ESTIMATION OF ADULT SKELETAL AGE-AT-DEATH USING THE SUGENO FUZZY INTEGRAL

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by

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The undersigned, appointed by the dean of the Graduate School, have examined the thesis entitled

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USING THE SUGENO FUZZY INTEGRAL

presented by Melissa Anderson, a candidate for the degree of master of arts, and hereby certify that, in their opinion, it is worthy of acceptance.

Professor Daniel Wescott

Professor Lisa Sattenspiel

Professor James Keller

DEDICATION

I would like to dedicate this thesis to my husband, Derek Anderson, for all of his support, inspiration, debates, assistance, and patience that made this possible.

ACKNOWLEDGEMENTS

I would like to thank my advisor, Dr. Daniel Wescott, for his advice and support for this thesis. Thank you to Daniel Wescott and Lyle Konigsberg who made their data from the Terry Collection available to me. I would also like to thank my other committee members, Dr. Lisa Sattenspiel and Dr. James Keller, for their advice and assistance in improving this thesis.

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ESTIMATION OF ADULT SKELETAL AGE-AT-DEATH USING THE SUGENO FUZZY INTEGRAL

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Abstract

Age-at-death of an individual skeleton is important to forensic and biological anthropologists for identification and demographic analysis, but it has been shown that current aging methods are often unreliable because of skeletal variation and taphonomic factors. Due to this, it seems necessary to explore different ways to account for this inherent inaccuracy in the aging methods to produce better results when determining age-at-death. Multifactorial methods have been shown to produce better results when determining age-at-death than single indicator methods. However, multifactoral methods are difficult to use for single skeletons and they rarely provide the investigator with information about the reliability of the estimate. The goal of this research is to examine the validity of the Sugeno fuzzy integral for modeling age-at-death of an individual skeleton.

The Sugeno fuzzy integral is an information fusion technique that can handle uncertainty that is inherent in the aging methods. Since the age determination methods are not intended to be a rigid set of typological standards but rather describe modal age changes, uncertainty is inherent in skeletal age determination. The Sugeno fuzzy integral allows the use of as many age indicators available, the condition of the skeleton, and the accuracy of the skeletal age indicators to produce a more informed decision of age-at-death in an adult skeleton. This method is described and examples are presented using three commonly used aging methods on a known-age skeletal sample from the Terry Collection.

CHAPTER 1: INTRODUCTION

The aim of this research is to develop a model that takes into account biological and taphonomic variability in adult skeletal age indicators when determining age-at-death. The goal is to use as much of the available data provided by a skeleton to develop a more informed decision about age-at-death. Age is important to forensic and biological anthropologists for identification and demographic analysis, but it has been shown that current aging methods are subject to skeletal variation (Schmitt et al. 2002). Due to this, it seems necessary to explore different ways to account for this inherent inaccuracy in the aging methods to produce better results when determining age. Multifactorial methods have been shown to produce better results when determining age-at-death than single indicator methods (Lovejoy et al. 1985a). This research examines the validity of the Sugeno integral for modeling age-at-death. The Sugeno integral allows the use of as many age indicators available, the condition of the skeleton, and the accuracy of the skeletal age indicators to produce a more informed decision of age-at-death in an adult skeleton.

Skeletal biologists view variability in adult skeletal age as inherent in determining an individual's age-at-death. Age assessment is only an approximation of age-at-death and inaccuracies increase with age. The rates at which a skeleton grows, develops, fuses, and degenerative processes can vary within an individual as well as between the different sexes (Schwartz 1995).

Aging methods are based on the assumption that the biological factors and the sequence of events that affect the aging skeleton are the same for all individuals within a population and often across populations. Furthermore, skeletal age indicators must have a relatively strong correlation between chronological and biological age. However, chronological age and biological age are not synonymous. Chronological age is a measure of the time that someone or something has existed. Biological age is the developmental or morphological category someone has reached. Chronological and biological age are often highly correlated. However, genetic variation, environmental factors, and taphonomic processes can all result in reducing the correlation between chronological and biological age. Figure 1-1 is a flow chart that demonstrates the different processes associated with biological age, all of which can reduce the correlation between chronological and biological ages.

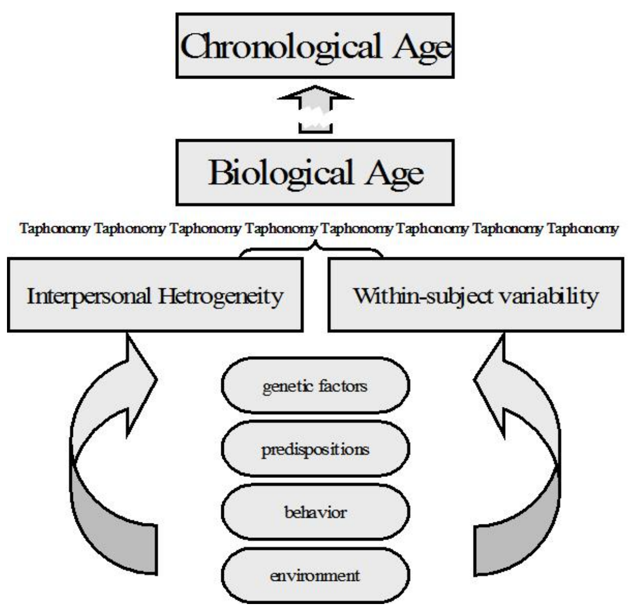


Figure 1-1. Flow chart showing some of the factors impacting biological age which is correlated with, but not always equivalent to, chronological age. (from Kemkes-Grottenthaler 2002:50)

The more accurate and precise a method is at estimating age-at-death from skeletal remains, the more readily it is used. The accuracy of the method is a measure of reliability which is how close the result can come to the chronological age (Soomer et al. 2003). Accurate age prediction is important for forensic and biological anthropology because it is vital for the description and analysis of skeletal remains (Lovejoy et al. 1985b). Forensic investigators rely on the accuracy of age indicators to determine the age of an individual based on skeletal remains, while biological anthropologists generally have a broader area of applicability for accurate age estimation, such as paleodemographic studies and independent research interest (Schmitt et al. 2002).

CHAPTER 2: BACKGROUND

Determination of skeletal age-at-death is based on standards and methods developed from collections of skeletons with documented biological data, such as age and sex. Some of the collections used to develop these methods include the Hamann-Todd collection, Terry collection, and American military personnel killed in the Korean War. Single age indicators are based on the growth, development, and deterioration of specific elements of the skeleton. Age is assessed by the indicators of growth and development in skeletally immature individuals, while age is usually determined by signs of deterioration for adults. The most common age indicators in adult skeletons used by anthropologists are dental attrition (Lovejoy 1985), cranial suture closure (Meindl and Lovejoy 1985), osteon count (bone histology) (Kerley and Ubelaker 1978), radiotransparency of the proximal humerus and femur (Ascadi and Nemeskeri 1970), morphology of the sternal rib end (Iscan 1989), auricular surface morphology (Lovejoy et al. 1985b), and pubic symphysis change (Todd 1920). These methods are commonly learned by most biological anthropologists, are nondestructive with the exception of bone histology, and are relatively easy to conduct. These single trait systems were first developed and were later used to create multifactorial methods.

Single Trait Systems

Single trait systems rely on one skeletal age indicator to determine an individual's age. In the past, there was a quest to find the single age indicator that was the most reliable and accurate at predicting age-at-death. The accuracy of determining age-at-death relies on a strong correlation between a biological feature and chronological age (Kemkes-Grottenthaler 2002). Accuracy can depend on the skeletal elements available for age analysis. Since each skeletal age indicator may have different developmental or degenerative stages, they also have their own accuracies to measure how well the aging method can predict chronological age. The use of single age indicators has limitations because it only considers the information from one source and is often quite unreliable (Schwartz 1995).

Understanding the variability involved in age-at-death estimation is important to the development of new techniques for different structures and in developing a better perception of the aging process of temporal and regional variations (Ubelaker 2000). Since age determination of an adult skeleton is based on well-tested methods, it is important to use them. Single age indicator methods are well published, tested, and accessible to all investigators. Since most investigators will be trained and have experience with the published aging methods, these will be the methods used for this research. The data collected for this research are from the pubic symphysis, auricular surface of the illium, and ectocranial suture closure.

Accuracy and Quality Indices

Due to the amount of unknown information about a skeleton in an archaeological or forensic case, it is important to include as much known or observable information as possible about the skeleton so that all factors available can be taken into consideration when determining skeletal age-at-death. The accuracy of the methods and condition of the skeleton become important because they are related to the overall assessment of the skeleton.

Accuracy Index

Accuracy in age estimation is how well the estimated or biological age conforms to the real chronological age, and relies on how strongly correlated the biological and chronological ages are to each other. There are many ways to determine accuracy, but the accuracy value used in this thesis is the correlation coefficient of the chronological and biological age indicator that is associated with each aging method (Katz and Suchey 1985; Meindl et al. 1985; Meindl and Lovejoy 1985). The correlation coefficient, when considering the relationship between chronological and biological age, can range from 0 to 1, with accuracy increasing as the correlation coefficient approaches one. The correlation coefficient can range from -1 to 1, but if there is ever a negative correlation the accuracy is set to 0. The correlation coefficient value is usually published with the descriptions of the methods or in articles examining the validity of the methods. Males and females differ in their relationship between biological and chronological age, and therefore the correlation coefficients can be valued differently for each sex, but this is not always the case. Table 2-1 provides a list of some commonly used age indicators and their correlation coefficients.

Table 2-1. List of commonly used coefficients of correlation between age indicators and age-at-death.

Indicator	Female	Male	Both Sexes	Reference
Endocranial Sutures	0.35	0.51	-	Ascadi and Nemeskeri (1970)
Humerus	0.34	0.44	-	Ascadi and Nemeskeri (1970)
Femur	0.58	0.56	-	Ascadi and Nemeskeri (1970)
Pubic Symphysis	0.64	0.57	0.57	Meindl et al. (1985)
Auricular Surface	-	-	0.72	Lovejoy et al. (1985b)
Dental Wear	-	-	0.7	Lovejoy (1985)
Ectocranial Sutures	0.34	0.59	0.56	Meindl and Lovejoy (1985)
Ectocranial Sutures	-	-	0.57 (L)[1] 0.5 (V)[2]	Meindl and Lovejoy (1985)

[1] Lateral; [2] Vault

There are biases with using correlation coefficients; however, it is the most commonly agreed upon notion of accuracy with respect to the aging methods. Some of the biases are that the traits used in age assessment are discrete and highly nonlinear due to the phases overlapping and intervals containing variable lengths (Kemkes-Grottenthaler 2002).

Quality Index

Quality is a distinctive characteristic or property of an object, process, or other thing. Quality is an additional piece of information that can be taken into consideration when analyzing a skeleton. Since the condition of the skeleton is dependent on environmental factors, the quality of a skeleton can affect the confidence in determining age-at-death. A metric is required in order to describe or determine these variations seen on the bony elements under consideration. Quality, as used in this thesis, is the weathering stages as defined by Behrensmeyer (1978). The weathering stages describe the bone's surface texture that "may be altered by heat, plant roots, worms, soil/sediment characteristics, scavengers, and human activity" (Buikstra and Ubelaker 1994:97). The phases take into account the taphonomic processes that may have affected the bones of an individual and, in this case, a bone's age indicator. Efremov (1940) described taphonomy as the study of the geological and biological processes that affect organic remains as they pass from the biosphere to the lithosphere. It can also be defined as the postmortem processes which affect "(1) the preservation, observation, or recovery of dead organisms, (2) the reconstruction of their biology or ecology, or (3) the reconstruction of the circumstances of their death" (Haglund and Sorg 1997:13). Weathering represents the bones' response to the immediate environment (Ubelaker 1997). As used here, the weathering stages do not represent the passage of time; rather, they represent the condition of the bone. It is important to take taphonomy into consideration because it can have differential effects on the bony element under consideration when assessing age.

Through the use of the bone weathering stages, the skeleton's preservation or condition can be evaluated. The values are associated specifically with the part of the skeleton for which the aging methods are being applied. If the bone is deteriorated but can still be used, the aging method will still be applied but it will be given a lower degree of consideration. Biological anthropologists have commonly adopted the bone weathering stages (sometimes slightly modified) presented by Behrensmeyer (1978). *Standards* (Buikstra and Ubelker 1994) uses a modified version of Behrensmeyer (1978) with six bone weathering stages (0-5), which can be seen and discussed in Figure 3-3. A score of 0 indicates that there is no signs of weathering and a score of 5 represent bone that is falling apart and splintering.

Problems with Skeletal Age Determination

Many factors will affect the accuracy and precision of skeletal age-at-death determination. Due to the progressive development of bones, skeletally immature and young adult individuals are more likely to be aged more precisely than older adult individuals. The skeletal developments of subadults are better documented and include factors such as tooth development and eruption and epiphyseal closure. Adult bones are in a continual process of change but these changes are usually degenerative and influenced by the activities and health of the individual as well as the amount of time that has elapsed (White 2005).

To develop standards or aging methods to age unknown skeletons, skeletal collections with known age skeletons are used. Known age skeletons must be used to infer the unknown. Most of the skeletal aging methods are based on a specific population, such as the Terry collection which contains mainly black and white adult skeletons with dates of birth ranging from 1822-1943. Due to this, the data collected does not necessarily take into account populations that do not have the same ethnic background as the collections, such as Native Americans. This can cause additional variation with the aging methods when applied to skeletons with other forms of ancestry or unknown ancestry.

Another factor that contributes to uncertainty is the age class categories or age ranges that each method divides the age continuum into. Skeletal age assessment does not provide an exact age, such as 20 years, but is instead broken up into age classes or ranges, such as 20-25 years or 30-40 years. Segmenting such a continuum into intervals leads to imprecision (White 2005). In addition, age ranges are not consistent with the number of years included. There is some inclusion and exclusion of numbers with each range or it may include a ten-year age range for younger individuals and a 50+ age range for older individuals. This is a cause for non-crisp boundaries and, therefore, a specific single age based on these methods cannot be reached. The most commonly used age classes are: fetus (before birth), infant (0-3 years), child (3-12 years), adolescent (12-20 years), young adult (20-35 years), middle adult (35-50 years), and old adult (50+ years) (Buikstra and Ubelaker 1994). Although these are the most commonly used categories for classification, each individual method has their own age classes or ranges associated with them. The variation present in aging techniques for middle aged or older adults does not necessarily indicate that the techniques need to be perfected as it reinforces that aging is an inconsistent process and the variation in the rates of aging increases over a life span (Klepinger 2006).

