but Sinha and Gupta (1995) found that it ages Indian males fairly accurately. When the McKern-Stewart system is applied, some elements of the Indian pubic bones develop one to three years earlier than the method suggests for individuals of European ancestry; yet others, like the dorsal plateau develop at later ages in the Indian population. The Hanihara and Suzuki method tends to overestimate the age of the Indian bones by one to six years until the age of 30. Between the ages of 31 and 39, the method then underestimates the ages by one to four years (Sinha and Gupta, 1995). Other than these broad generalizations, Sinha and Gupta (1995) do not present conclusions or discussions regarding their findings. They do not address the significance of their results or what implications their study has for applying Western methods to other populations. It would seem that Western methods are fairly accurate (there were both overestimates and underestimates of ages depending upon the method), but it is impossible to tell from such limited data.

The Suchey-Brooks Pubic Bone Aging Method

The ability to estimate age using the pubic symphyseal face gained more widespread recognition with the introduction of the Suchey-Brooks method in 1990. This method was developed using 1,225 pubic bones (739 males and 273 females) obtained from Los Angeles County autopsies and can be used to age individuals between 14 and 99 years old (Brooks and Suchey, 1990; Suchey and Katz, 1998). The Suchey-Brooks method is a revision of the modified Todd (1920) aging method developed by Katz and Suchey in 1986. The Suchey-Brooks method focuses on the total pattern of bone changes rather than individual elements or features and has six phases. Each of the phases is represented by two bones demonstrating an "early pattern" and a "later pattern" of development (Brooks and Suchey, 1990). Detailed phase descriptions, line drawings, and plaster casts are available to assist observers in assigning an appropriate phase (Suchey and Katz, 1998) (Figure 5).

Figure 5: Line drawings of the six male Suchey-Brooks pubic bone age phases (Buikstra and Ubelaker, 1994).



In 1980, according to Brooks and Suchey (1990), the Workshop of European Anthropologists recommended the Acsádi-Nemeskéri (1970) method as a system for age estimation based on pubic bone changes. Suchey and Brooks evaluated the Acsádi-Nemeskéri system using their modern collection and recently established method. Since casts for the Acsádi-Nemeskéri method were not available, Brooks and Suchey analyzed the technique based upon the descriptions and photographs in the 1970 publication (Brooks and Suchey, 1990). This method did not study many young individuals, as only 38% of the specimens were between the ages of 23 and 50 years old. Thus, the Acsádi-Nemeskéri study focused mainly on early and late morphological changes, with little attention paid to the intermediate morphologies. The study also used samples from a

Hungarian cemetery, but the original publication does not explain how the ages of the skeletons were obtained, or even if the skeletons were modern.

When the Suchey-Brooks collection was evaluated using the Acsádi-Nemeskéri method, almost half of the males and females did not fit into a phase. Brooks and Suchey (1990) believe that this is due in part to the lack of intermediate phases for the Acsádi-Nemeskéri method. This method focuses on the application of the symphyseal face for "calculating whether an individual is under 50, about 50, or above 50 years" (Brooks and Suchey, 1990:234). Brooks and Suchey conclude that the Acsádi-Nemeskéri method is not supported by the modern Suchey-Brooks sample.

Today, particularly in the United States, the Suchey-Brooks system is the most commonly used method for estimating age at death from the pubic bone (Baccino et al., 1999; Djurić et al., 2007; Chen et al., 2008; Hens et al., 2008; Buikstra and Komar, 2008). However, Suchey and Katz (1998) note that the successful use of the Suchey-Brooks technique depends on a scientist's ability to recognize key pubic bone features, understand the terminology, and analyze pubic bones from varying states of preservation. If these criteria are met, the use of the pubic bone for adult age estimation has been shown to be of value (Suchey and Katz, 1998).

Tests of the Suchey-Brooks Pubic Bone Aging Method

Numerous studies have been conducted to test the accuracy of the Suchey-Brooks (1990) method, especially for diverse populations. Saunders and colleagues (1992) tested four morphological methods of adult age estimation including the Suchey-Brooks technique. This study evaluated between 27 and 49 skeletons from a Canadian pioneer cemetery in Ontario; however, the age distribution of this sample was older, with most of the individuals being over 50 years old. The results indicate that the Suchey-Brooks pubic bone method tends to underage the individuals by an average of 18 years, and has high biases (up to 22.4 years for individuals older than 60 years). Saunders et al. (1992) conclude that the Suchey-Brooks published age phases are so broad and often overlap that only the youngest and oldest phases are mutually exclusive.

In 1996, Santos tested the Suchey-Brooks (1990) method on a sample from the "Museu de Antropologia" of the University of Coimbra, Portugal. The study sample consisted of 231 pelves of males and females between the ages of 16 and 95 years of age. The results of this study are not encouraging. For the Suchey-Brooks method, 85.4% of males and 76% of females were misclassified. Only Phase I (the youngest individuals) was found to be distinct from the other five phases. Santos (1996) states that the Suchey-Brooks pubic symphysis casts are useful for the application of the method, but the choice of two extreme morphologies (young phase and old phase) is a possible source of error. Santos feels that a third cast, representative of a middle phase, would be beneficial. She concludes that this method is inaccurate for older individuals, and that the cut-off age for using this method should be 40 years. She suggests that the main cause of error for this method is its broad age ranges.

Baccino and colleagues conducted a study in 1999 evaluating four methods of adult age estimation including a dental method, the sternal end of the fourth rib, the pubic symphyseal surface, and femoral cortical remodeling. An autopsy sample of 19 French individuals was assessed. With regards to the Suchey-Brooks pubic bone method, Baccino et al. (1999) note that it has the largest standard error and very high mean bias among different observers. Based upon this study they conclude that comprehensive approaches are superior to individual aging methods when it comes to aging unknown individuals.

In 2004, Schmitt tested two methods for estimating adult age at death: the Suchey-Brooks (1990) pubic symphysis aging method and the Lovejoy et al. (1985b) auricular surface method. This study was conducted on a Thai skeletal collection and evaluated 37 males and 29 females, but the collection only had 8 individuals younger than 40 years old. This was the first time that these aging techniques had been tested on an Asian skeletal sample. The overall results for the Suchey-Brooks method indicate that bias and inaccuracy increase with age and that the method tends to underage all individuals, except for the youngest age group. Only 11 females and 13 males fell within the Suchey-Brooks 95% confidence intervals. Because these confidence intervals are wide, according to Schmitt (2004), one would expect that more individuals from the sample would be correctly classified into an age phase. This study is not encouraging for the application of these methods to Asian populations, and should therefore be applied with caution. Based upon this information, the author encourages population-specific standards for age at death estimation methods.

A study was conducted in 2007 by Djurić and colleagues to test whether the Suchey-Brooks (1990) method could successfully age adult populations in the Balkans. This method is often used for forensic identification of war victims in the former Yugoslavia; thus, its accuracy needed to be demonstrated for this particular population. A modern Serbian sample of known age, consisting of 33 female and 52 male pairs of pubic bones collected from autopsy cases, was evaluated. Djurić et al. (2007) demonstrate that the Suchey-Brooks method has an accuracy of 89.74% for males and

72.0% for females. Although this level of accuracy is fairly high, Djurić and colleagues suggest that population-specific standards need to be established to avoid the problems that arise between the reference sample and the population being studied. Based upon this study, several adjustments to the original Suchey-Brooks method are proposed which could be useful for aging Serbian populations in the future.

Martrille and colleagues evaluated four age estimation indicators for adults of European and African ancestry in 2007. A sample of 218 American individuals ranging in age from 25 to 90 years of age was studied from the Terry Collection. The sample was chosen to represent a balanced distribution of sexes, ages, and ancestries. When the sample is divided into age groups, the Suchey-Brooks method is the most accurate for the youngest adults between the ages of 25 and 40 years, with an average error of 6.2 years. After 60 years of age, or the oldest group, all four aging methods become highly inaccurate (with average errors between 13.4 and 17.4 years), and all methods tend to overage young individuals and underage older individuals (Martrille et al., 2007). For young adults of African and European ancestry, Martrille et al. find that the Suchey-Brooks method is the most reliable, with the least amount of error between 3 and 4.7 years, but this does not hold true for older adults.

In 2008, Hens and colleagues tested the Suchey-Brooks (1990) and Lovejoy et al. (1985b) auricular surface aging methods on a known sample from the Sassari Collection at the Museum of Anthropology at the University of Bologna, Italy. The Suchey-Brooks method is quite accurate for the youngest adults, but bias and inaccuracy increase with age. After the age of 40 years, for both sexes, this method underestimates the ages of the individuals in the sample. This study demonstrates lower levels of inaccuracy and bias than both Schmitt (2004) and Saunders (1992), but the trends of over-aging the young and under-aging the old are similar. Overall, the results of this study suggest that the auricular surface aging method performs better than the Suchey-Brooks method, especially for older individuals (Hens et al., 2008).

Finally, Hartnett tested the accuracy of the Suchey-Brooks (1990) method on a modern, documented, autopsy-based sample in 2010. A sample of 419 males and 211 females of known sex, age, and ancestry from the Forensic Science Center (FSC) in Phoenix, Arizona were evaluated. Based upon the critiques of the Suchey-Brooks method in anthropological literature, Hartnett establishes three goals for this research: 1) to establish a new, documented sample for future education and research, 2) evaluate the Suchey-Brooks standards on a modern, large and diverse skeletal sample, and 3) propose revisions to the method that will increase its precision and accuracy (Hartnett, 2010).

The statistical analysis demonstrates that there are significant differences between the actual and observed ages and that there is significant inter-observer error. Hartnett describes a new phase 7, comprised of both males and females, for individuals over the age of 70 years. With this additional phase, older individuals can be aged more accurately because a phase and age range can be assigned, rather than stating that an individual is 50+ years of age. To conclude, Hartnett states that the Suchey-Brooks method is not an extremely accurate technique for estimating age at death.

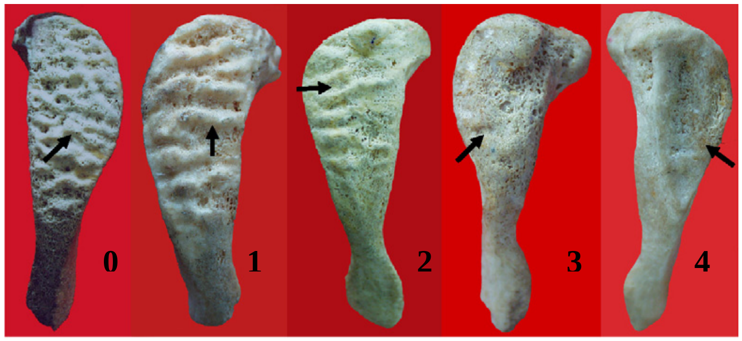
The Chen et al. Pubic Bone Aging Method

Focusing on multiple morphological features of the male pubic bone, Chen and colleagues developed a new method in 2008 for age estimation. For this study, 262 male pubic bones from Chinese Han individuals were analyzed (Chen et al., 2008). Using similar statistical analyses to Hanihara and Suzuki (1978), Chen and colleagues developed four equations for male age estimation: multiple regression analysis (MRA) and gradual regression analysis (GRA) were used to statistically analyze the nine features, while quantification theory model-I (QMI) and GRA were applied to compare with the MRA.

The Chen et al. (2008) study has two main goals. The first is to develop a method for age-at-death estimation based upon morphological changes. The second is to improve upon the aging methods of Hanihara and Suzuki (1978) and Suchey-Brooks (1990). Chen and colleagues believe that the Todd (1920), Hanihara and Suzuki (1978), and Suchey-Brooks (1990) methods have shortcomings. They note that their study overcomes these limitations by using a large sample size, separating specimens by sex (only used males), individually describing nine morphological indicators, and subdividing the nine features with distinct scores (Chen et al., 2008). They state that with the use of their statistical formulae, this method is highly reliable and that "age at death can be quantitatively estimated in people of Chinese male ancestry with a fairly high degree of accuracy" (Chen et al., 2008:42).

The Chen et al. (2008) pubic bone aging method employs nine indicators of morphological change to evaluate age-at-death. These indicators are "ridges and furrows on the symphyseal surface, ridge of pubic tubercle, lower extremity, ventral beveling, ossific nodules, dorsal margin, ventral rampart, general macroscopic changes of symphysial surface, and bone density of the symphysial surface" (Chen et al., 2008:36). Each of these nine features is divided into three-, four-, or five-stage categories and assigned a respective score of 0 through 2, 3, or 4. Each score has an accompanying

Figure 6: Example of ridges and furrows on the symphyseal surface: (0-4) (Chen et al., 2008).



Ridges and furrows on the symphysial surface: The ridges and furrows on the symphysial surface vary from individual to individual, and change with increasing age. Ridges and furrows on the symphysial surface were classified into five stages.

0: ridges and furrows alternate distinctly;
1: the furrows fill in and ridges and furrows alternate indistinctly;
2: the bone substance has a granular look with low, blunt ridges and shallow furrows;
3: the surface becomes flat and fine-textured, and/or again becomes more granular;
4: ridges and furrows disappear entirely and the surface becomes pitted and eroded.

descriptions. Figure 6 is an example of one of the Chen et al. photographs and scores. These descriptions are provided to assist observers in assigning a score.

The Chen et al. method examines both the right and left pubic bones, but does not elucidate whether an average is taken for the pair. The majority of literature on pubic bone aging methods does not explicitly state whether the right or left pubic bones have been evaluated; if both sides are assessed, most literature does not specify if an average is derived from both bones (Hanihara and Suzuki, 1978; Meindl et al., 1985; Brooks and Suchey, 1990). Only a few studies address this issue (Buckberry and Chamberlain, 2002; Hens et al. 2008). Hens et al. (2008) did not find significant differences when evaluating the right or left pubic bone. Although Buckberry and Chamberlain (2002) did not investigate the pubic bone, their results show no statistical difference between evaluating the right and left ilia. Subsequently, both Buckberry and Chamerlain (2002) and Hens et al. (2008) choose to analyze the left side when both right and left are available, and the side that is available for all other individuals.

As described in the Introduction chapter, Chen et al. (2008) state, via a forensic case report example, that their method can accurately age a Chinese male within one year from actual age at death. This is the only independent test of the method that they report. Additionally, Chen and colleagues do not present accuracy values, rates of error, or levels of significance for their method. These are distinct weaknesses of this method.

As this review has established, there are numerous methods which can be used to estimate the age of an individual from the pubic bone. The morphological changes of the pubis were recognized as early as the mid 18th century, but they were not attributed to the progression of age. As described above, many different systems have been developed to address age related changes in the pubic symphysis. However, there is still a discrepancy as to the upper age limits of pubic symphysis aging methods; some studies suggest that the upper limit is 40 years old (Todd, 1920; Hanihara and Suzuki, 1978; Suchey, Wisely, and Katz, 1986; Katz and Suchey, 1986; Santos, 1996; Hens et al., 2008), while others suggest that the upper limit is around 60 to 70 years old (Martrille et al., 2007; Chen et al., 2008; Hartnett, 2010).

All of these studies reveal that the pubic bone is the most frequently used anatomical feature for estimating the ages of unknown individuals. They also demonstrate that the assessment of age-at-death for adult human skeletal remains is central to both forensic and bioarchaeological analysis. Therefore, understanding the morphological development and remodeling of the pubic bone is crucial for all osteologists.

STUDY OBJECTIVES

As the previous chapter indicates, the anthropological literature is not lacking for adult age estimation methods which utilize the pubic bone. Although small, one gap in the literature is an independent test of the Chen et al. (2008) pubic aging method. The purpose of this thesis project, therefore, is to evaluate the Chen et al. (2008) pubic bone aging study, and to determine if the method can accurately estimate the age of individuals outside of the Chinese Han population. Despite the statements by Chen et al. that their method is highly accurate and reliable, their publication does not provide rates of error. This project will addresses this weakness, and contribute to the adult age estimation literature, by generating statistical data regarding error, significance, and accuracy via an independent evaluation of the Chen et al. method.

Furthermore, the Chen et al. (2008) publication does not discuss how accurate the method is for different age groups. This study will test three different age groups to assess the accuracy of the Chen et al. method for young, middle, and old individuals. Bias will also be evaluated for the three age groups.

The overall results of this project are expected to support the hypothesis that the Chen et al. pubic aging method can accurately assess age-at-death for the males of European ancestry in the Maricopa County Forensic Science Center collection. These results are expected because discontinuities in the aging process of the pubic bone are not common among different ancestries (Todd, 1921; Meindl et al., 1985)

An additional aspect of this project is to compare the accuracy of the Chen et al. method to the Suchey-Brooks method, which is currently the most accepted technique for estimating age from the pubic bones (Baccino et al., 1999). The purpose of this comparison is to demonstrate that the Chen et al. technique is not simply another method for estimating age; rather, it is an improved and more accurate method for estimating age-at-death using male pubic bones.

Research Questions and Hypotheses

Research Questions

The objective of this research is to address the following questions:

1. Will the Chen et al. (2008) method accurately assess age-at-death for males of European ancestry?
2. Will a revised Chen et al. method accurately assess age-at-death for males of European ancestry?
3. Will a revised Chen et al. method be more accurate than the Suchey-Brooks pubic aging method?
4. Which morphological features of the Chen et al. method are most predictive of age?
5. How accurate is the revised method for each age group?
6. What are the rates of error between and within the observers?

Research Hypotheses

1. The Chen et al. (2008) method will accurately assess age-at-death for non-Chinese males.
2. The revised method will be more accurate at assessing age-at-death for males of European ancestry than the Original Chen et al. method.
3. There will be no significant differences between the rates of accuracy and the R^2 values of the revised Chen et al. method and the Suchey-Brooks method.

