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Estimation of Skeletal Age-at-Death from Dental Root Translucency

Debra A. Prince
University of Tennessee - Knoxville

To the Graduate Council:

I am submitting herewith a dissertation written by Debra A. Prince entitled "Estimation of Skeletal Age-at-Death from Dental Root Translucency." I have examined the final electronic copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Anthropology.

Lyle W. Konigsberg, Major Professor

We have read this dissertation and recommend its acceptance:

Richard L. Jantz, Andrew Kramer, Murray K. Marks, David Etnier

Accepted for the Council:
Dixie L. Thompson

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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Vice Chancellor and Dean of
Graduate Studies

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ESTIMATION OF SKELETAL AGE-AT-DEATH FROM DENTAL ROOT TRANSLUCENCY

A Dissertation
Presented for the
Doctor of Philosophy
Degree
The University of Tennessee, Knoxville

Debra A. Prince
August 2004

DEDICATION

This dissertation is dedicated to my parents, Richard and Janet Prince and my grandmother, A. Betty Nedwick, for always encouraging me to pursue my dreams and inspiring me to achieve my goals.

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Many individuals were instrumental in this research. I would like to thank my committee members, Drs. Richard L. Jantz, Andrew Kramer, Murray K. Marks and David Etnier for their valuable feedback, not only in preparation of this research, but for insight, knowledge, and clarification over the past several years. I would especially like to thank Dr. Lyle W. Konigsberg, my chair, for encouraging me to pursue this field of research and for all of his countless hours of assistance with statistical applications and review of previous drafts. He has been an integral part of the success of this research and I will leave Tennessee a better researcher, teacher, and anthropologist because of his dedication. I hope my incessant badgering for information did not make him cringe when my face appeared in his doorway or when he heard my voice on the phone. He endured countless e-mails, phone calls and questions, for which I extend my gratitude. I would also like to thank Drs. Darryl Holman and Rick Paine for allowing me to bend their ears for several days straight while we were abroad. They offered much encouragement and advice on the completion of this research, for which I am grateful.

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ABSTRACT

Estimating the biological profile for an unknown individual is a crucial part of forensic anthropology, bioarchaeology and paleodemography. The current research deals with one aspect of the biological profile: estimation of skeletal age-at-death. Several methods are available to estimate skeletal age-at-death, but most involve placing a skeletal element into a phase category. This type of phase-oriented age estimation, in addition to improper statistical methodology, leads to several problems: 1) observer subjectivity; 2) large age ranges and open-ended intervals; 3) stages that overlap one another; 4) aging bias; 5) age mimicry; and 6) taphonomic problems. Solutions to these methodological and statistical problems were offered by utilizing two dental metric features, translucency of the root and periodontal recession, and applying appropriate statistical analysis. Three skeletal collections, The Robert J. Terry Anatomical Collection, The Baraybar Forensic Biosample Collection, and the Lauchheim Medieval Cemetery Collection, dental remains were analyzed. Single-rooted teeth were analyzed following Lamendin *et al*'s (1992) method. The data were analyzed in the *R* statistical package using Bayesian analysis and inverse calibration. Age-at-death estimates for the Baraybar sample were generated by two inverse calibration methods and Bayesian analysis. The three age estimates were compared to highlight inherent problems with the inverse calibration methods.

The results showed that the Bayesian analysis reduced severity of several of the problems associated with adult skeletal age-at-death estimations. The Bayesian age-at-death estimates produced a lower overall mean error and higher correlation with actual age as compared to the inverse calibration methods for the Baraybar Forensic Biosample

Collection. In addition, the Bayesian approach reduced aging bias, age mimicry, and the age ranges associated with the most probable age. The Baraybar Forensic Biosample Collection was used as a reference sample for the Lauchheim sample. Age-at-death estimates were also generated for this sample employing the two inverse calibration methods and Bayesian analysis.

This research lead to the conclusions that periodontal recession cannot be used as a univariate age indicator, due to its low correlation with chronological age. On the contrary, apical translucency yielded a high correlation with chronological age and was concluded to be an important age indicator. The Bayesian approach offered the most appropriate statistical analysis for the estimation of age-at-death with the current samples.

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CHAPTER 1

INTRODUCTION

1.1 Problems with Adult Phase-Aging Methodology

Estimation of adult skeletal age-at-death is one of the most important identifying features for an unknown individual but also one of the most difficult to achieve. Age-at-death estimates are vexing because they try to correlate physiological age and chronological age in a system that has differential development and deterioration. Variation in development and deterioration of the skeletal system differs among individuals as well as across populations and between the sexes (Hanihara 1952, Biggerstaff 1977, Brooks 1955, Zhang 1982, Jackes 1985, Moore-Jansen and Jantz 1986, Ýþcan *et al.* 1987, Katz and Suchey 1986, Ubelaker 1989, Konigsberg and Frankenberg 1992, Molleson *et al.* 1993, Plato *et al.* 1994, Kemkes-Grottenthaler 1996, Jackes 2000, Boldsen *et al.* 2002, Hoppa and Vaupel 2002b, Kemkes-Grottenthaler 2002, Prince and Ubelaker 2002, Ross and Konigsberg 2002, Komer 2003, Šlaus *et al.* 2003). Differences can be attributed to socioeconomic status, cultural differences, genetic differences, differences in behavior, environmental factors, diet, and disease (Buckberry and Chamberlain 2002, Kemkes-Grottenthaler 2002).

Despite these issues, several methods are available to estimate adult skeletal age-at-death, but most are associated with wide margins of error and are usually derived from techniques that employ methods of assessing degenerative changes in the skeleton, such as changes in the pubic symphyseal face (Todd 1920, Todd 1921a, Todd 1921b, Brooks 1955, Nemeskéri *et al.* 1960, McKern and Stewart 1957, Gilbert 1973, Gilbert and

McKern 1973, Suchey 1979, Meindl *et al.*1985, Katz and Suchey 1986, Brooks and Suchey 1990), the sternal ends of ribs (Ýþcan *et al.* 1984a, 1984b, 1985, Ýþcan and Loth 1986, Ýþcan *et al.* 1987), the auricular surface of the os coxae (Lovejoy *et al.* 1985, Buckberry and Chamberlain 2002), cranial suture closure (Todd and Lyon 1924, Montagu 1938, Singer 1953, Brooks 1955, Meindl and Lovejoy 1985), dental attrition (Gustafson 1950, Murphy 1959, Miles 1962, Brothwell 1963, Molnar 1971, Helm and Prydso 1979, Scott 1979, Smith 1984a, Cross *et al.* 1986, Dreier 1994, Lovejoy 1985, Lovejoy *et al.* 1985, Dahl *et al.* 1989, Song and Jia 1989, Johansson *et al.* 1993, Kim *et al.* 1995, Li and Ji 1995, Ajmal *et al.* 2001, Ball 2002), radiology of the proximal femur and clavicle (Walker and Lovejoy 1985). With these types of methods, physical anthropologists must subjectively place a skeletal element into an ordinal phase category. In so doing, there are several problems which arise: 1) the subjectivity of the observer leads to problems with inter- and intra-observer error; 2) large age ranges are produced when these types of phase-aging methods are utilized, in some cases a range may cover most of adult age (Suchey-Brooks Phase V: 25-83 years) and in several phase oriented aging methods, the last phase is an open-ended interval, for example, 50+ (Todd phase 10); 3) stages often overlap one another; 4) bias in overestimating age in younger individuals while underestimating age in older individuals occurs quite frequently; 5) age mimicry occurs when appropriate reference samples are not utilized and thus increases error estimates; 6) preservation problems lead to missing data, and 7) improper theoretical and statistical methodology has often been used to derive age-at-death estimates.

The first of these issues, inter- and intra-observer error, has been addressed by several authors and revolves around issues of subjectivity and repeatability (Charles *et al.* 1986, Ýþcan and Loth 1986, Katz and Suchey 1986, Ýþcan and Loth 1987, Saunders 1989, Saunders *et al.* 1992, Lynnerup *et al.* 1998, Baccino *et al.* 1999, Buckberry and Chamberlain 2002, Holman *et al.* 2002, Kemkes-Grottenthaler 2002, Paine and Boldsen 2002, Love and Müller 2002, Kimmerle *et al.* in prep,). Since a suite of morphological characteristics is being evaluated and then placed into a single-phase system, room for error occurs in a multitude of places (Boldsen *et al.* 2002, Holman *et al.* 2002). For example, when analyzing the pubic symphysis and trying to determine the corresponding Suchey-Brooks phase (Brooks and Suchey 1990) for that particular individual, for any of the six phases, there are multiple morphological changes to consider:

> "*Phase III*
> Symphyseal face shows lower extremity and *ventral rampart in process of completion*. There can be a continuation of fusing ossific nodules forming the upper extremity and along the ventral border. Symphyseal face is smooth or can continue to show distinct ridges. Dorsal plateau is complete. Absence of lipping of symphyseal dorsal margin; no bony ligamentous outgrowths" (Brooks and Suchey 1990: 232-233).

With the suite of morphological characteristics listed in the description above, the ventral rampart, the ossific nodule, the surface of the symphyseal face, lipping and outgrowths, the variability of the individual skeleton may place that pubic symphysis in between phases and generates problems of inter- and intra-observer error.

With this particular aging method, interobserver error has been documented because observers cannot distinguish between the building up (Phase III) and breaking down (Phase VI) of the ventral rampart (Kimmerle *et al.* in prep). In addition, the wording of the morphological changes for each phase is not clear, which may lead to misclassification. The description of Phase III notes that the surface of the symphyseal face can be either smooth or ridged. This variability may lead observers to misclassify the skeletal element, which is noted by the original authors: “Also of concern is the wide range of variability of Phase III through VI…in the SUCHEY-BROOKS method” (Brooks and Suchey 1990: 237).

These issues are not just present in the Suchey-Brooks or other pubic symphyseal methods, but all aging methods that rely on the observers’ subjective placement of a skeletal element into a phase category. The large portion of inter- and intra-observer error is attributed to the fact that these types of methods are unquantifiable (Paine and Boldsen 2002).

The second problem associated with phase-aging methods is the large age ranges that are produced, where several methods include the final phase as an open-ended interval of the older individuals (Boldsen *et al*. 2002, Kemkes-Grottenthaler 2002). Taking the Suchey-Brooks method as an example again, the phases have an average range of 34.8 years for females and 28.8 years for males, with the largest ranges for Phases III through VI, for both sexes. This same trend is produced with Ýþcan *et al’s* method (1984a, 1985) for estimating age-at-death from the fourth sternal rib where females have an average age range spanning 26.3 years and males have an average age range spanning 22.4 years. As seen with the Suchey-Brooks method, later phases produce wider age ranges, starting with Phase 3 for males and Phase 4 for females.

The Todd method (Todd 1921a, 1921b), based on a ten phase system for the pubic symphysis, has smaller age ranges per phase, as compared with the Suchey-Brooks method, but the last phase is presented as an open-ended interval of all individuals 50 years and older. Similarly, Lovejoy *et al.'s* (1985) method of estimating age-at-death from the auricular surface of the os coxae produces a final phase (Phase 8) with an associated age range containing individuals 60 years and older. It is desirable for age estimates to be more precise in capturing the right most tail of the age-at-death distribution (Hoppa and Vaupel 2002b).

The next problem addresses concerns that the ages attributed to each phase overlap one another. For all phase-oriented methods, each age range associated with a particular phase, is not unique to that phase: "…stages overlap substantially and are fraught with error, and information is sparse" (Love and Müller 2002: 181). When a particular age is associated with more than one phase, it reflects the underlying problems associated with the correlation between chronological age and phase (Kemkes-Grottenthaler 2002, Paine and Boldsen 2002, Wittwer-Backofen *et al.* 2004). Some authors have also pointed out that relevant information is lost when age-at-death estimates are derived from phase-oriented methods:

> "Assigning ages into categories constitutes a large loss of information regarding age-at-death of the individuals. Since many different ages are assigned into the same category, it is impossible to differentiate between various ages given the assigned category. Furthermore, the category assignments typically overlap with respect to the ages that are assigned into the categories. This means that skeletal remains of a given age-at-death *A* have a good chance to be assigned to each of several categories" (Love and Müller 2002: 183).

Since the relationship between chronological age and phase is non-linear, this will result in phases overlapping and age range intervals having varying lengths (Kemkes-Grottenthaler 2002).

A multitude of authors have reported bias in age estimates, which is often referred to as "attraction of the middle" (Solheim and Sundnes 1980, Bocquet-Appel and Masset 1982, Lipsinic *et al.* 1986, Masset 1989, Konigsberg and Frankenberg 1992, Bedford *et al.* 1993, Molleson *et al.* 1993, Aykroyd *et al.* 1996, Aykroyd *et al.* 1997, Boldsen *et al.* 2002, Hoppa and Vaupel 2002b, Kemkes-Grottenthaler 2002, Prince and Ubelaker 2002). In other words, there is a tendency to consistently overestimate age in younger individuals while underestimating age in older individuals, thus, in many cases the estimated ages are closer to the mean age than the actual chronological age (Aykroyd *et al.* 1996). This problem is partially attributed to statistical methodologies, where inverse calibration is utilized (Konigsberg *et al.*1998). The nature of this type of analysis is to regress towards the mean, so in the case of estimation of age-at-death, age estimates will shift in the direction of mean age, therefore creating this aging bias. In inverse calibration the independent variable, denoted as y, is the age indicator, for example, amount of apical translucency (T) and the dependent variable (i.e. fixed variable), denoted as x, is age. Age (x) would then be regressed on the amount of apical translucency (y). Unless the target sample (the unknown-age sample) and reference sample (the known-age sample) have similar age-at-death distributions, the age estimates will be biased toward the age-at-death distribution of the reference sample.

The next issue addresses concerns with age mimicry. Target sample age estimates are prone to mimicking the age-at-death distribution of the reference sample when appropriate course is not taken (Bocquet-Appel and Masset 1982, Van Gerven and Armelagos 1983, Bocquet-Appel and Masset 1985, Buikstra and Konigsberg 1985, Masset and Parzysz 1985, Bocquet-Appel 1986, Greene *et al.* 1986, Horowitz *et al.* 1988, Mensforth 1990, Konigsberg and Frankenberg 1992, Goodman 1993, Jackes 1993, Bocquet-Appel and Masset 1996, Aykroyd *et al.* 1997, Ousley and Jantz 1998, Jackes 2000, Milner *et al.* 2000, Boldsen *et al.* 2002, Holman *et al.* 2002, Hoppa and Vaupel 2002b, Kemkes-Grottenthaler 2002, Konigsberg and Frankenberg 2002, Love and Müller 2002, Usher 2002, Wittwer-Backofen and Buba 2002). As Konigsberg and Frankenberg (1992) point out, this problem has been well known and managed in the fisheries literature (Kimura 1977, Westrheim and Ricker 1978, Clark 1981, Bartoo and Parker 1983, Fournier and Breen 1983, Kimura and Chickuni 1987). Bocquet-Appel and Masset (1982) were the first to criticize and voice several important limitations surrounding age estimations for human skeletal remains. These researchers argued that the target age-at-death distribution was heavily influenced by the age-at-death distribution from the reference sample. Although Bocquet-Appel and Masset stated that this problem, along with aging bias and low correlation between age indicators and chronological age (both mentioned above) could not be overcome, several researchers (Buikstra and Konigsberg 1985, Gage 1988, Gage 1989, Lanphear 1989, Gage 1990, Mensforth 1990, Konigsberg and Frankenberg 1992, Konigsberg and Frankenberg 1994, Aykroyd *et al.* 1997, Konigsberg *et al.* 1997, Ousley and Jantz 1998, Boldsen *et al.* 2002, Herrmann and Konigsberg 2002, Holman *et al.* 2002, Hoppa and Vaupel 2002b, Kemkes-Grottenthaler 2002, Konigsberg and Frankenberg 2002, Konigsberg and Herrmann 2002, Love and Müller 2002, Wood *et al.* 2002) have provided adequate and ample solutions to the problems reported by Bocquet-Appel and Masset. Using appropriate reference samples and statistical methodologies, as will be addressed below, can eliminate age mimicry.

The next problem concerns missing data due to taphonomic processes. Most aging methods utilize skeletal elements that do not preserve well due to taphonomic reasons (Buikstra and Cook 1980, Wood *et al.* 1992, Jackes 1993, Larson 1997, Jackes 2000, Milner *et al.* 2002, Paine and Boldsen 2002, Wittwer-Backofen and Buba 2002). Preservation problems arise from burial practices, which result in the underrepresentation of certain age cohorts; soil condition, which causes skeletal decomposition; carnivore activity, which results in missing and damaged elements; and careless excavation techniques, which can lead to damaged skeletal elements. All of these issues hinder the applicability of the aging method (Wittwer-Backofen and Buba 2002). Skeletal elements such as the pubic symphysis, the auricular surface of the os coxae and sternal ends of the ribs are subject to preservation problems and are often missing from archaeological and forensic material.

The last problem to consider with adult estimations of age-at-death are improper theoretical framework and statistical methodology. An inherent paradox has been noted in the field of paleodemography when estimating age-at-death. Several researchers have pointed out that the target age-at-death distribution must be estimated prior to individual age estimation in the target sample (Konigsberg and Frankenberg 1992, Jackes 2000, Milner *et al.* 2000, Boldsen *et al.* 2002, Hoppa 2002, Hoppa and Vaupel 2002b). The probability density function for the entire target sample is necessary, because every skeleton has its own degree of error (Boldsen *et al.* 2002). This methodology, in turn, leads to an additional problem: how to produce the age-at-death distribution for the target samples, without the individual age estimates. This problem is solved with proper statistical methodology, which will be discussed below.

1.2 Solutions to Combat Issues with Adult Age-at-death Estimates

There are several ways to combat the problems related to age-at-death estimates and techniques mentioned above. The first two issues can be addressed by method and age indicator. Several aging methods eliminate the placement of a skeletal element in to a phase by employing dental metric features, which aid in several ways. Utilizing dental metric features, such as translucency of the root and periodontal recession, eliminates subjective categorical placement and also aids in reducing large age ranges that are usually associated with skeletal age-at-death estimates for adults. These two dental indicators capture the right-most tail of the age-at-death distribution, the older individuals, more accurately than phase oriented aging methods.

All of the problems associated with age-at-death estimates can be solved by the application of appropriate statistical methods. Most aging methods rely on linear regression or multiple regression analysis (Konigsberg *et al* 1998). The issue then falls to what is referred to as the "calibration problem" which refers to the issue of regressing which variable on the other (Konigsberg *et al.* 1997). Typically in physical anthropology, inverse calibration, described above, is utilized, where the reference sample age-at-death distribution is usually used as a prior distribution for age, which is inappropriate unless the target sample has a similar age-at-death distribution. Inverse calibration is a Bayesian approach, but proper priors and reference samples are necessary for unbiased estimates. Typically in forensic anthropology, inverse calibration is appropriate to use, because an appropriate reference sample can be obtained, for example *The Forensic Databank* at the University of Tennessee. When there is no prior, a vague prior, or an uninformative prior, classical calibration should be utilized instead of inverse calibration. Classical calibration produces maximum likelihood estimates (MLE), where the dependent variable, for example, the amount of apical translucency (*y*), is regressed on the independent variable, age (*x*) followed by solving for age (Konigsberg *et al.* 1998). Confidence intervals will be larger with classical calibration as compared to inverse calibration, but the results will be unbiased. In addition, Konigsberg *et al.* (1998) point out in their example of stature estimation of Lucy (A.L. 288-1) from femur length that although the inverse calibration produced a smaller confidence interval, her actual anatomical stature (estimated by Geissmann 1986) was not included in that interval. On the contrary, classical calibration captured Lucy's actual anatomical stature. In paleodemography, paleoanthropology, and bioarchaeology, classical calibration should be applied because it is usually impossible to determine the structure of the age-at-death distribution of the target sample. Therefore problems addressed above may occur.