Multifactorial Methods for Determining Age

There are two major factors that contribute to the errors in estimating age-at-death of an unknown specimen: the variation of the biological process and the investigator's ability to estimate age (Lovejoy et al 1997). Therefore, in order to eliminate some of these factors, as many age indicators as possible should be considered in order to make the best decision about age-at-death (Meindl et al. 1985). When multiple trait skeletal analysis began to produce better results than single trait analysis, more methods were developed to use multiple aging techniques to determine skeletal age-at-death. Multifactorial methods for skeletal age-at-death include the complex method, multifactorial summary age method, and transition analysis.

Complex Method

The complex method was introduced by Acsádi and Nemeskéri (1970) and co-utilizes changes in endocranial suture closure, proximal humerus, pubic symphysis morphology, and proximal femur. The assessment for the proximal humerus and femur involves analyzing structural changes in the spongy tissue. The authors recommend analyzing the pubic symphysis first. If the age is determined by the pubic symphysis to be less than 50 years, then it is suggested to use the lower limit values for each age range. If age is determined to be approximately 50 years, then the mean age values should be used for each skeletal element. If over 50 years, then the upper limit of the age range should be used for each skeletal element. Next, phases are assigned for the proximal humerus, endocranial suture closure, and proximal femur. The age phases are established by assessing morphological states, which result in determination of physiological age closest to chronological age (Acsádi and Nemeskéri 1970). The four age indicator phases are averaged and each is given equal weight. The authors determine the accuracy to be 80 – 85%, with a margin of error of ±2.5 years (Acsádi and Nemeskéri 1970).

There are several limitations associated with this method. First, the weighted average causes an attraction to the middle. Hence, this method tends to over age younger individuals under 40 years and under age older individuals over 70 years. Although this is not strictly a problem with this method, it is exacerbated by it. In addition, the pubic symphysis is given a more dominant role, which causes it to determine the limits of the age ranges. Also, due to the proximal humerus and femur needed to determine age and the use of radiographs or longitudinal sectioning, this method is not a valid comparison here because of the data that has been collected and lack of resources, such as access to radiographs.

Multifactorial Summary Age

The multifactorial summary age was developed by Lovejoy et al. (1985) using the Hamann-Todd collection, which has reliable documentation of age. It is designed to use as many age indicators as available, but the original study uses five indicators: auricular surface and pubic symphysis morphology, dental wear, ectocranial suture closure, and proximal femur radiographs. All skeletal age indicators are independently analyzed for the entire sample population. The skeletal age based on each indicator is used to generate an intercorrelation matrix that is subjected to principal component analysis. The first principal component is assumed to represent the true chronological age. The correlation with the first principal component of an indicator is its weight, then the weighted average of all age indicators is the final age of the individual (Lovejoy et al. 1985). It is reported that summary age produces an estimated age distribution that is statistically indistinguishable from the real distribution (Bedford et al 1993).

Limitations with using the summary age method are that it requires a population of skeletons, thus it is sensitive to the number and type of sampled skeletons. Individual skeletons in a collection are analyzed by seriation. Therefore, any individual skeleton not from this specific population cannot be reliably analyzed. A weighted average is produced; thus it has the same limitations of attraction to the middle as the complex method. This method is not comparable to the technique presented in this thesis because summary age is based on a population of skeletons. The goal of this work is to determine individual skeletal age without the use of a population.

Transition Analysis

Transition analysis uses skeletal traits that can be arranged into an invariant series of senescent stages (Boldsen et al. 200). The features included in the original analysis are five characteristics of the pubic symphysis, nine features from the iliac portion of the sacroiliac joint, and five suture segments. The scoring system involves a detailed skeletal age coding format incorporating various aspects of the features used, which is a new scoring system developed by the authors based on traditional approaches. The resulting information is then used to calculate a likelihood of death for a specific age. Because researchers accept that exact age is not likely to be recovered, this approach provides the foundation to use these point estimates for the construction of a probability density function defined over all ages. They are then able to calculate confidence intervals about point estimates. An internally consistent age distribution for a skeletal series is produced by combining multiple age indicators into a single probabilistic estimate (Wright and Yoder 2003).

Bayes' theorem is used by Boldsen et al. (2002) to calculate the age at death point estimates. One problem is in calculating the prior distribution, which the authors reference the use of population modeling, uniform priors, or the use of documentary information. Population modeling is required to determine the age-at-death distribution of an ancient population, which is usually not known or has to be estimated from the sample population. The authors use uniform prior or documentary information to calculate the prior. Additional limitations are that the information about the age structure is based on the populations that produced the skeleton (Boldsen et al. 2002). The number of samples and the range of observed ages need to be sufficient in order to acquire a meaningful age structure. Boldsen also points out that the aim is to determine the probability that death occurred at each possible age, not just the likelihood of occurring at a single age (Boldsen et al. 2002).

Fuzzy Set Theory

The information fusion technique presented here is based on fuzzy set theory. Uncertainty is typically regarded as undesirable in science. Uncertainty may arise from information that is "incomplete, imprecise, fragmentary, not fully reliable, vague, contradictory, or deficient in some other way" (Klir 1995:245). Because there are many different types of uncertainty, it is understandable that there would be different approaches to uncertainty modeling. In 1965, Zadeh (1965) challenged probability theory as the sole method for modeling uncertainty by introducing fuzzy sets. This is a theory whose objects are sets with boundaries that are not precise. Fuzzy set theory is not an imprecise science; it is the set boundaries that are imprecise. Elements in a fuzzy set belong to a degree (Klir 1995).

Fuzzy sets are not crisp sets (sets that define individuals as member or nonmember of a group), but are sets that allow for a grade of membership. "This grade corresponds to the degree of which that individual is similar or compatible with the concept represented by the fuzzy set" (Klir 1995:4). The grades are often represented by real number values ranging between 0 and 1, where larger values indicate a higher degree of set membership. Fuzzy set theory has been successfully applied to many problems, such as pattern recognition, logic and inference, robotics, computer vision, and control systems.

Fuzzy set theory provides a powerful framework in which to model the uncertainty present in age determination. Since the age determination methods are not intended to be a rigid set of typological standards but rather describe modal age changes, uncertainty is inherent in skeletal age determination (Meindl et al 1985). Not to mention, depending on the preservation and quality of the traits, each skeleton has its own degree of error or precision (Boldsen et al. 2002). As far as biological anthropology is concerned, no application of fuzzy set theory has been found to date.

CHAPTER 3: MATERIALS AND METHODS

Data Collection

The data analyzed in this thesis were collected as part of another study by Nicholas Herrmann, Daniel Wescott, and Lyle Konigsberg and made available by Lyle Konigsberg. Skeletal remains of known age from the Terry Collection were scored for pubic symphysis morphology using the Todd system (1920), auricular surface morphology using the Lovejoy et al. method (1985) and ectocranial suture closure following Meindl and Lovejoy (1985). Sample sizes by sex and decade of life are shown in Table 3-1. There are more males than females, with the greatest number of individuals being middle to old age adults.

The Terry Collection was developed in 1898 in the St. Louis, Missouri area by Robert J. Terry (Hunt and Albanese 2005). Skeletons were collected for the anatomy department at Washington University. Mildred Trotter continued the collection after Terry's retirement in 1941. The collection was moved to the Smithsonian Institution's National Museum of Natural History in 1967. It consists of 1,728 individuals with the majority between 20 and 80 years of age.

Table 3-1. Terry collection sample categorized by sex and age group.

Age Group[1]	Pubic Symphysis			Auricular Surface			Cranial Stuture		
	Male	Female	Total	Male	Female	Total	Male	Female	Total
0-9	0	0	0	0	0	0	0	0	0
10-19	4	4	8	5	7	12	7	7	14
20-29	67	44	111	71	48	119	70	49	119
30-39	86	54	140	86	55	141	87	55	142
40-49	83	56	139	81	60	141	84	59	143
50-59	80	60	140	81	66	147	80	67	147
60-69	51	42	93	51	46	97	50	45	95
70-79	28	29	57	27	32	59	30	31	61
80-89	21	30	51	21	32	53	22	33	55
90-99	2	11	13	2	13	15	2	13	15
100-109	0	2	2	0	2	2	0	2	2

[1]years

Pubic Symphysis: Todd Method

Changes in the morphology of the pubic symphysis for age determination are the focus of the Todd method (Todd 1920). The pubic symphysis has surface, age-related changes that continue after adult stature has been reached. These changes in the surface can be used for determining age-at death estimates. The Todd method is based on 306 individual males of known age at death. The observations involve breakdown or deterioration, billowing, ridging, ossification nodules, and texture of the ventral border, dorsal border, superior extremity and inferior extremity of the symphyseal face. The younger the individual, the more rugged the surface is with transverse ridges and furrows and lack of ossification nodules. As an individual ages, the surface of the pubic symphysis loses relief and develops a ventral border or rampart. Continual degeneration and erosion are associated with progressive age. Figure 3-1 indicates the location of the pubic symphysis on the pelvis. Figure 3-2 shows the stages and ages ranges associated with each stage.

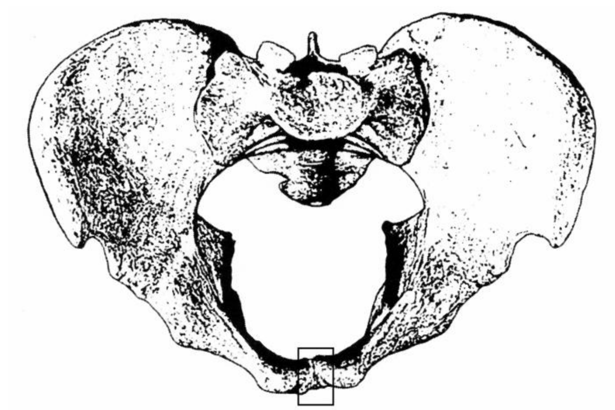
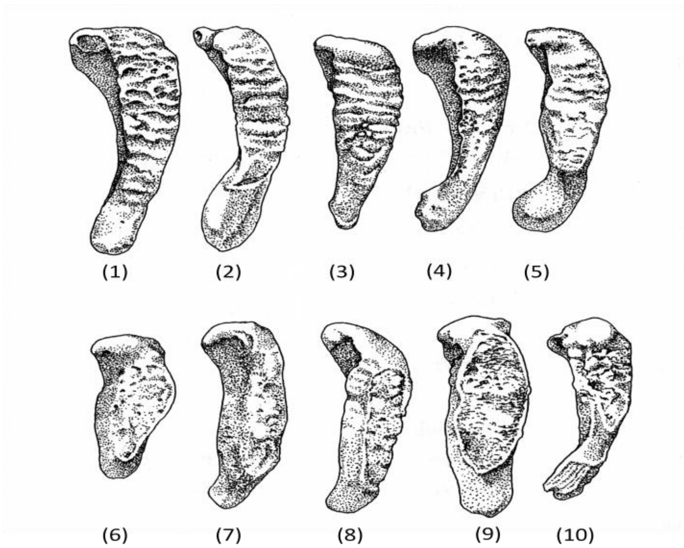


Figure 3-1. Image of a human pelvis. The box indicates the location of the pubic symphysis. (Image from Matshes et al. 2005



Stages	Age Ranges
1	18-19
2	20-21
3	22-24
4	25-26
5	27-30
6	30-35
7	35-39
8	39-44
9	45-50
10	50+

Figure 3-2. Todd (1920) method for scoring pubic symphysis morphology (left) with associated stage illustrations (right) (from Schwartz 1995).

Auricular Surface of the Illium

This method is based on the changes in the auricular and contiguous area of the posterior portion of the illium. The auricular surface is the area of subchondral bone forming the iliac portion of the sacroiliac joint (Figure 3-3). This method was first described by Lovejoy et al. in 1985. The features used for age analysis are the apex, superior and inferior demifaces of the auricular surface and the preauricular sulcus and retroauricular area (Figure 3-3). In particular, it is the analysis of the changes in these surfaces, which include surface granulation, microporosity, macroporosity, transverse organization, billowing, and striations. Younger individuals are associated with a fine-grained surface and regular pattern of billowing. As an individual ages, the surface becomes more coarse and billowing and striations are not as defined. Microporosity and macropor0sity develop with increasing age. Figure 3-3 illustrates where the auricular surface is located on the pelvis. The eight phases that are associated with the changes of the auricular surface are shown in Figure 3-4.

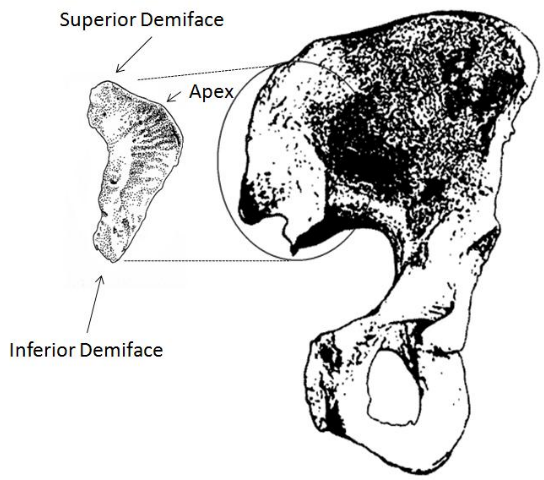


Figure 3-3. Image of where the auricular surface is located on the pelvis, as indicated by the circle. (Image from Matshes et al. 2005)

Stage	Age Range
1	20-24
2	25-29
3	30-34
4	35-39
5	40-44
6	45-49
7	50-59
8	60+

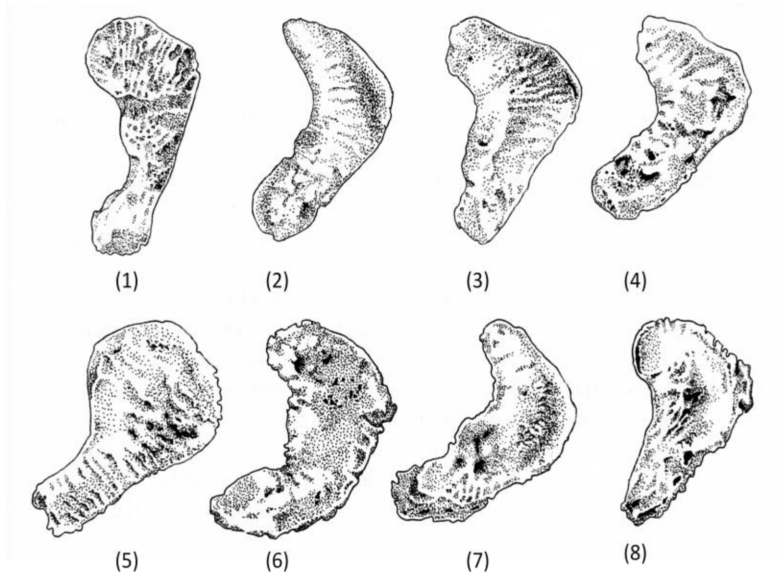


Figure 3-4. Lovejoy et al. (1985) method for scoring the auricular surface (right) with illustration of each stage (left) (from Schwartz 1995).