4. Based upon the data presented by Chen et al. (2008), it is hypothesized that ventral beveling, bone density of the symphysial surface, and the ventral rampart will be the morphological features most predictive of age.
5. The revised method will be most accurate for young adults (18-34 years) and middle adults (35-49 years). The revised method will be less accurate for old adults (50 years and above).
6. Both the inter- and intra-observer rates of error will be low.

MATERIALS AND METHODS

Materials

This research is based on a modern pubic bone and sternal fourth rib end collection curated at the Maricopa County Forensic Science Center (FSC) in Phoenix, Arizona. This skeletal sample was obtained between January 2005 and June 2006 from individuals of known age, ancestry, and sex. The specimens were acquired from autopsies conducted at the FSC and from donated cadavers at Barrow Neurological Institute in Phoenix, Arizona (Hartnett, 2007; Hartnett, 2010). This new skeletal sample, as indicated by Hartnett (2010:6), is an important, autopsy-based sample for all anthropologists to study, and "will provide a means for independent testing and re-evaluation of rib and pubic bone techniques." This research has utilized the FSC collection for just such an evaluation.

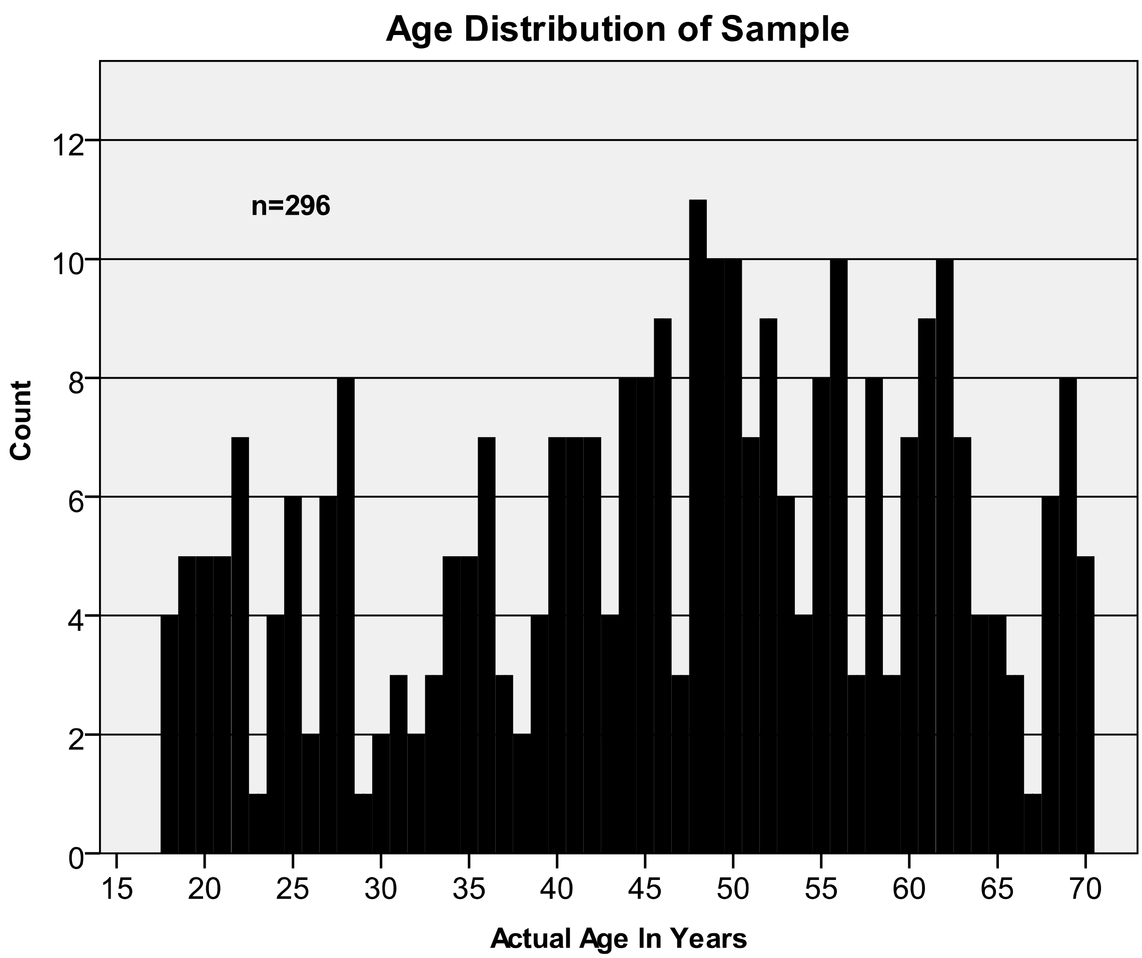
In order to directly replicate the Chen et al. method, only males were evaluated for this study. To age females, a new method would be required to address the greater variability seen in the female pubis (Katz and Suchey, 1986; Brooks and Suchey, 1990; Klepinger, 2006). Although females were not evaluated for this project, they are described here to provide a comprehensive understanding of the FSC collection (Table 1). The collection of 630 individuals is composed of 419 males and 211 females between the ages of 18 and 99 years old. The males range in age from 18 to 97 years old with a mean age of 52.6 years, and the females range from 18 to 99 years old

Table 1: Summary Statistics of the FSC Pubic Bone Sample from Hartnett (2007)

	N	Mean	SD	Age Range
Total Male Sample	419	52.6	19.0	18-97
Total Female Sample	211	59.2	21.4	18-99
Sample Total	630	54.8	20.1	18-99

with a mean age of 59.2 years (Figure 7). However, due to preservation issues, insufficient antemortem data, or pathological conditions, four males were eliminated from the sample; also, four males and two females are exclusively represented by rib ends (which are not pertinent to this project) reducing the available pubic bone sample to 620 individuals (411 males and 209 females) (Hartnett, 2007).

Figure 7:



The FSC collection is represented by Asians (n = 4), African Americans (n = 20), European ancestry (white) (n = 598), and Native Americans (n = 8). Individuals who were self-identified as Hispanic (n = 40) were included in the European ancestry category according to the FSC protocols (Hartnett, 2007; Hartnett, 2010). This project focuses exclusively on males of European ancestry between the ages of 18 and 70 years. Only individuals of European ancestry are evaluated to directly correspond with the homogeneous Chinese Han sample used by Chen et al. (2008). After females, individuals of non-European ancestry, individuals represented exclusively by ribs or with pathological pubic bones, and individuals over the age of 70 were excluded from the FSC collection, a sample of 296 male pubic bones was selected for analysis.

Methods

The objective of this research is to statistically evaluate the Chen et al. (2008) and Suchey-Brooks (1990) aging methods. The Chen et al. (2008) method is evaluated to determine if it is a valuable technique for use in the United States and whether it is more or less accurate than the Suchey-Brooks (1990) method.

The Chen et al. Method

To estimate age, the Chen et al. (2008) method uses four statistical equations: multiple regression analysis (MRA) and its gradual regression analysis (GRA) to statistically analyze the multiple features, and quantification theory Model-I (QMI) and GRA are applied simultaneously to compare with MRA. For this project's statistical analyses the equations are abbreviated as follows: MRA, MRA+GRA, QMI, and QMI+GRA.

Based upon the discussion of evaluating the right or left pubic bone in the Background chapter, a decision was made for this project to evaluate the left pubic bone of each individual. This decision reduces ambiguity for future research and eliminates one potential source of error. In the event that the left side is damaged or can not be scored, which occurred for ten individuals in this sample, the right side is scored.

However, the use of only the left pubic bone might present an inaccurate age assessment, especially if one bone of the pubic symphyses sustained trauma during life, or appears younger or older than the opposite side.

The Chen et al. method has an attenuated age distribution of 14 to 70 years. Therefore, only individuals between the ages of 18 and 70 (18 being the youngest individuals in the FSC collection, and 70 being the oldest age which the Chen et al. method can estimate) from the FSC collection are evaluated for this study. Based upon the age groups established by Buikstra and Ubelaker (1994), the FSC male pubic bones are divided as follows: Young adults (18-34 years), Middle adults (35-49 years) and Old adults (50 years and above) (Table 2). The sample is divided as such to gauge accuracy for younger and older individuals. Although not addressed in the original Chen et al. (2008) study, other researchers have established that older individuals are more difficult to age and produce more inaccurate age estimates (Todd, 1920; Hanihara and Suzuki, 1978; Katz and Suchey, 1986; Suchey and Katz, 1998; Baccino et al., 1999; Mulhern and Jones, 2005).

Table 2: Age Groups for FSC Sample

Age Groups	Age Range	n
Young Adult (1)	18-34 years	69
Middle Adult (2)	35-49 years	95
Old Adult (3)	50+ years	132

<u>The Suchey-Brooks Method</u>

The Suchey-Brooks pubic bone aging method, as discussed previously, is derived from an extensive autopsy sample of identified modern pubic bones. To apply this method, an observer must examine the unknown pubic symphysis and match it to the descriptions, line drawings, and/or casts depicting one of six morphological phases.

There are unisex descriptions, but separate casts, drawings, and descriptions for males and females are preferable (Brooks and Suchey, 1990).

<u>Intra- and Inter-Observer Error</u>

Each of the 296 pubic bones for this study was evaluated in accordance with the Chen et al. (2008) and Suchey-Brooks (1990) methods. The bones were examined by four Observers all with osteological experience: 1) the author, a forensic anthropology graduate student, 2) a professional forensic anthropologist, 3) a recent college graduate with a degree in anthropology, and 4) an undergraduate anthropology student. The author was self-trained in the Chen et al. (2008) method after having read the article and observing numerous bones to understand the features. All Observers were given tutorials by the author on how to use and apply the Chen et al. method before they began scoring the bones. All Observers were previously familiar with the use of the Suchey-Brooks method, having learned and applied it during their education and/or professional experiences. The Observers recorded their Chen et al. scores and Suchey-Brooks phase for each pubic bone on individual data-collection sheets. The actual age of each specimen was unknown to all Observers during the scoring process. The impetus for incorporating less experienced observers is to demonstrate the ease-of-use of this aging method. If Observers Three and Four are found to have lower accuracy rates, it is an indication that the method requires practice and training before proficiency is achieved—it *does not* imply that the method is ineffective for professional anthropologists.

Prior to evaluating the accuracy of the Chen et al. (2008) and Suchey-Brooks (1990) methods, inter- and intra-observer errors were tested. To measure intra-observer error, a random sample of 100 previously scored pubic bones was reassessed by the author; the bones were scored again for both the Chen et al. and the Suchey-Brooks methods. These data were evaluated by calculating Cohen's Kappa measurement of agreement and Pearson's correlation coefficient.

Inter-observer error was also evaluated for both the Chen et al. (2008) and the Suchey-Brooks (1990) methods. Observer Two scored 200 pubic bones via the Chen et al. method and 75 bones via the Suchey-Brooks method. Observers Three and Four scored the same 50 pubic bones using both methods. These data were evaluated using Pearson's correlation coefficient.

Statistical Analysis Part 1: Evaluation and Revision of the Chen et al. (2008) Method

This project generated statistical data concerning the accuracy, rates of error, and significance of the Chen et al. (2008) model's utility for aging male populations of European ancestry. The statistical analysis for this project was multifaceted; the Chen et al. model was tested and then revised based on the FSC sample, and later the Chen et al. and Suchey-Brooks methods were compared. All statistical analyses were performed using SPSS statistical software version 18.

To construct their four statistical models (MRA, MRA+GRA, QMI, and QMI+GRA), Chen and colleagues evaluated 262 male pubic bones from the Chinese Han population (Chen et al., 2008). Unlike the homogenous Chen et al. sample, the FSC collection is composed of multiple ancestral groups. In order to directly evaluate the Chen et al. model, and to determine its utility for aging additional populations, 296 male pubic bones of European ancestry from the FSC collection were scored as specified by the Chen et al. (2008) method.

The nine scores for each of the 296 left male pubic bones were input into the Original (published) Chen et al. MRA+GRA and QMI+GRA statistical models. These two models, as opposed to all four, were evaluated because the Chen et al. study favors the inclusion of the gradual regression analysis (GRA) when estimating an individual's age (Chen et al., 2008). Furthermore, when statistical analyses were run on the four equations using the FSC data, the inclusion of GRA produced slightly more accurate age estimates.

Based upon their popularity in forensic and bioarchaeological literature, bias and absolute mean error (referred to as "inaccuracy" in some articles) were applied to demonstrate the accuracy of the Chen et al. (2008) and Suchey-Brooks (1990) aging methods (Lovejoy et al., 1985a; Meindl et al., 1985; Meindl and Lovejoy; 1989; Schmitt, 2004; Mulhern and Jones, 2005; Martrille et al., 2007; Hens et al., 2008; Passalacqua, 2010). Both absolute mean error (AME) and bias were calculated for each pubic bone and for both Chen et al. Original statistical models (MRA+GRA and QMI+GRA).

Absolute mean error, or Σ |estimated age – actual age|/N, is the absolute difference between the estimated and actual ages. Bias, or Σ (estimated age – actual age)/N, is the difference between the estimated and actual ages. Bias demonstrates the average over- or under-aging of the individual's actual age, while absolute mean error demonstrates the average error from the individual's actual age (Lovejoy et al., 1985a; Meindl et al., 1985; Meindl and Lovejoy; 1989; Schmitt, 2004; Mulhern and Jones, 2005; Martrille et al., 2007; Hens et al., 2008; Passalacqua, 2010).

The second step in evaluating the Chen et al. (2008) method was to create revised statistical models based exclusively on the FSC sample. Using the raw data from the 296 left male pubic bones of European ancestry, new coefficients were generated for the nine Chen et al. morphological features. The coefficients were then used to produce four Revised statistical models (MRA, MRA+GRA, QMI, and QMI+GRA), which could be directly compared to the Original Chen et al. (2008) models (see Table 3). The MRA and QMI equations were entered into SPSS without modifications. The MRA+GRA and QMI+GRA equations required the use of a backwards stepwise regression with an F criterion of removal = 0.10 to replicate their complementary equations in the Chen et al. (2008) publication.

A stepwise regression adds or removes variables that do not make a significant contribution to the model (Agresti and Finlay, 2009). A backwards stepwise regression begins with all data and removes variables that do not significantly explain the variance of the model, while a forward stepwise regression begins with no data and adds variables that significantly explain variance. A backwards stepwise regression was applied here because it was more conservative and left more variables in place to explain the models.

Again, the two Revised models which include the gradual regression analysis (MRA+GRA and QMI+GRA) were the focus of statistical analysis. To test the models the data of all 296 previously scored pubic bones were input into the new models. Absolute mean error and bias were calculated for each pubic bone and for both Revised statistical models to demonstrate accuracy (Lovejoy et al., 1985a; Meindl et al., 1985; Meindl and Lovejoy; 1989; Schmitt, 2004; Mulhern and Jones, 2005; Hens et al., 2008; Passalacqua, 2010).

For both the Original and Revised Chen et al. models, frequencies of AME were generated. These brackets demonstrate how closely the estimated ages are to the actual ages. Frequency brackets were developed rather than using standard deviations because the Chen et al. method does not produce standard deviations—it just provides a point age estimate.

The frequencies were evaluated in brackets of one, five, ten, and fifteen years from the actual age values. Since these are absolute values, they represent 1, 5, 10 or 15 years either above or below an individual's actual age. They do not represent a range. The level of accuracy for each model was based upon the percentage (or frequency) within each of the brackets; the frequency represents the number of individuals who were accurately aged within that bracket. A high percentage indicates that more individuals fell within that bracket, and thus, is more accurate than models with lower percentages. For example, if 10% of the sample's AME derived from the *Original* Chen et al. model fell within one year of the actual age, while only 7% of the sample's AME derived from the *Revised* Chen et al. model fell within one year of the actual age, then the *Original* Chen et al. model had a higher level of accuracy for that one year bracket. The same is true for the five, ten, and fifteen year brackets.

To further evaluate the Revised Chen et al. models (MRA+GRA and QMI+GRA), statistical analyses were run on all 296 pubic bones. A forward stepwise regression was employed to determine which morphological features contributed most to the prediction of age (Buckberry and Chamberlain, 2002). A forward stepwise regression was applied here to obtain the fewest number of features that would significantly predict age (Agresti and Finlay, 2009; Field, 2009). To assess the relationships between each of the nine morphological features and age, Pearson's correlation coefficient was applied. To collectively assess the relationships between each of the nine features, Pearson's correlation coefficient was again applied. Finally, the accuracy of the Revised models was tested for each of the three age groups (young, middle, and old adults) in the FSC sample by employing bias and AME.

The accuracy of the Original and Revised Chen et al. models for each of the three age groups was assessed by calculating bias and absolute mean error. In addition, analysis of variance (ANOVA) was computed for each age group to determine if there was a significant difference between the mean biases and errors for each of the Chen et al. models. These values were derived from the ANOVA post hoc test. When significant f-values are found using ANOVA, a post hoc test allows for a more comprehensive exploration of the differences among the means, and to determine the significance of these differences (Huck, 2008).

Statistical Analysis Part 2: Comparison of the Chen et al. (2008) and Suchey-Brooks (1990) Models

In order to assess whether the Original and Revised Chen et al. models were more or less accurate than the Suchey-Brooks (1990) model, all 296 left male pubic bones of European ancestry were evaluated. Each of the 296 bones, which were previously scored in accordance with the Chen et al. method, were later assigned a phase in accordance with the Suchey-Brooks method. Absolute mean error and bias were calculated for the Suchey-Brooks model as a whole and for each of the three age groups.