1.3 How to Choose an Appropriate Age Indicator

When determining which skeletal element to use to estimate adult skeletal age-at-death, the problems outlined above must be considered. The skeletal element should be robust enough to withstand the issues addressed above. First of all, the age indicator must have a high correlation with chronological age (Hoppa and Vaupel 2002b, Kemkes-Grottenthaler 2002, Wittwer-Backofen 2002). If an indicator is a poor estimate of chronological age, then another skeletal element should be considered. The indicator and method should have high repeatability. This entails that the indicator and method are clearly defined and described and easy for others to learn and replicate. This will decrease inter-and intra-observer error. The skeletal element must be robust enough to withstand long-term internment and taphonomic effects. Methods that rely on anatomical regions that are rarely recovered from archaeological sites and forensic scenes will be of little practical use. Finally, an age indicator trait and method must be applicable to a variety of populations. In such, several validation studies across populations must be conducted. When employing any estimation technique, population specific and appropriate reference samples must be utilized (Ubelaker 1989, Konigsberg and Frankenberg 1992, Hoppa and Vaupel 2002, Jackes 2002, Prince and Ubelaker 2002, Ross and Konigsberg 2002, Komer 2003, Monzavi *et al*. 2003, Šlaus *et al.* 2003).

1.4 The Rostock Manifesto

As mentioned above, many methods that estimate adult age-at-death are based on improper theoretical and statistical methodologies. These include estimating point age estimates instead of estimating the entire probability density function for the target sample and using inverse calibration methods instead of classical calibration and Bayesian analysis (Gage 1989, Konigsberg and Frankenberg 1992).

In 1999, the Max Planck Institute for Demographic Research, under the direction of Dr. James W. Vaupel, brought several researchers together to discuss issues and problems relating to estimation of skeletal age-at-death. Their goal was to outline the issues, create methods to resolve the issues and disperse this knowledge to others. The accomplishments of these goals are outlined in *Paleodemography: Age distributions from skeletal samples* (Hoppa and Vaupel 2002a). Their major contribution to the scientific community was the four point *Rostock Manifesto*, which states:

1. "Working more meticulously with existing and new reference collections of skeletons of known age, osteologists must develop more reliable and more vigorously validated age indicator stages or categories that relate skeletal morphology to known chronological age.
2. Using these osteological data, anthropologists, demographers and statisticians must develop models and methods to estimate $\mathrm{Pr}(c \quad a)$, the probability of observing a suite of skeletal characteristics *c*, given known age *a*.
3. Osteologists must recognize that what is of interest in paleodemographic research is $\mathrm{Pr}(a \quad c)$, the probability that the skeletal remains are from a person who died at age *a*, given the evidence concerning *c*, the characteristics of the skeletal remains. This probability, $\mathrm{Pr}(a \quad c)$, is NOT equal to $\mathrm{Pr}(c \quad a)$, the latter being known from reference samples. Rather $\mathrm{Pr}(a \quad c)$, must be calculated from $\mathrm{Pr}(c \quad a)$ using Bayes' theorem. Even the most experienced and intelligent osteologists cannot make this calculation in their heads. Pencil and paper or a computer is required, as well as information concerning $f(a)$, the probability distribution of ages-at-death (i.e. lifespan) in the target population of interest.
4. This means that $f(a)$ must be estimated *before* $\mathrm{Pr}(a \quad c)$ can be assessed. That is to say, to calculate $\mathrm{Pr}(a \quad c)$ it is necessary to first estimate $f(a)$, the probability distribution of lifespans in the target population. To estimate $f(a)$ a model is needed of how the chance of death varies with age. Furthermore, a method is needed to relate empirical observations of skeletal characteristics in the target population to the probability of observing the skeletal characteristics in this population. The empirical observations generally will be counts of how many skeletons are classified into each of the stages categories *c*. The probability of these characteristics, $\mathrm{Pr}(c)$, is given by

$$\mathrm{Pr}(c) = \int_o^{v} \quad \mathrm{Pr}(c \quad a)\, f(a)\mathrm{d}a,$$

where ϖ is the upper limit of the human lifespan. The basic strategy is to choose the parameters of the model of the lifespan distribution $f(a)$, or the levels of mortality in various age categories in a nonparametric model, to maximize the "fit" between the observed frequencies of the morphological characteristics and the underlying probabilities of these characteristics" (Hoppa and Vaupel 2002: 2-3).

The Rostock Manifesto incorporates solutions for many of the problems outlined above. With more rigorous testing of age-at-death methods and indicators and applying appropriate statistical methodologies, age estimates will have smaller confidence intervals around age estimates, will be less prone to aging bias and age mimicry, and new techniques and methodologies may be discovered with higher correlations to chronological age.

1.5 Single-trait versus Multiple-trait Methods

Although the following research will pertain to just one age indicator, single-rooted teeth, it must be stressed that all possible aging methods must be conducted on recovered skeletal material. Important information, such as interpersonal variation, will be lost if all analysis is not completed (Kemkes-Grottenthaler 2002). Single-trait methods yield a narrow window of information about a specific age element, while multiple trait approaches yield a general picture of the sequential aging process (Kemkes-Grottenthaler 2002). Each age indicator and method has its own degree of error (Boldsen *et al.* 2002), and therefore all available skeletal elements should be analyzed. Multiple trait methods will be more accurate in assessing the morphological variation that occurs in a skeleton (Boldsen *et al.* 2002). In addition, several authors (Lipsinic *et al.* 1986, Brooks and Suchey 1990, Saunders *et al.* 1992, Goodman 1993, Russell 1996, Baccino *et al.* 1999, Kagerer and Grupe 2001, Boldsen *et al.* 2002, Kemkes-Grottenthaler 2002, Ubelaker *et al.* 1998) have recommended that multiple trait methods offer a more precise and complete estimate of age-at-death.

1.6 Lamendin's Age Indicators for Estimating Adult Age-at-death

Teeth are important aging elements because they have a vast postmortem longevity due to their highly mineralized composition. As such, they are the most durable structure in the human body, more resilient than bone, and highly resistant to physical and chemical influences. Many times they are the only skeletal remains recovered from forensic scenes and archaeological sites (Maples 1978, Marcsik *et al.* 1992, Ohtani 1995). Physical anthropologists utilize dental features in three main areas of research: paleontology, where teeth form the basis for many reconstructions of phylogenetic relationships; skeletal biology, where teeth are a medium by which individuals survive in their environment and populational adaptations to environmental factors are studied; and forensic anthropology, where teeth are used for identification purposes.

The purpose of the following research is two-fold: 1) to apply Lamendin *et al's* (1992) method and features of translucency of the root and periodontal recession to known age reference samples to generate Bayesian derived age-at-death distributions and confidence intervals for two target samples, and 2) to assess the accuracy, validity, and usefulness of this method applied to archaeological material.

1.7 Summary and Chapter Overview

This chapter has outlined several problems associated with age-at-death methods that rely on phase-oriented methods. Seven issues were addressed: 1) the subjectivity of the observer; 2) large age ranges and open-ended intervals; 3) stages that overlap one another; 4) aging bias; 5) age mimicry; 6) taphonomic issues; and 7) improper theoretical and statistical methodology. Solutions to these methodological and statistical problems were offered by utilizing two dental metric features, translucency of the root and periodontal recession, and applying appropriate statistical analysis, either inverse regression, when an appropriate reference sample can be determined, or classical calibration, when the age-at-death distribution of the target cannot be determined or matched.

The second chapter reviews several adult dental aging techniques, starting with Gösta Gustafson's method (1950), which analyzes six dental changes: attrition, secondary dentin deposits, cementum annulation apposition, translucency of the root, periodontal regression, and root resorption. Methods that are based on Gustafson's six dental features are then reviewed, focusing on Dalitz (1962), Johanson (1971), Maples (1978), Solheim (1993), and Ajmal *et al.* (2003). Next, single indicator methods are reviewed, starting with several of Gustafson's indicators, such as attrition, secondary dentin deposits, cementum annulation apposition, periodontal regression, and apical translucency. Root color and aspartic acid racemization are also discussed as univariate dental indicators of age. Lamendin *et al.*'s method (1992), which utilizes two of Gustafson's features, apical translucency and periodontal regression, is then summarized, followed by several studies which apply Lamendin's method, which include Foti *et al.* (2001), Prince and Ubelaker (2002) and Sarajliæ *et al.* (2003). Two studies (Ubelaker *et al.* 1998, Baccino *et al.* 1999) that compare Lamendin's method with skeletal age-at-death methods are also reviewed. Application of Lamendin's method to archaeological material by Sengupta *et al.* (1998, 1999), Marcsik *et al.* (1992), Drusini *et al.* (1991), and Lucy *et al.* (1995) conclude the literature review of adult dental aging methods.

Chapter three presents the materials and methodology for testing the hypothesis that utilizing Bayesian analysis with translucency of the root and periodontal recession will combat several of the issues outlined at the beginning of this chapter. Three collections are analyzed, the Robert J. Terry Collection, the Baraybar Forensic Biosample Collection, and the Lauchheim Medieval Cemetery. All teeth are analyzed following procedures outlined by Lamendin *et al.* (1992), except the periodontal recession measurement is not used for Lauchheim sample. The latter measurement varies slightly from Lamendin's original definition for logistic reasons. Two observers took the three measurements required for Lamendin's method for the Baraybar Forensic Biosample Collection sample to address issues of repeatability and inter-observer error. Following a Rostock Manifesto compliant analysis, Bayes' theorem was utilized to estimate ages-at-death for the Baraybar Forensic Biosample Collection sample and the Lauchheim sample. The Baraybar Forensic Biosample Collection was used as a reference sample for the Lauchheim material.

The results of the statistical analysis are presented in Chapter four. A repeated measures analysis of variance (ANOVA) was utilized to determine if a significant difference existed between the two observers. A comparison of aging between the Terry and Baraybar Collections is then presented. An analysis of variance (ANOVA) was utilized to determine whether these two known-aged samples aged differently. The results yielded from estimation of age-at-death for the Baraybar sample are then presented. Mean absolute errors are presented in age cohorts to visualize the error associated with varying decades. The mean absolute errors from the Bayesian approach are then compared to results from Lamendin *et al's* (1992) formula and Prince and Ubelaker's (2002) formulae. This comparison highlights the bias in estimating age-at-death from the two inverse calibrated methods. A Gompertz hazard model is estimated for Lauchheim using the Baraybar Forensic Biosample Collection sample as a reference sample for f(D|A). The probability density function (pdf) for age-at-death, assuming age at death is $\geq$ 17 years, from the Gompertz hazard model for the Lauchheim sample is then presented. The inverse calibration methods and the Bayesian analysis used to estimate ages-at-death for the Lauchheim sample are compared.

Chapter five discusses how the problems associated with estimating age-at-death from skeletal remains were addressed in this research. Advantages of employing a Bayesian method in lieu of inverse calibration are highlighted by comparing age-at-death estimations between the two methods for the Baraybar Forensic Biosample Collection and the Lauchheim sample. In particular, a reduction in aging bias and age mimicry are emphasized. Inter-observer error and issues revolving around repeatability are also discussed. Theoretical problems with confidence intervals are also touched upon in this chapter. Intrinsic factors that may affect the acquisition of apical translucency are discussed. Comparison of correlations among the three age-at-death estimations for the Lauchheim material concludes Chapter 5.

The last chapter offers concluding statements and insight into future research in this realm of physical anthropology.

CHAPTER 2

ADULT DENTAL AGING METHODS

Several researchers have developed techniques to determine age-at-death for adults by employing the dentition and dental morphology. Most methods involve assessing age-related changes in attrition (Zuhrt 1955, Miles 1962, 1963, Brothwell 1963, Lavelle 1970, Molnar 1971, Ito 1972, Lunt 1978, Miles 1978, Scott 1979, Smith 1984b, Lovejoy 1985, Brothwell 1989, Li and Ji 1995), secondary dentin deposits (Morse *et al.* 1993, Kvaal and Solheim 1994), cementum apposition (Charles *et al.* 1986, Condon *et al.* 1986, Wittwer-Backofen 2000, Wittwer-Backofen and Buba 2002, Wittwer-Backofen *et al.* 2004), apical translucency (Bang and Ramm 1970), periodontal recession (Solheim 1992, Borrman *et al.* 1995), root resorption (Borrman *et al.* 1995), acid racemization (Helfman and Bada 1975, Helfman and Bada 1976, Shimoyama and Harada 1984, Ogino *et al.* 1985, Masters 1986, Ritz *et al.* 1990, Ohtani and Yamamoto 1991, 1992, Ritz *et al.* 1993, Mörnstad *et al.* 1994, Ohtani 1994, 1995, Ohtani *et al.* 1995, Carolan *et al.* 1997), color change of the root (Ten Cate *et al.* 1977, Solheim 1988, Borrmann *et al.* 1995), or a combination of several of these indicators (Gustafson 1947, 1950, 1955, Johanson 1971, Maples 1978, Maples and Rice 1979, Matsikidia and Schultz 1982, Kashyap and Koteswara Rao 1990, Lamendin and Cambray 1980, Lamendin *et al.* 1992, Solheim 1993, Kvaal *et al.* 1995, Russell 1996). Several researchers have analyzed these features individually and mutifactorally.

2.1 Gustafson’s Adult Dental Aging Method

Gösta Gustafson, a Swedish stomatologist, was a pioneer in assessing age-related changes to the dentition and laid the foundation for utilizing dental microstructure to estimate age-at-death (Gustafson 1947, 1950, 1955). He assessed age-related changes in six features of the human dentition: attrition (A), secondary dentin deposits (S), translucency of the root (T), periodontal recession (P), cementum annulation apposition (thickness)(C), and root resorption(R). He assigned an arbitrary score (0, 1, 2, 3 points) to account for the degree of the dental change in each feature and assessed the amount of change by making longitudinal sections of the tooth. In the point system, increased score was equated with increased age. From linear regression analysis, Gustafson produced the following equation to yield a point estimate of age-at-death: $y=11.43 + 4.56X$, where y represents the estimated age, and X represents the total number of points from all the dental features. A correlation coefficient of 0.98 was produced from his analysis. To decease error in the age-at-death estimate, Gustafson stated that several teeth from the same individual should be assessed: “The precision of an estimation is increased by examining a number of teeth from the same individual, the error decreasing inversely proportional to the square root of the number of teeth” (Gustafson 1950:520). His results found that root translucency and secondary dentin deposits were the best indicators of age.

The advantage of this method is that it considers a number of different dental features and when possible, uses information from several teeth. Poor oral heath was found to influence the scoring and age estimates. Individuals with poor oral health produced higher age estimates than their actual age. Disadvantages of this method are that it is a destructive method (as longitudinal thin sections of teeth are required to assess the age-related change), the observer must have a thorough knowledge of dental histology to interpret the features, and the statistical analysis was incorrect.

Although the importance of Gustafson's research was evident, many authors (Dalitz 1962, Saunders 1965, Bang and Ramm 1970, Burns and Maples 1976, Johanson 1971, Maples 1978, Maples and Rice 1979, Metzger *et al.* 1980, Solheim and Sundnes 1980, Haertig *et al.* 1985, Nkhumeleni *et al.* 1989, Kashyap and Koteswara Rao 1990, Marcsik *et al.* 1992, Lamendin *et al.* 1992, Solheim 1993, Borrman *et al.* 1995, Lucy and Pollard 1995, Lucy *et al.* 1996, Aykroyd *et al.*1997, Ubelaker *et al.* 1998, Baccino *et al.* 1999, Monzavi *et al.* 2003) noted problems with his analysis, in particular, the statistical methodology, and tried to improve upon his foundation.

2.2 Modifications of Gustafson's Method

Dalitz (1962) was the first to offer a modified method based on Gustafson's dental features. He analyzed 128 incisors and canines extracted from 29 cadavers. His modifications included adding an extra phase at the latter end of the scale, therefore scoring dental changes from 0 to 4, and omitting cementum apposition and root resorption due to their low correlation with age. Age was estimated using multiple regression analysis, which weighted the remaining four dental changes. From this modified approach, a mean error (square root of the mean squared error) of 8.1 years was produced.

Johanson (1971), a student of Gustafson's, offered the next modified dental method based on Gustafson's method. He analyzed 162 teeth extracted from 46 individuals. Johanson (1971) also increased the number of ordinal phases in his modified method by adding intermediate stages of dental change, thus offering a method based on 7 phases instead of 4. He also used multiple regression with weighted coefficients, as Dalitz (1962) did, to estimate age-at-death. From his method, a mean error of 5.16 years was yielded.

From Gustafson's dental parameters, Maples (1978) offered an improved method which reduced the number of dental variables. Maples analyzed 355 teeth from dental extractions, of which 284 comprised the working sample and 71 the control sample. Maples tested each of Gustafson's dental features individually as well as in combination with the other features. His results yielded standard errors 20-30% lower than Gustafson, in most cases. M_2 provided the best results with APSCT (Attrition, Periodontosis, Secondary Dentin, Cementum, Transparency) and yielded a mean error of $\pm$5.00 years. His results revealed that "root resorption was by far the worst of the six changes (and) root transparency was the best, followed by secondary dentin, attrition, periodontosis and cementum" (Maples 1978:765). Secondary dentin deposits and translucency of the root were the best indicators to estimate age. In addition to having higher correlations with chronological age, Maples found that they were the easiest features to assess and less prone to pathological and taphonomic processes. Maples also stated that these two features can be utilized to estimate age-at-death in contemporary and archaeological material. Furthermore, there was no significant difference among ancestry groups or between the sexes.

In 1993, Solheim published a new method to estimate age from microscopic dental features. His goals were to create a method which utilized those features most highly correlated with age, to apply multiple regression analysis to determine which tooth type was most useful and to determine the interrelationship between the different dental parameters. His sample consisted of 1000 single-rooted teeth of known-age, which were obtained through dental clinic extractions, cadavers, and forensic cases. The teeth were obtained through several different dental clinics with different methods and reasons for extraction. He assessed changes in periodontal recession, attrition, secondary dentin deposits, color, cementum apposition (thickness), apical translucency, and surface roughness of the root. He preformed stepwise multiple regression to analyze the dental features and tooth type. Analyses were conducted including and excluding sex and tooth color because Solheim noted that these two features are not always discernable in forensic and archaeological teeth.

His results showed that periodontal recession was particularly high in teeth that were extracted, which is not surprising since most teeth were extracted due to periodontal pathologies. He also noted that the color was significantly darker in the teeth that were extracted from corpses. From this, Solheim suggested that color may not be suitable for use in forensic cases. His results also revealed that translucency of the root was significantly higher in darker teeth. Teeth that had rougher surfaces also had significantly broader cementum apposition and higher amounts of secondary dentin deposits.

Solheim found an inter-correlation between color and apical translucency in the maxillary first pre-molars and mandibular lateral incisors. Surprisingly, Solheim found a correlation between attrition and secondary dentin deposits in only two tooth types and therefore concluded that secondary dentin is only slightly influenced by attrition.