Ectocranial Suture Closure

The method is used to evaluate the degree of closure for cranial sutures follows Meindl and Lovejoy (1985). Ectocranial suture closures are more closely associated with extreme ages, such as very young and old. Individuals with fully open cranial sutures should be aged based on postcranial indicators (Meindl and Lovejoy 1985). The greater degree of closure, the older the individual is in most cases. Each suture has its own timing for fusion, thus can be correlated with a chronological age.

One centimeter lengths of suture were examined for degree of closure at ten locations (Figure 3-5). The landmarks include (1) midlambdoid, (2) lambda, (3) obelion, (4) anterior sagittal, (5) bregma, (6) midcoronal, (7) pterion, (8) sphenofrontal, (9) inferior sphenotemporal, and (10) superior sphenotemporal. These ten landmarks are then divided into vault and lateral systems. Sites 1-7 belong to the “vault system” and 6-

10 with the "lateral system". Closure is scored as 0 for open, 1 for minimal to moderate, 2 for significant (≥ 50%) but not complete closure across the site, and 3 for complete closure. A composite score is then calculated by adding the individual scores for each system. Each composite score is associated with a predetermined age range. For the ectocranial suture closure, Table 3-2 shows the composite score and the associated age range.

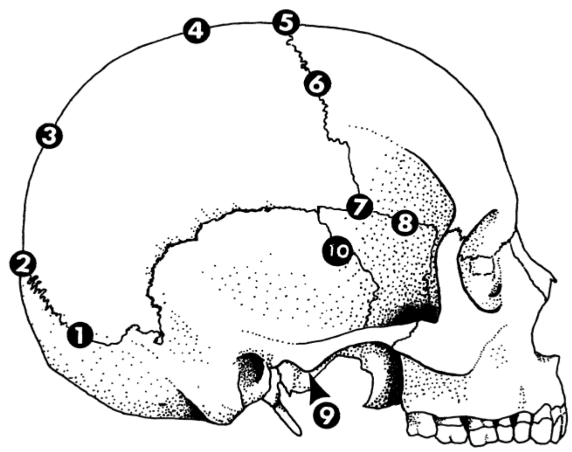


Figure 3-5. The landmarks used in ectocranial suture closure analysis. (Image from Meindl and Lovejoy 1985).

Table 3-2. Meindl and Lovejoy (1985) method for scoring ectocranial suture closures.

Ectocranial Lateral-Anterior Suture Closure	
Composite Score	Age Range
0	>50
1	19-48
2	25-49
3,4,5	23-68
6	23-63
7,8	32-65
9,10	33-76
11,12,13,14	34-68
15	Closed

Ectocranial Vault Suture Closure	
Composite Score	Age Range
0	>49
1,2	18-45
3,4,5,6	22-48
7,8,9,10,11	24-60
12,13,14,15	24-75
16,17,18	30-71
19,20	23-76
21	Closed

Accuracy Index and Quality Index

Correlation coefficients for each of the three aging methods were obtained from the literature and are used as an estimation of the method's accuracy. The quality of the specimen can greatly affect accuracy and should be considered in forensic anthropological and bioarcheological evaluations of age. Bone quality was evaluated and scored using the scale in Table 3-3. The scores follow the modified version of Behrensmeyer (1978) provided in *Standards* (Buikstra and Ubelaker 1994), but a stage 6 was added to take into account the absence of an age indicator. The quality indices are ordinal and arbitrarily assigned values. They must be decreasing values and no greater than one and no less than 0. They were assigned in this manner to indicate the least weathering as producing the best results (1) and the most weathering as producing poor or no results (0). However, the data used in this study were collected on museum specimens and therefore the quality index does not vary.

Table 3-3. Bone weathering stages and quality index (After Buikstra and Ubelaker 1994).

	Bone Weathering Stages	**Quality Index**
Stage 0:	Bone surface shows no sign of cracking or flaking due to weathering.	1
Stage 1:	Bone shows cracking, normally parallel to the fiber structure (e.g. longitudinal in long bones). Articular surfaces may show mosaic cracking.	0.8
Stage 2:	Outermost concentric thin layers of bone show flaking, usually associated with cracks, in that the bone edges along the cracks tend to separate and flake first. Long thin flakes, with one or more sides still attached to bone, are common in the initial part of Stage 2. Deeper and more extensive flaking follows, until the outermost bone is gone. Crack edges are usually angular in cross section.	0.6
Stage 3:	Bone surface is characterized by patches of rough, homogeneously weathered compact bone, resulting in a fiberous texture. In these patches, all the external, concentric layers of bone have been removed. Gradually the patches extend to cover the entire bone surface. Weathering does not penetrate deeper than 1.0-1.5 mm at this stage, and bone fibers are still firmly attached to each other. Crack edges usually are rounded in cross section.	0.4
Stage 4:	The bone surface is coarsely fibrous and rough in texture; large and small splinters occur and may be loose enough to fall away from the bone if it is moved. Weathering penetrated into inner cavities. Cracks are open and have splinters or rounded edges.	0.2
Stage 5:	Bone is falling apart, with large splinters. Bone easily broken by moving. Original bone shape may be difficult to determine. Cancellous bone usual exposed, when present, and may outlast all traces of the former more compact, outer parts of the bones.	0.1
Stage 6:	The bone or piece used for aging is not present.	0

Fuzzy Integral

When there is a complex decision to be made, many times there are multiple sources of information available. For example, when a leader of a country is faced with a complex decision, she relies on her advisors. She takes into account what the advisors are telling her and how much trust she has in them. Each “information source” provides a confidence in the goodness of a particular decision and the leader can fuse those confidences with how valuable those confidences are. When each advisor is independent, a weighted average may be appropriate. However, if certain groups of advisors are strongly confident in the decision, their combined worth can be more than just the sum of the individual people. For example, the leader thinks that advisors A and B both have an individual worth of 0.3. However, if advisors A and B agree on a decision, the leader believes their combined worth to be 1.0, independent of what the others say. This is clearly not probabilistic. Fuzzy measures produce a value of "worth" for each subset of information sources relative to answering in a particular question. Each information source will provide a confidence for a hypothesis. The fuzzy integral is a mechanism to fuse these two quite different types of evidence. (Example is from a personal correspondence with Dr. James Keller).

There are two fuzzy integrals: the Sugeno integral (Sugeno 1977) and the Choquet integral (Murofushi and Sugeno 1991). The Sugeno integral is used in this thesis because it is easier to conceptualize and the differentiable form of the Choquet integral is not needed. Fuzzy integrals have been used for hand writing recognition (Gader et al. 1996), computer vision (Tahani et al. 1990), face recognition (Keun-Chang and Pedrycz 2004), machinery fault diagnosis (Xiaofeng et al. 2006), and linguistic fuzzy integrals (Auephanwiriyakul et al. 2001).

The Sugeno integral is defined with respect to a fuzzy measure (Wang and Klir 1992). A fuzzy measure, g, is a real valued function defined on the power set of X (the universe of discourse), 2^X, with range [0,1], satisfying the following properties. Let A and B be two subsets from X.

1. Boundary conditions

   g(X) = 1 and g(Ø) = 0, where Ø is the empty set

2. Monotonicity

   g(A) ≤ g(B) if A ⊆ B

3. Continuity

   If $\{A_i\}$ is an increasing subsequence of subsets of X, then

   $g(\bigcup_{i=1}^{\infty} A_i) = \lim_{i \to \infty} g(A_i)$

Property 3 is not applicable when X is a finite set, as it is for this application. A fuzzy measure specifies the opinion of the "worth" or "goodness" of each subset of information sources in evaluating a particular hypothesis. Each information source gives a belief or confidence in the hypothesis and the measure lets you know how to weight that belief or confidence. A fuzzy measure g is called the Sugeno λ-fuzzy measure if it additionally satisfies the following property.

4. For all A, B ⊆ X with $A \cap B = \phi$

   $g(A \cup B) = g(A) + g(B) + \lambda g(A) g(B)$

   for some $\lambda > -1$

If λ equals zero, then rule 4 shows that g is a probability measure. For a fuzzy measure g, let $g^x = g(\{x\})$. The mapping $x \to g^x$ is called a fuzzy density function. If $X = \{x_1, x_2, \dots, x_n\}$, we sometimes write g^i to mean g^{x_i}. The fuzzy density value, g^i, is interpreted as the (possibly subjective) importance of the single information source x_i in determining the evaluation of a hypothesis. If g is a Sugeno λ-fuzzy measure, then only the densities must be provided, where λ is found by solving for

$$\lambda + 1 = \prod_{i=1}^{N} \left(1 + \lambda g^{i}\right). \quad \text{(Sugeno 1974).}$$

$\lambda\lambda$

When the total number of subsets is relatively small and the width of each subset is already known or can be manually determined, the g function can be specified, where the provided values satisfy properties 1-3 above. Depending on the selection of g, many familiar statistics can be recovered, such as the average, median, and even an ordered weighted average (Keller et al. 1994).

Once λ is found, assuming the use of the Sugeno λ fuzzy measure, the Sugeno integral can be calculated. The Sugeno integral, in its discrete form, is defined as:

$$\oint h \circ g = \bigvee_{i=1}^{N} \left(h(x_{(i)}) \wedge g(\{x_{(1)} \ldots x_{(i)}\}) \right)$$

Where x_i is the i^{th} information source (age indicator), $h(x_i)$ is the support of the hypothesis from the standpoint of x_i (the strength in the hypothesis that the skeleton is a particular age according to a single source), N is the number of age indicators used, and $x_{(i)}$ is the i^{th} sorted source, which are sorted in decreasing order according to the $h(x_i)$ values. The $h(x_i)$ values are dependent on the quality and if the aging method indicates that the age being tested falls within the age interval. Formally, this is the minimum of these two numbers. The $\vee$ in the Sugeno integral is a t-conorm and the $\wedge$ is a t-norm (Zadeh 1965). These are generally picked to be the maximum and minimum respectively for the Sugeno integral.

Program

The implementation of the fuzzy integral and all graphs produced are generated in MATLAB, which is a technical computing language and interactive environment that allows for data visualization, analysis, and numeric computation (http://www.mathworks.com/products/matlab/description1.html 2007). MATLAB is used in many domains such as image processing, pattern recognition, and bioinformatics.

Age-Graph Construction

The method proposed here is for obtaining skeletal age-at-death. It can be used by biological or forensic anthropologists to improve their analysis of the age-at-death of an adult skeleton. A benefit of this approach is that only one skeleton needs to be present to produce the desired results. Age or age range of the aging method, quality, and accuracy, all of which are collected from a skeleton, can be entered into a chart (Table 3-4).

Table 3-4. Example data collection sheet that is used to calculate the Sugeno integral.

Age Indicator		
Accuracy Index	Age Range	Quality Index

Aging methods generally provide age ranges for each phase. Each accuracy and quality index needs to be assigned for each individual age in a given age range. Once the age, accuracy, and quality indices are collected, a hypothesis is tested. The hypothesis is "the skeleton is age _____ (a specific age, not range)".

The Sugeno integral, as defined above, is repeatedly applied once for each possible age to the collected information reported in Table 3-4. Every age, in discrete one year increments from 1 to 110, is tested and the age indicators provide input based on if the age being tested is in their respective interval range. The result of the Sugeno integral, one for each individual age tested, is the maximum of the minimums of g and h at each x-axis unit. The idea behind the minimum calculations are that they are a pessimistic operation, where h is the confidence in the decision from the ith sorted source and g is how much confidence we have in a subset of sources (the 1st sorted source to the ith) therefore, there should only be as much confidence in the decision as the belief in the sources. If g is less than h, there is less confidence in the decision than what the source is telling us. If g is greater than or equal to h, then we are confident in what the source is telling us. The best pessimistic agreement, what the Sugeno integral produces, is shown by the dashed circle in Figure 3-6.

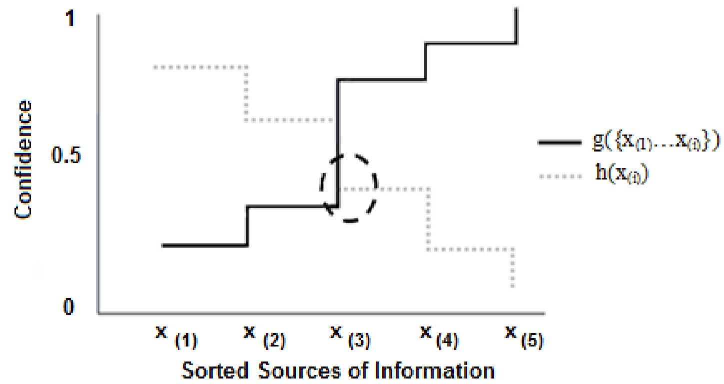


Figure 3-6. The best pessimistic agreement between g and h in the Sugeno integral. The dotted circle is the maximum of the minimums of *g* and *h* at each x-axis unit.

Figure 3-7 is a flow chart that shows all of the variables used by the Sugeno integral. Each individual age indicator and its skeletal quality are used, along with the accuracies of each indicator, and the λ measure.

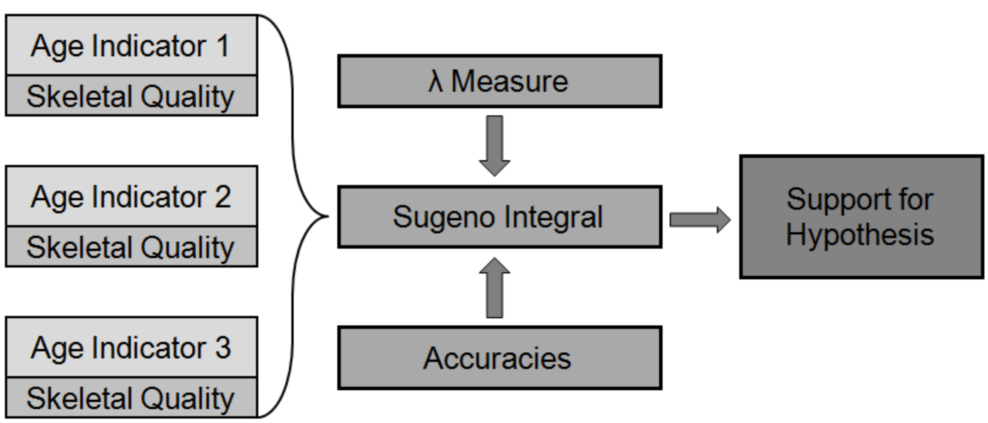


Figure 3-7. Flow chart illustrating how and what information is used for the Sugeno integral.