Accuracy was evaluated by comparing the biases and frequencies of AME for the Original Chen et al. (2008) model, the Revised Chen et al. model and the Suchey-Brooks (1990) model. The frequencies were again evaluated in brackets of one, five, ten, and fifteen years from the actual age values; the model with the highest percentage of absolute mean error values for each of the brackets was the most accurate. As stated previously, the absolute mean error for the Chen et al. model is the sum of the absolute difference between the *estimated* and actual age divided by the sample size. For the Suchey-Brooks model, the absolute mean error is the sum of the absolute difference between the *mean* and actual age divided by the sample size (Σ |*mean* age – actual age|/N), which is in keeping with the forensic and bioarchaeological literature (Martrille et al., 2007; Passalacqua, 2010).

To support this analysis of accuracy, R^2 values were also evaluated for the Chen et al. models and the Suchey-Brooks model. Derived from the data of the 296 left male pubic bones of European ancestry, linear multiple regressions were run for both the Original and Revised Chen et al. MRA+GRA and QMI+GRA models and a linear regression was run for the Suchey-Brooks model. The R^2 values, or the coefficients of determination, provide the proportion of variance in Y explained by X (Hamilton, 1992; Agresti and Finlay, 2009). In this case X is the aging model (Chen et al. and Suchey-Brooks) while Y is actual age at death. These values were compared and the higher the R^2 the more accurate the model. Pearson's correlation coefficients were calculated to determine the relationship between the aging models and actual age.

The accuracy of the Suchey-Brooks method was also assessed for each of the three age groups. In addition to bias and absolute mean error, analysis of variance (ANOVA) was calculated to determine if there was a significant difference between the mean errors and biases produced by the Suchey-Brooks method and the Original and Revised Chen et al. methods. These values were derived from the ANOVA post hoc test.

RESULTS

Test of the Original Chen et al. Models

The scores for each of the 296 FSC pubic bones were input into the published Original Chen et al. (2008) multiple regression analysis (MRA and MRA+GRA) and the quantification theory model-I equations (QMI and QMI+GRA):

<u>MRA</u>: $Y = 16.97 + 0.42X_1 + 1.48X_2 + 1.88X_3 + 2.51X_4 – 0.43X_5 + 1.76X_6 + 3.25X_7 – 0.66X_8 + 7.31X_9$

<u>MRA+GRA</u>: $Y = 16.79 + 1.76X_2 + 1.71X_3 + 2.47X_4 + 1.68X_6 + 3.03X_7 + 7.30X_9$

<u>QMI</u>: $Y = 15.93 + 1.43X_{1-1} + 2.22X_{1-2} + 2.02X_{1-3} + 1.43X_{1-4} + 1.72X_{2-1} + 2.87X_{2-2} + 1.49X_{3-1} + 2.99X_{3-2} + 5.64X_{3-3} + 1.35X_{4-1} + 4.36X_{4-2} + 8.83X_{4-3} + 0.48X_{5-1} + 2.29X_{5-2} + 1.01X_{6-1} + 3.92X_{6-2} + 5.46X_{6-3} + 1.92X_{7-1} + 4.40X_{7-2} – 0.34X_{8-1} + 0.66X_{8-2} + 5.61X_{9-1} + 9.62X_{9-2} + 19.45X_{9-3}$

<u>QMI+GRA</u>: $Y = 16.45 + 0.89X_{1-2} + 2.56X_{2-1} + 3.99X_{2-2} + 1.32X_{3-1} + 3.10X_{3-2} + 5.75X_{3-3} + 1.44X_{4-1} + 4.70X_{4-2} + 9.18X_{4-3} + 1.49X_{5-2} + 1.32X_{6-1} + 4.21X_{6-2} + 5.76X_{6-3} + 2.37X_{7-1} + 4.86X_{7-2} + 5.62X_{9-1} + 9.62X_{9-2} + 19.45X_{9-3}$

Absolute mean error and bias were calculated. As the histograms in Figure 8 demonstrate, the Original Chen et al. models have high frequencies of low absolute mean error, with the average error (AME) being approximately 9 years from the specimens' actual ages (AME = 9.18 and 9.19, respectively). The histograms in Figure 9 illustrate that the average biases for the Original Chen et al. models are positive (higher distribution of bars above the 0 line), which indicates an average over-estimation of the specimens' actual age. The average biases are also low (MRA+GRA Bias = 1.82 and QMI+GRA Bias = 1.51).

Figure 8:

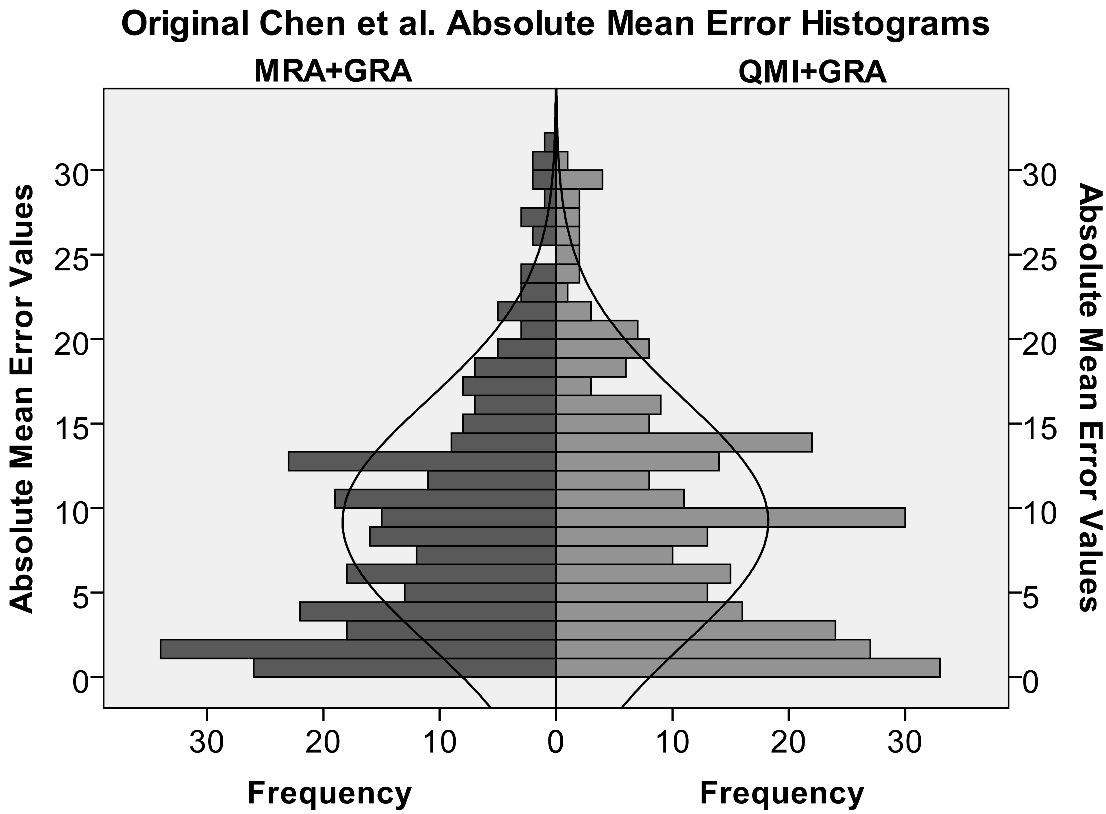
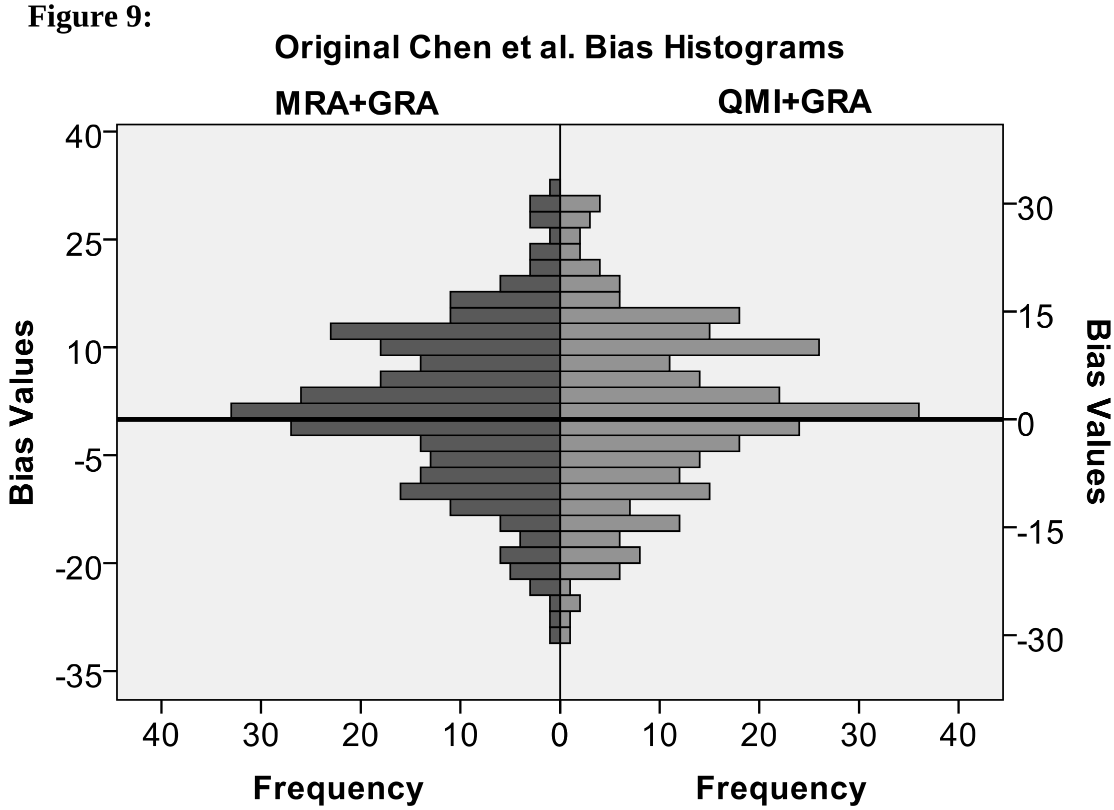


Figure 9:



Revision of Original Chen et al. Models

Based upon the FSC data for each of the 296 bones, Revised Chen et al. models were developed. New regression constants, coefficients, and standard deviations were produced for the multiple regression analysis and its gradual regression analysis (MRA and MRA+GRA) as well as the quantification theory model-I and its gradual regression analysis (QMI and QMI+GRA) (see Table 3):

MRA: $Y = 12.69 + 2.57X_1 + 2.83X_2 + 0.36X_3 + 0.60X_4 – 1.59X_5 + 0.49X_6 + 7.78X_7 + 0.07X_8 + 2.04X_9$

MRA+GRA: $Y = 15.27 + 2.88X_1 + 3.37X_6 + 8.25X_7 + 2.13X_9$

QMI: $Y = 19.93 – 0.65X_{1\text{-}1} + 3.90X_{1\text{-}2} + 10.55X_{1\text{-}3} + 10.70X_{1\text{-}4} + 0.14X_{2\text{-}1} + 4.05X_{2\text{-}2} – 0.53X_{3\text{-}1} + 3.56X_{3\text{-}2} + 3.25X_{3\text{-}3} + 2.46X_{4\text{-}1} + 2.56X_{4\text{-}2} + 2.40X_{4\text{-}3} – 4.25X_{5\text{-}1} – 6.63X_{5\text{-}2} + 0.79X_{6\text{-}1} + 6.97X_{6\text{-}2} + 9.46X_{6\text{-}3} + 4.25X_{7\text{-}1} + 11.77X_{7\text{-}2} – 2.43X_{8\text{-}1} – 5.52X_{8\text{-}2} + 3.55X_{9\text{-}1} + 6.24X_{9\text{-}2} + 6.58X_{9\text{-}3}$

QMI+GRA: $Y = 21.27 + 5.74X_{1\text{-}3} + 7.29X_{1\text{-}4} + 7.91X_{6\text{-}2} + 10.61X_{6\text{-}3} + 8.39X_{7\text{-}1} + 16.22X_{7\text{-}2} + 2.57X_{9\text{-}2}$

To test the accuracy of these Revised models, bias and AME were calculated. The results of the Revised models, as well as the Original Chen et al. and Suchey-Brooks models, are described in the sections that follow.

Accuracy of the Models

Frequencies of Absolute Mean Error

As previously stated in the Methods chapter, frequencies of absolute mean error (AME) were generated for all three models: Original Chen et al., Revised Chen et al., and Suchey-Brooks. The frequencies were evaluated in brackets of one, five, ten, and fifteen years from the actual age values. The level of accuracy for each model was based upon the percentage (or frequency) of individuals that fell within each of the brackets. A

Table 3: Evaluation Criteria of Male Pubic Symphyses and Regression Coefficients for Original and Revised Chen et al. Multiple Regression Analysis (MRA), Gradual Regression Analysis, and Quantification Theory Model-I (QMI)

	Morphological Feature	Scores and Descriptions	Original Chen et al. Model				Revised Chen et al. Model			
			MRA	MRA+GRA	QMI	QMI+GRA	MRA	MRA+GRA	QMI	QMI+GRA
X_1	Ridges and furrows	0: Alternate distinctly	0.42	0	0	0	2.57	2.88	0	0
		1: Furrows fill in, alternate indistinctly			1.43	0			-0.7	0
		2: Granular, blunt ridges, shallow furrows			2.22	0.89			3.90	0
		3: Flat and fine-textured, may be granular			2.02	0			10.55	5.74
		4: Disappearance, pitting and erosion			1.43	0			10.70	7.29
X_2	Ridges of pubic tubercle	0: Tubercle completed	1.48	1.76	0	0	2.83	0	0	0
		1: Tubercle almost gone			1.72	2.56			0.14	0
		2: Tubercle completely disappeared			2.87	3.99			4.05	0
X_3	Lower extremity	0: No appearance of lower	1.88	1.71	0	0	0.36	0	0	0
		1: Appearance of dividing line			1.49	1.32			-0.53	0
		2: Presence of "V" angle			2.99	3.10			3.56	0
		3: Atrophy of "V" angle			5.64	5.75			3.25	0
X_4	Ventral rampart	0: No appearance	2.51	2.47	0	0	0.60	0	0	0
		1: Local ventral rampart			1.35	1.44			2.46	0

Table 2 (cont'd)

	Morphological Feature	Scores and Descriptions	Original Chen et al. Model				Revised Chen et al. Model			
			MRA	MRA+GRA	QMI	QMI+GRA	MRA	MRA+GRA	QMI	QMI+GRA
		2: Fully developed			4.36	4.70			2.56	0
		3: Wider or nodular in			8.83	9.18			2.40	0
X_5	Ossific nodule	0: No appearance	-0.43	0	0	0	-1.59	0	0	0
		1: Appearance			0.48	0			-4.25	0
		2: Fusion and disappearance			2.29	1.49			-6.63	0
X_6	Dorsal margin	0: No appearance	1.76	1.68	0	0	0.49	3.73	0	0
		1: Edged margin without plateau			1.01	1.32			0.79	0
		2: Plateau and lipping of dorsal margin			3.92	4.21			6.97	7.91
		3: Middle destruction,			5.46	5.76			9.46	10.61
X_7	Ventral beveling	0: No appearance	3.25	3.03	0	0	7.78	8.25	0	0
		1: Clear edged margin			1.92	2.37			4.25	8.39
		2: Flattening or disappearance			4.40	4.86			11.77	16.22
X_8	Macroscopic changes	0: Prominence of symphyseal surface	-0.66	0	0	0	0.07	0	0	0

Table 2 (cont'd)

	Morphological Feature	Scores and Descriptions	Original Chen et al. Model				Revised Chen et al. Model			
			MRA	MRA+GRA	QMI	QMI+GRA	MRA	MRA+GRA	QMI	QMI+GRA
		1: Irregular surface			-0.34	0			-2.43	0
		2: Flatness or fovea, clear periphery			0.66	0			-5.52	0
X_9	Bone density	0: Ridges, or rough with no ridges	7.31	7.30	0	0	2.04	2.13	0	0
		1: Smooth, dense and solid			5.61	5.62			3.55	0
		2: Concavo-convex or dense porosity			9.62	9.62			6.24	2.57
		3: Big pits and/or loss of density			19.45	19.45			6.58	0

Original Chen et al. Models Constants and Standard Deviations (SD)
MRA: Constant = 16.97; SD = 2.13
MRA+GRA: Constant = 16.79; SD = 2.14
QMI: Constant = 15.93; SD = 1.96
QMI+GRA: Constant = 16.45; SD = 1.97

Revised Chen et al. Models Constants and Standard Deviations (SD)
MRA: Constant = 12.69; SD = 9.54
MRA+GRA: Constant = 15.27; SD = 9.52
QMI: Constant = 19.93; SD = 9.78
QMI+GRA: Constant = 21.27; SD = 9.63

higher percentage per bracket represents higher accuracy. As mentioned before, these values do not represent a range; rather, they represent the number of years either above or below actual age.

The most accurate model for aging this sample varies by frequency bracket, as shown in Table 4 and Figures 10 through 14. The most accurate model for one year from actual age is the Original Chen et al. MRA+GRA (10.8%). This percentage indicates that if the Original Chen MRA+GRA model is used, almost 11% of individuals will be assigned an estimated age within one year from their actual age at death. Figure 10 provides a visual assessment of this same information; vertical lines are placed at 1, 5, 10, and 15 years from actual age and the percentages are derived from the "amount" of the histogram which is to the left of the lines. In this figure, 10.8% of the histogram value is to the left of the one year line.