Solheim produced separate formulae for each tooth type to estimate age from these dental parameters, but noted that mandibular canines and second pre-molars had the weakest correlation with actual age. Correlation coefficients ranged from 0.76 for mandibular second pre-molars to 0.91 for maxillary central incisors, when sex and color were excluded and to 0.78 and 0.89, respectively, when sex and color were included.

Ajmal *et al.* (2001) compared three methods, Gustafson's method modified by Kashyap and Koteswara Rao (1990), Gustafson's method modified by Johanson (1971), and the Average Stage Attrition (ASA) method (Li and Ji 1995). These researchers analyzed 100 non-pathological, extracted, single-rooted teeth from an Indian population. Two observers performed the three methods and concluded that the ASA method was more accurate and reliable than the two modified Gustafson methods, with Kashyap and Koteswara Rao's method yielding the worst results. Among the modified Gustafson methods, apical translucency was the most important feature yielding the highest correlation with chronological age. Root resorption was the least useful parameter from Johanson's method, while cementum apposition thickness was the least useful from Kashyap and Koteswara Rao's method.

An aging bias was noted with all of methods. Females' ages were overestimated independent of which method was used and the same trend was found for mandibular teeth.

2.3 Dental Attrition

Dental wear, or attrition, is the erosion of the occlusal or incisal surface of teeth and the contact points between teeth caused during mastication. Attrition has proved useful in age-at-death estimations (Gustafson 1950, Murphy 1959, Miles 1962, Brothwell 1963, Molnar 1971, Helm and Prydso 1979, Scott 1979, Smith 1984a, 1984b, Cross *et al.* 1986, Dreier 1994, Lovejoy 1985, Lovejoy *et al.* 1985, Brothwell 1989, Dahl *et al.* 1989, Song and Jia 1989, Ubelaker 1989, Johansson *et al.* 1993, Buikstra and Ubelaker 1994, Kim *et al.* 1995, Li and Ji 1995, Ajmal *et al.* 2001, Ball 2002). Most dental wear methods subjectively place a tooth into an ordinal phase owing to the amount of attrition observed.

Dental wear as an estimator of age has been used on prehistoric populations since the beginning of the 20th century (Nicholls 1914, Bödecker 1925, Cambell 1925, Leigh 1925). Since most methods employing dental wear were developed on prehistoric archaeological samples, which were not known-age, its usefulness, reliability, and applicability have been questioned. Several authors combated this problem by equating dental wear with other age indicators throughout the skeleton. Some methods employing dental wear assess subadult age first by means of dental formation and eruption and then score the amount of attrition. From this baseline, the researchers then extrapolate the dental wear for the adults and thus estimate their age (Zuhrt 1955, Miles 1962, 1963, 1978).

Assessment of dental wear in molars has proved very useful in age estimates due to molar eruption patterns (Miles 1962, 1963, 1978, Brothwell 1963, Lavelle 1970, Molnar 1971, Lunt 1978, Smith 1984b, Brothwell 1989, Li and Ji 1995). The first permanent molar (M_1) erupts at approximately 6 years of age, the second permanent molar (M_2) erupts at approximately age 12 and the third molar (M_3) erupts at approximately age 18, though the latter is highly variable. From this eruption pattern, the difference in wear between M_1 and M_2 and M_2 and M_3 reflects approximately 6 years of wear. From this internal calibration, an entire skeletal sample can be estimated for age by dental attrition.

Other researchers calibrated the amount of dental wear against pubic symphyseal age (Lavelle 1970, Nowell 1978, Lovejoy 1985). These researchers applied the internal calibration of molar wear, described above, and determined that dental wear was as reliable as pubic symphyseal aging. In addition, several researchers also tested Miles' (1962, 1963) method against known age samples (Kiser *et al.* 1983, Lovejoy *et al.* 1985). This research concluded that Miles' method was reliable for estimating age-at-death.

There have been several studies with conflicting results about sexual dimorphism and dental attrition. Some research determined that sex yielded a significant difference in analysis of dental wear. In most research females showed precocious dental wear as compared to males (Heithersay 1960, Molnar 1971, Molnar *et al.* 1983a, 1983b, McKee and Molnar 1988). But other research indicated that sex did not have a significant effect (Hojo 1954, Murphy 1959, Pal 1971, Lunt 1978, Tomenchuk and Mayhall 1979, Li and Ji 1995).

Studies that determined a significant difference between the sexes were derived from archaeological samples, where a division of labor was responsible for the observed differences. Differences observed between males and females in dental wear can be attributed to differences in diet, where males ingested softer foods (Heithersay 1960) and food preparation processes, where women would use their teeth as tools (Pedersen 1952).

As mentioned above, population specifics are crucial when employing any aging method on skeletal or dental remains and those who analyze dental wear stress this important point (Brothwell 1963, Lavelle 1970, Molnar 1971, Smith 1972, Smith 1984a, 1984b, Brothwell 1989).

The best known and widely utilized dental wear method in North American bioarchaeology was developed by Murphy (1959) who describes 8 stages of wear for all tooth types based on Australian aboriginal populations. This method produced a very good correlation between age and dental wear, but when applied to other populations, did not fare as well. Owing to this, Smith (1984b) utilized Murphy’s method in her research and produced a summary diagram, which has been widely used in estimation of age-at-death (Hillson 1996, Buikstra and Ubelaker 1994).

There are several factors that can lead to attrition other than tooth-on-tooth contact from mastication. Bruxism, the grinding or tapping of teeth, generates greater forces than mastication and also leads to the wear on the occlusal and incisal tooth surfaces (Hillson 1996). The form of the temporomandibular joint (Johansson *et al.* 1991, Johansson 1992) and the size and shape of the mandibular condyles (Owen *et al.* 1991) has also been linked to heavy attrition. Population difference due to diet have also been noted (Molnar 1971, 1972, Maples 1978, Ajmal *et al.* 2001).

Deliberate dental modification and anomalous wear also contributes to increased attrition. Deliberate modifications include therapeutic dental work, such as silver amalgam and resin restorations, crowns, and inlays. Anomalous modifications include wear from items such as toothpicks, needles, reeds and pipes.

Several researchers, depending upon temporal and population factors, have also reported that sexual dimorphism is an important factor in dental wear with females reported to have significantly heavier wear (Molnar 1971, Molnar *et al.* 1983, and McKee and Molnar 1988). Others note that the sex of an individual does not influence wear (Pal 1971, Lunt 1978).

There are a few disadvantages of using dental wear to estimate adult age-at-death. These methods are subjective and, therefore, prone to the problems outlined in the previous chapter. In addition, there are several factors other than age which cause dental attrition, as mentioned above. Another consideration, pointed out by Walker *et al.* (1991), is that larger teeth wear slower than smaller ones, which leads to differential wear.

Although there are multifactoral causes, ordinal scoring of dental attrition has several advantages in age-at-death estimates. Scoring the amount of wear observed can be done fairly quickly and large collections can be scored in a relatively small amount of time. As mentioned above, teeth have a considerable postmortem longevity and therefore, they are sometimes the only skeletal feature that can yield age related information. This method is non-destructive and the teeth need not be removed from the jaws to score.

2.4 Secondary Dentin Deposits

Microscopically, dentin is comprised of intertubular dentin, which is formed during odonotogenesis, and dentin tubules, which contain the odontoblastic processes

(Schroeder 1991). Peritubular dentin, which lines the inner walls of the dentin tubuli (Schroeder 1991), is deposited gradually throughout life. Peritubular dentin has a higher mineralized content than intertubular dentin due to the differences in their organic matrix, the former comprised of mucopolysacharides, while the latter is comprised of collagen (Schroeder 1991). Since peritubular dentin is gradually deposited throughout life, the pulp cavity is gradually reduced, in addition to the diameter of the dentin tubuli. Primary dentin consists of all dentin that is formed until completion of the root (Schroeder 1991). Dentin deposited after the completion of the root is termed secondary dentin (Schroeder 1991).

Deposition of secondary dentin was thought to be influenced by the amount of attrition, where dentin would be deposited in the lining of the pulp chamber to combat the loss of the crown, but several authors have reported a weak correlation between attrition and secondary dentin deposits (Philippas 1961, Solheim 1993, Kvaal *et al.* 1995). Other extrinsic factors have also been attributed to influencing secondary dentin deposits, such as changes in osmotic pressure throughout the tooth (Philippas 1961).

The amount of secondary dentin deposition has been used to estimate age at-death, with relatively high correlations with age (Philippas 1961, Moore 1970, Ito 1975, Lantelme *et al.* 1976, Feng 1985, Nitzan *et al.* 1986, Solheim 1992, Kvaal *et al.* 1994). Dalitz (1962) and Johanson (1971) found correlation coefficients of 0.55 and 0.66 respectively, when they measured the reduction in length of the pulp chamber, following Gustafson (1950). Moore (1970) found similar results, with correlation coefficients of 0.62, while Ito (1975) found a wider range of correlation coefficients for different teeth, ranging from 0.107 to 0.698. Ito (1975) also reported a mean error of ± 7.3 years from this method. Philippas (1961) found a correlation coefficient of -0.75 between the height of the pulp chamber in the first molar and chronological age.

Solheim (1992) analyzed 1000 extracted teeth of known-age from the states of Washington and Oregon. The sample ranged in age-at-extraction from 14-99 years. All tooth types, except molars, were represented in the sample, which consisted of 100 teeth from each tooth type, 50 from each side. Teeth were extractions from dental clinics, forensic cases, and anatomy classes. The purpose of their study was to 1) analyze different methods of measuring secondary dentin deposits, 2) analyze the relationship between secondary dentin deposits and chronological age, 3) determine if secondary dentin deposits are applicable to use solely as an indicator of age, 4) determine if sex, reason for extraction, and periodontal disease influence secondary dentin deposits, and 5) employ multiple regression analysis for each tooth.

Secondary dentin deposits were measured and analyzed under a stereomicroscope with an attached eyepiece. Teeth were sectioned and ground following the half-tooth technique (Solheim 1984) applied to the mid-pulpal area of the labial-lingual plane. Three scoring methods were compared: Gustafson's (1947), Dalitz's (1962), and Johanson's (1971), where scores were doubled to avoid half units. Teeth were marked on the labial surface at the cej, the mid-root, the mid-point between the cej and the mid-root, and the mid-point between the mid-root and the apex. The total widths of the tooth and pulp were measured at these four locations. In the case of bifurcated roots, the mean measurement was used in analysis. Correlations were made between chronological age and tooth age, which is the chronological age minus the mean age of root completion.

Since a paired t-test yielded no significant difference between the right and left sides, only the right side was used in further analysis. There was no significant difference between tooth age and chronological age. Although Gustafson's (1947) and Dalitz's (1962) scoring methods both yielded strong correlations with chronological age, Johanson's (1971) method produced the highest correlation between secondary dentin deposits and chronological age. Maxillary teeth produced slightly higher correlations than mandibular teeth of the same type. Maxillary first premolars yielded the highest correlation coefficient, 0.74, followed by maxillary canines, 0.72, and mandibular canines, 0.67, from Johanson's (1971) method.

The strongest correlation between the ratio of the sum of the total root widths and sum of the pulp widths was found in the maxillary lateral incisors and mandibular second premolars, -0.81 and –0.61, respectively. The cervical margin produced the strongest correlation with age in the mandibular central incisors, r = -0.74. A strong negative correlation was also produced for the area of coronal pulp, r = -0.49 to -0.72, with the maxillary central incisors producing the latter value. From multiple regression analysis, a strong correlation was produced with chronological age, r = 0.70 to 0.83, where the highest correlations were produced with the maxillary and mandibular central incisors. The weakest correlations were from premolars.

Solheim (1992) found that the pulp width at the cervical margin was most strongly correlated with chronological age and this correlation decreased towards the apex. The author notes that the size of the pulp is influenced by the size of the root. He also noted that the border between primary and secondary dentin was difficult to discern, therefore, he suggested that pulp width could be used as an indirect measure of secondary dentin deposits. The author concluded that this single indicator is a relatively reliable method to estimate age-at-death with comparable correlations with chronological age as he found with color (Solheim 1988) and apical translucency (Solheim 1989).

Kvaal *et al.* (1994) examined the relationship between the deposit of peritubular dentin and chronological age. They analyzed 58 mandibular central and lateral incisors, which were extracted for identification purposes (N=5), periodontal disease (N=21), caries or periapical infection (N=9) and orthodontic purposes (N=15). Eight teeth were omitted due to technical reasons. The sample ranged in age from 31-89 years, with mean age-at-extraction of 59.6 years. A notch was made at mid-root on the mesial and distal surfaces. The teeth were then ground parallel to the lingual root surface, cleaned in an ultrasonic bath in a solution of 0.5% sodium hypochlorite, dehydrated, and sputter-coated with gold palladium alloy to a thickness of approximately 30nm. Two observers analyzed the teeth, with one observer repeating measurements for intra-observer variation. The teeth were analyzed under a scanning electron microscope (SEM), where the number of dentin tubuli was counted in the central area between the mesial and distal notches at mid-root at 2000X magnification with the aid of a counting grid. The actual area analyzed was 43ìm x 28ìm. Three areas were measured and the average measurement was used in the analysis. The diameters of the tubuli were measured with vernier calipers.

Peritubular dentin could not be distinguished from intertubular dentin; therefore, the teeth were etched in 35% orthophosphoric acid for 2 minutes, which dissolved the peritubular dentin. Teeth were then rinsed under tap water and reanalyzed. The second set of measurements were subtracted from the original measurements to obtain the thickness of the peritubular dentin.

Although the number of dentin tubuli decreased with age, it did not yield a significant correlation with age. No occluded tubuli were found in individuals less than 45 years. The thickness of the peritubular dentin did yield a significant correlation with chronological age, r = 0.51, $p < 0.01$ (Kvaal *et al.* 1994). Teeth extracted due to caries yielded the highest correlation with age, r = 0.88, with teeth extracted for other orthodontic reasons yielding the next highest, r = 0.66. Periodontal disease was found to influence the peritubular deposit in the mid-root. No intra-observer variation was produced, but inter-observer variation produced a significant, although slight, difference. The authors concluded that peritubular thickness was a better indicator of age than dentin tubuli diameter and stated that this method is applicable for use in forensic cases and archaeological material.

2.5 Dental Radiographs

Radiographs are an excellent source for assessing age-related changes in the dentition and have been used to assess Gustafson's method (Matsikidis and Schultz 1982), secondary dentin deposits (Morse *et al.* 1993, Kvaal and Solheim 1994), and proportions of the tooth (Kvaal *et al.* 1995). Techniques that utilize dental radiographs are completely non-destructive, offer simple procedures, and can be used on forensic and archaeological material as well as living individuals (Kvaal *et al.* 1995). In addition, taking dental radiographs is common practice in dental clinics which offers a large resource.

Kvaal *et al.* (1995) analyzed 100 periapical dental radiographs from individuals who ranged in age from 20-87 years, with a mean age of 42.6 years. Their goal was to assess the relationship between age and pulpal size in a non-destructive manner without extractions. In their preliminary study of 20 radiographs, they found a strong correlation between mandibular lateral incisors, canines, and first premolars and maxillary central and lateral incisors and second premolars with chronological age. There was no significant difference between the right and left sides. Only individuals where measurements could be made on all six teeth listed above were included in their main study. Several measurements were taken directly from the radiographs, which included: maximum tooth length, pulp length and root length on the mesial surface from the cementoenamel junction (cej) to the apex of the root, root width and pulp width. Measurements were taken with vernier calipers except for the root and pulp width measurements which were taken at three points, at the cej, at mid-root, and at the mid-point between these two with a stereomicroscope with a measuring eyepiece. The authors analyzed four ratios: tooth/root length, pulp/root length, pulp/tooth length, and pulp/root width at the three points mentioned above. All ratios yielded a significant correlation with age except tooth/root length. Tooth width was found to have a higher correlation to age than length, which has also been noted in other studies (Prapanpoch *et al.* 1971, Kambe *et al.* 1991, Kvaal and Solheim 1994). In Kvaal *et al*'s (1995) study only maxillary central incisor yielded a better correlation between length and age.

Kvaal *et al.* (1995) concluded that taking measurements from periapical dental radiographs is a reliable and useful aging technique because it produced significant relationships between the dental observations and chronological age and it is a non-destructive method, with many applications. The authors noted two problems with this research: sampling bias, where individuals were mainly from lower-socioeconmic backgrounds and few older individuals retained the six teeth, and the inability to distinguish between secondary dentin and tertiary dentin on the radiographs.

2.6 IBAS Image Analysis

López-Nicolás *et al.* (1990, 1993, 1996) provided a method of estimating age-at-death from teeth by analyzing pulpal dimensions, apical translucency, secondary dentin deposits, and crown length with computer-assisted image analysis (IBAS). Their goal was to overcome limitations of previous methods, particularly small sample sizes and subjectivity of assessments. These researchers analyzed polished, longitudinal thin sections to quantify parameters with a significant correlation with age. Parameters were measured with an IBAS-I semiautomatic image analysis system (Kontron). The IBAS-I image analysis system was connected to a video camera which transmitted the tooth image directly to a computer monitor.

They found that pulp thickness at the cej, secondary dentin deposits, translucency, complete pulp area, crown length, and periodontal recession produced a goodness of fit correlation coefficient of 0.425, which explained 18.1% of the variance. They concluded that translucency of the root was the best indicator of chronological age, explaining 12.45% of the variance. The next best indicators were secondary dentin deposits and complete pulp area and they reported that canines produced the best correlation with age using these dental features. Their results yielded no significant difference between the sexes or dental arch.

2.7 Cementum Annulation Apposition

Cementum is a mineralized, avascular connective tissue, varying in thickness across the length of the root, coating the roots of teeth located between the dentin and periodontal ligament (Schroeder 1991). The primary function of cementum is to anchor the collagen fibers of the periodontal ligament to the tooth, thus anchoring the tooth to the alveolar bone (Schroeder 1991). Cementum also performs adaptive and reparative processes to orthopedic forces and trauma to the root (Schroeder 1991). Cementum is laid down in two forms, acellular and cellular, of which, five types of cementum can be distinguished in human teeth: acellular, afibrillar cementum; acellular extrinsic fiber cementum; cellular mixed fiber cementum; cellular intrinsic fiber cementum; and intermediate cementum (Schroeder 1991, Kagerer and Grupe 2001). Intermediate cementum, which is acellular, lines the entire root in a very thin sheath. An additional, thicker layer of acellular cementum is laid at the cervical region of the tooth, while cellular cementum is laid down on the remaining one-half to two-thirds of the tooth (Schroeder 1991).

Broomell (1898) was the first to note that the correlation between cementum thickness and chronological age was independent of functional stresses. Azaz *et al.* (1974) analyzed 60 impacted, non-pathological permanent premolars and canines (9-70 years of age) and 10 erupted non-pathological premolars and canines (9-75 years of age) to determine whether the cementum apposition was a result of functional stresses or age. They took longitudinal thin sections and measured the thickness of the cementum band at the cervical, middle and apical thirds of each tooth. Hypercementosis was observed in 14 of the impacted teeth. Their results yielded a correlation coefficient of 0.872 with age from the cervical margin, and 0.860 from the middle third of the root. The apical third of the root could not be evaluated because several roots were still developing. The authors concluded that interdependence exists between thickness of cementum and age and therefore, cementum is directly related to aging of the tooth.