Example of the Sugeno Integral

The Sugeno integral fuses together h and g, where g is accuracy (confidences in subsets of sources) and h is what the sources are telling us, which is the minimum of the quality index value and the {0,1} age test, which tests if the age indicator says that the skeleton is the age being tested. The following is an example of how the Sugeno integral fuses together the information. The hypothesis is the skeleton is age 28.

1. The h and g values are provided and λ is calculated from the g values.

   $h(x_1)=0.6$ $g(x_1)=0.6$
   $h(x_2)=0.9$ $g(x_2)=0.7$
   $h(x_3)=0.2$ $g(x_3)=0.3$

   $\lambda = -0.8543$

2. Sort the sources in decreasing order according to their h values.

   $h(x_{(1)}) = h(x_2) = 0.9$
   $h(x_{(2)}) = h(x_1) = 0.6$
   $h(x_{(3)}) = h(x_3) = 0.2$

3. Calculate the required g subset values.

   g calculations: $g(A \cup B) = g(A) + g(B) + \lambda g(A)g(B)$

   $g(x_{(1)}) = \mathbf{0.7}$
   $g(x_{(1)}, x_{(2)}) = (0.7+0.6+(-0.8543*0.7*0.6)) = \mathbf{0\ .9412}$
   $g(\{x_{(1)}, x_{(2)}\}, x_{(3)}) = (0.9412 + 0.3 + (-0.8543*0.9412*0.3)) \approx \mathbf{1}$

4. Calculate the Sugeno integral. From i=1 to N, take the minimum of the h value of the ith sorted source and the g value of the 1st sorted source to the ith sorted source (this is a subset). Take the maximum of the N values.

   Sugeno integral = $\max(\min(h(x_{(1)}), g(x_{(1)})), \min(h(x_{(2)}), g(x_{(1)}, x_{(2)})),$
   $\min(h(x_{(3)}), g(\{x_{(1)}, x_{(2)}\}, x_{(3)})))$
   $= \max(\min(0.9,0.7), \min(0.6,0.9412), \min(0.2,1))$

   Maximum of the minimums = (0.7, 0.6, 0.2) = **0.7**

The best pessimistic agreement, or the support in the hypothesis, is 0.7 for the skeleton is age 28. The support in the hypothesis is the best (maximum) pessimistic (minimum) agreement. This process is repeated and each age from 1-110 is tested.

Graph Categories

Once all of the possible age hypotheses have been tested, the numbers produced by the Sugeno integral are used to form a graph that simplifies the subsequent analysis phase. As illustrated in Figure 3-8, at least four different potential graph cases are possible: specific, interval, reconsideration, and inconclusive.

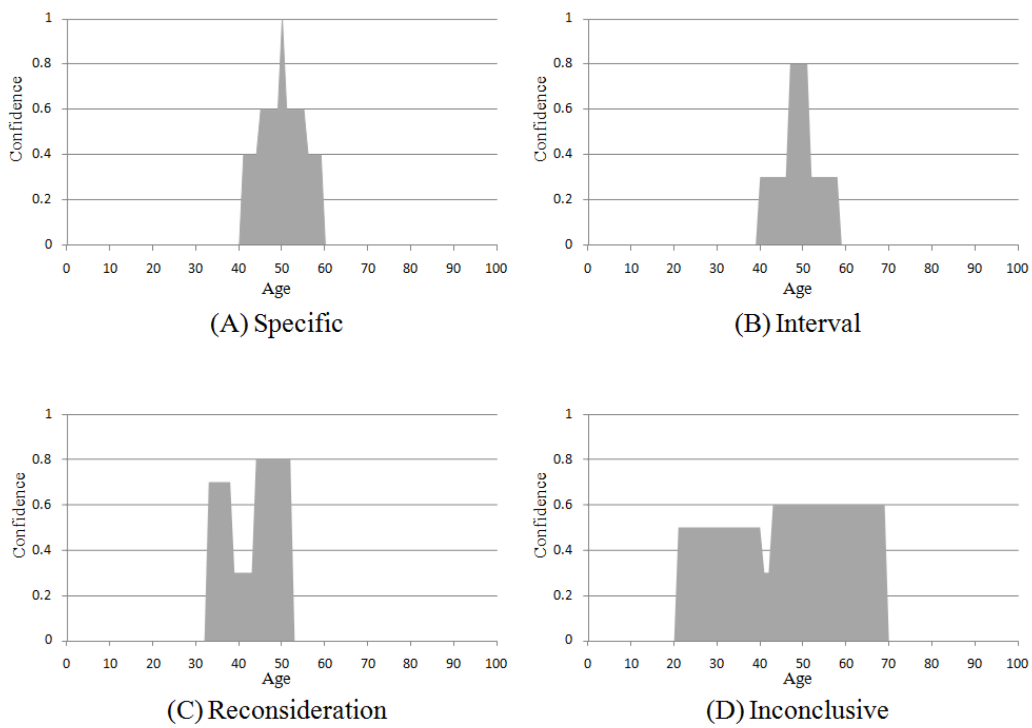


Figure 3-8. Potential graph categories for the Sugeno integral results.

Graph A in Figure 3-8 indicates that there is agreement between all sources and they indicate a single age. Graph B specifies that only an interval age range can be determined. If Graph C is produced, there is disagreement between sources and it is recommended the investigator reevaluate the scores or attempt to determine why the disagreement is present. Graph D, an inconclusive graph, is where the length of the maximum interval is greater than or equal to 30, and therefore the confidence in the age estimation is low and no decision about age can be made.

Graph Classification

The next step, after forming a graph from the Sugeno integral results, is classifying each graph according to the four categories described in the last section. Specific age is determined according to the width of the maximum value interval. For specific age, there can only be one maximum value interval. An interval is defined here with respect to two ages, *a* and *b*. These ages are on the x-axis of the graphs. The *a* age must be smaller than or equal to the *b* age. An interval is all of the ages between and including *a* and *b*. All points in the interval must share the same support in the hypothesis value, which is the y-axis of the graphs. It is classified as specific age if this width is one. The graphs that contain a single interval whose length is 29 or less years are labeled as an interval graph. Again, there can only be one maximum value interval in this case. Reconsideration is a graph that has more than one interval, where each interval has a length of 29 or less years. Lastly, inconclusive contains results where the largest confident interval has a length of 30 or more years.

The graph classification scheme described above can be expressed as a decision tree. This hierarchal structure reports the set of tests and the order in which to apply them to classify a graph. Each test is stated as a yes or no question.

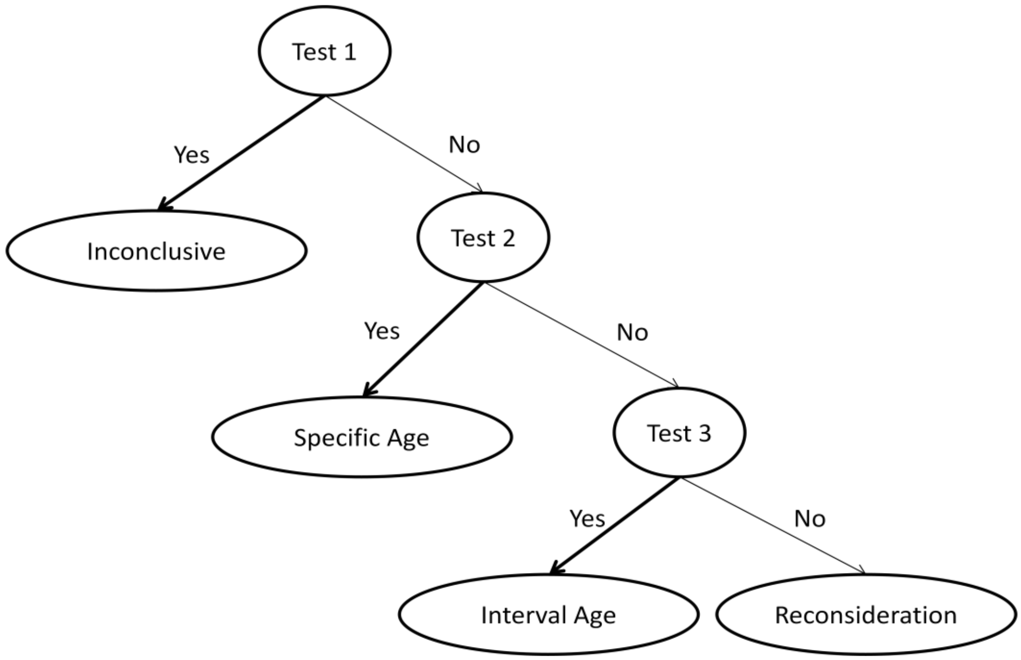


Figure 3-9. Decision Tree showing the sequence of tests taken from the top of the tree downward to classify the Sugeno integral results.

- Test one: Is the length of the maximum interval greater than or equal to 30? If the answer is yes, then the graph is placed in the inconclusive category, if not, then the next test is conducted.
- Test 2: Is the length of the maximum interval equal to 1 and is there just one maximum interval? If yes, the result is specific age.
- Test 3: Is the length of the maximum interval 29 or less years and is there just one maximum interval? If yes, the result is age interval.

Any graph not applicable to the first three tests is labeled as reconsideration.

Program Output

In addition to producing the type of graph, the maximum support in the hypothesis value or confidence is reported and ages included in each interval are provided. In the case of reconsideration, a sorted list, in decreasing order, is produced from the top *k* intervals. A *k* of 2 is chosen here; therefore the top two intervals are reported. Two was selected because with this data set there are only one or two maximum intervals present.

CHAPTER 4: RESULTS AND ANALYSIS

The aging methods, skeletal quality, and accuracy indices are used by the Sugeno integral to produce a confidence that the skeleton is an age (best pessimistic agreement), which are assembled together to produce graphical results. These graphs are classified, by a computer program, according to specific, interval, reconsideration, and inconclusive. Table 4-1 illustrates the accuracy values for this data set, which are the correlation coefficients that are published with or about the aging methods. Since the Terry Collection contains skeletons that are from a museum collection and are in good condition, a quality of 1.0 was assigned to all skeletons.

Table 4-1. Accuracy indices used in the Sugeno integral.

	Pubic Symphysis	Auricular Surface	Ectocranial Suture Closure
Male	0.57	-	0.59
Female	0.64	-	0.34
Both Sexes	-	0.72	-

From the data set, 735 skeletons have all age indicators present and produced classifiable graphs. Of the seven hundred and thirty nine skeletons, 412 are males and 323 are females. Table 4-2 details the breakdown of the sex of skeletons per decade.

Table 4-2. Table illustrating the breakdown of this data set according to sex and decade.

Decade	Females	Males	Total
0-9	0	0	0
10-19	1	3	4
20-29	43	66	109
30-39	52	85	137
40-49	55	81	136
50-59	60	79	139
60-69	41	50	91
70-79	28	26	54
80-89	30	20	50
90-99	11	2	13
100-109	2	0	2
Total	323	412	735

Distance between Chronological and Biological Age-at-Death

A biological age-at-death metric is used to understand how well the graphs correspond with chronological age-at-death. If the true chronological age falls within the maximum Sugeno integral interval, then it is classified as *In Interval*. If it falls outside of this interval, then the absolute value of the difference between the chronological age and the nearest maximum interval end point is used. If this value is less than or equal to 5 years, it is classified as 1-5, less than or equal to 10 years is classified as 6-10, and greater than 10 years is labeled >10. Figure 3-10 gives the biological and chronological age-at-death difference for the Terry collection data set. As can be seen in Figure 4-1, there are 182 skeletons classified as *In Interval* and 252 classified as 1-5. These are considered to be the best categories for classification and together make up 59% of the data. Therefore, over half of the data fell within 5 years of the maximum interval. For the case of reconsideration, the top two intervals are used.

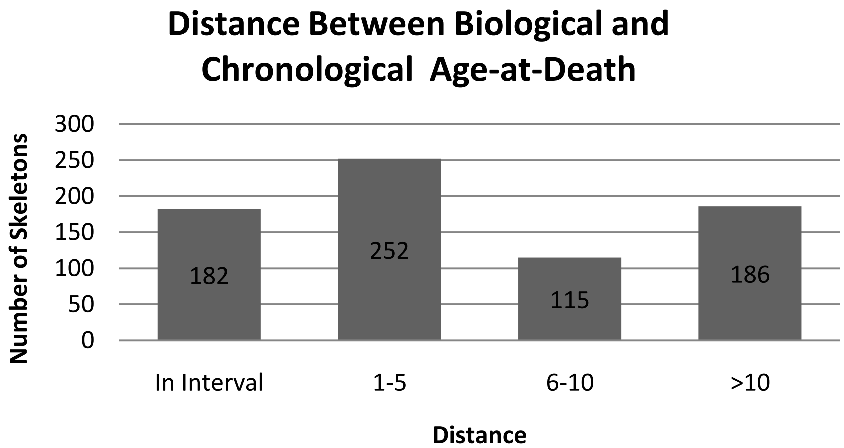


Figure 4-1. Distance between biological and chronological age-at-death for the data set.

Comparison of Sugeno Integral to Individual Aging Methods

Qualitatively the Sugeno integral results produce graph categories, but quantitatively the Sugeno integral finds better results than the individual aging methods by using the maximum intervals. An individual aging method, which is the pubic symphysis, auricular surface, and the ectocranial sutures for this case, is determined to have found the biological age-at-death if the chronological age falls into the aging method's interval. The ectocranial sutures are not included in this comparison because all of the age ranges are larger than 10 years and, therefore, they do not produce a meaningful comparable quantity. The following is a measure of how many skeletons fall into the Sugeno integral's maximum interval, or the top two for reconsideration, verses each individual aging method. The width of the interval that the age fell into is recorded and used to classify the results into 0-5, 6-10 and >10 categories. This is a measure of precision. The Sugeno integral produces better results than the single aging methods for all cases except for greater 10 (Table 4-3). This is desired because it indicates that the Sugeno integral is finding more accurate, smaller interval results.

Table 4-3. Sugeno integral results compared to the individual aging methods with respect to the category *In the Interval* and the width of the interval.

In the Interval			
	Width of Interval		
	0-5	6-10	> 10
Sugeno Results	119	58	5
%	16.00%	8.00%	0.70%
Pubic Symphysis	52	37	88
%	7.00%	5%	12%
Auricular Surface	87	45	82
%	12%	6%	11%

The next analysis is for the distance from the maximum interval endpoints categories, 0-5, 6-10 and greater than 10, and is separated according to the width of the interval. Tables 4-4, 4-5, and 4-6 show these results. The results show that for 0-5 years (Table 4-4), which is the best classified category, the width of the interval for the Sugeno integral is small and it correctly classifies more skeletons than the individual aging methods. This demonstrates that the Sugeno integral finds results where the chronological and biological age-at-death are close to one another and the interval is small, therefore there results are more precise. In the case of 6-10 (Table 4-5), the Sugeno integral and individual aging methods produce similar results. Lastly, in the greater than 10 category (Table 4-6) the individual aging methods classify more skeletons than the Sugeno integral. However, this is the worst classification category and because the Sugeno integral did so well in the 0-5 category and were similar in the 6-10 category, there are less skeletons for the Sugeno integral to classify.