The most accurate model for five years from actual age is Suchey-Brooks (38.9%) (Figure 14), and for both ten and fifteen years it is the Revised MRA+GRA (65.7% and 87.3%) (Figure 12). As both Table 4 and Figures 10 through 14 demonstrate, age at death will be accurately estimated within 15 years for between 79% and 87% of individuals depending upon the model used. The most accurate model for 15 years from actual age is the Revised Chen et al. MRA+GRA at 87.3% (Figure 12); thus, when this model is applied, 87% of individuals will be assigned an estimated aged within 15 years

Table 4: Frequencies of Absolute Mean Error (AME)

	1 year*	5 years*	10 years*	15 years*
Revised Chen et al. MRA+GRA Model	7.8%	37.3%	65.7%	87.3%
Revised Chen et al. QMI+GRA Model	5.9%	38.6%	63.4%	85.1%
Suchey-Brooks Model	9.5%	38.9%	63.9%	78.7%
Original Chen et al. MRA+GRA Model	10.8%	35.3%	59.8%	85.3%
Original Chen et al. QMI+GRA Model	9.8%	33.3%	62.7%	85.3%

* Within 1, 5, 10, or 15 year(s) of actual age

Figure 10:

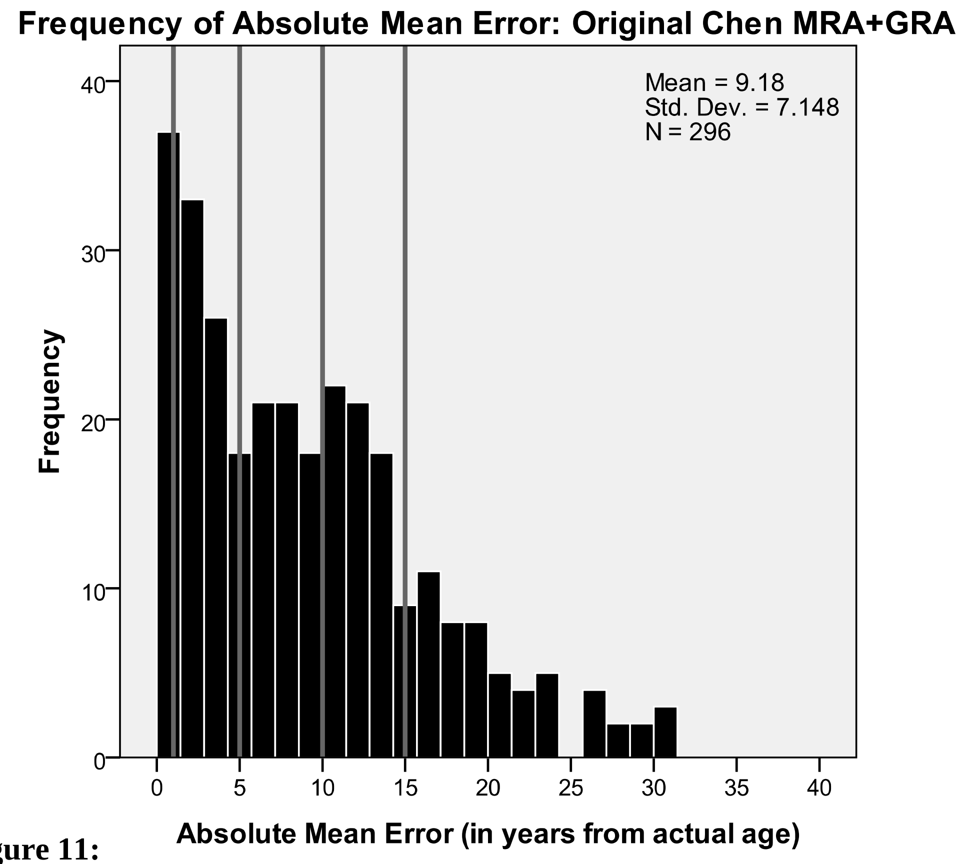


Figure 11:

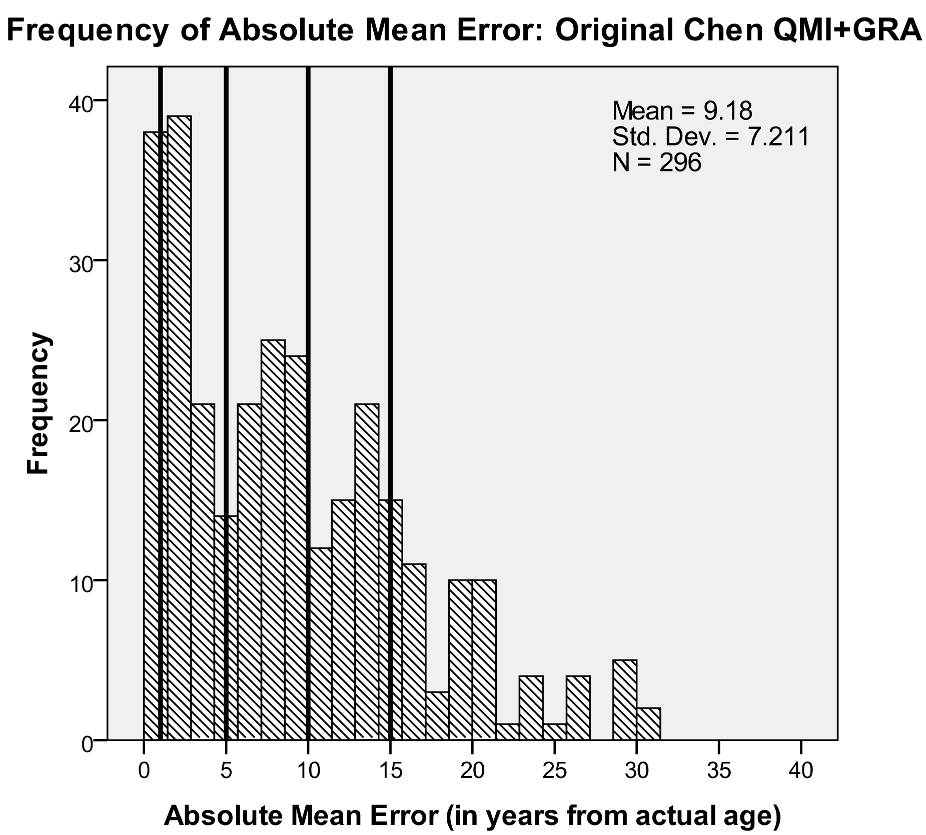


Figure 12:

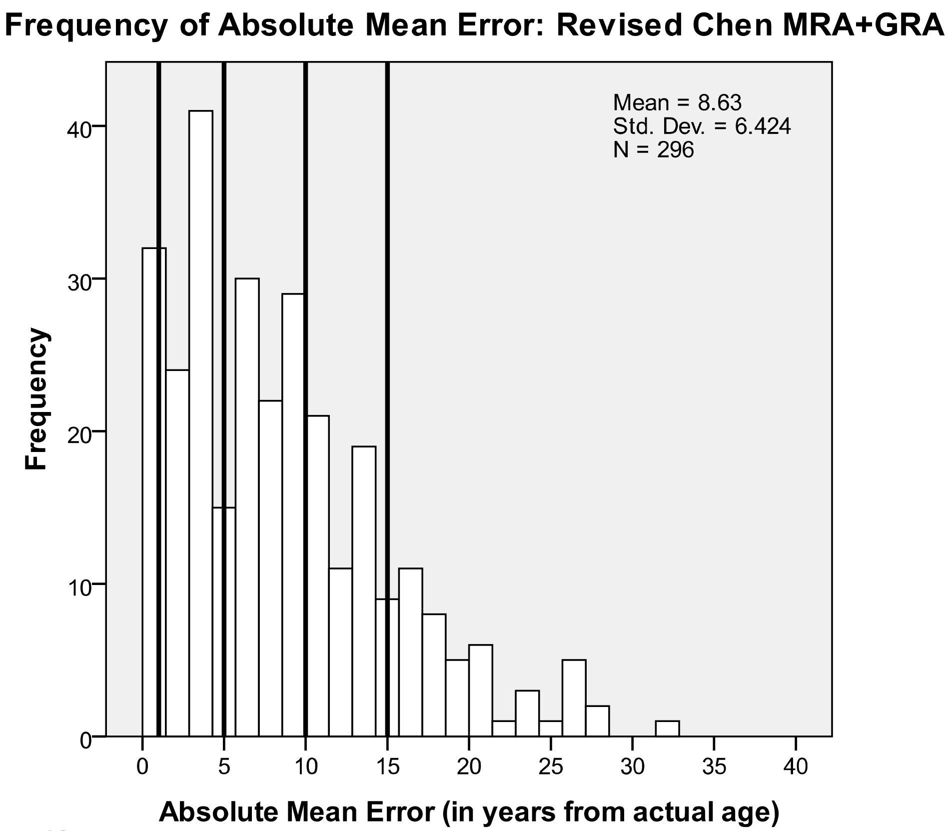


Figure 13:

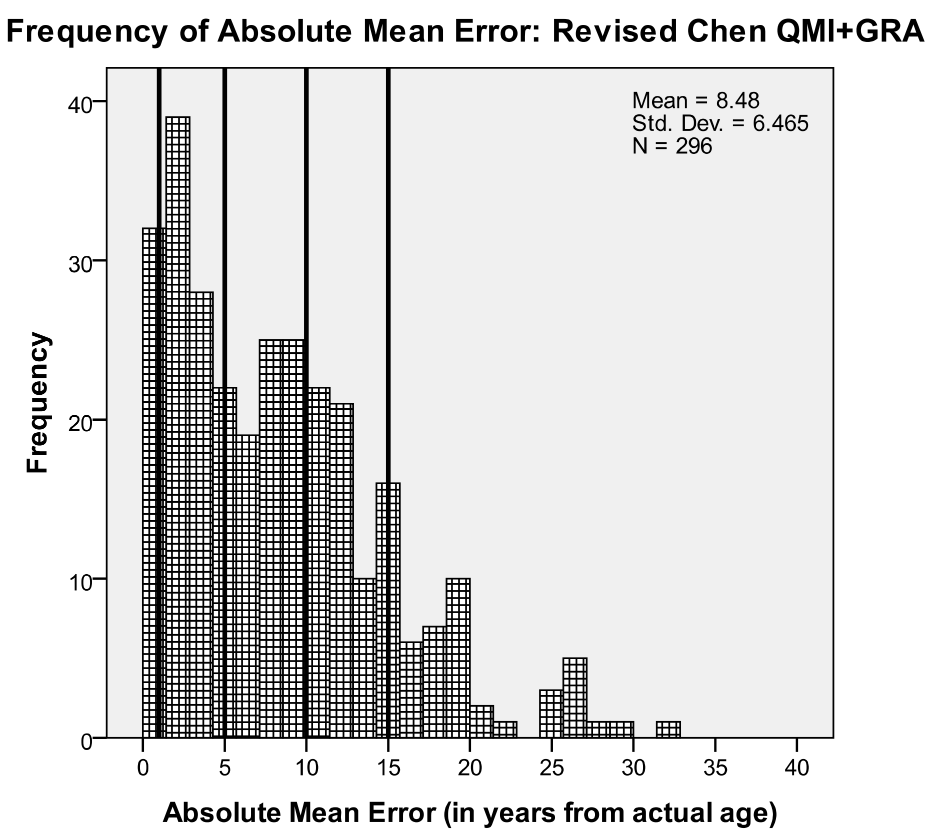
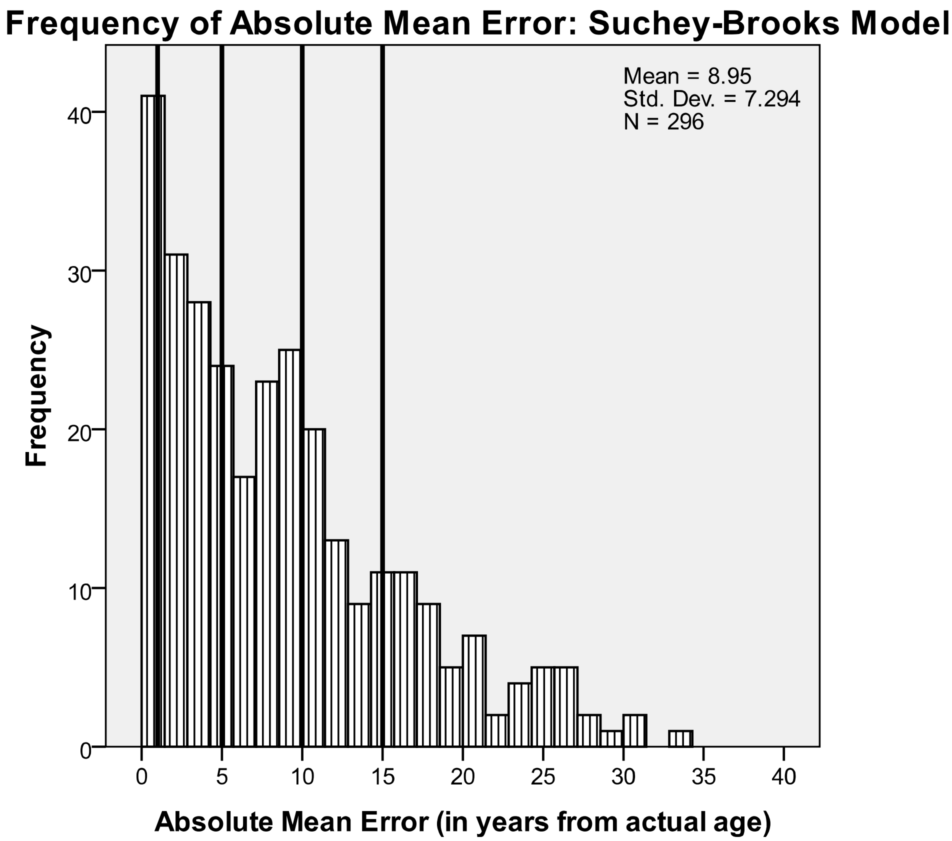


Figure 14:



from their actual age at death. However, the Suchey-Brooks model is far less accurate at 15 years with only 79% of individuals being assessed correctly within 15 years from their actual age at death.

Absolute Mean Error for All Models

Table 5 and Figure 15 represent the overall error for each model. The Original Chen models have an average error of approximately 9 years from the individual's actual age. The Revised Chen models are slightly more accurate, with an average error between 8.48 and 8.63 years from actual age. The

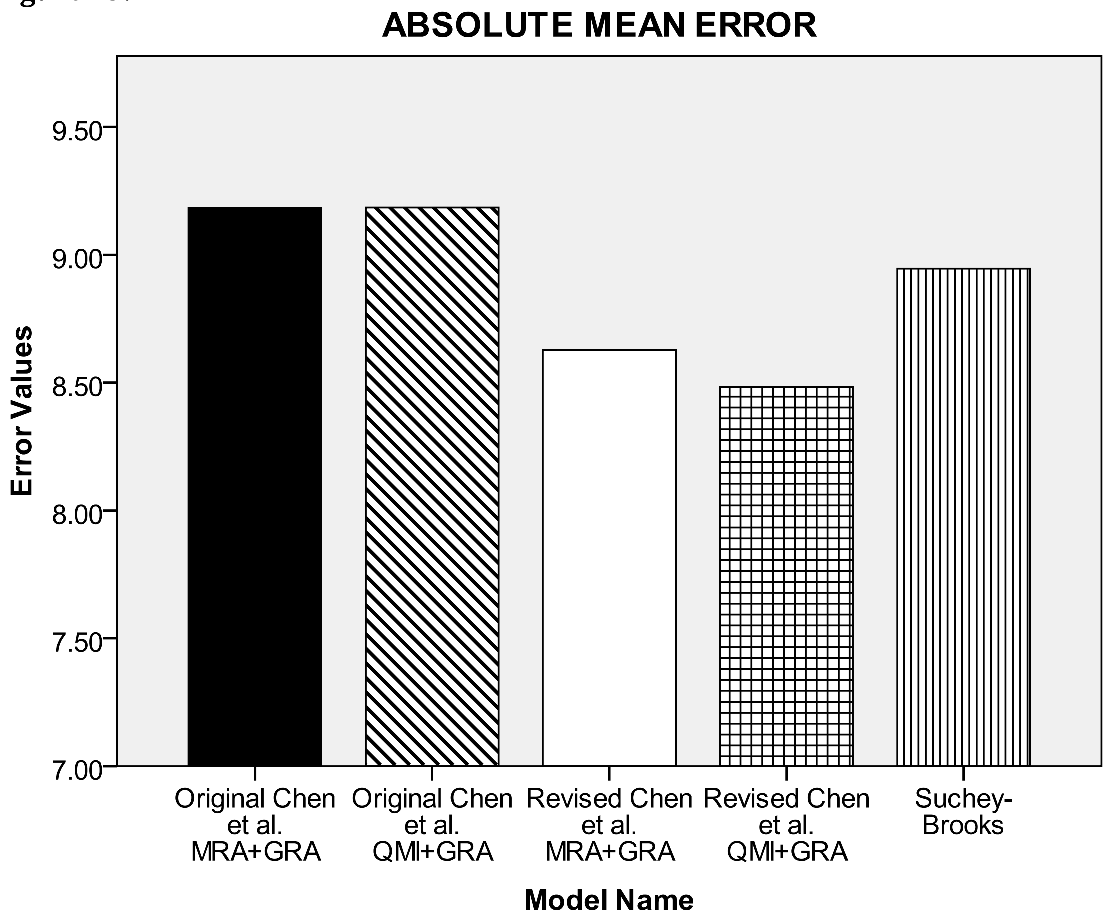
Table 5: Absolute Mean Error for each Model

Revised Chen et al. MRA+GRA Model	8.628
Revised Chen et al. QMI+GRA Model	8.483
Suchey-Brooks Model	8.946
Original Chen et al. MRA+GRA Model	9.182
Original Chen et al. QMI+GRA Model	9.185

n = 296

Suchey-Brooks model has an average error in between the Chen et al. models at 8.95 years from actual age; however, this is derived from the Suchey-Brooks mean age per phase. Thus, for the FSC sample, the Revised Chen et al. models have the least amount of error from an individual's actual age.