The first age-at-death estimates utilizing cementum apposition measured the thickness of the band of cementum in longitudinal thin sections after Gustafson's methodology (Gustafson 1947, 1950, 1955, Johanson 1971, Azaz *et al.* 1974, Maples 1978, Nitzan *et al.* 1986, Kashyap and Koteswara Rao 1990, Solheim 1993). In mammalian aging studies, incremental cementum annuli were counted from transverse thin sections. Stott *et al.* (1982) were the first to apply this methodology to human teeth. Incremental bands of cementum are laid down in alternating light and dark bands:

> "One pair of dark and light bands each constitutes one incremental line, the number of which – added to the year of eruption of the respective tooth – results in the histological age of the individual under study" (Kagerer and Grupe 2001:75).

Each pair of light and dark bands is considered to equate to one year of life (Stott *et al.* 1982, Kagerer and Grupe 2001). Counting of cementum annuli has been very reliable and accurate to provide estimates of age for seasonal animals, such as, moose (Sergeant and Pimlott 1959, Gasaway *et al.* 1978), seal (Mansfield and Fisher 1960), caribou (McEwan 1963), deer (Low and Cowan 1963, Gilbert 1966, Ransom 1966, Douglas

1970, Lockard 1972), bison (Novakowski 1965), bear (Free and Sauer 1966, Marks and Erickson 1966, Sauer *et al.* 1966, Stoneberg and Jonkel 1966), coyote (Linhart and Knowlton 1967), elk (Keiss 1969), bat (Linhart 1973), fox (Monson *et al.* 1973), badger (Crowe and Strickland 1975), otter (Tabor and Wright 1977), squirrel (Adams and Watkins 1967, Fogl and Mosby 1978), and common marmoset (Stott *et al.* 1980). Differences have been noted between human cementum annuli and other mammals: "Compared to other mammalian teeth, the incremental lines in human teeth are much closer together and are more numerous" (Kvaal and Solheim 1995:225). Several factors have been attributed to the cause of this "annual" apposition, such as seasonal changes, "UV-radiation dose, climatic parameters, differential food quality, and hormonal status" (Kagerer and Grupe 2001:75).

Several researchers followed this procedure of counting cementum annuli in humans to estimate age-at-death, instead of measuring the thickness of the band (Stott *et al.* 1982, Naylor *et al.* 1985, Charles *et al.* 1986, Condon *et al.* 1986, Lipsinic *et al* . 1986, Miller *et al.* 1988, Groâkopf 1989, Solheim 1990, Stein and Corcoran 1994, Kvaal and Solheim 1995, Renz *et al.* 1997, Geuser *et al.* 1999, Wittwer-Backofen 2000, Jankauskas *et al.* 2001, Kagerer and Grupe 2001, Wittwer-Backofen and Buba 2002, Wittwer-Backofen *et al.* 2004). Conflicting results on the reliability and accuracy of counting cementum annuli have been reported. Several researchers reported problems with this technique and report that it is an unreliable technique to estimate age-at-death (Lipsinic *et al.* 1986, Lucas and Loth 1986, Miller *et al.* 1988), while others state that it is a moderately reliable technique (Charles *et al.* 1986, Condon *et al.* 1986, Stein and Corcoran 1994), and others still, claim that it is a highly reliable method, and that poor results are produced by incorrect procedures, rather than inherent flaws with the method itself (Stott *et al.* 1982, Groâkopf 1989, Wittwer-Backofen 2000, Kagerer and Grupe 2001, Wittwer-Backofen and Buba 2002, Wittwer-Backofen *et al.* 2004). In addition, several authors have reported that cementum annuli aging is more reliable and produces higher correlations with age in the younger age groups (Lipsinic *et al.* 1986, Condon *et al.* 1986, Miller *et al.* 1988, Stein and Corcoran 1994, Kvaal and Solheim 1995); thus, studies with a lower mean age will produce higher correlations (Kvaal and Solheim 1995).

Conflicting results are also reported on the effects of periodontal disease and cementum annulations. Several authors report that periodontal disease increases the error rate of this method (Condon *et al.* 1986, Kvaal and Solheim 1995). Some go as far as to say that cementum annuli production is halted by periodontal disease (Kagerer and Grupe 2001), while other authors report that periodontal disease has no effect on cementum annuli (Großkopf *et al.* 1996, Wittwer-Backofen 2000, Wittwer-Backofen and Buba 2002, Wittwer-Backofen *et al.* 2004). Issues surrounding the effects of hypercementosis have not been addressed (Kagerer and Grupe 2001). Doubling cases, which refers to observing twice as many incremental lines as predicted, have been reported by several authors (Condon *et al.* 1986, Stein and Corcoran 1994, Jacobshagen 1999, Wittwer-Backofen 2000). All methods available for age estimation should be utilized in order to detect doubling cases (Kagerer and Grupe 2001).

Stott *et al.* (1982) were the first to analyze and count cementum annulations to estimate age-at-death in humans. They examined 10 teeth from 3 cadavers. Several procedures were carried out. Mineralized transverse thin sections were cut with a low impact, diamond blade saw. The first cut removed 2mm from the apical root. Sections measuring 100-150 ìm were then taken from that apical 2mm point to the neck of the tooth. Sections were rinsed in distilled water, stained, and dehydrated. Bright field microscopy and black and white photography were used to analyze the cementum annuli. Only dark lines were counted and the number of lines observed was added to the eruption age of the tooth. From their small sample the authors concluded that this is a very good method for estimating age-at-death. The three individuals in the analysis were 57, 67, and 76 years of age. Estimated ages were 57.5-58, 63-70, and 76.5-78 years, respectively.

Naylor *et al.* (1985) investigated different procedures that would aid in the enhancement of the cementum annuli. They took transverse thin sections from the apex of the root to the neck. Sections were taken at 50, 75 and 100 ìm thicknesses. Sections were dehydrated, cleaned in an ultrasonic bath, stained, dehydrated again and mounted. Several different stains were used to aid in the enhancement of the cementum annuli. Cresyl fast (echt) violet in 70% alcohol faired best. The authors also found that counts were more accurate when taken off of the photograph rather than reading directly from the microscope.

Lipsinic *et al.* (1986) tested Stott *et al.'s* (1982) method utilizing various stains. They analyzed 31 non-pathological, maxillary first premolars of known age. Undecalcified sections contained many artifacts, therefore, rendering lines difficult to observe. Better results were obtained using decalcified teeth which were stained with double hematoxylin and eosin. Three observers viewed the sections under light microscopy at 100X. At least two sections were viewed per tooth and the cementum annuli counts were averaged for the three observers. The mean eruption age was added to the mean line counts to obtain the estimated age.

The authors obtained a correlation coefficient of 0.51, implying that only 26% of the variation in the number of lines was explained by age. They did note that if one tooth was eliminated the correlation coefficient increased to 0.8447. They also noted that age bias occurred with the older individuals. Lipsinic *et al.* (1986) concluded that cementum annulation counts are not a reliable method to estimate age-at-death in humans.

Two sister studies, Charles *et al.* (1986) and Condon *et al.* (1986) evaluated different sectioning techniques (mineralized versus demineralized), intra- and inter-tooth variability, and intra- and inter-observer error. Ten transverse thin sections, 80 ìm thick, from mandibular canines were analyzed following the method outlined by Stott *et al.* (1982). The sample consisted of 42 mandibular canines and first premolars extracted from cadavers and 10 mandibular first premolars extracted from dental patients. These were demineralized and sectioned longitudinally (7ìm thick). In the latter, micrographs were taken at 400X.

At this point in the research, the authors noted that not all teeth produced countable sections and high intra-observer error was reported. In addition, there were four maxillary second premolars which yielded cases of doubling, which all involved male subjects, 30-59 years old. The authors also reported inter-tooth variability, which involved canines consistently producing higher counts than premolars from the same individual. On average, canines produced 10 more rings than noted in premolars. They also noted that demineralized sections were clearly preferable and that the primary factor for inaccuracy was due to sections being mineralized. Charles *et al.* (1986) stated that longitudinal thin sections should not be used to count cementum annuli because lines could be superimposed on one another, leading to inaccurate line counts and thus, inaccurate age estimates. They reported a 5% interobserver error and 2% intraobserver error utilizing cementum annuli counts which is more reliable than error found with the auricular surface and the pubic symphysis.

In Condon *et al.* (1986), the authors reported a correlation coefficient between age and cementum annuli of 0.78 and a standard error of 9.6 years. Males produced a higher standard error from which the authors concluded that sex specific equations should be used. Although the authors report that over all cementum annuli aging is an unbiased method, they state that individuals are consistently over aged until the 4^{th} decade. They found that overall inaccuracy was 6 years, without bias, and concluded that cementum annuli aging is the best single indicator method.

Miller *et al.* (1988) analyzed 100 single-rooted teeth, from 100 individuals ranging in age from 9-78 years, with a mean age of 55.3 years and a standard deviation of 13.1 years. They took both longitudinal and transverse thin sections of varying thickness and determined that 350ìm transverse thin sections taken from the mid-point of the root produced optimal counting. The section that produced the most rings per tooth was photographed with black and white film. Cementum annuli were counted on the computer screen under 90x magnification. Four observers counted the cementum annuli and their average count was added to the mean eruption age to obtain the estimated age-at-death. Only 71% of the sample yielded countable sections. In sections where annuli were not countable, the authors noted that these annuli were obscured, indistinct, or not visible. Their results yielded a 5.7% accuracy within 5 years of the actual age, but over

85% of the sample yielded age estimates that were more than 10 years off from the actual age. They noted that this method was more accurate for individuals 35 years and younger. They concluded that cementum annuli aging is neither a reliable nor appropriate aging method for humans:

> "The analysis of data from 71 specimens using this method indicated that determining the chronological age of humans from cemental annulations in teeth is not possible" (Miller *et al*. 1988:142).

Groâkopf (1989) analyzed cremated teeth from a Pre-Roman Iron Age site located in Schleswig Holstein, Germany. She embedded the teeth in Biodur ® resin and took transverse thin sections, which were then ground to 100 ìm. Sections were then cleaned, etched, neutralized, cleaned again, and dehydrated. The author noted that the cementum annuli could not be seen as well as in normal, modern teeth, but concluded that cementum annuli aging was applicable to cremated teeth:

> "…incremental lines can also be demonstrated in cremated teeth. Due to the fact that the cremated remains are altered extensively with respect to morphologic and structural features, this seems to be a surprising result. However, it corresponds to microradiographic results, which demonstrate the preservation of the micromorphologic distribution of the mineral content even after thermal influences in bones" (Groâkopf 1989:310).

Stein and Corcoran (1994) analyzed 52 extracted teeth from 42 individuals. Longitudinal and transverse thin sections were taken. The authors noted that longitudinal sections allow for the entire root surface to be observed and that transverse sections allow for a series of observations to be observed. They concluded that transverse sections were easier to replicate in addition to eliminating distortions caused by longitudinal sections. They stated their results were better than those reported by Lipsinic *et al.* (1986). The authors reported 3 cases of doubling and that ages above 55 were subject to aging bias, in which they were underaged. Individuals younger than 55 yielded accurate age estimates and the authors concluded that cementum annuli aging is a, “moderately reliable means to estimate the age in humans” (Stein and Corcoran 1994:270).

Kvaal and Solheim (1995) analyzed cementum annulation apposition in order to determine 1) the correlation between cementum annuli and chronological age, 2) if one cemental ring corresponds to one year of life, 3) the best tooth type, 4) a formula for estimation of age-at-death, and 5) if results are reproducible. They analyzed 95 extracted teeth, 25 from Washington State, USA and 68 from Norway, in which 4 were extracted from cadavers (group I), 28 had periodontal disease (group II), 24 had caries and related diseases (group III), and 39 were extracted for orthodontic purposes (group IV). Individuals ranged in age from 13-89 years, with a mean age of 52.6 years. Instead of adding the number of cementum annuli to mean eruption age as other authors have done, Kvaal and Solheim (1995) added cementum annuli counts to the mean age of root completion, which they called “tooth age”.

Teeth were demineralized, washed, and embedded in paraffin wax. Four to five longitudinal thin sections, 5-7ìm thick were taken after the crown and cervical portion of the tooth were removed. Sections were stained with cresyl violet and analyzed using a fluorescence microscope, which caused the light bands to fluoresce red, while the dark bands did not. Lines were counted on the computer screen. Three sections per tooth were counted, with the highest count recorded (method 1). Two weeks later, counts were taken again, but cellular and acellular cementum were analyzed (method 2).

Method 1 produced a correlation coefficient of 0.84 between the number of lines and tooth age and a correlation coefficient of 0.84 between the number of lines and chronological age. Method 2 yielded a correlation coefficient of 0.73 between the number of lines and tooth age and 0.74 between the number of lines and chronological age. A significant difference was produced between observers, but intraobserver error was not significant. Sex did not yield a significant difference. Mandibular second premolars produced the highest correlation between lines and chronological age.

Kvaal and Solheim (1995) stated that higher correlations between line counts and age were produced in the younger age groups and they concluded that:

> "The present study indicates that estimates based on the number of incremental lines give only an inkling of the age for individuals over 50 yr while for those above 30 yr the results…should be interpreted cautiously" (Kvaal and Solheim 1995:228).

Renz *et al.* (1997) analyzed premolars from clinical extractions and followed procedures outlined by Stott *et al.* (1982). They took transverse thin sections from the middle third of the root and ground them to 100-150ìm thick. They analyzed the sections and then reanalyzed the sections stained with cresyl violet. Four different methods were employed to analyze the thin sections: bright-field light microscopy (LM), bright-field LM and confocal laser scanning microscopy (CLSM), bright-field LM and transmission electron microscopy (TEM), and bright-field LM and electron-disperse X-ray analysis (EDX) in a scanning electron microscope (SEM). The authors found that staining had no effect on the visibility of the cementum annuli. They also noted that lines could not be seen in every section:

> "Focus-plane plays an important role: Cemental rings can be

> seen only in a small focus range, often superimposed by other microstructures that appear more grandular. The thickness of the polished, ground sections, the medium in which the sections were examined, the selected focus-plane, and the adjusted "illumination" were the main factors affecting visibility of cemental annulations" (Renz *et al.* 1997:474).

They also reported that very few lines were visible after sections were dried and that visibility increased after dehydration in EtOH and infiltration with Spurr's resin. Cementum annuli were not visible with the EDX, therefore rendering this type of analysis ineffective. They concluded that the CLSM was better than the LM, although the same features were seen with both.

Kagerer and Grupe (2001) analyzed extracted teeth in order to address whether pathological conditions affect cementum apposition, and to determine if life-history parameters can be observed in the lines. Individuals consented to participate in this study and filled out a detailed questionnaire, which included:

> "pregnancies, malnutrition, pathologies of the mineral metabolism, renal disorders, other metabolic dysfunctions, surgeries and hereditary anomalies of teeth and jaws, and certain life-style parameters like smoking habits, frequent long distance travels, regular medication, etc." (Kagerer and Grupe 2001:76).

Ninety-one roots from 80 teeth were sectioned, which included 14 incisors, 8 canines, 24 premolars, and 34 molars. The crown was removed and transverse thin sections, 70ìm thick, were taken from the cervical margin to the root apex. A minimum of 4 images and a maximum of 19 were taken with a Nikon camera N905. Image adjustment was conducted in Adobe Photoshop 4.0. The number of cemental lines was counted and added to the mean eruption age according to sex. A mean difference of 5.7 years was obtained. When pathological specimens were eliminated the mean difference was ± 2-3 years. The authors found that pathological effects did increase error, but that this method offers more precise age estimates than macroscopic assessment of the skeleton. The authors state that all methods available for age estimation should be utilized to detect doubling cases. Kagerer and Grupe (2001) noted several advantages of cementum annuli aging: this method offers a very low mean error, as noted above, pregnancies, renal disease and skeletal trauma could be detected in the cementum annuli, and this method works independent of reference samples, except for mean eruption age.

Wittwer-Backofen *et al.* (2004) analyzed the largest sample, which consisted of 433 dental extractions of single-rooted teeth. Seventy teeth from 63 individuals did not produce countable lines, which decreased the sample to 363 teeth, of which 226 were from male patients and 137 were from female patients. The teeth were stained in order to assess the amount of periodontal recession, which was measured on all four surfaces of the tooth. The crown of each tooth was embedded and non-decalcified, transverse thin sections, 70-80 ìm, were taken from the apical third of the root. Sections were analyzed under bright-field transmitted light at 200-400X, and images were scanned into a computer database. Images were counted on the computer screen and mean line count was added to mean eruption age to estimate age. The approximate mean error was ± 3 years with a difference of more than 5 years being produced in only 2.2% of cases. Aging bias was observed between males and females in maxillary canines and mandibular second premolars. The authors noted that although female individuals over 70 years were underestimated in age, there was no significant influence of sex, age, periodontal disease, or tooth type. Central incisors yielded the lowest mean error of ±2.5 years.

2.8 Root Color

Several researchers have noted that teeth become darker with age (Bhussry and Emmel 1955, Biedow 1963, Rheinwald 1966, Tsuchiya 1973, Ten Cate *et al.* 1977, Solheim 1988, Lackovic and Wood 2000). Color change has been noted in both enamel and dentin. Several factors have been attributed to color change noted in teeth, such as an increase in nitrogen in enamel (Bhussry and Emmel 1955), change in the refractive index between enamel and saliva, as a result from fracturing (de Jonge 1950), and deposits of blood products in dentin (Rheinwald 1966). Although the assessment of color change is a subjective technique, forensic odontologists have found it to be a reliable and useful method to estimate age-at-death (Ten Cate *et al.* 1977, Solheim 1988, Lackovic and Wood 2000).

Ten Cate *et al*. (1977) analyzed root color change as an indicator of chronological age. In their study, the color of root dentin was compared to known-aged standards. The amount of change was assessed and the teeth were arranged in 5-year age cohorts. All age estimates were within ± 10 years of actual age. Sex did not yield a significant difference. The authors concluded that this was a useful method, but that training was required to assess the degree of color change.

Solheim (1988) analyzed 1000 extracted teeth of known-age from Washington and Oregon States, which ranged in age-at-extraction from 14-99 years. All tooth types except molars were represented in the sample, which consisted of 100 teeth from each tooth type, 50 from each side. Teeth were extractions from dental clinics, forensic cases, and anatomy classes. Crown color was estimated by comparing the tooth to a dental shade guide in both a wet and dry state under a fluorescent light. Three different color guides were utilized: Trubyte, Bioform, and Dentsply International. The root was then ground approximately 0.5mm along the longitudinal axis, in order to remove the cementum and to expose the root dentin. The reflected light was measured at the mid-root level with the aid of a super Speedmaster reflection densitometer. As with the crown, readings were also taken in a wet and dry state. From multiple regression analysis, correlation coefficients ranging from 0.77 to 0.87 were obtained. In the crown, a 5-grade scale was found to yield the highest correlations with chronological age, except for maxillary canines. The weakest correlation was found between the Trubyte dental shade guide and age, as compared with the other methods of measuring color. The author found that visually ranking dentin color and using the spectophotometer increased the correlation with age, although on an individual basis the visual assessment yielded a higher correlation with age than spectophotometry. He noted that use of yellow reflection, rather than total reflection, improved the correlation with the spectrophotometry. Dry assessment yielded a significantly better correlation than assessment of color in the wet state, independent of which method was being utilized.