Table 4-4. Percentage of skeletons that are 0-5 years from the maximum intervals and width of that interval.

0-5 Years			
	Width of Interval		
	0-5	6-10	>10
Sugeno Integral	35%	19%	5%
Pubic Symphysis	22%	15%	13%
Auricular Surface	30%	14%	14%

Table 4-5. Percentage of skeletons that are 6-10 years from the maximum intervals and width of that interval.

6-10 Years			
	Width of Interval		
	0-5	6-10	>10
Sugeno Integral	10%	5%	2%
Pubic Symphysis	9%	7%	1%
Auricular Surface	10%	4%	2%

Table 4-6. Percentage of skeletons that are >10 years from the maximum intervals and width of that interval.

Greater than 10 Years			
	Width of Interval		
	0-5	6-10	>10
Sugeno Integral	16%	9%	1%
Pubic Symphysis	18%	13%	2%
Auricular Surface	14%	9%	3%

Graph Examples

A selective set of examples are included in this section to highlight the utility of the Sugeno integral. The dashed line on the graphs indicates the individual's chronological age. Table 4-7 indicates how many graphs are present for each classification type.

Table 4-7. Number of skeletons classified for the four graph type categories.

Graph Type	Number of Skeletons
Specific	63
Interval	335
Reconsideration	330
Inconclusive	7

Specific Age Graph Type

Sixty-three skeletons were classified as specific age. Three of these skeletons had the chronological age equal to the Sugeno integral result. There are 22 females and 41 males in this graph category. Table 4-8 details the chronological age breakdown included in this category according to decade and sex.

Table 4-8. Specific age breakdown of chronological age and sex.

Specific Age per Decade	Female	Male	Total
0-9	0	0	0
10-19	0	0	0
20-29	6	13	19
30-39	5	10	15
40-49	1	5	6
50-59	2	9	11
60-69	3	1	4
70-79	1	1	2
80-89	2	2	4
90-99	1	0	1
100-109	1	0	1
Total	22	41	63

Of the 63 individuals with specific age classification, the chronological age was within the estimated biological age-at-death interval for 3 individual and eighteen were classified as 1-5 years. Twenty-five were with 6-10 years and 17 had a difference that was greater than 10 years. For the data set, 8.6% of the graphs are classified as specific age. Figure 4-2 displays the percentage of the total per decade of chronological age distribution. This demonstrates that the 2.6% of the 20-29 year olds are classified as specific age.

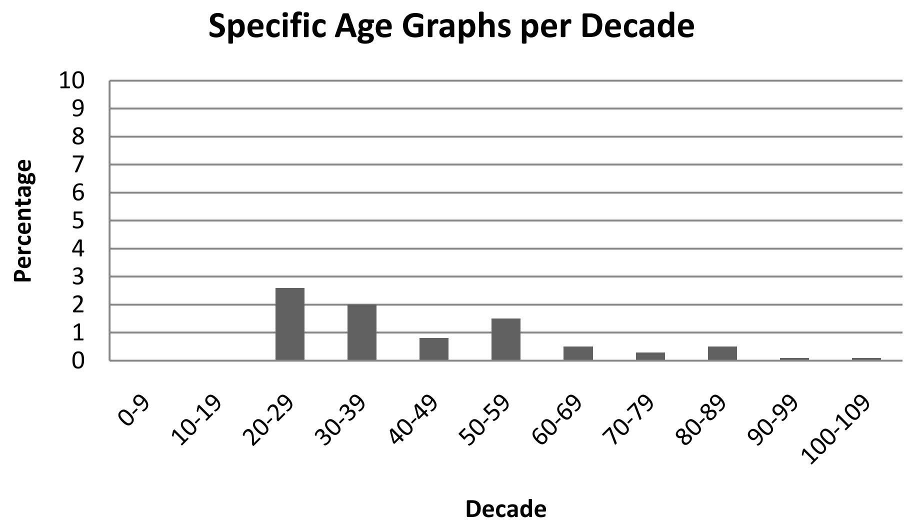
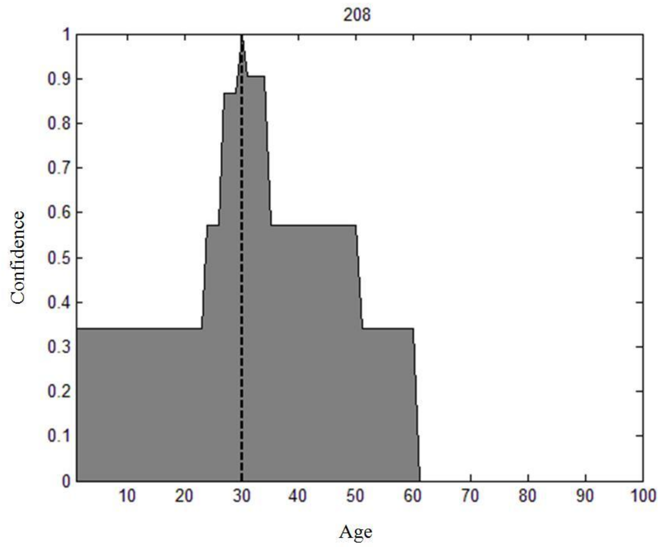


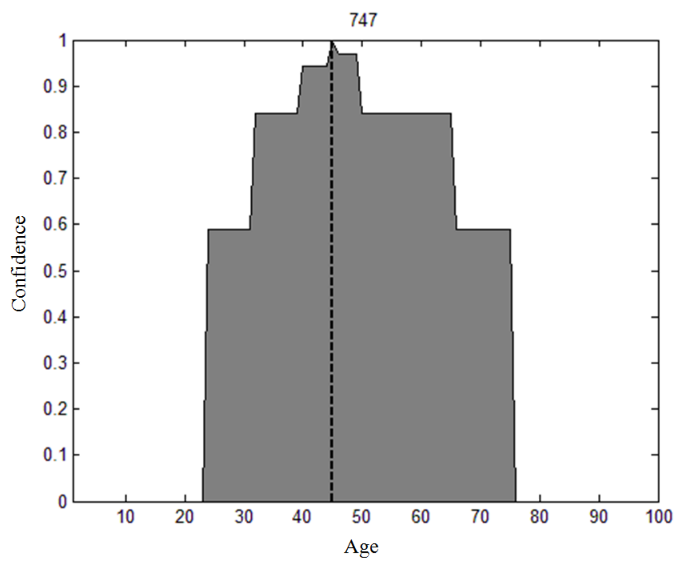
Figure 4-2. Percentage of skeletons labeled as "specific age" for each decade with respect to the entire data set.

The following three graphs were selected to demonstrate skeletons classified as specific age. For each case the skeleton identification, chronological age, sex, Sugeno integral age range, and the aging method inputs are provided.



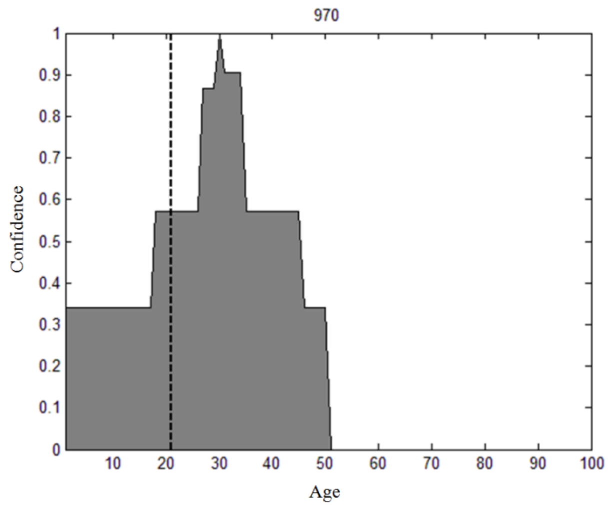
Skeleton	208
Chronological Age	30 yrs
Sex	Female
Sugeno Age Range	30 yrs
Pubic Symphysis	27-30 yrs
Auricular Surface	30-34 yrs
Ectocranial Suture – Vault	24-60 yrs
Ectocranial Suture - Lateral-Anterior	< 50 yrs

Figure 4-3. Graph of Sugeno integral age range for Terry Skeleton 208 illustrating a "specific age" type graph. The peak represents the single maximum age point and the dashed line indicates the chronological age. The intervals in the table represent input of age range for each of the aging methods.



Skeleton	747
Chronological Age	45 yrs
Sex	Male
Sugeno Age Range	45 yrs
Pubic Symphysis	40-45 yrs
Auricular Surface	45-49 yrs
Ectocranial Suture – Vault	24-75 yrs
Ectocranial Suture - Lateral-Anterior	32-65 yrs

Figure 4-4. Graph of Sugeno integral age range for Terry Skeleton 747 illustrating a "specific age" type graph. The peak represents the single maximum age point and the dashed line indicates the chronological age. The intervals in the table represent input of age range for each of the aging methods.



Skeleton	970
Chronological Age	21 yrs
Sex	Female
Sugeno Age Range	30 yrs
Pubic Symphysis	27-30 yrs
Auricular Surface	30-34 yrs
Ectocranial Suture – Vault	18-45 yrs
Ectocranial Suture - Lateral-Anterior	< 50 yrs

Figure 4-5. Graph of Sugeno integral age range for Terry Skeleton 970 illustrating a "specific age" type graph. The peak represents the single maximum age point and the dashed line indicates the chronological age. The intervals in the table represent input of age range for each of the aging methods.

This category represents the ideal in age-at-death determination. It indicates that all methods are in agreement as to a single age-at-death of a skeleton. For example, skeleton 208 (Figure 4-3) is a 30 year old with age ranges of 27-30 (pubic symphysis), 30-34 (auricular surface) and 24-60 and < 50 (ectocranial sutures). Since a common age of 30 is found among all aging methods, an age of 30 is determined to be the skeletal age-at-death of this individual. It is interesting that there are as many specific age category graphs as there are because all of the inputs from the aging methods are in the form of age ranges, not an individual age.

Interval Graph Type

There are 335 graphs classified as interval. Of those, 62 had the chronological age fall in the maximum interval. One hundred and forty five of the skeletons are female and 190 are male.   The chronological age per decade and sex distribution can be seen in Table 4-9. Three skeletons of this graph type are also shown below.

Table 4-9. Interval breakdown of chronological age and sex.

Interval per Decade	Female	Male	Total
0-9	0	0	0
10-19	1	3	4
20-29	15	32	47
30-39	21	36	57
40-49	21	43	64
50-59	36	29	65
60-69	12	21	33
70-79	17	14	31
80-89	15	11	26
90-99	6	1	7
100-109	1	0	1
Total	145	190	335

The interval graph type is the largest category, with 335 graphs, which is 45.6% of the graphs classified. This is to be expected due to all of the aging method inputs being in the form of age ranges or intervals themselves. Overall, as can be seen in Figure 4-6, categories of 20-79 are populated with the majority of the data. Since there generally is an overall uniform trend across the decades, this category provides better information about age-at-death determination because it is not heavily populated with younger or older individuals which are a primary source of problems with age determination. Of the 335 individuals with interval age classification, 62 skeletons have a chronological age within the interval of the estimated biological age-at-death. Ninety-seven skeletons were 1-5 years and 52 had were 6-10 years of the maximum interval.

One hundred and twenty-four skeletons were greater than 10 years from the maximum interval.

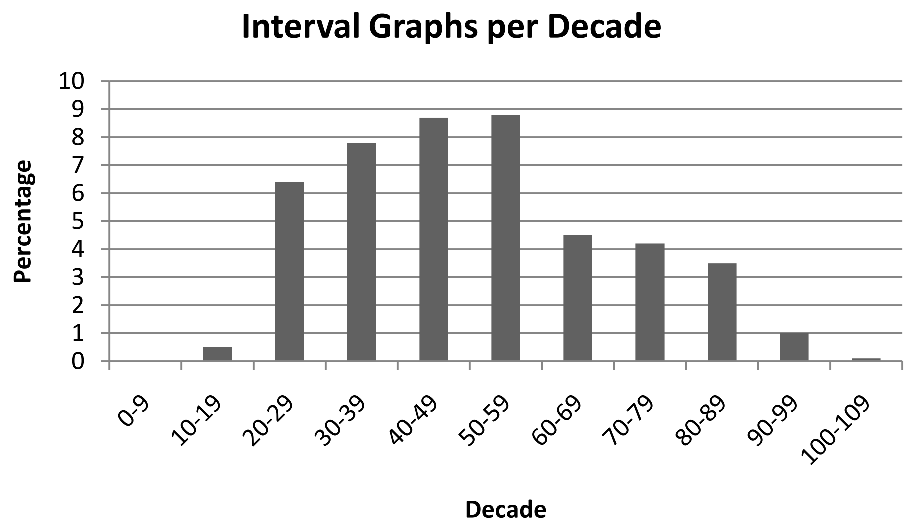
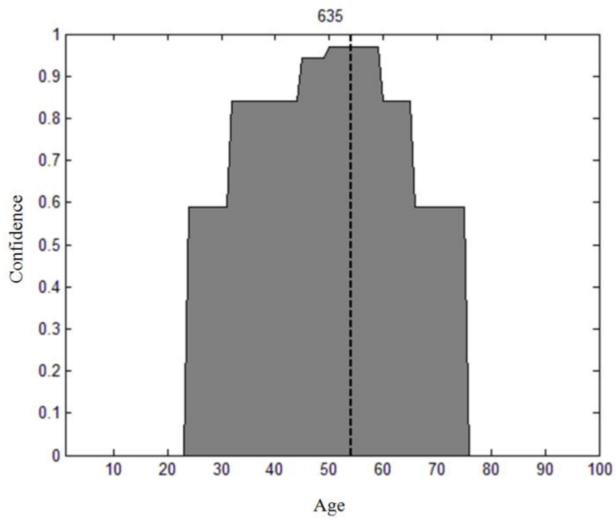


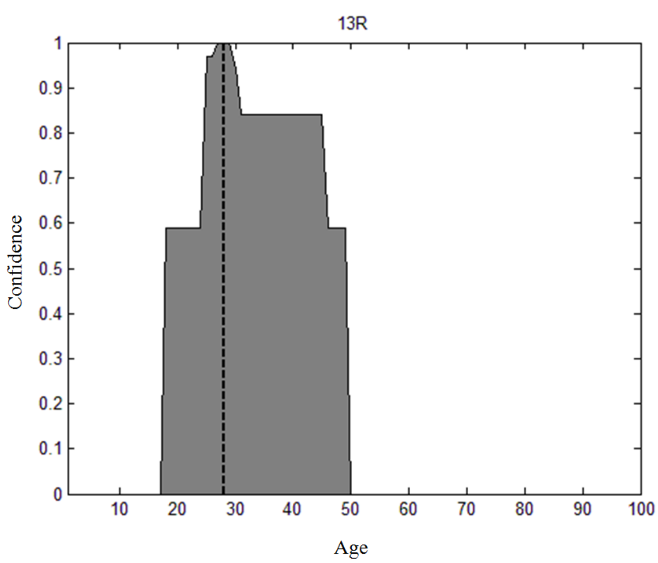
Figure 4-6. Percentage of skeletons labeled as “interval” for each decade, compared to the entire data set.