Figure 15:



Bias for All Models

Table 6 and Figure 16 demonstrate the over-estimation and under-estimation of age for each model. The Original Chen et al. models over-age individuals by approximately 1.5 to 2 years while the Revised Chen

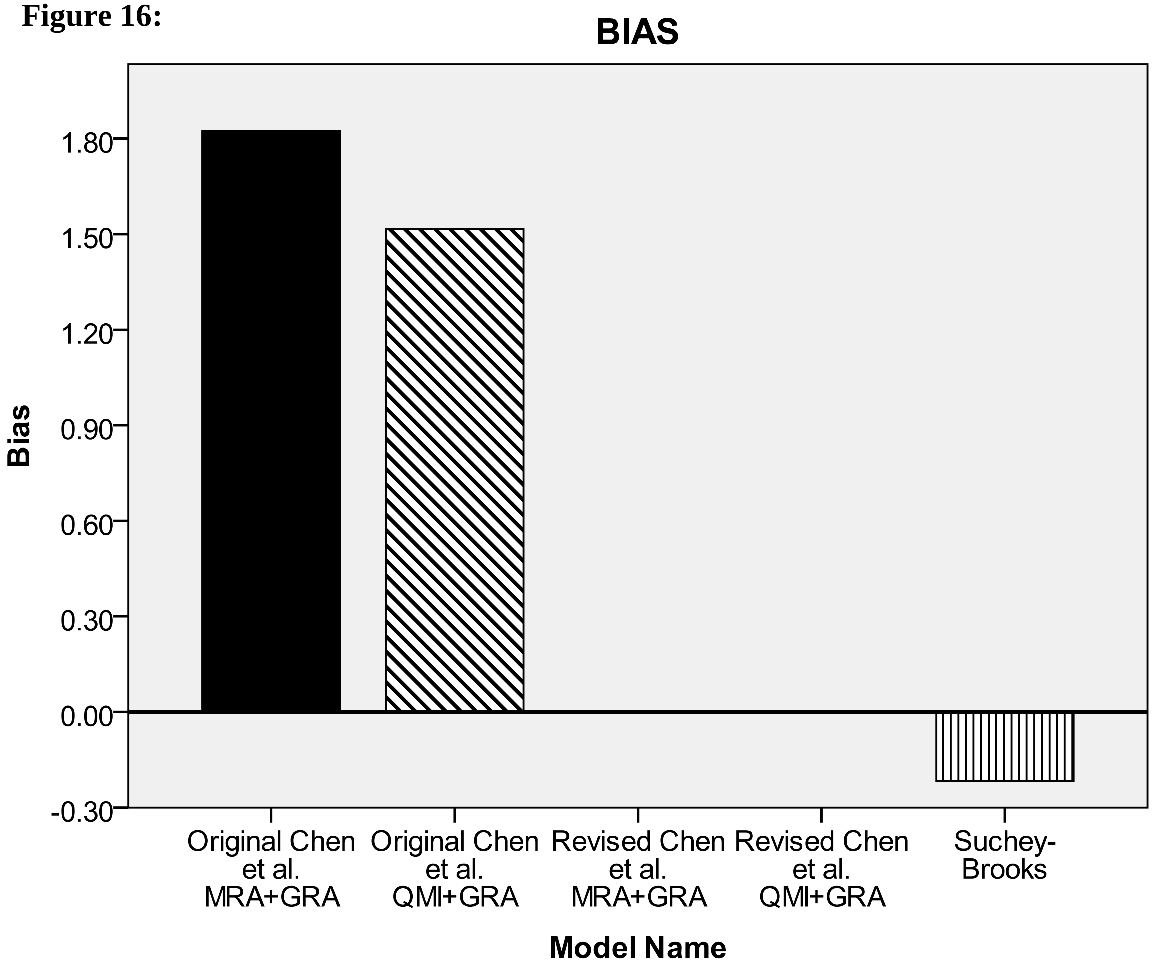
Table 6: Bias for Each Model

Revised Chen et al. MRA+GRA Model	0.000
Revised Chen et al. QMI+GRA Model	0.000
Suchey-Brooks Model	-0.217
Original Chen et al. MRA+GRA Model	1.824
Original Chen et al. QMI+GRA Model	1.516

n = 296

et al. models have no bias. The Revised models equally over-age young individuals and

Figure 16:



under-age old individuals which negates their influence and results in a lack of bias, as seen in the scatterplots (Figure 17 and 18). The Suchey-Brooks model consistently under-ages the sample resulting in a negative bias (-0.22); again, this is from the mean age and does not consider the full 95% range. For the FSC sample, the Revised Chen et al. models have the lowest bias, although all models have biases of less than 2 years.

Variance and Correlation

Variance, designated as R^2, was generated from regressions of each model and actual age. These values provide the proportion of variance of age explained by the aging models (Hamilton, 1992). As demonstrated in Figure 19, the Revised Chen et al. MRA+GRA model explains almost 50% (R^2 = 0.491) of the variance in actual age. The remaining 50% of the variance is unexplained by the aging models, but could be explained by factors not addressed in these regressions (e.g. an individual's lifestyle, health, environment, etc.) (Hamilton, 1992). The Revised Chen et al. models explain the most variance in age (MRA+GRA R^2 = 0.491; QMI+GRA R^2 = 0.487) followed by the Suchey-Brooks model (R^2 = 0.454). The Original Chen et al. models explain the smallest amount of variance, with the Original QMI+GRA explaining the least at 42%. Despite the differences between the models, they are all within a fairly close range of R^2 = 0.42 – 0.49; thus, they explain between 42% and almost 50% of the variance in actual age.

Figure 17:

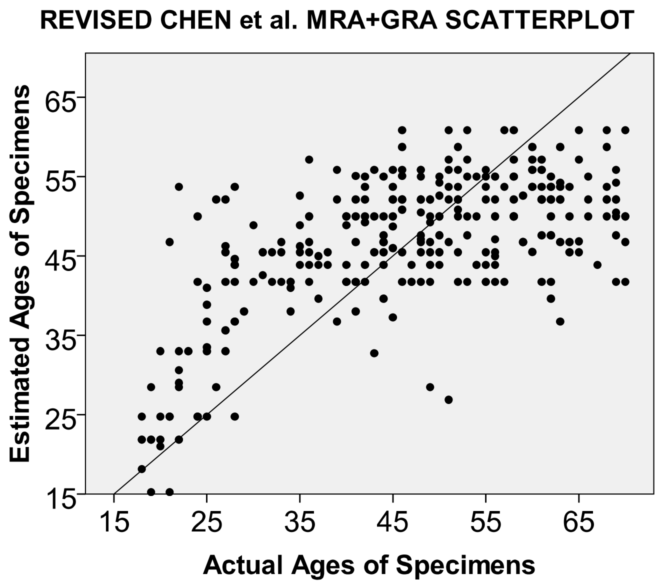


Figure 18:

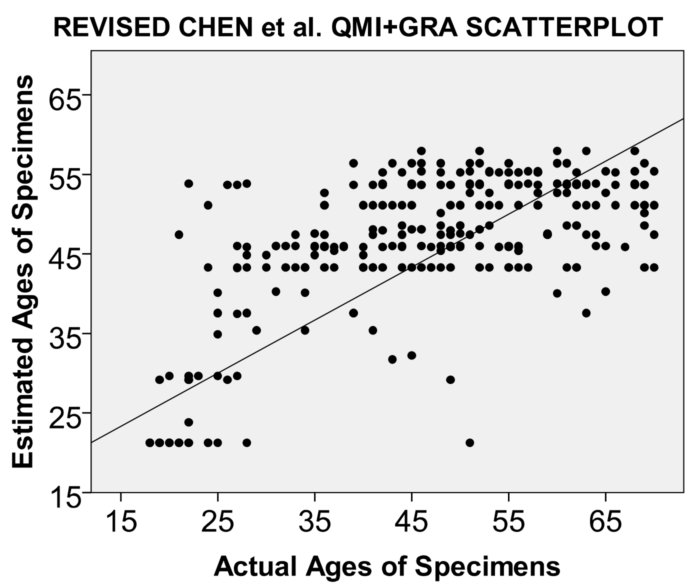
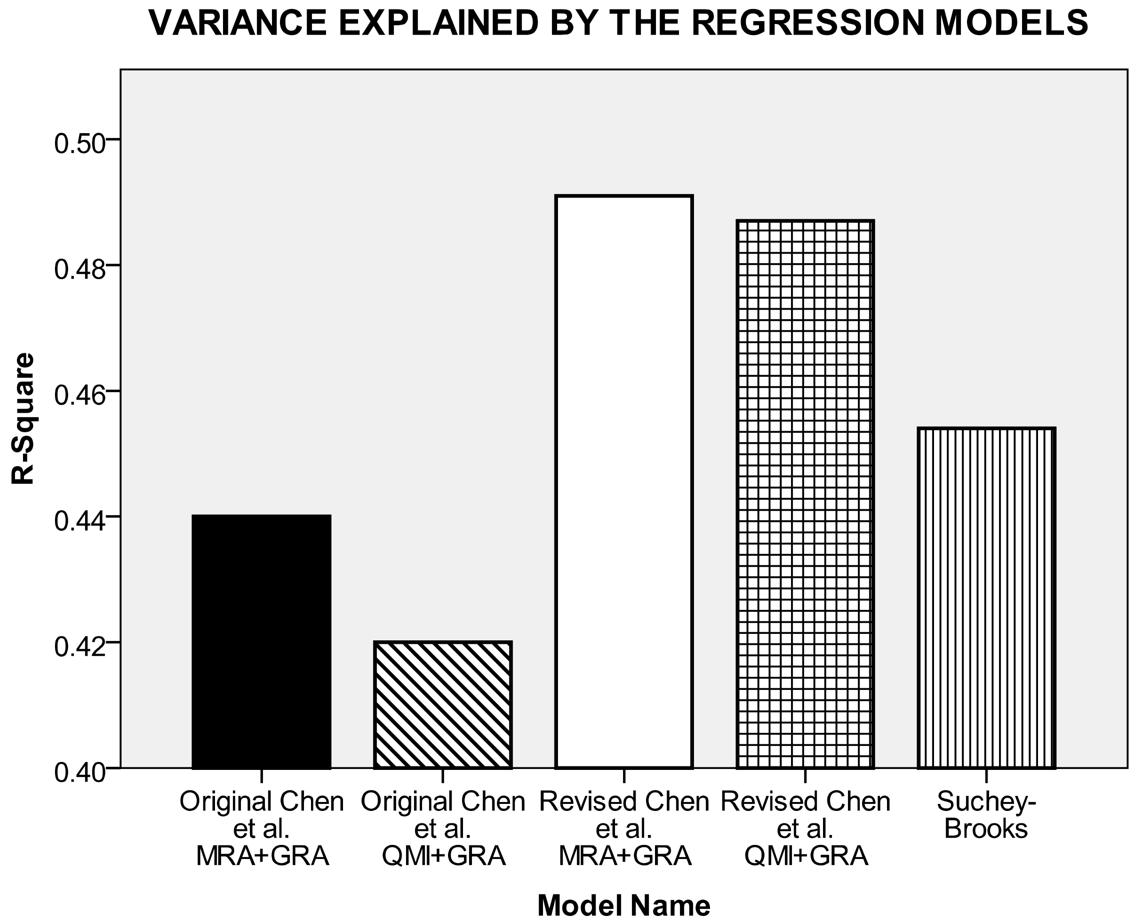


Figure 19:



Pearson's correlation coefficient was calculated to determine the relationship between each of the aging models and actual age. Pearson's correlation coefficient measures the linear relationship between two variables and assumes normal distribution of the sample (Hamilton, 1992; Field, 2009).

All correlations are positive and statistically significant at the 0.01 level (Table 7). The strongest correlation is derived from the Suchey-Brooks model ($r = 0.674$) which indicates that for every one standard deviation increase in the Suchey-Brooks model the predicted value of actual age will increase by 0.674 standard deviations. The weakest correlation with actual age is the Original Chen et al. QMI+GRA model ($r = 0.603$) which also explains the least amount of variance (R^2) as discussed above. Collectively, these correlations are fairly strong signifying that there is a positive relationship between the models and actual age.

Table 7: Pearson's Correlations (r) between Models and Actual Age

	Correlation Coefficients
Revised Chen et al. MRA+GRA	0.662
Revised Chen et al. QMI+GRA	0.670
Original Chen et al. MRA+GRA	0.615
Original Chen et al. QMI+GRA	0.603
Suchey-Brooks	0.674

$p < 0.01$; 2-tailed test; n = 296

The Morphological Features Most Predictive of Age

A forward stepwise regression (with a criterion of F to enter = 0.05) was calculated to determine which of the nine Chen et al. morphological features were most predictive on an individual's age at death. The dependent variable was actual age and the independent variables were each of the nine features. As stated in the Methods section, a stepwise regression adds or removes variables that do not make a significant contribution to the model (Agresti and Finlay, 2009). A forward stepwise regression begins with only the constant (β_0), and adds variables that significantly predict the outcome of the model. One variable is added at a time until the most variance is predicted/explained (Field, 2009).

Based upon Observer One's scores for all nine morphological features, the following explain the most variance in the Chen et al. (2008) model: features 7, 1, 6, and 9—ventral beveling, ridges and furrows of the symphyseal surface, dorsal margin, and bone density of the symphyseal surface. As the R^2 values in Table 8 demonstrate, feature 7 alone explains 35% of the variance in actual age. Only 9% more variance in age is explained when all four features (7, 1, 6, and 9) are included in the regression (Step 4 R^2 = 0.44, or 44%) (Field, 2009). These R^2 values are all significant at the 0.05 level.

The standardized coefficients in Table 8 represent the conversion of each feature into a standard unit of measurement (standard deviation). This allows for a direct comparison of all features (Field, 2009). All of the coefficients are positive, so as the

Table 8: Forward Stepwise Regression Analysis of the Chen et al. Morphological Features and Actual Age

		Constant (β_0)	Standardized Coefficients (β_1)	SD	R^2	SE
Step 1		28.77*			0.35	1.53
	Feature 7		0.59*	0.67		1.01
Step 2		16.83*			0.41	2.66
	Feature 7		0.46*			1.10
	Feature 1		0.28*	0.74		1.00
Step 3		13.42*			0.43	2.81
	Feature 7		0.41*			1.13
	Feature 1		0.22*			1.05
	Feature 6		0.17*	0.65		1.16
Step 4		15.27*			0.44	2.92
	Feature 7		0.38*			1.15
	Feature 1		0.15**			1.21
	Feature 6		0.17*			1.16
	Feature 9		0.13**	0.86		1.00

* $p < 0.0$ ** $p < 0.05$

score for each feature increases, actual age will also increase. For example, if the scores for feature 7 increase by one standard deviation (0.67 units), actual age will increase by 0.59 standard deviations, holding all other variables constant.

Relationships between the Morphological Features and Age

To establish the relationship between each of the nine Chen et al. (2008) morphological features and age, both Pearson's (r) and Spearman's (ρ) correlations were calculated. Pearson's correlation coefficients were stronger than Spearman's, so the Pearson's data are presented in Table 9.

The correlations between the nine features and actual age are not very strong (Table 9). The strongest correlation with actual age is feature 7 (ventral beveling; r = 0.592). This indicates that if the score of feature 7 increases by one standard deviation, the actual age of an individual will also increase by 0.592 standard deviations. Conversely, the weakest correlation with actual age is feature 5 (ossific nodule; r = 0.397). If the score of feature 5 increases by one standard deviation, the actual age of an individual will only increase by approximately 0.4 standard deviations. All correlations are positive and significant at the 0.01 level.

Table 9: Pearson's Correlations (r) between Morphological Features and Actual Age

Feature	Correlation Coefficients
7	0.592
4	0.532
3	0.522
1	0.499
9	0.472
6	0.462
8	0.406
2	0.402
5	0.397

$p < 0.01$; 2-tailed test; n = 296

Relationships between All Morphological Features

Pearson's correlation coefficient was calculated to determine the relationship between each of the nine Chen et al. (2008) morphological features. All correlations are positive and are statistically significant at the 0.01 level. The strongest correlation, as shown in Table 10, is between feature 5 (ossific nodule) and feature 2 (ridge of the pubic tubercle) (r = 0.824). Thus, if the score of feature 5 increases by one standard deviation, the score of feature 2 will increase by 0.824 standard deviations, and vice versa. The weakest correlation is between features 9 (bone density of the symphyseal surface) and 6 (dorsal margin) (r = 0.391). This correlation is positive, which indicates that both values will increase concurrently, but only by 0.391 standard deviations.