There was no significant difference between the right and left sides, between chronological age and tooth age (age minus age at root completion of the tooth), reason for extraction, or between the sexes. There was a weak association between darkness of the tooth and post-mortem versus pre-mortem sampling which was significant for a number of different tooth types. The author noted that several factors caused discoloration, which was different from the color change he was assessing to estimate age. Discoloration was a result of pulp necrosis and tetracycline staining. In addition, a reddish/purple discoloration was noted in deceased individuals. The author concluded that assessment of dental color as an indicator of age is a reliable method:

> "…the correlation was found to be stronger than the correlation reported for most other variables which have been advocated in methods for age estimations, except for translucency measurements… " (Solheim 1988:118).

Lackovic and Wood (2000) assessed root color change in known-age and sex extracted teeth to estimate chronological age. They had three main goals: 1) to evaluate the reliability and applicability of tooth root color change as an indicator of age, 2) to determine if a significant difference existed between anterior (non-molar teeth) and posterior (molar) teeth and surfaces, and 3) to determine if a linear relationship exists between tooth root cyan, magenta, yellow, and black coloration and age. To test these hypotheses, three experiments were conducted.

The first experiment analyzed 21 teeth from 2 age cohorts, 20-24 year old females and 70-74 year old females, in which the authors measured 6 points for percentage of yellow saturation. Their results indicated that the mesial surface from the 20-24 year old females was significantly different from the other three surfaces in percentage of yellow saturation, while the mesial surface was significantly less saturated. In the 70-74 year old females, a significant difference was found between all surfaces, except the distal surface. To assess differences between anterior and posterior teeth, 21 teeth, 11 molars and 10 non-molars, were analyzed from the 20-24 year old females. The results produced a significant difference on the buccal-lingual surfaces between the molar and non-molar teeth, therefore yielding a significant difference between anterior and posterior teeth. In addition, 40 teeth, 20 molars and 20 non-molars representing both sexes, were analyzed from each 5-year age cohort, starting at 15-19 year olds through 80-84 year olds. Four points were assessed on the teeth to assess the amount of color change. The results from the third test yielded a positive increase in the percent of measured color with age. The highest correlation for males and females was cyan and chronological age, r = 0.93, with the next highest being magenta, r = 0.93 and 0.81 for males and females, respectively.

Lackovic and Wood (2000) point out several advantages of this aging method. This method does not require tedious lab techniques – it can be performed with minimal dental anatomy knowledge, and it is a non-destructive and inexpensive method. Some disadvantages include that the teeth must be extracted and taphonomic conditions may influence the coloration of the tooth root. The authors conclude that this aging method is a reliable and useful method:

> "With the lowest correlation value of 0.806 and the majority of the values above 0.9, these data clearly indicate an important and indisputable relationship between root colouration and age and from a forensic dental viewpoint this correlation could prove to be quite useful when the age of found remains needs to be estimated" (Lackovic and Wood 2000:41).

2.9 Aspartic Acid Racemization

All components of teeth have been evaluated for their usefulness of aspartic acid racemization in estimating age-at-death: enamel (Helfman and Bada 1975, Ohtani and Yamamoto 1992), dentin (Helfman and Bada 1976, Shimoyama and Harada 1984, Masters 1986, Ritz *et al.* 1990, Ohtani and Yamamoto 1991, 1992, Ritz *et al.* 1993, Mörnstad *et al.* 1994, Carolan *et al.* 1997), and cementum (Ohtani 1995, Ohtani *et al.* 1995). This process assesses the changes in living tissue over time:

> "The racemization of amino acids is a reversible first-order reaction, which is relatively rapid in living tissues that have a slow metabolic rate. The amino acids composing proteins are L-enantiomers. However, over the course of time, amino acids undergo racemization with an increased ratio of D-enantiomers, metamorphosing into a racemate (King and Bada 1979). Aspartic acid shows a high racemization reaction rate and is considered to provide useful information on changes occurring in living tissues over time" (Ohtani 1995: 805).

Ohtani (1995) evaluated the correlation of the D- and L- aspartic acids in cementum with chronological age, the rate of the racemizing reaction, and compared the results with those obtained from similar analysis with enamel and dentin. They analyzed 32 teeth, comprised of 8 central incisors, 8 lateral incisors, 8 first premolars and 8 second premolars, which were from known-age and sex extractions. Longitudinal thin sections, 1mm in thickness, were taken from each tooth and the layer of cementum was isolated from the sections, with a surgical blade.

Higher correlations were produced between the incisors and chronological age, than the premolars, although the difference was not significant: r = 0.997 for lateral incisors, r = 0.991 for central incisors, r = 0.988 for first premolars and r = 0.984 for second premolars. Cementum yielded the fastest reaction, followed by dentin and then enamel. Overall, dentin had the highest correlation with age, followed by cementum and then enamel, r = 0.992, r = 0.988, and r = 0.961, respectively. The authors concluded that aspartic acid racemization is a precise and useful method to estimate age-at-death.

Master (1986) evaluated the effects of postmortem changes to aspartic acid racemization. She analyzed 6 dentin sections from individuals who ranged in states of preservation: 4 teeth were extracted from recently deceased individuals, 1 tooth was removed from skeletal remains which were exposed on the surface for 51 days in February and March, and 1 tooth was from an individual whose remains were exhumed after 8 years of interment. For three cases, actual age was not known, so comparison was made between the D/L ratio and the estimated dental age (maturation and attrition).

A correlation coefficient of 0.999 was obtained when one individual was removed from the analysis. The tooth from the exposed skeletal remains yielded a higher age estimate than actual age (actual age was 26 years; aspartic acid racemization age range was 35-43 years). This individual was retested, but the same D/L ratios were produced. The author noted that the remains were exposed to fluctuating temperatures and precipitation prior to their discovery, which may have increased the rate of racemization. She concludes that aspartic acid racemization is a more accurate method of estimating age-at-death than other skeletal methods, especially in older individuals, but notes that postmortem conditions may effect the racemization rate. She suggests that further studies be conducted with a larger sample to test for such effects.

2.10 Periodontal Recession

Periodontosis, or gingival recession, is caused by "the degeneration of the soft tissue surrounding the tooth (as) it progresses from the neck to the apex of the root" (Lamendin *et al.* 1992:1374) following the alveolar bone recession. Although periodontal recession has a positive correlation with age, there are several factors that can contribute to the periodontal recession other than age, including inflammation of the periodontium (van der Velden 1984), poor dental hygiene (Foti *et al.* 2001, Prince and Ubelaker 2002), and extrinsic irritation (Foti *et al.* 2001).

Several researchers note the difficulty in assessing the amount of periodontal recession in modern and archaeological teeth (Gustafson 1950, Maples 1978, Foti *et al.* 2001), but Lamendin *et al.* (1992) state that the amount of periodontal recession can be assessed because it “appears as a smooth and yellowish area below the enamel and darker than it but clearer than the rest of the root” (Lamendin *et al.* 1992:1374). In addition, several authors have noted that periodontal recession has a very weak correlation with age (Maples 1978, Solheim 1992, Borrman *et al.* 1995) and others have stated that periodontal recession cannot be used to estimate age-at-death by itself (Foti *et al.* 2001). Solheim (1992) has conducted the only research which tests the usefulness of periodontal recession alone to estimate age. He analyzed 1000 intact teeth and measured from the cej to the most coronal portion of the periodontal ligament. He found a significant correlation between age and periodontal recession, although it was considered a very weak correlation.

2.11 Translucency of the Root

Paultauf was the first to describe the phenomenon of dental transparency in 1903 (Marcsik *et al.* 1992) and this feature has been used to estimate age-at-death for nearly a century (Sengupta *et al*. 1998). A direct relationship was discovered between chronological age and amount of transparency; as age increases, the amount of transparency in the tooth root also increases (Gustafson 1950, Marcsik *et al.* 1992, Hillison 1996). The forensic pathologist, Professor Lacassagne, was the first to utilize apical translucency as an indicator of chronological age in 1889 (Johanson 1971, Wilson 1989, Russell 1996).

This physiological feature does not typically appear before age 18, and is the "result of gradual mineralization of the peritubular dentine which leads eventually to obliteration of the dentine tubules" (López-Nicolás *et al.* 1993:2). Translucency of the root should not be confused with sclerotic dentin found in the crown, which is a result of pathological conditions (Pindborg 1970, Mendis and Darling 1979). Vasiliadis *et al.*(1983a) compared apical translucency in pathological and non-pathological teeth and concluded that the development of translucency of the root is independent of pathological conditions.

Several authors have reported that translucency of the root is the best dental indicator of age and most closely correlated to chronological age (Gustafson 1950, Miles 1963, Bang and Ramm 1970, Johanson 1971, Maples 1978, Metzger 1980, Solheim and Sundnes 1980, Kósa *et al.* 1983, Vasiliadis *et al.* 1983, Sognnaes *et al.* 1985, Lorensten and Solheim 1989, Solheim 1989, López-Nicolás *et al.* 1990, 1993, 1996, Sengupta *et al.* 1998, 1999, Ajmal *et al.* 2001). However, translucency apposition may be influenced by genetic, environmental, and cultural factors (López-Nicolás *et al.* 1996).

Translucency of the root can been analyzed in longitudinal thin sections (see Gustafson 1947, 1950, 1955, Dechaume *et al.* 1960, Nalbandian *et al.* 1960, Johanson 1971, Solheim and Sundnes 1980, Vasiliadis *et al.* 1983, Whittaker and Bakri 1996, Sengupta *et al.* 1998, 1999) or on intact teeth (see Bang and Ramm 1970, Colonna *et al.* 1984, Solheim 1989, Drusini *et al.* 1991, Lamendin *et al.* 1992, Prince and Ubelaker 2002, Sarajliæ *et al.* 2003). Translucency of the root can be seen macroscopically, but is enhanced with the aid of a lightbox. There are several advantages of taking measurements directly from intact teeth: it is non-destructive, less expensive and less time consuming than other methods and it is not necessary to have a complete knowledge of dental histology.

Quantifications of apical translucency have been suggested in several different formats: subject indices (Gustafson 1947, 1950, 1955, Johanson 1971), direct measurement from the apex towards the cej (Miles 1963, Bang and Ramm 1970, Sengupta *et al.* 1998, 1999), area of translucency (Lorentsen and Solheim 1989, Sengupta *et al.* 1998, 1999), length expressed as a proportion of the total root (Lamendin and Cambray 1980, Drusini *et al.* 1991, Lamendin *et al.* 1992, Thomas *et al.* 1994, Sengupta *et al.* 1998, 1999, Prince and Ubelaker 2002, Sarajliæ *et al.* 2003), area expressed as a proportion of the total root area (Johnson 1968, Vasiliadis *et al.* 1983, Drusini *et al.* 1991, Sengupta *et al.* 1998, 1999), computer-assisted image analysis (López-Nicolás *et al.*1990, 1993, 1996, Drusini *et al.* 1991, Sengupta *et al.* 1998, 1999), and by total volume (Rathod *et al.* 1993, Manly and Hodge 1939).

Several researchers have found a significant difference between the sexes (Lorentsen and Solheim 1989, Prince and Ubelaker 2002), while others have not (Drusini *et al.* 1991, Lamendin *et al.* 1992). Lorentsen and Solheim (1989) suggested that sexual dimorphism in translucency may be attributed to differences in masticatory forces. Similarly, ancestry variation has been noted by several authors (Whittaker and Bakri 1996, Prince and Ubelaker 2002).

As with any aging indicator, taphonomic processes may affect the properties and visual assessment of apical translucency. These processes include water insults, soil conditions, temperature and humidity, and faunal, fungal, or bacterial scavenger activity (Sengupta *et al.* 1999). As Sengupta *et al.* (1999) note, Clement (1963):

> "described the most common post-mortem changes in the dentine as the appearance of irregular canals emanating from either the pulp via the predentine, or from the exterior via the cementum of the roots" (Sengupta *et al.* 1999:896).

López-Nicolás *et al.* (1993) tested the properties associated with apical translucency using IBAS image analysis. Their goal was to examine the number of dentin tubules and the tubule diameters to determine their applicability in estimation of age-at-death. The researchers cut longitudinal thin sections which were 1mm in thickness. Sections were then cut transversely from the cej to the apex of the root, which were approximately 0.25mm to 0.50mm thick to assess the dentin tubules. The number of tubules and their corresponding diameters were measured under 2000X magnification. Their results yielded a significant correlation between the number of tubules and chronological age, r= -0.2046. Their results also yielded a significant correlation between the number of dentin tubules and the maximum tubule diameter, r= -0.3246. Although this analysis provided significant correlations, they are very weak and would probably not be useful in age estimation (López-Nicolás *et al.* 1993).

2.12 Lamendin's Method

Lamendin and co-workers (1992) analyzed 306 single-rooted teeth extracted from 208 oral surgery patients. The sample consisted of 135 males and 73 females, of which 198 had a European ancestry (French) and 10 an African ancestry. The sample ranged in age from 22-90 years. The researchers also tested their method on 45 teeth from 24 forensic cases. The forensic sample contained individuals only from ages 30 to 69 years old, with a mean age of 44.4 years. To obtain the estimated age-at-death, three simple measurements were taken from the labial surface of each tooth and recorded in millimeters: root height (RH), the maximum distance from the apex of the root to the cementoenamel junction (cej), which is the portion of the tooth that separates the enamel covered crown from the cementum covered root; periodontal regression, the maximum distance from the cej to the line of soft tissue attachment; and translucency of the root, measured with the aid of a lightbox from the apex of the root toward the cej. From multiple regression analysis, Lamendin *et al.* (1992) established the following equation to estimate age at death: $A=(0.18*P) + (0.42*T) + 25.53$, where A represents age in years, P represents the periodontal measurement*100/RH, and T represents the translucency of the root measurement*100/RH. These researchers produced a mean error of $\pm$ 10 years on their working sample and $\pm$ 8.4 years on their forensic control sample.

There are several advantages to using Lamendin *et al's* (1992) method. This method is preferable for application as compared to other methods because it offers a quick, simple and reliable technique employing dental microstructure. In addition, this method is non-destructive, therefore, no thin sections are needed. Several dental aging methods require analysis of thin sections of teeth, and a vast knowledge of dental histology is necessary to assess most features. Lamendin's method does not require a background in dental histology, expensive equipment, or equipment that is difficult to obtain.

2.13 Applications of Lamendin's Technique

Although apical translucency has been reported to be a very reliable indicator of age, periodontal recession has serious limitations. Foti *et al.* (2001) point out that several intrinsic and extrinsic factors can influence periodontal recession other than age:

> "As far as Lamendin's method is concerned, many factors, independent of age, act upon the attachment level, which may be pathological. These factors are bad hygiene, physical, chemical or mechanical irritation, and there are also predisposing factors such as specific morphology, systematic diseases and drug treatment" (Foti *et al.* 2001:101).

These researchers tested Lamendin's method on 71 incisors and canines which were extracted due to periodontal disease. Two observers measured each tooth and then measured a sub-set for intra-observer error assessment. Their results showed a typical aging bias, underestimating age in older individuals and overestimating age in younger individuals. Age estimates were more accurate for males, and females were underestimated in age more frequently. There was no significant difference between maxillary and mandibular teeth, or tooth type. There was no significant difference between observers using Lamendin's method. Their results also yielded no correlation between periodontal recession and chronological age. They concluded that Lamendin's technique cannot be used on teeth with periodontal disease. Supporting the conclusions made by Foti *et al.* (2001), Solheim (1992) also concluded that periodontal recession as a single indicator for estimation of age-at-death was not possible.

In order to assess the accuracy and applicability of Lamendin's method, Prince and Ubelaker (2002) analyzed 400 single-rooted teeth extracted from 355 individuals from the Terry Anatomical Collection, housed at the Smithsonian's National Museum of Natural History. A mean absolute error of 8.23 years, with a standard deviation of 6.87

years was produced employing Lamendin's method and formula. To further assess the accuracy of this method, Prince and Ubelaker (2002) analyzed the mean error of age cohorts, broken into 10 year segments. Lamendin's method was found to be the most accurate for the 30-69 year old age groups, which holds true for the original Lamendin study and the Terry Collection sample. Once outside this range, below 30 and above 70, mean errors increase greatly. Applying Lamendin's technique to the Terry Collection produced the typical aging bias mentioned previously, where older individuals were underestimated in age, while younger individuals were overestimated in age.

The authors created new formulae separating individuals by sex and ancestry and included root height, which significantly lowered the mean errors further, in order to make the age-at-death estimates more applicable to skeletal remains recovered in the US. Lamendin's method and formula (1992) and Prince and Ubelaker's formula for white males (2002) were evaluated by Sarajliæ and colleagues (2003). These researchers analyzed 415 single rooted teeth, maxillary and mandibular incisors and canines, from 100 individuals of known age and sex whose remains were exhumed from 8 sites located in Bosnia and Herzegovina. All individuals in the sample were male and ranged in age from 23 to 68.83 years, with a mean age-at-death of 45.04 years and a standard deviation of 11.5 years.

Following the procedures outlined by Lamendin, Sarajliæ *et al.* (2003) found an overall mean error of 8.42 years from Prince and Ubelaker's formula and 8.77 years from Lamendin's formula. Prince and Ubelaker's formula yielded a significantly lower overall mean error at less than the 0.001 level. This research generated the lowest mean errors for the 20-49 year olds independent of which formula was used. As with any regression based aging method, Sarajliæ *et al.* found that with both Lamendin's formula and Prince and Ubelaker's formula, younger individuals were overestimated in age, while older individuals were underestimated in age. Maxillary central incisors produced the lowest mean error, as was also found in Lamendin's and Prince and Ubelaker's research. Sarajliæ *et al.* (2003) concluded that Lamendin's method and Prince and Ubelaker's modified formula are both suitable for use in a Bosnian population.

Several studies have investigated the accuracy of Lamendin *et al*'s (1992) method in comparison to other skeletal aging techniques (Ubelaker *et al.* 1998, Baccino *et al.* 1999). Baccino and colleagues (1999) compared four single indicator methods, which were single-rooted teeth (Lamendin *et al.* 1992), 4^{th} sternal rib ends (Ýþcan *et al.* 1984a, 1984b, 1985), the pubic symphysis (Brooks and Suchey 1990), and femoral cortical bone remodeling (Kerley 1965, Kerley and Ubelaker 1978). They also compared three multifactoral methods, which included the Average method (Baccino *et al.* 1999), the Global method (Baccino *et al.* 1999) and the Two-Step method (Baccino and Zerilli 1997).

The techniques were applied to 19 adult individuals, 15 males and 4 females, who ranged in age-at-death from 19-54 years, with a mean of 37.6 years and a standard deviation of 10.0 years. All individuals had a European (French) ancestry. Two observers performed each of the seven methods on the 19 individuals and a third observer performed only Lamendin's technique on the sample. Both observers who tested all seven methods, yielded the most accurate estimates employing the multifactoral methods: "The present study strongly suggests that comprehensive approaches to age estimation that consider multiple age indicators are superior to isolated methods" (Baccino *et al.*

1999:936). Among the individual methods, both observers yielded the most accurate age estimates employing Lamendin's single-rooted tooth technique, despite lack of experience with this method.