The following three graphs were selected to demonstrate skeletons classified as interval. For each case the skeleton identification, chronological age, sex, Sugeno integral age range, and the aging method inputs are provided.



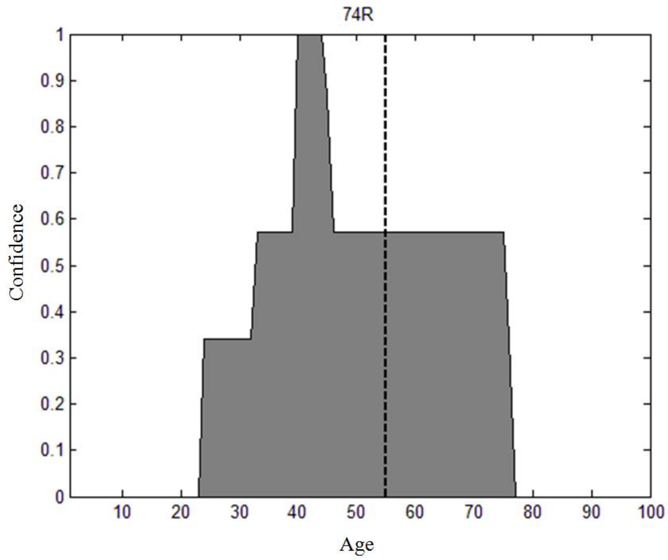
Skeleton	635
Chronological Age	54 yrs
Sex	Male
Sugeno Age Range	50-59 yrs
Pubic Symphysis	45-49 yrs
Auricular Surface	50-59 yrs
Ectocranial Suture – Vault	24-75 yrs
Ectocranial Suture - Lateral-Anterior	32-65 yrs

Figure 4-7. Graph of Sugeno integral age range for Terry Skeleton 635 illustrating an "interval" type graph. The dashed line in the graph indicates the chronological age and the intervals in the table represent input of age range for each of the aging methods.



Skeleton	13R
Chronological Age	28 yrs
Sex	Male
Sugeno Age Range	27-29 yrs
Pubic Symphysis	27-30 yrs
Auricular Surface	25-29 yrs
Ectocranial Suture – Vault	18-45 yrs
Ectocranial Suture - Lateral-Anterior	25-49 yrs

Figure 4-8. Graph of Sugeno integral age range for Terry Skeleton 13R illustrating an "interval" type graph. The dashed line in the graph indicates the chronological age and the intervals in the table represent input of age range for each of the aging methods.



Skeleton	74R
Chronological Age	55 yrs
Sex	Female
Sugeno Age Range	40-44 yrs
Pubic Symphysis	40-45 yrs
Auricular Surface	40-44 yrs
Ectocranial Suture – Vault	24-75 yrs
Ectocranial Suture - Lateral-Anterior	33-76 yrs

Figure 4-9. Graph of Sugeno integral age range for Terry Skeleton 74R illustrating an "interval" type graph. The dashed line in the graph indicates the chronological age and the intervals in the table represent input of age range for each of the aging methods.

As can be seen from skeleton 13R (Figure 4-8), the age indicators with larger accuracies are the age ranges that are more likely to be included in the final analysis of the graph. In graph 13R, for example, the Sugeno integral age range is 27-29. The pubic symphysis is found to be 27-30, auricular surface age range is 25-29, and the ectocranial sutures are 18-45 and 25-49. With the auricular surface and ectocranial sutures having the largest accuracies, the age range with the largest confidence includes their limits.

Reconsideration Graph Type

The number of graphs classified as reconsideration is 330. Of that, 65 had the chronological age fall in the maximum interval with the highest confidence. There are 150 females and 180 males in this category. The chronological age per decade and sex distribution can be seen in Table 4-10. Again, three skeletons of this type were chosen and are demonstrated below. The second maximum interval is provided as well because there is more than one interval for the graph.

Table 4-10. Reconsideration breakdown of chronological age and sex.

Reconsideration per Decade	Female	Male	Total
0-9	0	0	0
10-19	0	0	0
20-29	22	21	43
30-39	26	38	64
40-49	33	33	66
50-59	19	41	60
60-69	26	28	54
70-79	10	11	21
80-89	10	7	17
90-99	4	1	5
100-109	0	0	0
Total	150	180	330

For the distribution per decade, the range is from 20-99 with the largest group being 40-49 making up 9 % of the data. Figure 4-10 gives the distribution per decade for reconsideration graph types. Due to inaccuracies increasing with older individuals, the large percentage of older individuals in this graph classification could provide some explanation as to why there are conflicting aging methods and why this graph category is populated more than desired. Of the 330 individuals with reconsideration as a classification, 114 skeletons fell within the two maximum intervals and 54 skeletons have an estimated biological age within 1-5 years of the chronological age-at-death. Sixty-four skeletons were within 6-10 years and 98 had a difference that was greater than 10 years.

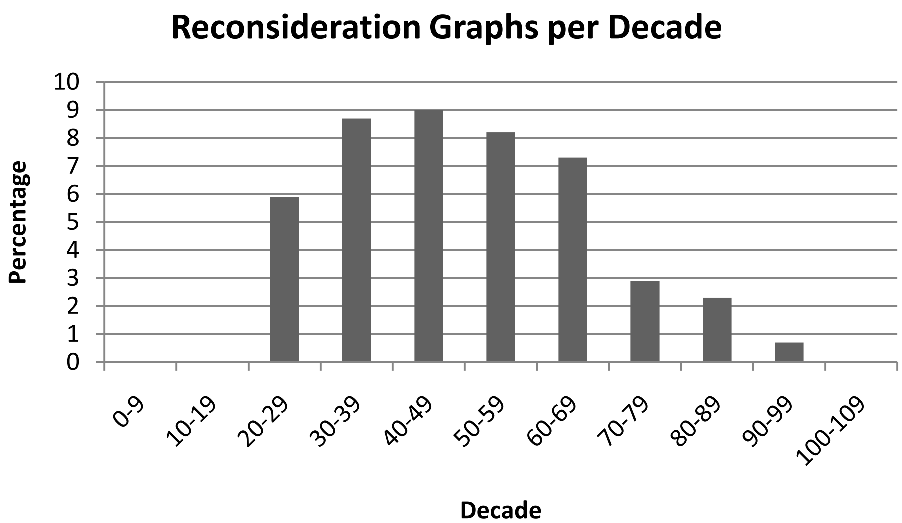
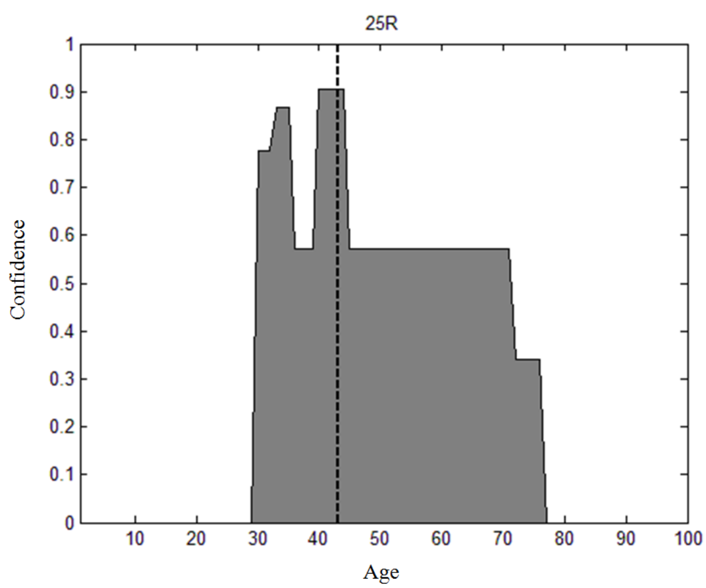
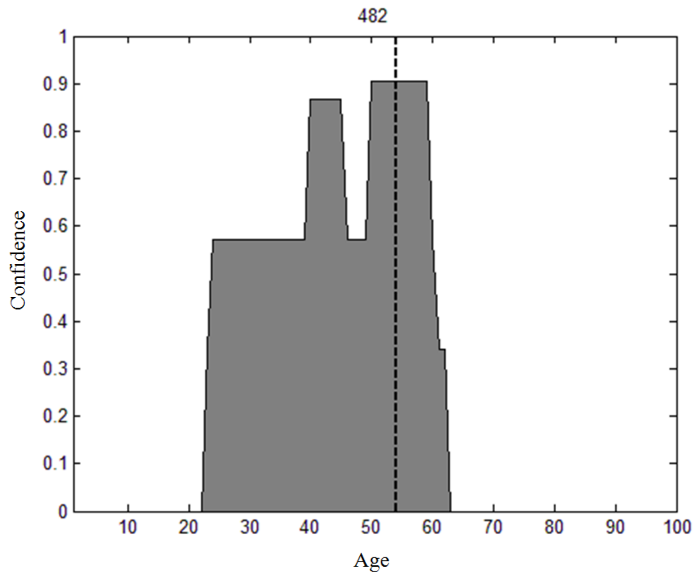


Figure 4-10. Percentage of skeletons labeled as “reconsideration” for each decade, compared to the entire data set.



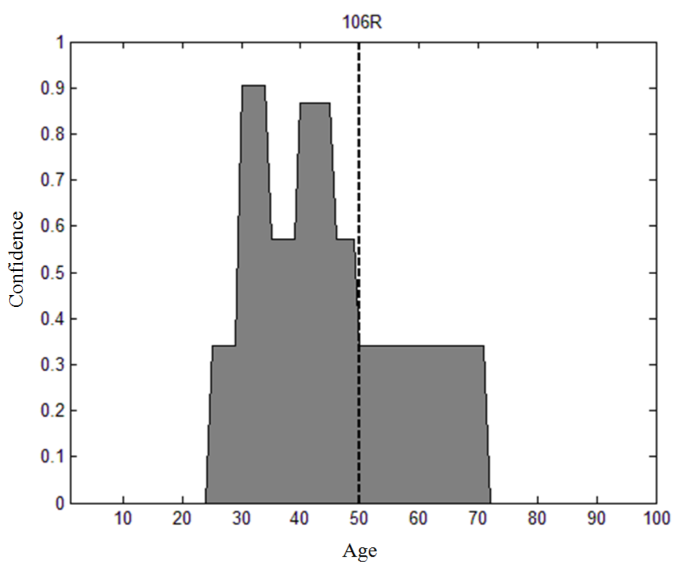
Skeleton	25R
Chronological Age	43 yrs
Sex	Female
Sugeno Age Range 1	40-44 yrs
Sugeno Age Range 2	33-35 yrs
Pubic Symphysis	30-35 yrs
Auricular Surface	40-44 yrs
Ectocranial Suture - Vault	30-71 yrs
Ectocranial Suture - Lateral-Anterior	33-76 yrs

Figure 4-11. Graph of Sugeno integral age ranges for Terry Skeleton 25R illustrating a “reconsideration” type graph. The line in the graph indicates the chronological age, while the two peaks indicate age range 1 and 2. The intervals in the table represent input of age range for each of the aging methods.



Skeleton	482
Chronological Age	54 yrs
Sex	Female
Sugeno Age Range 1	50-59 yrs
Sugeno Age Range 2	40-45 yrs
Pubic Symphysis	40-45 yrs
Auricular Surface	50-59 yrs
Ectocranial Suture - Vault	24-60 yrs
Ectocranial Suture - Lateral-Anterior	23-63 yrs

Figure 4-12. Graph of Sugeno integral age ranges for Terry Skeleton 482 illustrating a "reconsideration" type graph. The line in the graph indicates the chronological age, while the two peaks indicate age range 1 and 2. The intervals in the table represent input of age range for each of the aging methods.



Skeleton	106R
Chronological Age	50 yrs
Sex	Female
Sugeno Age Range 1	30-34 yrs
Sugeno Age Range 2	40-45 yrs
Pubic Symphysis	40-45 yrs
Auricular Surface	30-34 yrs
Ectocranial Suture – Vault	30-71 yrs
Ectocranial Suture - Lateral-Anterior	25-49 yrs

Figure 4-13. Graph of Sugeno integral age ranges for Terry Skeleton 106R illustrating a "reconsideration" type graph. The line in the graph indicates the chronological age, while the two peaks indicate age range 1 and 2. The intervals in the table represent input of age range for each of the aging methods.

This graph type contains the second largest number of skeletons with 330. Due to the conflicting information from the age indicators and the limited number of age indicators, this quantity is what might be expected. When all of the aging methods do not overlap, but there is some agreement between pairs of them, this creates two different agreements with a high confidence. In the case of skeleton 482 (Figure 4-12), there is disagreement between the two indicators with the largest accuracies, the pubic symphysis and auricular surface. This results in two age intervals for the skeleton. This is the trend for the reconsideration graph types.

Inconclusive Graph Type

There are 7 skeletons, 1%, classified as type inconclusive (Figure 4-14). Six are female and one is male. Three of these results have the chronological age fall in the maximum interval. The chronological age per decade and sex distribution can be seen in Table 4-11. Three skeletons of this type are displayed after Table 4-11.

Table 4-11. Inconclusive breakdown of chronological age and sex.