Table 10: Pearson's Correlation Coefficients (r) for All Nine Chen et al. Morphological Features

	Feature 1	2	3	4	5	6	7	8	9
Feature 1	1	0.565	0.597	0.628	0.563	0.483	0.485	0.587	0.652
2	0.565	1	0.558	0.571	0.824	0.493	0.449	0.559	0.369
3	0.597	0.558	1	0.726	0.569	0.573	6.664	0.593	0.551
4	0.628	0.571	0.726	1	0.589	0.550	0.672	0.597	0.568
5	0.563	0.824	0.569	0.589	1	0.520	0.464	0.562	0.393
6	0.483	0.493	0.573	0.550	0.520	1	0.448	0.479	0.391
7	0.485	0.449	6.664	0.672	0.464	0.448	1	0.469	0.476
8	0.587	0.559	0.593	0.597	0.562	0.479	0.469	1	0.412
9	0.652	0.369	0.551	0.568	0.393	0.391	0.476	0.412	1

All p-values significant at the 0.01 level; 2-tailed; n = 296

strongest correlation

weakest correlation

Accuracy for Age Groups

Bias and Absolute Mean Error

As stated previously, the FSC sample is divided into three age groups to gauge accuracy for younger and older individuals. Table 11 provides the summary statistics for each age group.

Table 11: Summary Statistics for FSC Sample by Age Group*

	Young Adult	Middle Adult	Old Adult
N	69	95	132
Mean	25.33	43.03	59.03
SD	4.87	4.36	6.08

*Young Adult: 18-34 years; Middle Adult 35-49 years; Old Adult: 50+ years

Accuracy was evaluated by measures of bias and absolute mean error for each model (Tables 12a and 12b). For all models except Suchey-Brooks, absolute mean error is lowest for the middle and old adults. The highest error is derived from the Original Chen et al. QMI+GRA model for the young adult group (AME = 10.96 years).

Bias is both positive and negative for each model which indicates that the models both under- and over-estimate actual age. The highest bias (farthest from an individual's actual age) is again derived from the Original Chen et al. QMI+GRA model for the young adult group (Bias = over-estimated age by 10.50 years). The lowest bias is derived from the Suchey-Brooks model for the middle adult group (Bias = over-estimated age by 3.38 years).

As Figure 20 demonstrates, the young adults have higher levels of error when compared to the middle and old adults (with the exception of the Suchey-Brooks model). However, this could be a reflection of the unbalanced sample sizes. Collectively the middle adult group shows the least amount of error. For the young adult group, the Suchey-Brooks model has the least error. For the middle adult group, the Revised

Table 12a: Absolute Mean Error (AME) and Bias† for each Model by Age Group

Age Group	n	Original Chen et al. MRA+GRA		Original Chen et al. QMI+GRA	
		AME*	Bias	AME*	Bias
Young Adult (1)	69	10.862	10.485	10.957	10.500
Middle Adult (2)	95	8.285	6.998	7.772	6.668
Old Adult (3)	132	8.949	-6.427	9.275	-6.888

*Absolute Mean Error: Σ |estimated age – actual age|/N

**Absolute Mean Error: (Σ |mean age – actual age|/N)

†Bias: Σ (estimated age – actual age)/N

Table 12b: Absolute Mean Error (AME) and Bias† for each Model by Age Group

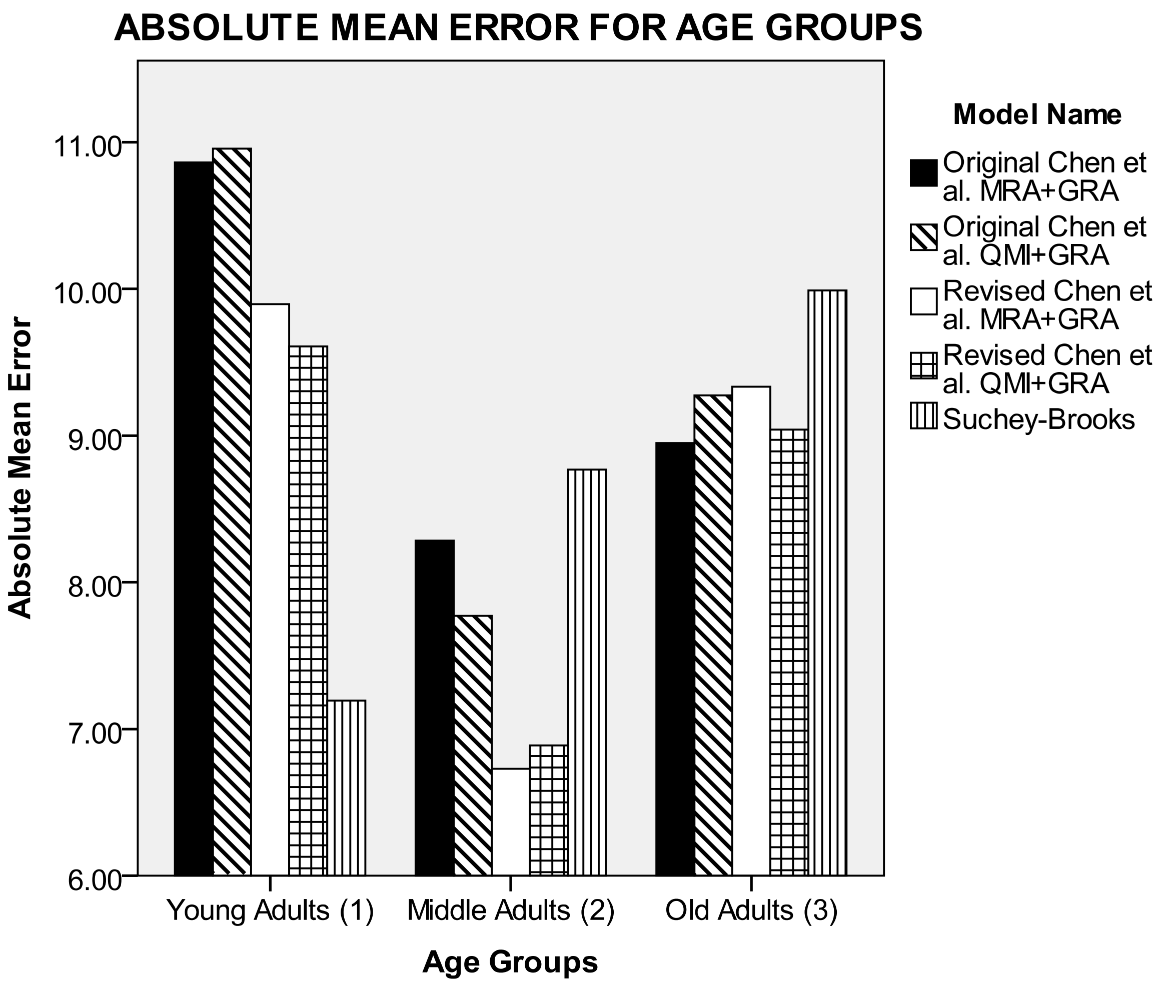
Age Group	n	Revised Chen et al. MRA+GRA		Revised Chen et al. QMI+GRA		Suchey-Brooks	
		AME*	Bias	AME*	Bias	AME**	Bias
Young Adult (1)	69	9.896	9.514	9.609	9.105	7.194	6.168
Middle Adult (2)	95	6.728	4.546	6.889	4.923	8.768	3.375
Old Adult (3)	132	9.332	-8.244	9.041	-8.301	9.990	-6.186

*Absolute Mean Error: Σ |estimated age – actual age|/N

**Absolute Mean Error: (Σ |*mean* age – actual age|/N)

†Bias: Σ (estimated age -- actual age)/N

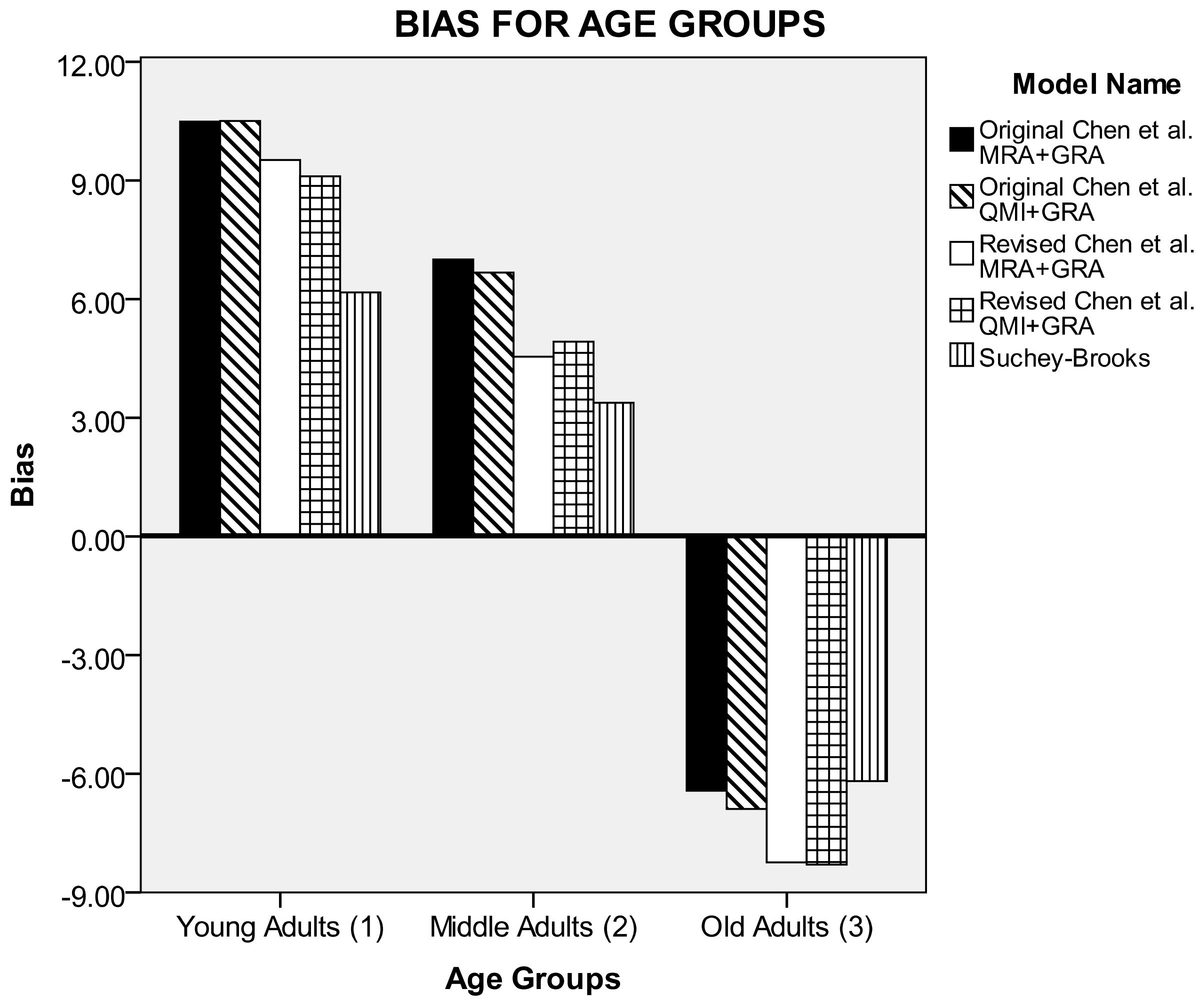
Figure 20:



Chen et al. MRA+GRA model has the least error and for the old adult group, the Original Chen et al. MRA+GRA model has the least error. Overall, the Original Chen et al. models have the highest error for both the young and middle adult groups. The Revised Chen et al. models have the lowest error for the middle adult group and the second highest error for both the young and old adult groups. The Suchey-Brooks model follows a linear trend with the least amount of error for the young adults and the most error for the old adults.

Figure 21 shows that the young and middle adults tend to be over-aged while the old adults tend to be under-aged. The Suchey-Brooks model has the least amount of bias

Figure 21:



(either over-estimation or under-estimation of actual age) for each of the three age groups. The middle adult group shows the least bias overall, which corresponds to the absolute mean error results discussed above. The Original Chen et al. models have the highest bias for both the young and middle adult groups, but have lower biases for the old adult group than the Revised Chen et al. models. The Revised Chen et al. models have the highest bias for the old adults and the second highest biases for the young and middle adults.

Analysis of Variance (ANOVA)

Analysis of variance was calculated to determine if there was a difference between the mean biases and errors for each of the three age groups. As Figures 20 and 21 demonstrate, there are differences between each of the models, but ANOVA was

Table 13: Analysis of Variance (ANOVA) of Absolute Mean Error and Bias for Each Model by Age Group

	Absolute Mean Error	Bias
	F	F
Young Adults (1)	2.53*	3.06*
Middle Adults (2)	2.15	3.17*
Old Adults (3)	0.46	1.56

*p<0.05; 2-tailed test

applied to establish if these differences were statistically significant. For ANOVA, the null hypothesis states that all means are equal, while the alternative hypothesis states that at least two of the means are unequal. If the null hypothesis is false, the f-value will be larger than 1.0 (Agresti and Finlay, 2009). As Table 13 shows, the f-values are larger than 1.0 for both the young and middle adults which indicates that the null hypothesis is rejected and the alternative hypothesis is supported. Three of the four f-values for the young and middle adults are significant at the 0.05 level. The f-values for the old adults are not larger than 1.0, but they are also not significant at the 0.05 level. Because significant f-values were found using ANOVA, a post hoc test was evaluated. This post hoc test also allowed for comparisons between each of the five models for each of the three age groups.

As Tables 14 and 15 demonstrate, there are significant differences between some of the models for the young adult and middle adult groups. For both bias and absolute mean error, it is only the Suchey-Brooks model which is different from the Chen et al. models. Table 14 shows that the young adult group has significant absolute mean error differences between the Suchey-Brooks model and both Original Chen et al. models as well as the Revised MRA+GRA model. For the middle adult group, there are significant

Table 14: Analysis of Variance (ANOVA) Post Hoc Comparisons for Absolute Mean Error for Each Age Group

Young Adults (1)			Middle Adults (2)		
Models		**Significance**	**Models**		**Significance**
Original MRA+GRA	Original QMI+GRA	0.982	Original MRA+GRA	Original QMI+GRA	0.444
	Revised MRA+GRA	0.472		Revised MRA+GRA	0.066
	Revised QMI+GRA	0.350		Revised QMI+GRA	0.100
	Suchey-Brooks	0.007*		Suchey-Brooks	0.568
Original QMI+GRA	Revised MRA+GRA	0.457	Original QMI+GRA	Revised MRA+GRA	0.284
	Revised QMI+GRA	0.339		Revised QMI+GRA	0.377
	Suchey-Brooks	0.006*		Suchey-Brooks	0.181
Revised MRA+GRA	Revised QMI+GRA	0.830	Revised MRA+GRA	Revised QMI+GRA	0.850
	Suchey-Brooks	0.045*		Suchey-Brooks	0.016*
Revised QMI+GRA	Suchey-Brooks	0.073	Revised QMI+GRA	Suchey-Brooks	0.027*

*p<0.05; 2-tailed test

Table 14 (cont'd)

Models		Significance
	Old Adults (3)	
Original MRA+GRA	Original QMI+GRA	0.567
	Revised MRA+GRA	0.654
	Revised QMI+GRA	0.914
	Suchey-Brooks	0.223
Original QMI+GRA	Revised MRA+GRA	0.901
	Revised QMI+GRA	0.642
	Suchey-Brooks	0.518
Revised MRA+GRA	Revised QMI+GRA	0.733
	Suchey-Brooks	0.441
Revised QMI+GRA	Suchey-Brooks	0.261

Table 15: Analysis of Variance (ANOVA) Post Hoc Comparisons for Bias for Each Age Group

Young Adults (1)			Middle Adults (2)		
Models		**Significance**	**Models**		**Significance**
Original MRA+GRA	Original QMI+GRA	0.985	Original MRA+GRA	Original QMI+GRA	0.444
	Revised MRA+GRA	0.501		Revised MRA+GRA	0.066
	Revised QMI+GRA	0.338		Revised QMI+GRA	0.100
	Suchey-Brooks	0.003*		Suchey-Brooks	0.568
Original QMI+GRA	Revised MRA+GRA	0.489	Original QMI+GRA	Revised MRA+GRA	0.284
	Revised QMI+GRA	0.329		Revised QMI+GRA	0.377
	Suchey-Brooks	0.003*		Suchey-Brooks	0.181
Revised MRA+GRA	Revised QMI+GRA	0.776	Revised MRA+GRA	Revised QMI+GRA	0.850
	Suchey-Brooks	0.021*		Suchey-Brooks	0.016*
Revised QMI+GRA	Suchey-Brooks	0.042*	Revised QMI+GRA	Suchey-Brooks	0.027*

*p<0.05; 2-tailed test

Table 15 (cont'd)

Models	Old Adults (3)	Significance
Original MRA+GRA	Original QMI+GRA	0.546
	Revised MRA+GRA	0.105
	Revised QMI+GRA	0.095
	Suchey-Brooks	0.829
Original QMI+GRA	Revised MRA+GRA	0.308
	Revised QMI+GRA	0.285
	Suchey-Brooks	0.414
Revised MRA+GRA	Revised QMI+GRA	0.959
	Suchey-Brooks	0.067
Revised QMI+GRA	Suchey-Brooks	0.060

error differences between the Suchey-Brooks model and both of the Revised Chen et al. models. Table 15 indicates that for the young adult group, the bias for the Suchey-Brooks model is different from all of the other models, but for the middle adults, Suchey-Brooks is only different from the Revised Chen et al. models. There are no significant differences between any of the aging models for the old adult group.