2.14 Methods Applied to Archaeological Samples

Except for dental attrition, there have only been a small number of analyses of dental aging methods applied to archaeological material (Sengupta *et al.* 1999). Research analyzing translucency of the root and periodontal recession resulted in conflicting conclusions of their usefulness and applicability of estimating age-at-death in archaeological samples. Some researchers concluded that apical translucency and periodontal recession were extremely hard to determine in archaeological samples (Vlèek and Mrklas 1975, Marcsik *et al.* 1992, Sengupta *et al.* 1999) owing to soil apposition in the tooth root, preservation issues of the tooth and decomposition of the gingiva. Other researchers concluded that translucency of the root was a good indicator to estimate age-at-death and would be a useful indicator to estimate age-at-death in both contemporary and archaeological samples (Acsádi and Nemeskéri 1970, Maples 1978, Colonna *et al.* 1984, Drusini *et al.* 1991). In addition, Hillson (personal communication sited in Russell 1996) "reports that although the dentin does not appear transparent in some archaeological teeth, under backscatter EM, the difference between patent and occluded dentinal tubules can be differentiated in some of these teeth."

Marcsik *et al.* (1992) analyzed 200 mandibular incisors from the 8th century and 50 polished sections of mandibular incisors from the 8th and 10th centuries to assess if translucency of the root was applicable in estimating age-at-death for archaeological samples. They compared dental age with skeletal age which was estimated from the pubic symphysis, epyphyseal closure, and endocranial suture closure (after Acsádi and Nemeskéri 1970). All individuals in the sample were adult. Regression equations from Miles (1963) and Bang and Ramm (1970) were utilized to estimate age-at-death from observed apical translucency. Dental age consistently yielded higher age estimates than the skeletal age, particularly with Bang and Ramm's (1970) formula. In 36% of their cases, no translucency of the root was observed, which was attributed to soil conditions.

Based on Kósa's study (1984), Marcsik *et al.* studied changes in the dentin under SEM (scanning electron microscope) but did not find a significant correlation:

> "The dentine tubules become narrower with increasing age…but change in size, even if examined in a great number of samples is not significant" (Marcsik *et al.* 1992:537).

From their results, the authors concluded that translucency of the root is extremely hard to determine in archaeological samples, "the radicular tubulae are filled with soil so it becomes impossible to determine the degree of transparency in the dentin" (Marcsik *et al.* 1992:530). But despite limitations, Marcsik *et al.* (1992) state that "determination of dental root transparency may have value in age estimations of archaeological populations…" and "…may be important for age determination if the bones are fragmentary or insufficient" (Marcsik *et al.* 1992:537).

Drusini *et al.* (1991) analyzed modern and historic teeth in order to address if translucency of the root was applicable to buried historic samples, and if regression formulae developed from modern samples were suitable to estimate age-at-death for historic samples. They tested two methods of measuring translucency of the root: direct measurement with vernier calipers and measurement made with an IBAS 2000 computerized densitometric analyzer. Their sample contained 152 single-rooted teeth of known-age and sex comprised from two sub-samples. Their modern sample contained 86 single-rooted teeth, 50 anterior teeth and 36 premolars, and their historic sample contained 66 single-rooted teeth, 33 anterior teeth and 33 premolars. The historic sample was obtained from individuals who were buried in Italy between 1890 and 1930. They measured the maximum apical translucency (h) and the root height (H) of each tooth with the vernier calipers and the IBAS system. In the latter, black and white photographs were taken and measurements were made from the photographs. After calibration was complete with the IBAS system, measurements were made semiautomatically.

They expressed the translucency of the root as a proportional index: h*100/H and regressed that index against age. A regression formula was generated for both measurement methods. The regression formulae were tested on three control samples, which contained 14 modern anterior teeth, 33 historic anterior teeth, and 33 historic premolars. From their control samples, the premolars yielded the highest correlation coefficients between age and proportion of apical translucency, independent of sample and which measuring methods were applied, r = 0.84 for calipers and r = 0.81 for IBAS. With the historic sample premolars, 48.49% of the measurements with calipers and 45.46% measured with the IBAS produced ages ±5 years, which are similar to Colonna *et al.'s* (1984) results. Drusini *et al.* (1991) state that utilizing translucency of the root to estimate age-at-death in samples buried for approximately 100 years is a reliable technique:

> "The results demonstrate that regression formulae obtained

> from a recent sample of teeth can determine the age at death of skeletons buried for approximately 100 years with a reasonable degree of accuracy (>45% for errors of ±5 years)" (Drusini *et al.* 1991:28).

Although they noted that measurements taken with the calipers yielded a slightly higher correlation with age, it was not a significant difference. In addition, the authors state a preference for the IBAS system, stating that although it is more expensive, if offers a quicker and easier system of measurement and stores information that can be used for later research and analysis.

Lucy *et al.* (1995) analyzed modern and archaeological teeth to assess the applicability of Gustafson's six dental features to archaeological material. Although they utilized Gustafson's six features, they used modifications of his method to carry out analyses. They followed Johanson's (1971) method of assessing the degree of dental change, except for apical translucency, where they followed the method outlined by Bang and Ramm (1970), who took direct measurements of translucency. Estimated ages were made from Johanson's (1971) formula, Bang and Ramm's (1970) formula, and Maples and Rice's (1979) modified Gustafson formula. They analyzed a sub-sample of the modern extracted teeth, which consisted of 24 teeth from 17 individuals. Longitudinal thin sections (300 ìm) were taken through the center of the roots and multiple-rooted teeth were sectioned through each root. A total of 35 thin sections was assessed for amount of dental change with each section being treated as a separate individual. Another study was conducted to assess differences in the same tooth with multiple roots, as well as different teeth from the same individual. In order to assess how well each formula fared they compared the average absolute deviations (the average difference between the estimated age and actual age) from each formula and compared the quoted standard errors with the ones produced in this study.

Their results showed that Johanson's (1971) method was slightly better than Maples and Rice (1979) and Bang and Ramm's (1970), with average absolute deviations of 4.5 years, 5.03 years, and 5.15 years respectively. The authors then assessed a very small sample of 8 teeth from 4 skeletons from the Medieval Hospital cemetery at Chichester. One incisor and one molar from each skeleton were analyzed. Dental age was correlated with skeletal age, where skeletal age was estimated from the pubic symphysis, epiphyseal closure, M_3 eruption, and sternal rib ends (all as described in Bass 1987).

Lucy *et al.* (1995) found that the initial examination of the teeth showed that they were in excellent condition, but they encountered problems when the longitudinal sections were taken, which then rendered only one tooth eligible for analysis of all six features:

> "External appearances indicated that all the teeth were in an excellent state of preservation: however, when the sections were examined, all but one tooth had extensive damage to the internal macrostructure which obliterated transparent root dentine,…and displayed a pinkish tinge throughout the dentine" (Lucy *et al.* 1995:423).

The tooth coded for all six dental features yielded a dental age estimate of 46.7 years ± 4.0 years, which corresponded well with the skeletal age estimate of 35+ years. The authors noted that the other five features could be analyzed in three individuals. Omitting the translucency of the root allowed for a dental age estimation, but the error was slightly larger than when all six features were utilized:

> "One further fortuitous advantage of this approach is that for archaeological teeth, where diagenesis may have altered the internal structure and obliterated the sclerotic dentine, the modified Gustafson model can be used alone to provide an age estimate with a slightly larger error term" (Lucy *et al.*1995:424).

Sengupta *et al.* (1998) analyzed 100 dental arches that were excavated from St. Peter's Church, Barton-on-Humber and dated between the 8th and 19th centuries. They analyzed a second sample containing 220 photographs of crania of reports from the *Prehistoric Man in Denmark* (Bröste 1956). These photographs contained dentitions dating to the Mesolithic up to the Bronze Age. Both samples' dentitions were inventoried to ascertain which teeth are most frequently recovered from archaeological remains. No distinctions were made between antemortem and postmortem tooth loss. Their results revealed that the maxillary first molar was the tooth most often present from the prehistoric Danish material, while the mandibular canine was the most present from the Barton-on-Humber material. The authors concluded that the best tooth for this analysis is the mandibular canine because it is most frequently present, it is single-rooted, it has a long and straight root, and is less susceptible to carious lesions.

In addition, non-carious, extracted modern teeth of known-age and non-carious archaeological teeth of unknown-age and origin were analyzed to obtain the best sectioning, embedding, and analysis procedures for archaeological teeth. Three buccolingual longitudinal thin sections were taken from each tooth. Sengupta *et al.* (1998) found that the archaeological material was very fragile, and fractured and fragmented when sections were taken. To combat this issue, the teeth were embedded in epoxy resin and infiltrated with methyl methacrylate. This procedure aided in the durability of the archaeological teeth and allowed for sections to be taken without fracturing or fragmenting the specimen. Sections of 150ìm thickness were found to yield the best results for analysis.

Several stains were analyzed to determine if they aided in distinguishing the root dentin translucency from the opaque dentin by improving the contrast between the two. The authors found that storage of the section for two days in ammoniated Indian ink provided the best contrast, but that it was not a significant difference and therefore opted to omit any staining procedure. High performance MicroScale TM/TC image analysis software was utilized to capture and analyze images of each section. Four measurements were taken from the sections, length of the translucency in mm, percentage of translucency (translucency/root height), area of translucency (pixels), and percentage area of translucency (area of translucency/area of root). Apical translucency was assessed on all four sides. The maximum amount of translucency was recorded for each tooth. In instances where there were differing amounts of translucency the average between the maximum and minimum measurement was used.

No intra- or inter-observer error was found when measurements were taken from the longitudinal thin sections. No intra-observer error was found when measurements were taken directly from the intact teeth, but inter-observer error yielded a significant difference, p=.03.

Sengupta *et al.* (1999) wanted to analyze the apical translucency in known-age archaeological material and compare its applicability and reliability to known-age modern material. They analyzed 56 non-pathological, mandibular canines of known-age extracted from dental clinics and forensic cases and 61 non-pathological, mandibular canines from a known-age archaeological collection, the Christchurch Spitalfields Collection. The Spitalfields Collection contains individuals from exhumed nineteenth century burials, where records of date of birth, date of death and in some cases occupation were available (Molleson *et al.* 1993).

Sengupta *et al.* (1999) cut three buccolingual longitudinal sections, which were then ground to 100 ìm. These researchers then categorized the translucency of the root into three groups: measurable root translucency, "chalky" dentin, and unaffected tubular dentin. They expressed the measurable root translucency as a direct measure, as a percentage of the total root, area, and area percentage measured with image-analysis. Their results produced a much higher correlation between age and translucency as a percentage of root height in the modern sample as compared with the archaeological sample, 0.73 and 0.52 respectively. In addition, they found no teeth in the modern sample to exhibit "chalky" dentin, while several teeth from the archaeological sample exhibited this feature. These researchers concluded that root translucency should not be utilized to estimate age-at-death for archaeological material, and some forensic material, until more research has been compiled between translucency and taphonomic processes:

> "We conclude that until it is possible to distinguish between root dentine translucency and taphonomic changes, the translucency may not be useful in estimating chronological age in archaeological material. Chalkiness of the dentine is the most obvious manifestation of taphonomic alteration and was seen in samples of as recent deposition as 132 years. As exclusion of the obviously affected samples did not significantly improve the associations of root dentine translucency and age, and a body is still of forensic interest at 70 years, deposition, it is possible that the same problems may compromise the ability to determine age at death in teeth still of medicolegal significance" (Sengupta *et al.* 1999:897).

2.15 Summary

Several methods utilized to estimate age-at-death by means of the dentition have been presented. Most methods have been based after Gustafson's (1950) features of dental attrition, secondary dentin deposits, cementum annulation apposition, and translucency of the root. Many authors suggest that measurement of apical translucency is the best univariate age indicator, although some concern has been noted regarding its utility with archaeological material. Two destructive methods, aspartic acid racemization and counting tooth cementum annuli, have both produced exceptionally high correlations with age by several different authors. Although these methods are destructive, they offer extremely valuable demographic information. Again, as with apical translucency, both methods are prone to increased error with increased antiquity of the dental material, in addition to other taphonomic factors.

CHAPTER 3

MATERIALS AND METHODOLOGY

As mentioned above, aging techniques based on osteomorphological changes throughout the skeleton are prone to several theoretical, methodological, and statistical problems. To test the hypothesis that utilizing translucency of the root and periodontal recession as estimators of age-at-death for adults will be valid, will be reliable, and will decrease the large age ranges associated with adult age estimates compared to subjective methods, three samples were obtained and analyzed. In order to test this hypothesis known-age samples were necessary. This research analyzed two modern samples of known-age, sex, and ancestry, the Robert J. Terry Anatomical Skeletal Collection and the Baraybar Forensic Biosample Collection, and one archaeological sample of unknown age from the Lauchheim Medieval Cemetery (late 5th to 7th centuries) located in Southern Germany.

There have been several notational methods for dental charting, all of which have been devised as a shorthand to quickly identify a tooth without writing the entire cumbersome anatomic description (Sopher 1976, Hillson 1996). Today, there are over thirty different systems for charting teeth (Clark 1991). In 1971, the Fédération Dentaire Internationale (FDI) devised a system which is used throughout the world by several organizations, such as Interpol, World Health Organization, and the International Association of Dental Research (Figure 1). This system provides a unique two-digit number for each tooth. The first number in the pair represents the quadrants and the second number delineates the tooth, numbered from mesial to distal. Any number

				55	54	53	52	51	61	62	63	64	65				
	18	17	16	15	14	13	12	11	21	22	23	24	25	26	27	28	
R																	**L**
	48	47	46	45	44	43	42	41	31	32	33	34	35	36	37	38	
				85	84	83	82	81	71	72	73	74	75				

Figure 1. FDI Dental Charting System.

beginning with 1 represents the permanent maxillary right quadrant, 2 represents permanent maxillary left, 3 permanent mandibular left, and 4 permanent mandibular right. Deciduous quadrants are delineated with the first numbers 5-8 in the same fashion. This system allows for quick entry into a computer database with a unique number representing each tooth and was utilized for the following research.

3.1 Sample

3.2 Robert J. Terry Anatomical Skeletal Collection

The Robert J. Terry Collection is an anatomical skeletal collection housed at the Smithsonian Institution’s National Museum of Natural History in Washington D.C. The skeletons were collected between 1900 and 1965 (Susman 1997) by Robert J. Terry, who was professor of Anatomy and head of the Anatomy Department at Washington University Medical School in St. Louis, Missouri from 1900-1941. This collection contains 1728 skeletons of known age-at-death, sex, ancestry, pathological conditions, and in most cases cause of death (Susman 1997, Hunt 2004). The cadavers were originally obtained for use in the Washington University Medical School gross anatomy classes and the skeletal remains were processed and curated for future research and analysis (Usher 2002, Hunt 2004). Terry obtained the cadavers via two means: unclaimed and indigent bodies were handed over from the state's morgues while other individuals willed their bodies to be donated for medical research (Usher 2002, Hunt 2004). Individuals in the collection were born between 1822 and 1943 and were from lower to middle socioeconomic status:

> "The cadavers predominantly consisted of individuals whose bodies became property of the state when they were not claimed, or whose relatives signed over the remains to the state. The early part of the collection is predominantly composed of people of lower incomes, but the latter component of the collection comes from middle or upper middle incomes" (Hunt 2004).

After Terry retired in 1941, Mildred Trotter continued to retain and curate the skeletal remains from the anatomy department at Washington University Medical School and upon her retirement in 1967, transferred the collection to the Smithsonian Institution's National Museum of Natural History's Anthropology Department for future curation (Hunt 2004).

The Terry Collection has been criticized as an inappropriate reference collection for testing and developing aging methods for several reasons (Usher 2002). Although the age-at-death distribution ranges from 16 to 102 years, the age-at-death distribution is skewed towards older adult individuals with the majority of the collection being 45 years and older, due to the circumstances surrounding the procurement of the remains (Table 1). In addition, reported ages-at-death of the Terry Collection skeletons have been questioned because there is not documented material to verify and corroborate the

Table 1: Age Distribution of the Robert J. Terry Anatomical Skeletal Collection broken into age cohorts and by sex and ancestry. Reproduced from Hunt 2004*with author's permission.

Age	**0-20**	**21-30**	**31-40**	**41-50**	**51-60**	**61-70**	**71-80**	**81-90**	**91-100**	**101-110**
Black Males	20	83	114	104	110	70	30	8	2	0
White Males	7	10	30	77	107	129	80	15	0	0
Black Females	21	53	61	66	58	52	45	17	6	2
White Females	13	7	11	29	56	80	6	42	4	0

reported ages of several individuals in the collection. Usher (2002) states that an appropriate reference collection should contain "verified ages that have used vital records to collaborate a self-reported age" (Usher 2002:31). She also points out that good reference collections will capture the variation present in the target population, therefore including individuals of "various socioeconomic statuses, races, and health" (Usher 2002:31). Issues pertaining to uniformitarianism have also been addressed. Biological uniformitarianism relies on the assumption that the "biological processes related to mortality and fertility in humans were the same in the past as they are in the present" (Hoppa 2002:10). This assumption carries two implications for paleodemographic research, as pointed out by Howell (1976) and Hoppa (2002). The theory of biological uniformitarianism "assumes that humans have not changed over time with respect to their biological responses to the environment (and that) biological development of age-related morphology in humans is the same in populations that are separated in either time or space" (Hoppa 2002:10-11). Since the skeletons in the Terry Collection were obtained during the early 20th century, age-progressive changes are assumed to follow biological uniformitarianism, but this may not be an accurate assumption. For example, secular change regarding stature and cranial morphology in the United States has been documented in anatomical collections, including the Terry Collection (Meadows and Jantz 1995, Jantz and Jantz 1999, Jantz and Meadows-Jantz 2000, Jantz 2001). These analyses point out that a combination of environmental and phenotypic plasticity is responsible for changes in long bone length and cranial morphology. Therefore, these factors may also affect biological processes related to age.

To combat issues regarding the Terry Collection as an appropriate reference collection, Erickson (1982) analyzed proximal femora from 106 white females from the Terry Collection whose remains were unclaimed, 26 femora from white females whose remains were willed to the Terry Collection, and 26 femora from white females whose remains were willed to the George Washington University Medical Center, in order to determine if a significant difference existed between the willed and unclaimed groups. The author concluded that although a slight difference was found between the two groups, that it was not profound enough to invalidate most age estimation techniques developed and applied to the Terry Collection. The author notes that rather than socio-economic status, differences among the groups could be attributed to secular change and small sample sizes, which could be ascertained by future research on willed collections.

3.3 Terry Collection Sample

The sample from the Terry Collection consists of 400 single-rooted teeth of known age, sex and ancestry from 355 individuals. Teeth were manually dislodged or had already fallen out of the alveolus. Of the 355 individuals in the sample, 93 were black females, 72 were white females, 97 were black males and 93 were white males. The sample ranged in age-at-death from 25–99 years, with a mean age-at-death of 52.85 years and a standard deviation of 15.08 years. A histogram of the age-at-death distribution from the Terry Collection sample is represented in Figure 2.

All single-rooted teeth are represented in this sample: 38 right maxillary central incisors, 34 left maxillary central incisors, 20 right lateral incisors, 29 lateral left incisors, 32 right maxillary canines, 30 left maxillary canines, 5 right maxillary first premolars, 6 left maxillary first premolars, 7 right maxillary second premolars, 4 left maxillary second premolars, 16 right mandibular central incisors, 23 left mandibular central incisors, 20 right mandibular lateral incisors, 22 left mandibular lateral incisors, 27 right mandibular canines, 26 left mandibular canines, 19 right mandibular first premolars, 16 left mandibular first premolars, 14 right mandibular second premolars, and 12 left mandibular second premolars (Figure 3).