Inconclusive per Decade	Female	Male	Total
0-9	0	0	0
10-19	0	0	0
20-29	0	0	0
30-39	0	1	1
40-49	0	0	0
50-59	3	0	3
60-69	0	0	0
70-79	0	0	0
80-89	3	0	3
90-99	0	0	0
100-109	0	0	0
Total	6	1	7

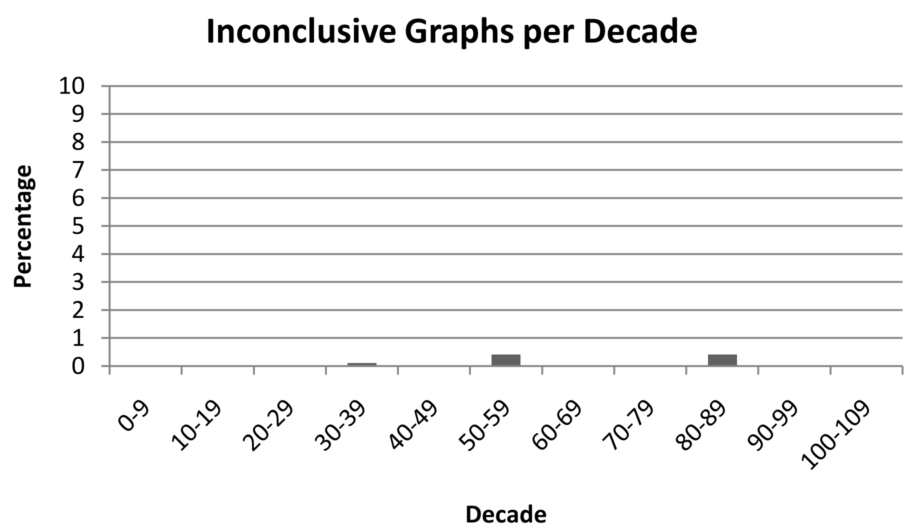
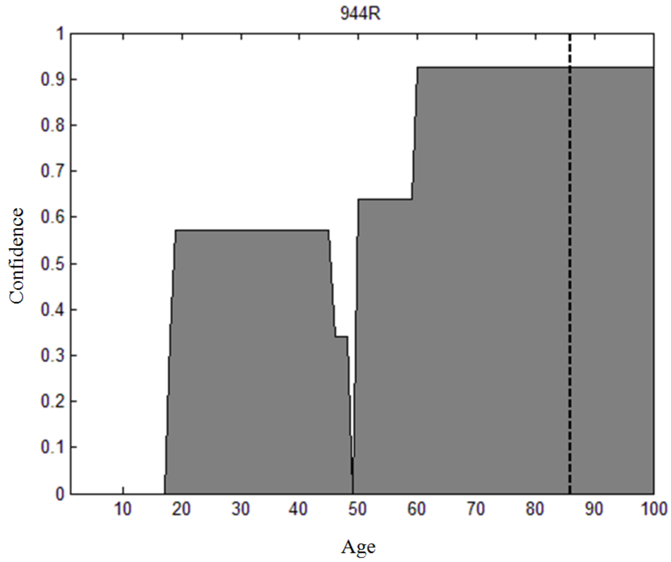
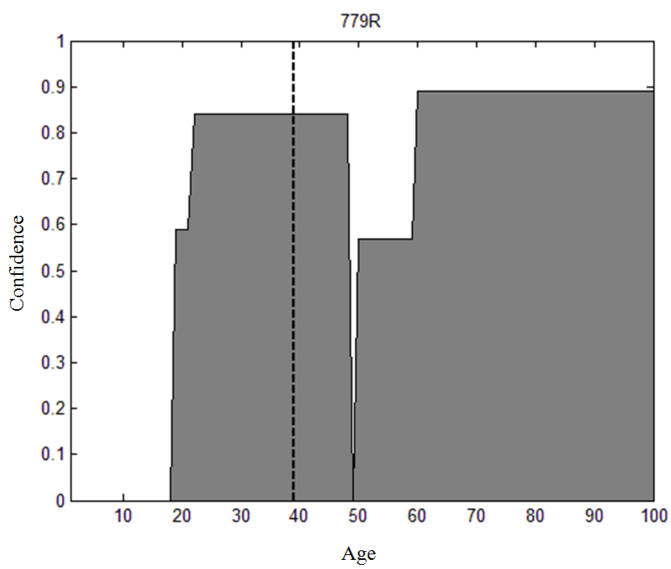


Figure 4-14. Percentage of skeletons labeled as "inconclusive" for each decade, compared to the entire data set.



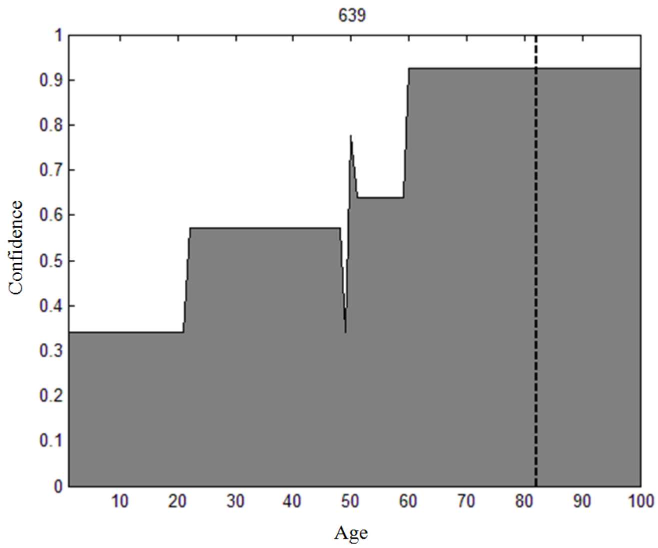
Skeleton	944R
Chronological Age	86 yrs
Sex	Female
Sugeno Age Range 1	60-100 yrs
Sugeno Age Range 2	50-59 yrs
Pubic Symphysis	40-45 yrs
Auricular Surface	60+ yrs
Ectocranial Suture – Vault	24-75 yrs
Ectocranial Suture - Lateral-Anterior	23-68 yrs

Figure 4-15. Graph of Sugeno integral age ranges for Terry Skeleton 944R illustrating an “inconclusive” type graph. The dashed line in the graph indicates the chronological age, while the two peaks show age range 1 and 2. The intervals in the table represent input of age range for each of the aging methods.



Skeleton	779R
Chronological Age	39 yrs
Sex	Male
Sugeno Age Range 1	60-100 yrs
Sugeno Age Range 2	22-48 yrs
Pubic Symphysis	50+ yrs
Auricular Surface	60+ yrs
Ectocranial Suture – Vault	22-48 yrs
Ectocranial Suture - Lateral-Anterior	19-48 yrs

Figure 4-16. Graph of Sugeno integral age ranges for Terry Skeleton 779R illustrating an “inconclusive” type graph. The dashed line in the graph indicates the chronological age, while the two peaks show age range 1 and 2. The intervals in the table represent input of age range for each of the aging methods.



Skeleton	639
Chronological Age	82 yrs
Sex	Female
Sugeno Age Range 1	60-100 yrs
Sugeno Age Range 2	50 yrs
Pubic Symphysis	50+ yrs
Auricular Surface	60+ yrs
Ectocranial Suture – Vault	22-48 yrs
Ectocranial Suture - Lateral-Anterior	< 50 yrs

Figure 4-17. Graph of Sugeno integral age ranges for Terry Skeleton 639 illustrating an "inconclusive" type graph. The dashed line in the graph indicates the chronological age, while the two peaks show age range 1 and 2. The intervals in the table represent input of age range for each of the aging methods.

There were only seven inconclusive graph types. This is encouraging because that indicates that most of the data is in agreement in some form. Of the seven inconsideration cases, three fell within the maximum interval where one skeleton has an estimated biological age within 1-5 years of the chronological age-at-death. Two skeletons were within 6-10 years and one had a difference that was greater than 10 years.

Six of the seven graphs are skeletons whose chronological age is 50+. Being classified as this type of graph at an older age could be attributed to the greater degree of inaccuracy of the aging methods with older individuals (Klepinger 2006). The individual skeleton that was 39, skeleton 779R (Figure 4-16) as shown in the previous section has a pubic symphysis as 50+ and auricular surface as 60+. However, because it is a male, the accuracy for the ectocranial sutures is higher, 0.59. This is larger than the accuracy for the pubic symphysis, which for a male is 0.57. Due to the great discrepancy among the aging methods and large age ranges, the methods do not agree with a large degree of confidence. Therefore, the result is classified as inconclusive. The other skeletons follow the same trend for this graph classification. The older the individual is according to the aging methods, the less accurate they become, such as the pubic symphysis classifying as 50+ and auricular surface as 60+. This will create a large interval and lead to an inconclusive classification.

Hypothetical Cases

Due to the limited amount of information collected from the Terry Collection, the range of the Sugeno integral cannot be fully understood for different situations of age-at-death determination of a skeleton. Since the data collected did not contain information for more than three age indicators nor varying skeletal quality, the following hypothetical scenarios are provided to demonstrate the cases that are not present in the collected data. The scenarios are (1) a skeleton with all methods in agreement on a specific age with a quality of 1.0, (2) the same example with varying qualities, (3) two skeletons from the existing data set with varying qualities, and (4) a skeleton with disagreement among all of the aging methods. These cases demonstrate the range of the Sugeno integral for this specific problem of determining skeletal age-at-death. The results from the hypothetical data are what were anticipated. Table 4-12 gives a list of the aging methods with their accuracy indices (correlation coefficients) that will be used for the hypothetical scenarios.

Table 4-12. A list of the seven aging methods with their accuracy indices according to sex.

Aging Method	Accuracy Index		
	Male	Female	Both Sexes
Pubic Symphysis	0.57	0.64	-
Auricular Surface	-	-	0.74
Ectocranial Sutures	0.59	0.34	-
Sternal Rib Ends[1]	-	-	0.75
Endocranial Sutures	0.35	0.51	-
Proximal Humerus	0.34	0.44	-
Proximal Femur	0.58	0.56	-

[1] (Dudar 1993)

Case 1: A male with a chronological age of 38 with a quality of 1.0 with eight aging methods (Table 4-13) used to determine age-at-death.

Table 4-13. Aging methods used for hypothetical case 1 and their corresponding age ranges used.

Aging Method	Age Range
Pubic Symphysis	35-39
Auricular Surface	35-39
Ectocranial Sutures - vault	24-75
Ectocranial Sutures- lateral	23-63
Sternal Rib Ends	33-42
Endocranial Sutures	35-39
Proximal Humerus	37-86
Proximal Femur	25-76

Figure 4-18. Result of hypothetical case 1. The dashed line indicates chronological age and the peak indicates the maximum Sugeno age range. Resulting maximum interval is 37-39.

For hypothetical case 1, the chronological age is 38 and all of the methods are in agreement with a skeletal quality of 1.0. This produces an interval, which includes the chronological age that clearly can be seen from the resulting graph (Figure 4-18). The age range with the highest confidence is 37-39. This case represents the best possible scenario due to the skeleton being of the highest quality and all of the methods being in agreement. The results produce an age range that includes the age-at-death.

Case 2: Same aging methods and age ranges as case I (Table 4-13) except it includes varying qualities, given in Table 4-14.

Table 4-14. Aging methods used for case 2 with their corresponding qualities.

Aging Method	Quality
Pubic Symphysis	0.6
Auricular Surface	0.8
Ectocranial Sutures	0.2
Sternal Rib Ends	0.5
Endocranial Sutures	0.4
Proximal Humerus	0.3
Proximal Femur	0.7

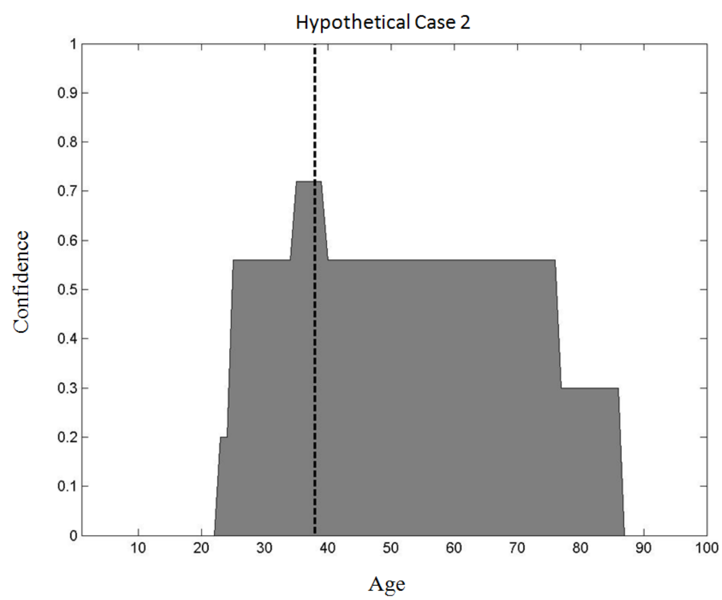


Figure 4-19. Result of hypothetical case 2. The dashed line indicates chronological age and the peak is the maximum Sugeno integral age range. Resulting maximum interval is 35-39.

Hypothetical case 2 has the same input as case 1, but the qualities are varied. The qualities were chosen at random. The interval 35-39 has the highest confidence (Figure 4-19). This still contains the 37-39 interval from case 1, however the age range is less precise now. The age-at-death of the skeleton can still be determined although the skeletal quality is low for certain age indicators.

Case 3: This case uses existing data from skeletons 208 (Figure 4-3) and 13R (Figure 4-8) with varying qualities (Table 4-15). A review of the data for skeletons 208 and 13R is shown in Figure 4-20.

Skeleton	208
Chronological Age	30 yrs
Sex	Female
Sugeno Age Range	30 yrs
Pubic Symphysis	27-30 yrs
Auricular Surface	30-34 yrs
Ectocranial Suture – Vault	24-60 yrs
Ectocranial Suture - Lateral-Anterior	< 50 yrs

Skeleton	13R
Chronological Age	28 yrs
Sex	Male
Sugeno Age Range	27-29 yrs
Pubic Symphysis	27-30 yrs
Auricular Surface	25-29 yrs
Ectocranial Suture – Vault	18-45 yrs
Ectocranial Suture - Lateral-Anterior	25-49 yrs

Figure 4-20. Data for Terry skeleton 208 and 13R.

Table 4-15. Quality indices for each aging method in hypothetical case 3.