Intra- and Inter-Observer Error

Intra-Observer Error

Cohen's Kappa measure of agreement and Pearson's correlation coefficient were used to measure intra-observer error for a random sample of 100 previously scored pubic bones. "Cohen's kappa measures the agreement between two observations, while taking into account any agreement that would occur by chance" (Hefner, 2009:991). The closer the resulting value is to 1 the higher the agreement. Cohen's Kappa was calculated for each of the nine Chen et al. (2008) morphological features and for the Suchey-Brooks (1990) model. Feature 2 (ridges of the pubic tubercle, κ = 0.885) has the highest intra-observer agreement, while Feature 1 (ridges and furrows of the symphyseal surface, κ = 0.505) has the lowest inter-observer agreement (Table 16). As such, Feature 1 has the highest intra-observer error rate.

Table 16: Intra-Observer Cohen's Kappa Measure of Agreement (κ) for the Chen et al. Morphological Features and the Suchey-Brooks Method*

	κ	SE
Feature 1 vs. Feature 1	0.505	0.073
Feature 2 vs. Feature 2	0.885	0.114
Feature 3 vs. Feature 3	0.624	0.070
Feature 4 vs. Feature 4	0.615	0.073
Feature 5 vs. Feature 5	0.858	0.092
Feature 6 vs. Feature 6	0.621	0.074
Feature 7 vs. Feature 7	0.662	0.070
Feature 8 vs. Feature 8	0.666	0.077
Feature 9 vs. Feature 9	0.631	0.063
Suchey-Brooks Method	0.628	0.061

* n = 100

Based upon the Pearson's correlation calculations, the Suchey-Brooks method is more correlated between the first and second rounds of scoring than is the published Chen et al. method (Table 17). The correlations between the scoring rounds of Observer One are positive and fairly strong (r=0.796 and 0.906). This indicates that if Observer One's scoring improves by one standard deviation during the first round, Observer One's scoring will improve during the second round by 0.796 and 0.906 standard deviations for each of the methods. Both correlations are significant at the 0.01 level. Based upon these correlations, the Chen et al. method has a higher intra-observer error rate than does the Suchey-Brooks method.

Table 17: Intra-Obsersver Pearson's Correlations (r) for the Chen et al. and Suchey-Brooks Methods

Methods	Correlation Coefficients
Chen et al.	0.796
Suchey-Brooks	0.906

$p < 0.01$; 2-tailed test; $n = 100$

Inter-Observer Error

Inter-observer error was also evaluated for both the Chen et al. and the Suchey-Brooks methods. Observer Two scored 200 pubic bones via the Chen et al. method and a subsample of 75 of those 200 bones via the Suchey-Brooks method. Observers Three and Four scored the same 50 pubic bones for both methods. Pearson's correlation coefficients were calculated to compare Observer One with Observers Two, Three, and Four.

As Table 18 indicates, the highest correlation for the Chen et al. method is between Observers One and Four (r = 0.694), while the highest correlation for the Suchey-Brooks method is between Observers One and Three (r = 0.885). All of the correlations are positive between Observer One and the additional Observers. All correlations are significant at either the 0.01 level or the 0.05 level. Overall, the Suchey-Brooks method has higher r-values which suggests that this method has lower inter-observer error than the Chen et al. method.

Table 18: Inter-Observer Pearson's Correlations (r)

	n	Chen et al. Method	Suchey-Brooks Method
Observer 1 vs. Observer 2*	200	0.640	0.790
Observer 1 vs. Observer 3*	50	0.693	0.885
Observer 1 vs. Observer 4**	50	0.694	0.746

*p < 0.01; 2-tailed test **p < 0.05; 2-tailed test

DISCUSSION

As the previous chapter demonstrates, the Chen et al. method can accurately age males of European ancestry. Based upon frequencies of mean error, almost 90% of individuals' estimated ages will fall within 15 years of their actual age at death. Therefore, this method has the potential to be a useful aging technique in the United States. In particular, the most accurate model for estimating age for this sample is the Revised QMI+GRA, based upon the lowest error, no bias, and a high correlation with actual age.

The Revised Chen et al. Model Compared to the Suchey-Brooks Model

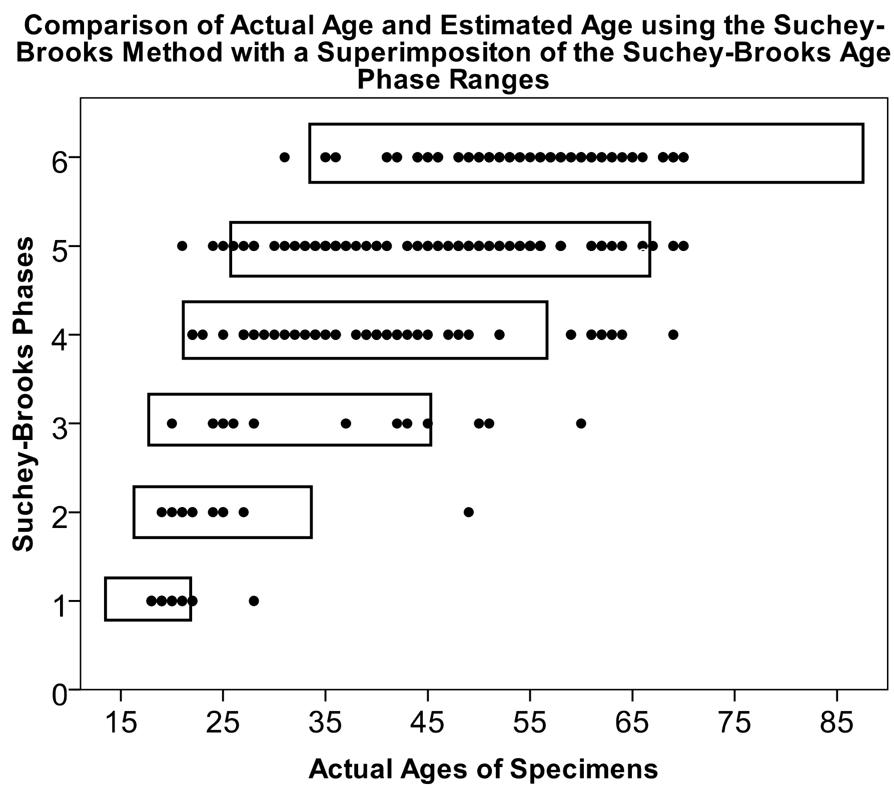
One of the most significant research questions in this thesis asks whether a Revised Chen et al. method will be more accurate for estimating age than the Suchey-Brooks method. While it is important to evaluate whether the Chen et al. method is capable of accurately estimating age for males of European ancestry, it is imperative to test the claim by Chen et al.—that their method is accurate within one year of actual age—with that of the standard currently used in the United States—the Suchey-Brooks method.

When the data are evaluated for the whole sample the Revised Chen et al. models (both MRA+GRA and QMI+GRA collectively) are more accurate than the Suchey-Brooks model. The Revised models are the most accurate for the 1 year frequency bracket; have the lowest amounts of error; demonstrate no bias; and explain the highest amount of variance in age.

When the absolute mean error data are considered for the Revised Chen and Suchey-Brooks models, the Revised models have an average error of approximately 8 years while the Suchey-Brooks model has an average error of approximately 9 years. While this does not initially suggest a large difference, it must briefly be considered that for the Suchey-Brooks model this only represents the mean age at death. If the full 95% age range is to be considered, the Revised Chen models are in fact much more accurate.

However, the results for the Suchey-Brooks model are interesting. It is the only model whose average bias is negative, which results in under-aging of the specimens by 0.20 years. This tendency to under-estimate the age of the sample is consistent with previous research (Schmitt, 2004; Djurić et al., 2007; Hens et al., 2008). Even more interesting is that this model has the highest correlation with actual age (r = 0.674). Even though the data in this study only represent the mean Suchey-Brooks ages, Figure 22 indicates that the majority of the samples' estimated ages do fall within the Suchey-Brooks phase ranges.

Figure 22:



Analysis of the age group data indicates that the Suchey-Brooks model is distinct as it has a steady pattern of increasing absolute mean error. As Figure 20 shows, the Suchey-Brooks model has the lowest error for the young adults and steadily increases across the middle and old adults. This is consistent with other evaluations of the Suchey-Brooks method (Suchey et al., 1986; Djurić et al., 2007; Martrille et al., 2007). This model also has the least amount of bias for each age group which indicates that it is more consistent than the Chen et al. models with regards to over- and under-estimation of actual age.

When variance (R^2 values) is compared between the Revised Chen et al. models and the Suchey-Brooks model they are virtually the same—Suchey-Brooks $R^2 = 0.454$ while the Revised MRA+GRA $R^2 = 0.491$ and Revised QMI+GRA $R^2 = 0.487$. Therefore, these models all explain almost 50% of the variance in age for this sample. This measure of model comparison suggests that the Suchey-Brooks and Revised Chen et al. models are equally accurate for estimating age for this sample.

Review of the intra- and inter-observer error correlation data indicate that the Suchey-Brooks model is more consistent and reliable within and between observers than the Chen et al. model (Tables 17 and 18). For intra-observer error the correlation scores (r) are 0.796 for the Chen et al. model and 0.906 for the Suchey-Brooks model. The Suchey-Brooks model demonstrates a 12% higher correlation than the Chen et al. model. For inter-observer error, Suchey-Brooks is 19% more correlated than Chen et al. between Observer One and Observer Two, while between Observer One and Observer Three, Suchey-Brooks is 22% more correlated. Finally, the Suchey-Brooks model has a 7% higher correlation than the Chen et al. model between Observer One and Observer Four.

Accuracy for Older Ages

Most studies have found that pubic aging methods are more accurate for younger individuals and are of little use for older individuals (Lovejoy et al., 1985a; Suchey et al., 1986; Brooks and Suchey, 1990; Komar, 2003; Martrille et al., 2007; Hens, 2008). As Hartnett (2010:6) states, “anthropologists have generally accepted that pubic bone morphology cannot be used to determine the age of older individuals accurately.” In fact, when statistically analyzing the male pubic bone sample which would be used to develop the Suchey-Brooks method, Suchey and colleagues removed individuals over the age of 40 which improved their statistical results (Suchey et al., 1986; Katz and Suchey, 1986).

In contrast to these previous studies, this research found that the middle adult group (ages 35 – 49) is the most accurately aged. All models except Suchey-Brooks have the lowest absolute mean errors for this group, and all models except for the Original MRA+GRA have the least amount of bias. This suggests that the Chen et al. method (in particular the Revised models) is unique among pubic bone age estimation techniques, since it is most accurate for the middle adult age category. As noted above, this is not a typical result for adult age estimation methods, and is thus, distinctive. Further research is required, especially for additional ancestral groups and for females, but the data from this study indicate that the Chen et al. method can be used to age adults between 35 and 49 years old.

Variance and Correlation

Compared to the variance (R^2) results from other age estimation studies, both the Chen et al. models and the Suchey-Brooks models from this study do not explain as much variance in actual age. The R^2 values from this study are as follows: Original Chen MRA+GRA = 0.440; Original Chen QMI+GRA = 0.420; Revised Chen MRA+GRA =

0.491; Revised Chen QMI+GRA = 0.487; and Suchey-Brooks = 0.454 (Figure 19). When evaluating research based on the pubic bone, Hanihara and Suzuki (1978) report an R^2 of 0.85 while Katz and Suchey (1986) report an R^2 of 0.83. This means that Hanihara and Suzuki developed a model which can explain 85% of the variance in actual age and Katz and Suchey's model explains 83% of the variance in actual age. İşcan, Loth, and Wright (1984; 1985) also report high variance values in their studies on age estimation from the sternal rib. For males they report an R^2 of 0.85, but for females it was slightly less at an R^2 of 0.76.

The lower R^2 values presented in this study simply indicate that these models are not incorporating all variables which explain actual age. As noted in the Results chapter, the remaining 50% of the variance may be explained by factors which are not addressed in this study, such as an individual's lifestyle, health, or environment.

Correlation data (r) between this study (Table 7) and other aging methods also indicate that the Chen et al. and Suchey-Brooks models are not extremely well correlated with actual age. For example, original research evaluating the pubic bone by Hanihara and Suzuki (1978), McKern and Stewart (1957), and Suchey et al. (1986) report correlation values of 0.92, 0.90, and 0.72, respectively. After Suchey et al. (1986) removed individuals over the age of 40 years, their correlation increased to 0.78. One original study by Meindl and Lovejoy (1985) on ectocranial suture age estimation did present much lower correlations at 0.50 for the vault sutures and 0.57 for the lateral-anterior cranial sutures. This study does not evaluate the pubic bone, but it is an interesting comparison for correlation values from different adult age estimation methods.

When correlations are compared between the present study and other age estimation studies conducted on samples other than the reference sample, however, the data are much more consistent. Lovejoy et al. (1985a) tested numerous aging methods, but specifically for Todd's (1920) pubic method, they report a correlation of 0.57. After revisions of Todd's phases, the authors report a correlation of 0.78 (Lovejoy et al., 1985a). Bedford et al. (1993) later tested Lovejoy et al.'s (1985a) multifactorial age estimation method and produce correlations between 0.27 and 0.66. The correlations for the pubic bones alone are between 0.53 and 0.60. Osborne et al. (2004) and Falys et al. (2006) both tested auricular surface aging methods and report correlations between composite scores and actual ages of 0.59. The correlation values from studies applying age estimation methods to different samples than those from the original research are all much closer to the correlations reported for this study. Thus, this research (with correlation values between 0.60 and 0.67) demonstrates comparable correlations between the aging models and actual ages when the reference sample is not used.

Intra- and Inter-Observer Error

When the Chen et al. morphological features are assessed for intra-observer error, Feature 2 (ridges of the pubic tubercle) has the highest intra-observer agreement, and thus, the lowest error, while Feature 1 (ridges and furrows of the symphyseal surface) has the highest intra-observer error rate. When the Chen et al. and Suchey-Brooks models are compared, Chen et al. has a higher intra-observer error rate than does the Suchey-Brooks method. As stated above, the Suchey-Brooks model demonstrates a 12% higher correlation than the Chen et al. model for Observer One. This indicates that the Suchey-Brooks method is more consistent during different intervals of age assessment.

With regards to inter-observer error, the Suchey-Brooks method has lower error than does the Chen et al. method. However, all r-values for both methods are above 0.60 which indicates fairly strong correlations. This data reveal that the Chen et al. method can be learned with relative ease and can be applied by individuals with limited osteological experience.

Limitations

There are a few limitations which should be noted: limitations of the Chen et al. method and limitations of this study. The primary limitation of the Chen et al. method is subjectivity. The evaluation of the nine morphological features requires an observer to be familiar with the features, their developmental stages, and associated scores. Time and practice are required before an observer can appropriately assign a score for each feature. The scoring system is also problematic and challenging due to translation issues in the published article. This may have influenced the raw data scores, and is the reason why the author modified the language of the scoring criteria (see Appendix 2 and 3). Additionally, the pubic bone must be intact for the Chen et al. method to be employed. A completely intact pubic bone may not always be available in a forensic case or bioarchaeological material, which is a considerable limitation for this method.

A limitation of this study, rather than the Chen et al. method, involves defining accuracy for the Chen et al. and Suchey-Brooks techniques. The data derived from these methods are inherently different; the Chen et al. method provides a point age estimate, while the Suchey-Books method produces a mean and a 95% confidence range. Each of these methods was developed with different goals in mind; the Chen et al. method intended to provide a specific age estimate based upon nine features while the Suchey-

Brooks method offered a wide age range which encompassed changes from a large sample (however, this wide age range is one of the limitations of the Suchey-Brooks model).

Calculating absolute mean errors based upon two different forms of data (point age estimate and a mean) does raise the question of the internal validity of this study, but these data are what each method provides. For example, when applying the Suchey-Brooks method to an unknown male, practitioners will state that the individual is a Phase 4; he is approximately 35.2 years old (the mean), but is within a range of 23-57 years of age. Thus, the mean is what practitioners use as the estimated age even though it is not the age of every male assigned to Phase 4. As such, absolute mean error (from a point estimate or a mean) is the best way to define and assess accuracy for both methods, even if they are innately different forms of data.

Finally, the data for this research may be slightly skewed due to the age distribution of the study collection. Many of the individuals in the sample are above the age of 49 years (n = 132) which could have influenced the age group results. Furthermore, the Chen et al. method (2008) is not generalizable to both sexes; it must only be applied to males which eliminates its potential utility for half of the population.

CONCLUSION

The purpose of this thesis project was to evaluate the Chen et al. pubic bone aging study, and to determine if the method could accurately estimate the age of individuals outside of the Chinese Han population. The overall results of this project were expected to support the hypothesis that the Chen et al. method could accurately assess age at death for the males of European ancestry in the Maricopa County Forensic Science Center sample. Furthermore, this project compared the accuracy of the Chen et al. method to the Suchey-Brooks method, which is currently the most accepted technique for estimating age from the pubic bones. This comparison was made in order to test whether the Chen et al. technique is an improved and more accurate method for estimating age at death using male pubic bones.

The majority of the hypotheses for this research are supported by the data. The first two hypotheses state that the Chen et al. method will be able to accurately estimate age for males of European ancestry and that a revision of the method will be the most accurate. Both the Original and Revised Chen et al. methods are able to accurately age the males in this sample and both methods have an average error of approximately 8 to 9 years from an individual's actual age, which is fairly low for adult aging methods.