3.4 Baraybar Forensic Biosample Collection

The Baraybar Forensic Biosample Collection contains individuals from several Provinces in the Balkans. The collection consists of skeletal remains and teeth which were taken at the time of autopsy by The International Criminal Tribunal for the Former

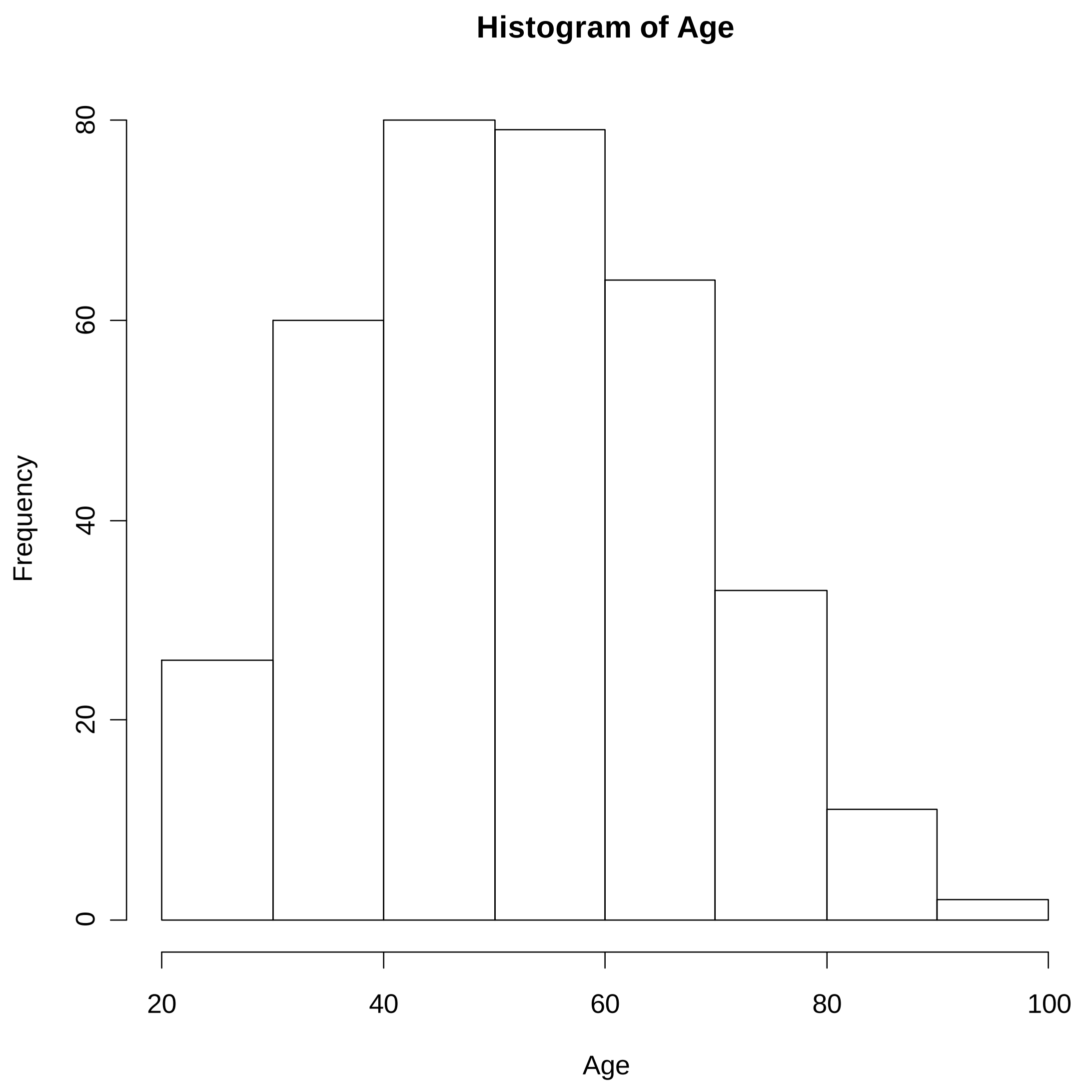

Figure 2. Age-at-death distribution of the Terry Collection sample.

Number of teeth	7	5	32	20	38	34	29	30	6	4
	15	14	13	12	11	21	22	23	24	25
R										**L**
	45	44	43	42	41	31	32	33	34	35
Number of teeth	14	19	27	20	16	23	22	26	16	12

Figure 3. Known-age tooth distribution for the Terry Collection using FDI code.

Yugoslavia (ICTY) and contains pubic symphyses, sternal ends of 1st ribs, sternal ends of 3rd through 5th ribs, histological sections from clavicles, and single-rooted teeth. These ICTY autopsies were conducted between 1996 and 2000 (Kimmerle *et al.* in prep). This collection contains individuals whose ages-at-death range throughout the entire life-span and include both sexes.

Since this collection contains individuals from Kosovo, Bosnia-Herzegovina, and Croatia, the collection contains both positively identified individuals and unidentified individuals. Because relatives returned soon after the genocide in Kosovo and could identify individuals, over 75% of the positively identified individuals are from Kosovo (Kimmerle *et al*. in prep). In Bosnia-Herzegovina and Croatia, the majority of individuals were exhumed from mass graves, where remains were commingled and fragmentary, thus making positive identifications at the time of autopsy implausible (Kimmerle *et al.* in prep). In contrast, individuals in Kosovo were killed but not buried in mass graves, which resulted in the majority of these individuals being positively identified:

> "The reason that so many positive identifications were made at the time of autopsy in Kosovo has to due with the events that unfolded during the conflict that besieged that Province between

> 1998-1999. Unlike BiH (Bosnia-Herzegovina) and Croatia where numerous individuals were buried in mass graves; victims in Kosovo were often killed by Serbian authorities in or near their homes but not buried. Subsequently, family members or neighbours who returned to the area would later bury the dead. As a result, the majority of graves exhumed and autopsied by the ICTY were identified individuals located in single-interment graves within pre-existing cemeteries" (Kimmerle *et al.* in prep).

3.5 Baraybar Forensic Biosample Collection Sample

The sample obtained from the Baraybar Forensic Biosample Collection consists of 401 single-rooted teeth of known age and sex. Of the 401 individuals represented in the sample, 359 are male, ranging in age-at-death from 18–90 years, with a mean age-at-death of 48.16 years and a standard deviation of 16.63 years and 42 are female, ranging in age-at-death from 19–88 years, with a mean age-at-death of 47.70 years and a standard deviation of 19.31 years. The entire sample has a mean age-at-death of 48.29 years with a standard deviation of 16.91. A histogram of the age-at-death distribution for the Baraybar Biosample Collection sample is represented in Figure 4. All single-rooted teeth are represented in the sample except right and left maxillary first premolars (Figure 5). The tooth sample consists of 41 right maxillary central incisors, 39 left maxillary central incisors, 11 right lateral incisors, 16 lateral left incisors, 26 right maxillary canines, 22 left maxillary canines, 5, 15 right maxillary second premolars, 2 left maxillary second premolars, 17 right mandibular central incisors, 17 left mandibular central incisors, 24 right mandibular lateral incisors, 37 left mandibular lateral incisors, 64 right mandibular canines, 68 left mandibular canines, 4 right mandibular first premolars, 6 left mandibular first premolars, 2 right mandibular second premolars, and 3 left mandibular second

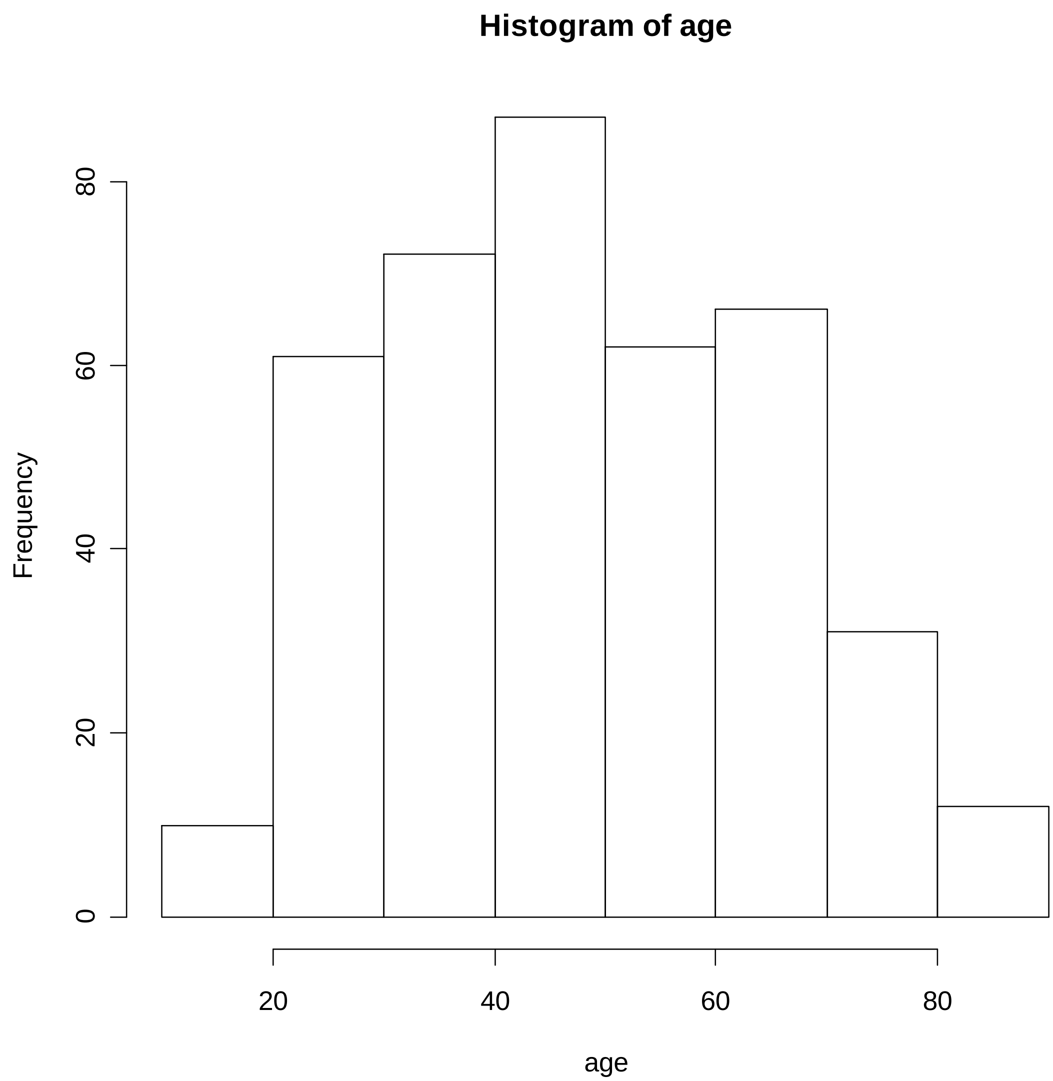

Figure 4. Age-at-death distribution for the Baraybar Forensic Biosample Collection sample.

Number of teeth	15	0	26	11	41	39	16	22	0	2
	15	14	13	12	11	21	22	23	24	25
R										**L**
	45	44	43	42	41	31	32	33	34	35
Number of teeth	2	4	64	24	17	17	37	68	6	3

Figure 5. Known-age tooth distribution for the Baraybar Forensic Biosample Collection using FDI code.

premolars.

3.6 Lauchheim Medieval Cemetery Archaeological Sample

The Lauchheim medieval cemetery is located in Lauchheim, Baden-Württemberg, Germany. The cemetery site is dated to approximately A.D. 550-750 and an Alamannic village settlement site that is associated with the cemetery was inhabited from the 6th to the 12th centuries (Stork 2001). Yearly excavation of the cemetery ensued from 1986-1996, uncovering 1,308 graves containing approximately 1,370 individuals, and an estimated 40 additional graves are situated under a concrete base of a modern factory building and are therefore unattainable (Stork 2001). Ten graves were destroyed by the initial construction of the factory building.

The burials are in an east-west alignment, with the earliest portion of the cemetery dating to the 5th century located in the west end, the middle portion dating to the 6th century and the east end of the cemetery dating to the 7th century (Stork 2001). Multiple burials as well as secondary burials were encountered during excavation of the cemetery. Over 15,000 grave good artifacts were collected from the burials, which included several elaborate fibulas, numerous iron made weapons, glass and pottery objects, wood-worked objects, including an elaborately engraved cradle, jewelry, and belt buckles.

Excavations at the Alamannic settlement village began in 1989 and are currently underway. The settlement site is approximately 12 hectares and is located north of the cemetery (Stork 2001). Analysis of the settlement site uncovered several farmsteads, barns, and an iron smelting craftsmanship throughout the entire duration of the settlement (Stork 2001).

3.7 Lauchheim Medieval Cemetery Sample

The sample obtained from Lauchheim consists of 263 single-rooted teeth extracted from 211 individuals, of which 93 are estimated as females, 23 are estimated as probably female, 70 are estimated as male, 12 are estimated as probably male, and 13 are undetermined. Sex estimations were based after *Recommendations of Age and Sex Estimations in the Skeleton* (Ferembach *et al.* 1979) for the entire skeletal collection. The sample available for analysis consists of 31 maxillary central incisors, 32 mandibular central incisors, 15 maxillary lateral incisors, 22 mandibular lateral incisors, 67 maxillary canines, 40 mandibular canines, 8 maxillary first premolars, 22 mandibular first premolar, 9 maxillary second premolars, and 13 mandibular second premolars.

3.8 Methodology

A Mitutoyo Digital Extended Point Jaw Caliper was used to take all measurements and a light-box was used to illuminate the translucency of the root.

Measurements were directly imported into a *Microsoft Excel* database by a Mitutoyo Caliper PC Interface keyboard link. All data were analyzed in the *R* statistical package (Ihaka and Gentleman 1996, Cribari-Neto and Zarkos 1999, Ripley 2001, Dalgaard 2002, http://www.r-project.org/).

Measurements were taken from each tooth following Lamendin's method (Lamendin *et al.* 1992). All measurements were recorded in millimeters and taken from the labial surface. All observations were taken blindly with respect to demographic information. Three measurements are required to employ Lamendin's method: root height, which is the maximum distance between the apex of the root and the cementoenamel junction (cej) (Figure 6); periodontal recession, which is the maximum distance between the cej to the line of soft tissue attachment (Figure 7); and translucency of the root, which is measured from the apex of the root toward the cej and is enhanced with the aid of a lightbox (Figure 8). This physiological feature does not typically appear before age 20, and is the result of hydroxyapatite crystals depositing in the dentin tubuli (Lamendin *et al.* 1992). Again, this translucency should not be confused with sclerotic dentin, which is found in the crown and is a result of pathological conditions. To assess repeatability and inter-observer error, one additional observer with no prior experience with Lamendin's method also took the three measurements for the Baraybar Forensic Biosample Collection sample following the procedures outlined above. Since there was no means to assess the line of soft tissue attachment in the Lauchheim archaeological material, the periodontal recession measurement varied slightly. For this sample, the periodontal recession measurement was taken from the cej to the alveolar margin of the tooth in socket.

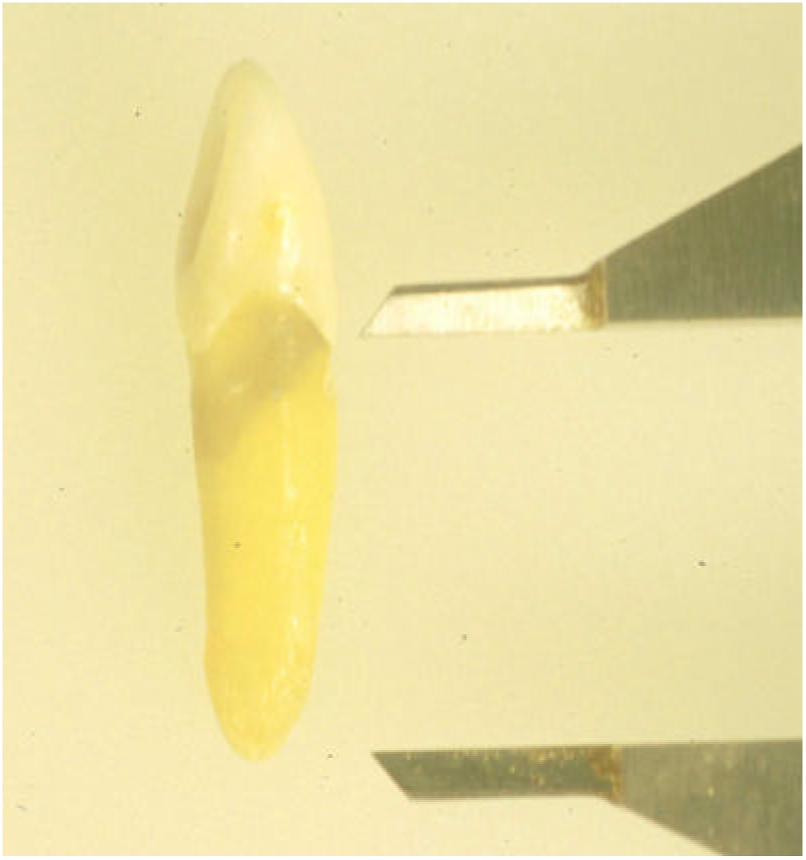

Figure 6. Root height measurement.

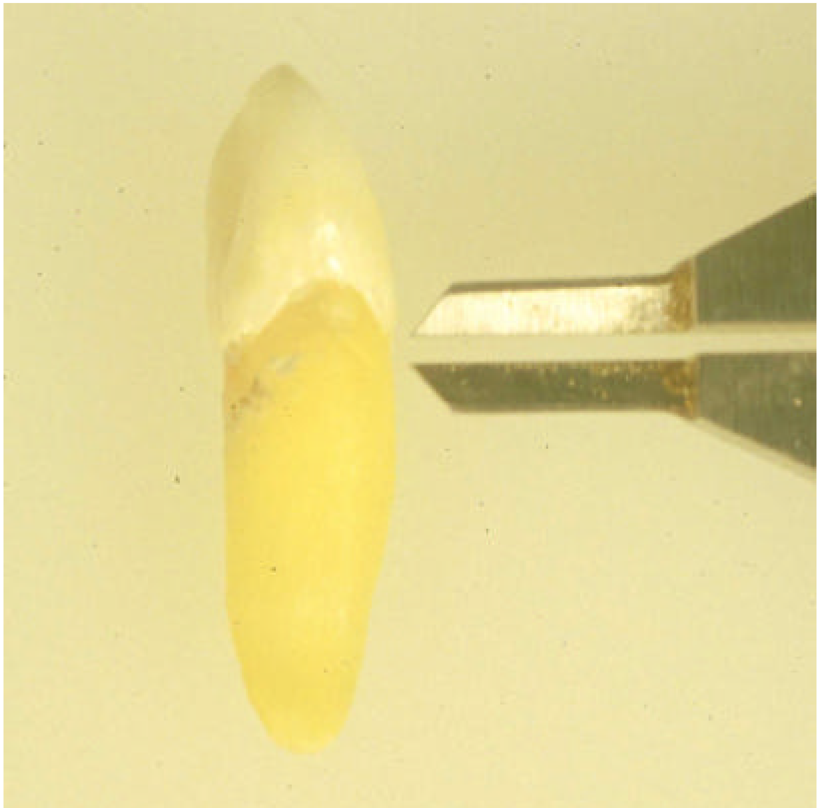

Figure 7. Periodontal recession measurement for known-aged samples.