Aging Method	Quality
Pubic Symphysis	0.6
Auricular Surface	0.4
Ectocranial Sutures	0.8

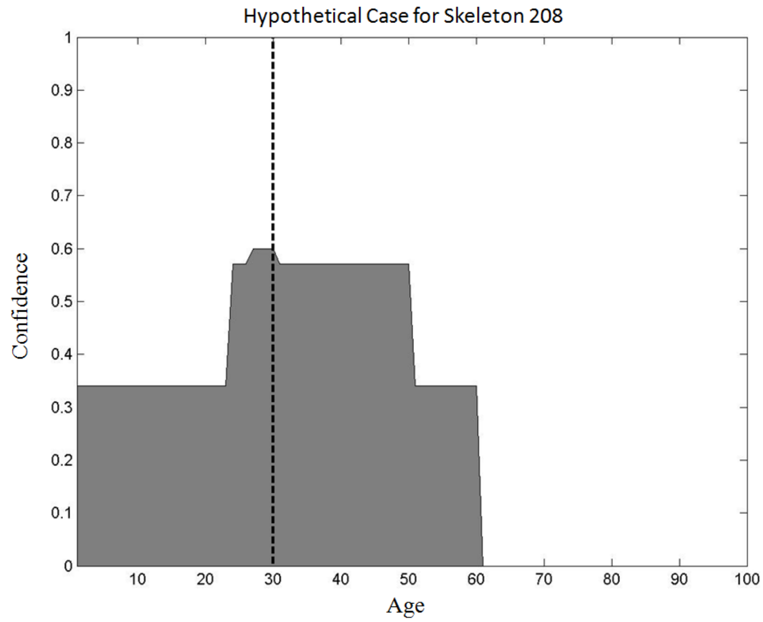


Figure 4-21. Result of hypothetical case 3 for Terry skeleton 208. The dashed line indicates chronological age. Sugeno age range is indicated by the peak on the graph. Resulting maximum interval for 208 is 27-30

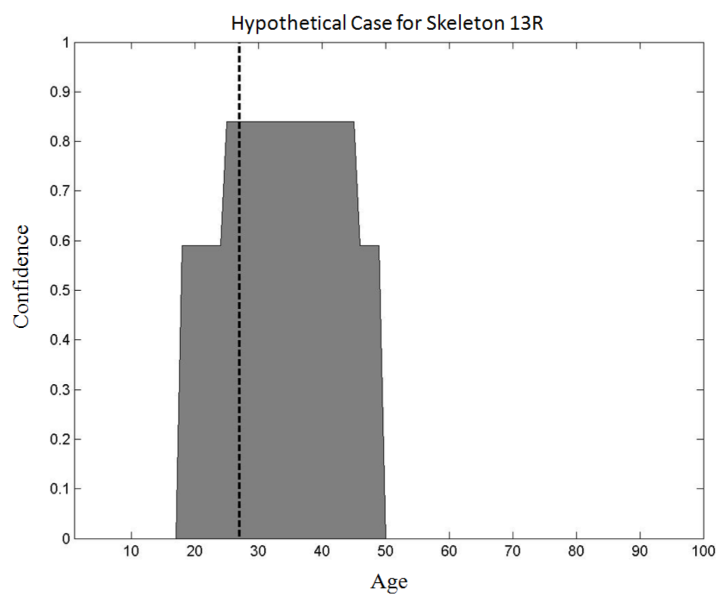


Figure 4-22. Result of hypothetical case 3 for Terry skeleton 13R. The dashed line indicates chronological age and Sugeno age range is demonstrated by the peak. Resulting maximum interval for 13R is 25-45.

Existing data from Terry Collection skeletons 208 and 13R are used in hypothetical case 3, but the qualities are changed. Again, these quantities are chosen at random. The chronological age for skeleton 208 is 30. The age range found by the Sugeno integral is 27-30. Although skeleton 208 is classified as a specific age graph with a quality of 1.0, the different qualities produced an interval age that still includes the chronological age (Figure 4-21). For skeleton 13R, the chronological age is 28. This graph, with the original data, is classified as an interval graph type with a Sugeno age range of 27-29. Changing the qualities changed the results of this graph (Figure 4-22). The new age range is 25-45. This shows that the quality input can have an impact on the result of the age-at-death analysis. With the quality not being a 1.0, the quality or this part of the *h* value is demonstrated here to be an important factor for age-at-death determination.

Case 4: No Terry collection data is used for this case. It is a female with a chronological age 27 and a quality of 1.0. All methods are not in agreement (Table 4-16).

Table 4-16. Aging methods used for hypothetical case 4 with corresponding age ranges.

Aging Method	Age Range
Pubic Symphysis	22-24
Auricular Surface	25-29
Ectocranial Sutures - vault	24-75
Ectocranial Sutures- lateral	32-65
Sternal Rib Ends	33-36
Endocranial Sutures	55-59
Proximal Humerus	38-48
Proximal Femur	18-45

Figure 4-23. Result of hypothetical case 4. The dashed line indicates chronological age. Multiple peaks are the Sugeno age ranges.

Hypothetical case 4 provides an example of a skeleton with a 1.0 quality where all of the methods are not in agreement with each other. As can be seen from the graph produced (Figure 4-23), there are too many intervals created to make a conclusion about age-at-death. By setting the quality at a 1.0, the importance of the accuracies of the age indicators can be seen. The methods with the greatest accuracies have the largest impact, such as the sternal rib ends with an accuracy of 0.75 producing the largest confident interval of 33-36. There is some overlap among the age indicators, but they do not agree overall. This is an extreme example, but it demonstrates a case of the inconclusive graph type. When this occurs, it is an indication to the observer that the data needs to be reanalyzed or something is not "typical" about the skeleton.

Under and Over Estimation of Age-at-Death

The results of the Sugeno integral can only be as good as the information provided by the skeleton and the observer. Since the aging methods are not as accurate as chronological age increases, it will be difficult to improve on this aspect of aging. Aging younger individuals also poses a problem. There is a tendency to overestimate the age of young individuals and underestimate the age of older individuals (Klepinger 2006). Overestimation of a young adult is not difficult because underestimation would place them in the age class of a child. Underestimation of older individuals is due to the aging methods not able to be developed for their age classes due to low samples in the collections.

Over aging and under aging individuals is apparent in the results. Under aging is where skeletal age-at-death or biological age is younger than the chronological age. This tends to happen to older individuals. When the chronological age is older than the biological age, then this is over aging and usually happens to younger individuals. Over and under aging is measured here by where the chronological age falls in relation to the interval. If the interval comes after the chronological age, then this is determined to be over aging. This classification is only used when chronological age does not fall in the maximum interval. When chronological age comes after the interval, this is under aging. Of the four graph types, only specific age, interval and reconsideration can be used to measure under and over aging. Inconclusive is not used because there are no specific intervals to use for this measurement. Figure 4-24 demonstrates the under and over age estimation distributions for the three graph types.

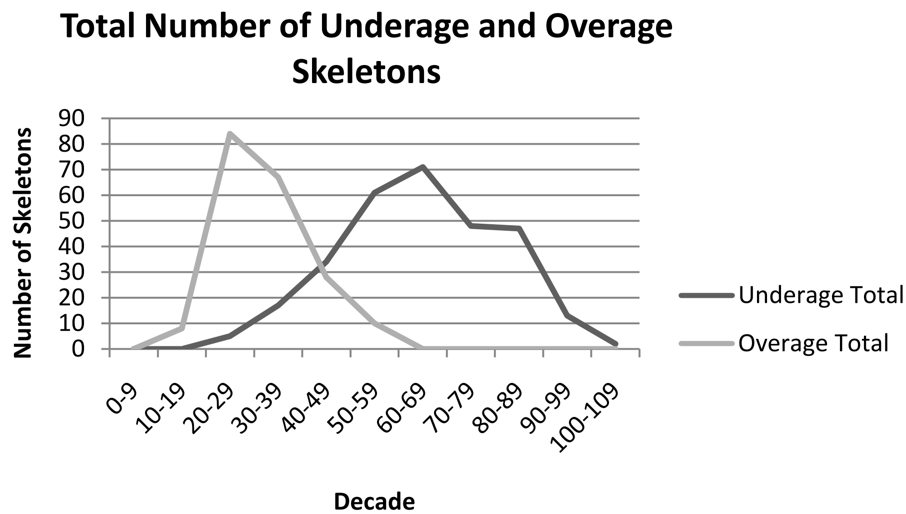


Figure 4-24. Total number of under and over aged skeletons.

Table 4-17. Under aged per decade for each graph type.

Decade	Specific Age Graphs	Interval Graphs	Reconsideration Graphs	Total
0-9	0	0	0	0
10-19	0	0	0	0
20-29	0	5	0	5
30-39	8	8	1	17
40-49	4	27	3	34
50-59	10	39	12	61
60-69	4	29	38	71
70-79	2	31	15	48
80-89	4	26	17	47
90-99	1	7	5	13
100-109	1	1	0	2
Total	34	173	91	298

Table 4-18. Over aged per decade for each graph type.

Decade	Specific Age Graphs	Interval Graphs	Reconsideration Graphs	Total
0-9	0	0	0	0
10-19	1	7	0	8
20-29	19	32	33	84
30-39	6	36	25	67
40-49	0	20	8	28
50-59	1	8	1	10
60-69	0	0	0	0
70-79	0	0	0	0
80-89	0	0	0	0
90-99	0	0	0	0
100-109	0	0	0	0
Total	27	103	67	197

For specific age graphs, 34 of the graphs were under aged, meaning that the chronological age fell after the Sugeno integral determined biological age. Of those, shown in Table 4-17, the majority of the chronological ages fell between 30-59 (22 individuals). Fifty-three percent of the graphs are classified as under age. The majority of the skeletons that were over aged were between 20-39. There was only one skeleton over aged after 40 years. Thus, the younger individuals for this graph type were aged older than their chronological age. Forty-two percent of the graphs are classified as over age. The large percentage of over and under aging is understandable because there is a very small interval (1) for the graph to be classified as the correct age. Therefore, the majority of the graphs will be over age or under age. As demonstrated by the accuracy of the age indicators, the older individuals were estimated as under age and older individuals were over age.

As for under aging and over aging for interval graphs, 51% of the individuals for this graph type are under aged and 31% of the individuals are over aged. For under aged skeletons, the majority of them fall between 40 and 89 (152 individuals). This shows that the majority of the under aged individuals are older. The majority of the over aged individuals fall between 20-49 (88 individuals), which demonstrates that younger individuals are being over aged. As can be seen from the under age and over age distributions, the aging methods do have a tendency to under age the older individuals and over age the younger individuals.

For reconsideration graphs, 28% are under aged and 20% are over aged. The age ranges for the majority of the under aged individuals is 50-89, consisting of 82 individuals. For over aged individuals, the majority of the individuals fall between 20-49 and contain 66 individuals. As with the other graph types, this demonstrates the under aging of older individuals and over aging of the younger individuals.

CHAPTER 5: DISCUSSION

Given the difficulty of accurate age-at-death analysis for an individual skeleton, such as the inaccuracies and discrepancies observed among the various aging methods, the results found by using the Sugeno integral are encouraging. The Sugeno integral produces results that are used to answer inquiries such as: what is the most confident age-at-death estimation, what is the most confident age interval, and what type of age-at-death graph is this skeleton based on a pre-defined set of user specified graph types? Due to the limited amount of information gathered from the Terry collection (only three aging methods all with a quality of 1.0), the results are not far from what would be expected when looking at the overlap from the input age ranges from each aging method. The most common discrepancy among the graphs can be attributed to the three methods not finding the same age within 10 years of each other. Lastly, the hypothetical scenarios demonstrate the range of the Sugeno integral by using additional age indicators and their accuracies and ranging qualities.

The results reinforce the already known notion that inaccuracies are present in the age indicators to determine age-at-death of a skeleton. Not every age-at-death will be reached with any amount of information due to the inherent flaws in the aging methods, such as over aging younger individuals and under aging older individuals. In general, the classifications of the graphs are encouraging. There are very few inconclusive, with the majority of the graphs being classified as interval. This is promising due to the fact that the inputs of the aging methods are in the form of age ranges/intervals.

As for the other multifactorial methods used to analyze skeletal age-at-death, they do not take into consideration as much information as the Sugeno integral. The complex method, summary age, and transition analysis multifactorial methods are not directly applicable as a comparison to the Sugeno integral results produced here. They are based on populations, which is not the way that the Sugeno integral is being used for this data. The Sugeno integral also incorporates more information than the other methods. It takes into account the variable accuracies associated with each method, along with the weathering or quality of the skeletal element. The goal is not to model a population to produce likelihood estimates, rather to produce results that can be used to assess the age of an individual skeleton without using any knowledge about the population that it came from. The fuzzy integral is type of non-linear tendency assessment. The integral will be between the minimum and maximum of the *h* values. As discussed in the background section, the summary age technique is a weighted average. The contribution of the summary age technique is an intercorrelation matrix found from a skeletal population, which is used for discovering the weights. A future extension of the Sugeno integral to skeletal age-at-death estimation could be the incorporation of these weights if a population is present. Transition analysis uses population distributions, which might also be able to be incorporated into a Sugeno integral approach.

For all fields that use skeletal age assessment, there are different approaches that can be taken with the Sugeno integral. One option involves incorporating the confidence in the observer, in place of the accuracy of the aging methods. Instead of assigning a quality to the skeleton, as done here, if there are multiple observers, a confidence in their expertise could be assigned. For example, a student learning to determine skeletal age would be assigned a lower value than her instructor or multiple experts could be assigned different confidences depending on their respective amount of time and experience applying the aging methods. This would allow for the modeling of multiple perspectives among experts in the Sugeno Integral and could be a first step towards the topic of further analyzing interobserver error.

Another addition is to further analyze the accuracy value for the aging methods, because there are multiple correlation coefficients associated with the aging methods due to different population samples being analyzed and different observers and researchers. Another way to vary the parameters is to fuzzify the age indicator inputs themselves, rather than assigning values to the individual ages within an age range. For example, the researcher indicates how confident she is that the chronological age is in the age interval. The age indicator could indicate that the age range is 30-45, but the researcher believes, due to experience or skeletal markers, that the age-at-death is more likely towards the end of the interval, say 40-45. Therefore, the researcher could place a larger confidence for 40-45 than for 30-39 for this specific age indicator.

A last idea related to varying the Sugeno Integral inputs is to fuzzify the age indicator intervals. Currently, each age indicator specifies an age interval, such as 30-45, and the skeleton is believed to, at least as it relates to the modeling of, equally come from any age within this interval. A crisp cutoff point, such as the ages 30 and 45, is not realistic. Fuzzy sets could be used to model the confidence that an individual died at a specific age within the interval. The fuzzy sets could be specified by the researcher so that confidence drops around the boundary points, hence fuzzifying the boundary conditions, or population information could be gathered and used to formulate a fuzzy set that specifies the confidence of age-at-death across the age interval. This would change the current {0,1} age test component of the h value to a real valued [0,1] number.

Beyond these variations in applying the Sugeno Integral, there are more domain specific advantages that the results provide. The graphical results produced by the Sugeno integral can be a valuable resource, especially for forensic anthropologists testifying in court cases. Expert witnesses, such as forensic anthropologists, need to make sure that the techniques they are using have been subject to peer review and publications (*Daubert v. Merrell Dow Pharmaceuticals* No. 92-102 509 US 579, 1993). Anthropologists will present their results or opinions to the court if the judge rules the information admissible. Providing graphical results to a court, such as the one produced by the Sugeno integral, could provide a clearer understanding of age-at-death determination and how the expert reached a decision. A potential contribution is in the areas of paleodemography and bioarchaeology for the reconstruction of past populations. The objective for future work would be discovering ways to model and include information such as mortality, fertility, age-at-death distributions, and/or prior distributions in the Sugeno integral.

As Ubelaker (2000) describes, the "scientific progress in the estimation of age at death involves greater awareness of the variation involved, new techniques available for different structures, and greater appreciation of the importance of regional and temporal variation in the aging process". The Sugeno integral provides the initial framework to take into account the various and varying processes involved with skeletal age-at-death analysis.

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