The next hypothesis states that there will be no significant differences between the rates of accuracy and the R^2 values of the Revised Chen et al. and the Suchey-Brooks models. As the previous chapter discusses, there are some interesting differences between the models, but with regard to accuracy and variance they are virtually indistinguishable. The Revised Chen and Suchey-Brooks models have almost identical variance values and also have very similar correlation values with actual age. However, these models are significantly different when the sample is distributed into age groups.

Based upon the data presented by Chen et al., it was hypothesized that ventral beveling, bone density of the symphysial surface, and the ventral rampart would be the morphological features most predictive of age. Assessment of the sample reveals that ventral beveling and bone density are among the most predictive of age. Ridges and furrows of the symphyseal surface and the dorsal margin are included based upon the forward stepwise regression analysis. The ventral rampart is not among the features most predictive of age in this sample.

The fifth hypothesis states that the Revised method will be most accurate for young adults (18-34 years) and middle adults (35-49 years), and less accurate for old adults (50 years and above). This was partially refuted by the data as the Revised Chen et al. models are most accurate for the middle adults followed by the old adults. It is the Suchey-Brooks model which is most accurate for aging the young adults. The accuracy of aging the middle adult group is an important aspect of this research, and one which is not often seen with adult aging models.

Finally inter- and intra-observer error rates are addressed in the last hypothesis which states that both levels of error will be low. For both intra- and inter-observer tests the correlations are high indicating low levels of error. Among all observers, the Suchey-Brooks model has the highest level of correlation, and thus, the least amount of error. However, the r-values for the Chen et al. method are all moderately high, indicating fairly strong correlations. This signifies that the Chen et al. method can be learned with relative ease and can be applied by individuals with limited osteological experience, as well as professional anthropologists.

Most authors who have developed or tested aging methods have noted that using only one skeletal element in isolation is not advisable for estimating adult age at death (Brooks, 1955; Acsádi and Nemeskéri, 1970; Meindl and Lovejoy, 1985; Lovejoy et al., 1985a; Krogman and İşcan, 1986; İşcan and Loth, 1989; and Baccino et al., 1999; Buikstra and Komar, 2008). They fervently argue that multiple skeletal elements and/or methods should be applied to properly age an individual. The Chen et al. method does not use multiple skeletal elements, but it does employ multiple features of one bone to estimate age. Additionally, the Suchey-Brooks method only uses one bone.

I strongly support the use of multiple bones and multiple methods to estimate adult age at death. Especially if the remains are damaged or missing elements, multiple techniques should be utilized to accurately estimate age. Skeletal remains should not be viewed as disjointed bones but should be thought of, and analyzed, as the whole individual that they once were. Bones age at different rates due to variable stresses on the body, so when available, all bones useful for age estimation should be evaluated.

Although it has been demonstrated that the Chen et al. method is accurate, I do have some reservations regarding the technique. When applied to a North American sample, the method is not nearly as accurate as it is in China. For this sample, ages are rarely (between 5.9% and 10.8%) correctly estimated within one year of actual age; thus, the claim by Chen et al. that their method can accurately estimate age within one year of an individual's actual age at death is not substantiated by this research. This outcome is to be expected, however, since this study is not testing the original reference sample, but it may reduce the method's utility in the United States. This method can be challenging to implement and the published descriptions and photographs may be ambiguous. Based upon these limitations, and until more research is conducted to test this aging technique, I believe that the Chen et al. method should be applied in conjunction with other, more rigorously studied, adult aging methods.

This research does not imply that the Suchey-Brooks method should be supplanted by the Chen et al. method. If the Chen et al. method was significantly more accurate than the Suchey-Brooks method, further consideration for abandoning Suchey-Boroks would be warranted. This is not the case. This study does, however, suggest that the Chen et al. method is comparable, with regards to accuracy, to the Suchey-Brooks method for estimating age for this particular male sample.

If specific age groups are being considered, however, the Revised Chen methods are more accurate than the Suchey-Brooks method for males between the ages of 35 and 49 years. The ability of the Revised Chen et al. models to accurately age individuals in the middle adult group is the precise reason why this method should be used.

The ability of the Chen et al. method to accurately age this group is a significant contribution to the forensic and bioarchaeological disciplines. Aging this older group is often challenging, so the Chen et al. method is a unique tool for physical anthropologists. To conclude, I believe that if an anthropologist is willing to take the time to learn the technique and apply it to complete, modern pubic bones, the Chen et al. method can be used to accurately assess age at death for males of European ancestry.

APPENDICES

Appendix 1: **Table 19**: Nine Morphological Features of the Pubic Bone and Associated Scores (Chen et al., 2008)

Feature Name	Score and Description
1. Ridges and furrows of symphyseal surface	0: ridges and furrows alternate distinctly 1: the furrows fill in and ridges and furrows alternate indistinctly 2: the bone substance has a granular look with low, blunt ridges and shallow furrows 3: the surface becomes flat and fine-textured, and/or again becomes more granular 4: ridges and furrows disappear entirely and the surface becomes pitted and eroded
2. Ridges of the pubic tubercle	0: ridges on pubic tubercle completed 1: ridges on pubic tubercle almost gone 2: ridges on pubic tubercle completely disappeared
3. Lower extremity of the symphysial surface	0: no appearance of lower extremity 1: appearance of dividing line between symphysial surface and inferior ramus of pubis 2: forming a "V" angle 3: atrophy or disappearance of "V" angle
4. Ventral rampart	0: no appearance of ventral rampart 1: local ventral rampart 2: fully developed ventral rampart 3: ventral rampart becomes wider or nodular in superior portion
5. Ossific nodule	0: no appearance of ossific nodule 1: appearance of ossific nodule 2: fusion and disappearance of ossific nodule
6. Dorsal margin	0: no appearance of dorsal margin 1: edged margin without a plateau 2: forming a plateau and lip-like thickness and extension in superior part of dorsal margin 3: middle destruction or generalized atrophy of dorsal margin
7. Ventral beveling	0: no appearance of ventral beveling 1: clear-edged margin with a right angle between ventral beveling and the symphyseal surface

Table 18 cont'd

	2: ventral beveling becomes flat in the lower portion or disappears
8. General macroscopic changes of the symphyseal surface	0: prominence of symphyseal surface 1: irregular surface 2: flatness, or fovea inferior with clear periphery
9. Bone density of the symphyseal surface	0: ridged or rough with no ridge 1: smooth, dense and solid 2: concavo-convex or with dense pores on surface 3: big pits and/or loss of density

Appendix 2: Revised Descriptions for the Nine Morphological Features of the Pubic Bone

Feature 1: Ridges and Furrows of the Symphyseal Surface
The ridges and furrows in young individuals are very prominent and have an order of alternating in a distinct pattern. With age, the furrows begin to fill in and the pattern is less orderly and clear eventually resulting in blunt ridges and shallow furrows. The surface may begin to appear granular. The ridge and furrow pattern disappears and the surface becomes flat and fine-textured. With advanced age the surface can become pitted and eroded.

Feature 2: Ridges of the Pubic Tubercle
These are horizontal ridges that connect the superior surface of the symphyseal face with the ventral side of the pubis. They are prominent and well formed in the young but begin to fade and disappear with age. The final stage is the disappearance of the ridges and/or a completed pubic tubercle.

Feature 3: Lower Extremity of the Symphysial Surface
This refers to the dividing line between the inferior symphyseal face and the superior ischiopubic ramus. There is no evidence of this line in the young. A line or ridge begins to develop and eventually forms a "V" shape (2a in Appendix 4) or "U" shape (2b) separating the face from the ramus. With age the "V" or "U" begins to atrophy (3a) and disappear (3b) resulting in a flat surface.

Feature 4: Ventral Rampart
The ventral rampart develops to form the ventral margin of the symphysial face (the ventral half of the symphyseal rim). The ventral rampart begins to develop locally on the inferior aspect of the face, or the superior aspect of the face (or sometimes both) and grows towards the midline. A hiatus in the superior ventral aspect can be present even in mature adults. With advanced age the ventral rampart may become wider or nodular in the middle and/or superior aspect(s).

Feature 5: Ossific Nodule
This is a nodule of bone found on the superior aspect of the symphyseal face which aids in the formation of the superior portion of the ventral rampart and upper extremity of the symphyseal rim. The nodule is not present in the young. It appears in the mid-twenties, according to Scheuer and Black (2004), and later becomes incorporated with the ventral rampart and symphyseal face (2a in Appendix 4) and disappears (2b).

Feature 6: Dorsal Margin
The dorsal margin develops to form the dorsal half of the symphyseal rim. In the young there is not a true distinction separating the dorsal symphyseal face from the dorsal side of the pubis. With age a slight edge develops in this region that is palpable. The ridge later extends backwards and flattens forming a plateau. With advanced age the dorsal margins atrophies, and in some cases a cavitation or localized breakdown occurs in the middle or superior aspect.

Feature 7: Ventral Beveling
The ventral bevel is one aspect of the ventral margin. It forms a palpable right angle between the symphyseal face and the ventral aspect of the pubis. The sharpness of this bevel later becomes blunt, and after the ventral margin is fully developed this bevel becomes flat and can disappear.

Feature 8: General Macroscopic Changes of the Symphyseal Surface
This feature addresses the macroscopic topography of the symphyseal surface. The surface is initially raised above the surrounding pubis when observed from the ventral or dorsal side. It is billowy due to the ridges and furrows. As the ridges and furrows fill in the surface becomes irregular and more flat. The final stage is a flat surface, or one depressed below the symphyseal rim when viewed from the ventral or dorsal aspect.

Feature 9: Bone Density of the Symphyseal Surface
Bone density describes the quality of the bone on the symphyseal surface. The bone is dense with ridges and furrows (0a in Appendix 4), or it is rough with no distinct ridges (0b). The surface then becomes smooth, but is still dense and solid. The surface later becomes irregular and may show evidence of microporosity and/or macroporosity (2a and 2b). In advanced age the bone looses density and may have large pits on the surface.

Appendix 3: **Table 20**: Revised Nine Morphological Features of the Pubic Bone and Associated Scores

Feature Name	Score and Description
1. Ridges and furrows of symphyseal surface	0: ridges and furrows alternate in a regular pattern 1: the furrows fill in and ridges and furrows alternate irregularly 2: the bone substance has a granular look with low, blunt ridges and shallow furrows 3: the surface becomes flat and fine-textured, and/or again becomes more granular 4: ridges and furrows disappear entirely and the surface may become pitted and eroded
2. Ridges of the pubic tubercle	0: ridges are present 1: ridges are fading or are almost gone 2: ridges completely disappeared and /or pubic tubercle
3. Lower extremity of the symphysial surface	0: no appearance of lower extremity 1: appearance of dividing line between symphysial surface and inferior ramus of pubis 2: presence of a "V" angle 3: atrophy or disappearance of "V" angle
4. Ventral rampart	0: no appearance of ventral rampart 1: local ventral rampart 2: fully developed ventral rampart, may have hiatus 3: ventral rampart becomes wider or nodular in middle and/or superior portion(s)
5. Ossific nodule	0: no appearance of ossific nodule 1: presence of ossific nodule 2: incorporation and disappearance of ossific nodule
6. Dorsal margin	0: no appearance of dorsal margin 1: edged margin without a plateau 2: forming a plateau with lipping 3: middle destruction or generalized atrophy of dorsal margin
7. Ventral beveling	0: no appearance of ventral beveling

Table 19 cont'd

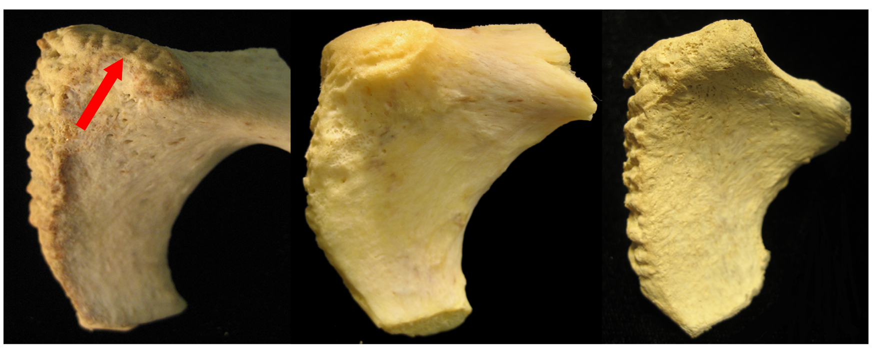
	1: palpable right angle between ventral and symphyseal surfaces 2: right angle becomes flat in the lower portion or disappears
8. General macroscopic changes of the symphyseal surface	0: symphyseal surface is raised and billowy 1: irregular surface 2: flat or depressed with clear periphery
9. Bone density of the symphyseal surface	0: ridges and furrows, or rough with no distinct ridges and furrows 1: smooth, dense and solid 2: irregular, some microporosity and/or macroporosity 3: big pits and/or loss of density

Appendix 4: Revised Images of the Nine Chen et al. Morphological Features of the Pubic Bone

Figure 23: Feature 1: Ridges and Furrows of the Symphyseal Surface

0 **1** **2** **3** **4**

Figure 24: Feature 2: Ridges of the Pubic Tubercle



0 **1** **2**

Figure 25: Feature 3: Lower Extremity of the Symphysial Surface

0 **1** **2a** **2b** **3a** **3b**

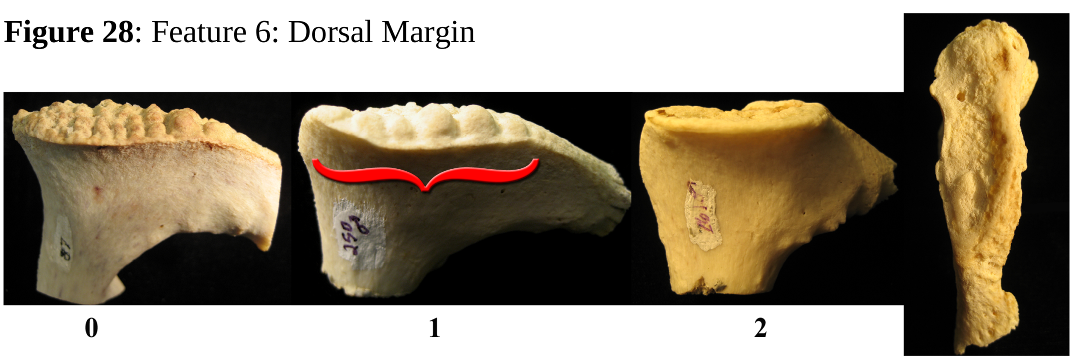
Figure 26: Feature 4: Ventral Rampart

0 1 2 3

Figure 27: Feature 5: Ossific Nodule

0 1 1 2a 2b

Figure 28: Feature 6: Dorsal Margin



0 1 2 3

Figure 29: Feature 7: Ventral Beveling

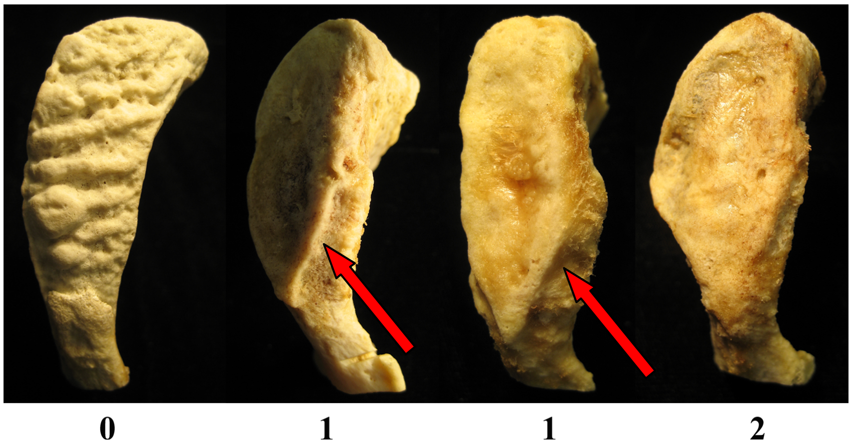
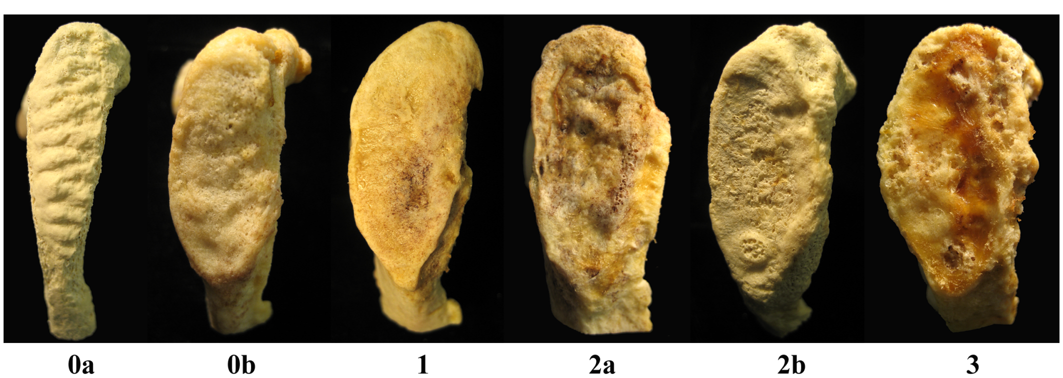


Figure 30: Feature 8: General Macroscopic Changes of the Symphyseal Surface

Figure 31: Feature 9: Bone Density of the Symphyseal Surface



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