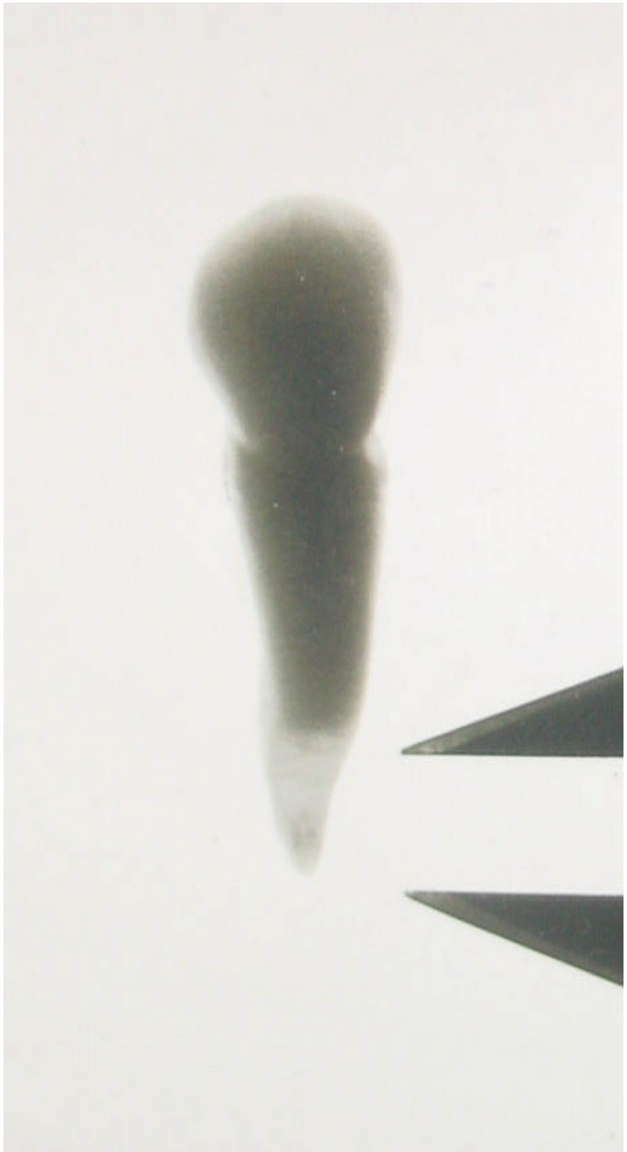

Figure 8. Apical translucency measurement.

3.9 Age Estimation

Bayes' theorem was utilized to estimate age-at-death from Lamendin's parameters. A Bayesian approach relies on three important concepts: prior probability, the likelihood, and posterior probability (Lucy *et al.* 1996). The prior probability is the unconditional probability of death at exact age A, denoted as f(A). The likelihood, denoted as f(D|A), is the probability of getting the observed dental data (translucency or periodontal recession), denoted as D, conditional on the individual being exact age A, though in likelihood terminology one speaks of the likelihood of the individual being exact age A conditional on the observed dental data. The posterior probability, denoted as f(A|D), is the product of the likelihood of the individual being exact age A conditional on the dental data with the prior probability of being exact age A, divided by the probability of the observed dental data.

Therefore, the posterior probability is proportional to the product of the prior probability and the likelihood and Bayes' Theorem can be written as:

$$f(A|D) = \frac{f(D|A)*f(A)}{\int f(D|A)*f(A)} \qquad (3.1)$$

In equation (3.1) f(D|A) is estimated by the regression of the translucency (converted to a z-score) on the known age in the sample of interest. f(A) is the probability density that an individual dies at exact age A, and is found by fitting a Gompertz hazard model to the known ages.

For paleodemographic applications f(A) is not available and must instead be estimated. To do this the log-likelihood of the Gompertz hazard parameters conditional on the observed dental data can be written as:

$$\ln LK(\grave{e}|\, y) = \sum_{i=1}^{m} \ln \left(\int_{17}^{120} f(y_{\mathrm{i}}\,|a) f(a\text{-}17|\,\grave{e}) da \right) \tag{3.2}$$

In equation (3.2), theta denotes the hazard parameters, *y* denotes the apical translucency measurements, and *m* represents the number of cases without a zero translucency. The integration across age from 17 to 120 years in equation (3.2) produces the unconditional probability density of observing a given translucency in the archaeological sample. The sum of these log probabilities is then equal to the log-likelihood. Maximizing this log-likelihood across *è* gives the most likely set of Gompertz parameters, which are in turn used in equation (3.1) to generate f(A).

This approach has been employed in forensic and paleodemographic applications to estimate age (Lucy *et al.* 1996, Aykroyd *et al*. 1990, Aykroyd *et al.* 1996), stature (Ross and Konigsberg 2002, Konigsberg *et al.* 1998) sex (Konigsberg and Hens 1998) and ancestry (Foreman *et al.* 1997). This research has pointed out that if an appropriate prior is available, for example as in forensic anthropology, then this form of Bayesian analysis should be utilized (equation 3.1). When an appropriate reference sample is not available, as in paleodemography, then MLE (equation 3.2) should be utilized. These approaches offer the best estimates in forensic anthropology and paleodemographic analysis.

CHAPTER 4

RESULTS

A repeated measures analysis of variance (ANOVA) was utilized to determine if a significant difference existed between the two observers for the Baraybar sample. The two known-age samples, the Terry Collection and the Baraybar Forensic Biosample Collection, were compared to assess whether the two samples aged differently. An analysis of variance (ANOVA) was utilized to make this determination. Bayes' theorem and two inverse calibration methods (Lamendin *et al.* 1992, Prince and Ubelaker 2002) were then employed to estimate ages-at-death for the Baraybar Forensic Biosample Collection sample.

4.1 Comparison of Measurements from the Two Observers

As mentioned above, a repeated measures ANOVA was utilized to determine if there was a significant difference between the two observers for the Baraybar sample. The results yielded no significant difference for root height and translucency of the root (Table 2 and 3) but the periodontal recession measurement did yield a significant difference between observers (Table 4).

4.2 Comparison of Aging Between the Terry and the Baraybar Collections

To determine whether the individuals in the Terry Collection and the Baraybar Forensic Biosample Collection aged differently, an analysis of variance (ANOVA) was utilized in the *R* statistical package. This statistical test evaluates the amount of

Table 2. Root height repeated measures ANOVA results.

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Observer	1	0.01915	0.01915	0.1129	0.737
CaseNo	423	3408.1	8.1	47.5082	<2e-16 ***
Residuals	423	71.7	0.2		

Significance codes: 0 `***' 0.001 `**' 0.01 `*' 0.05 `.' 0.1 ` ' 1

Table 3. Apical translucency repeated measures ANOVA results.

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Observer	1	2.2	2.2	1.99	0.1591
CaseNo	423	5051.0	11.9	10.61	<2e-16 ***
Residuals	423	476.1	1.1		

Significance codes: 0 `***' 0.001 `**' 0.01 `*' 0.05 `.' 0.1 ` ' 1

Table 4. Periodontal recession repeated measures ANOVA results.

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Observer	1	179.34	179.34	219.5215	< 2.2e-16 ***
CaseNo	423	2870.55	6.79	8.3068	< 2.2e-16 ***
Residuals	423	345.57	0.82		

Significance codes: 0 `***' 0.001 `**' 0.01 `*' 0.05 `.' 0.1 ` ' 1 translucency controlling for age, where translucency was expressed as a percentage of root height (T/RH). Specifically, this would determine if translucency of the root progresses in the same manner in the different populations. The results from the homogeneity of slopes ANOVA are depicted in Figure 9 and Table 5. Since this linear model is constrained 0 to 1, the apical translucent percentage of root height was converted into z-scores so that a linear model would be appropriate. The interaction between the two collections (coded as "Site:Age" in Table 5) yields a significant difference, with a p-value <0.001. In addition, an F-statistic of 284.8, with 752 degrees of freedom and a p-value $< 2.2e-16$ was produced. This analysis shows that the Terry and Baraybar Collections do age differently. In general, the Terry Collection sample yielded higher amounts of apical translucency for any given age. The Baraybar Forensic Biosample Collection was thought to be a more appropriate reference sample for the Lauchheim material for several reasons. The Baraybar material, which is from the Balkans, is geographically closer to Germany, than the Terry Collection, which is comprised of American whites and blacks. In addition, the Terry Collection has been questioned as an appropriate reference collection, as mentioned in the previous chapter. For these reasons, the Baraybar Forensic Biosample Collection was used as a reference sample for the Lauchheim material.

4.3 Bayesian Approach Applied to the Baraybar Collection

Applying Bayes' theorem, equation (3.1) to the Baraybar Forensic Biosample Collection, a mean error of 1.51 years was produced with an absolute mean error of 9.01

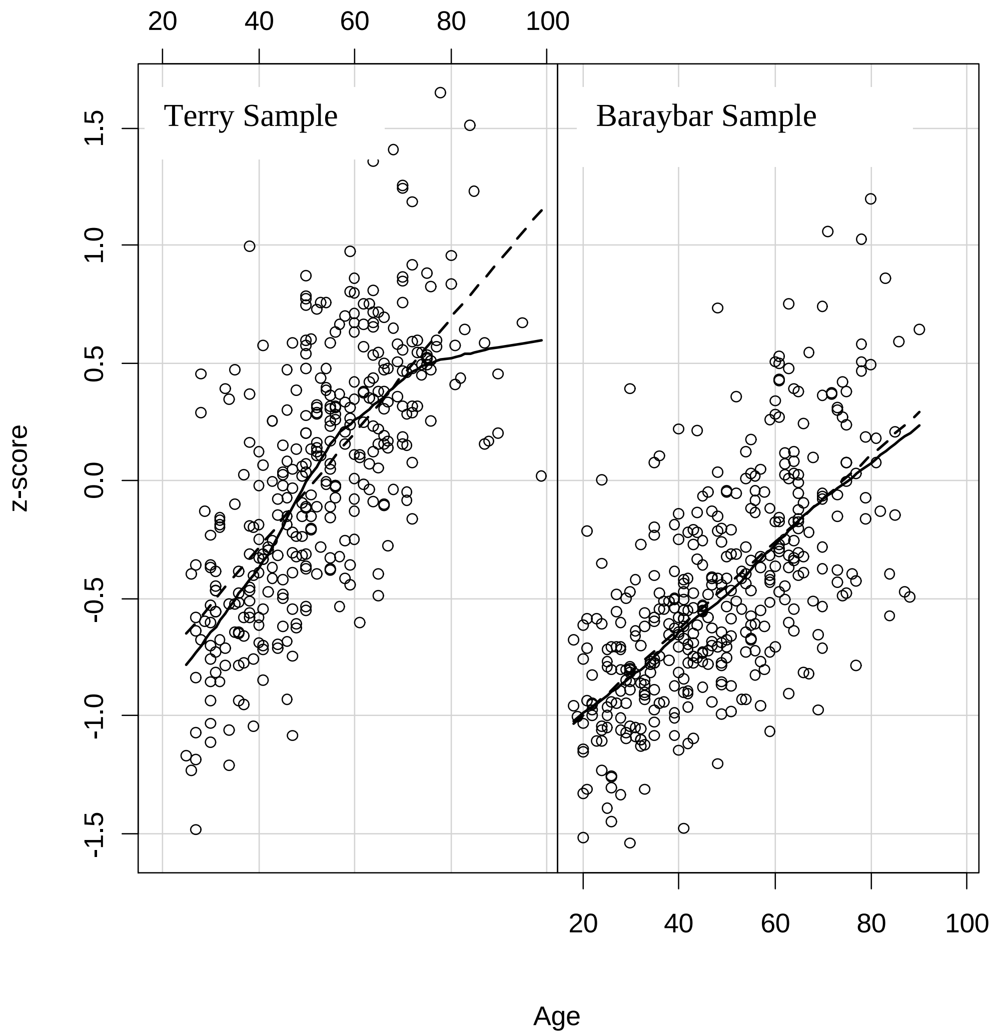

Figure 9. ANOVA results comparing translucency z-scores for the Terry and Baraybar samples. Dashed line represents the regression line and the connected line represents the Loess regression line.

Table 5. Results of the ANOVA between the Terry and Balkan samples.

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	-1.259574	0.076401	-16.486	< 2e-16 ***
Site	-0.086601	0.097020	-0.893	0.37235
Age	0.024366	0.001390	17.525	< 2e-16 ***
Site:Age	-0.006433	0.001816	-3.543	0.00042 ***
Significance codes:	0 `***' 0.001 `**' 0.01 `*' 0.05 `.' 0.1 ` ' 1			

years (see Appendix A for the actual and estimated ages-at-death). As with the previous research mentioned above, the sample was broken into age cohorts (Table 6, Figure 10). A correlation coefficient of 0.73 was produced between the predicted ages and the actual ages using a Bayesian approach to estimate age-at-death for this sample (Figure 11). To assess the accuracy of the Bayesian approach, the mean errors and absolute mean errors were compared to Lamendin's inverse calibration formula and Prince and Ubelaker's inverse calibration formulae for white males and females (Figure 12). The Bayesian aging shows a difference in the older age groups (60+ years) and the young age group (18-29 years) when compared to the multiple regression formulae.

The mean errors were also compared to assess bias (Figure 13). As mentioned above, traditional multiple regression tends to consistently underestimate age in older individuals while overestimating age in younger individuals. Although this under aging and over aging still occurs with Bayesian aging, the overall effect is reduced. This effect can be seen in Figure 13. Both the Lamendin and Prince and Ubelaker 18-29 year olds are all overestimated in age. This is inherent in the regression formulae used, for they each have a constant added at the end of the equations, 25.53 years with Lamendin's

Table 6. Mean absolute error using Bayes' theorem for the Baraybar Forensic Biosample Collection sample.

Age Intervals (years)	<20	25-29	30-39	40-49	50-59	60-69	70-79	80-89	90+	Total
Number of Teeth	3	58	72	88	65	63	38	13	1	401
MAE (years)	15.9	8.88	7.69	7.96	8.63	8.29	12.3	17.4	17.6	9.01

Figure 10. Mean absolute error for the Baraybar Forensic Biosample Collection sample.

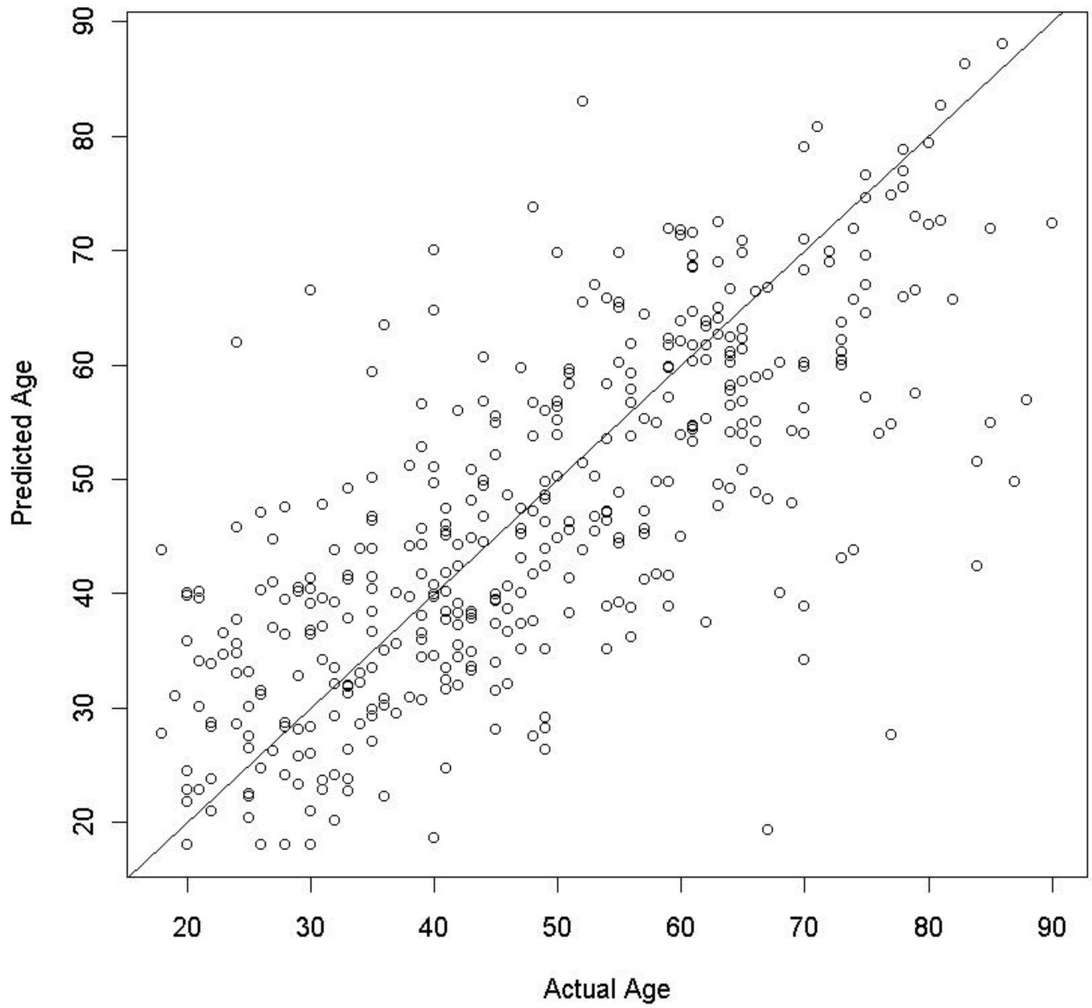

Figure 11. Actual age versus predicted age-at-death for the Baraybar Forensic Biosample Collection sample.

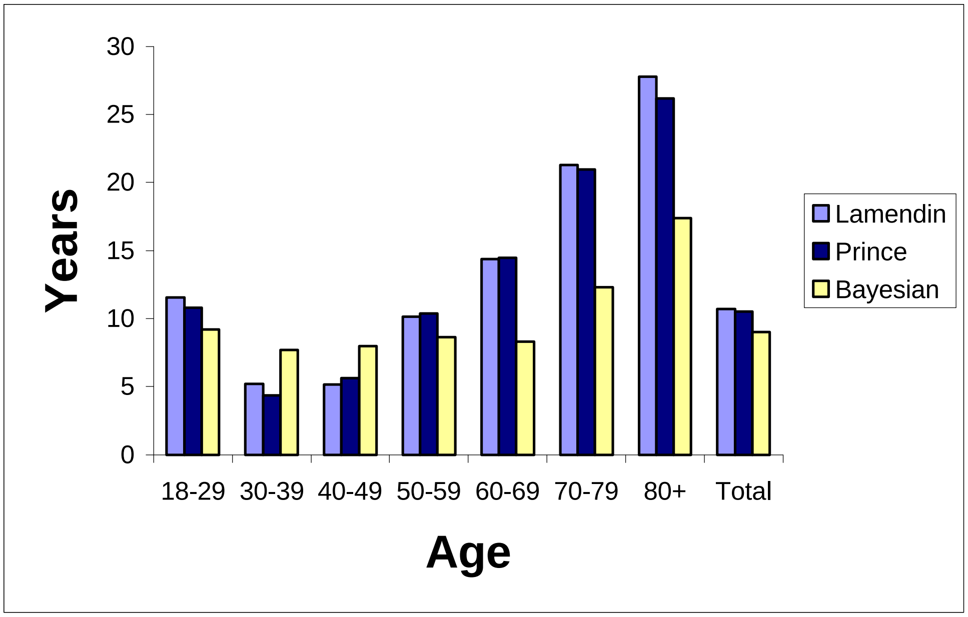

Figure 12. Comparison of mean absolute errors among the three formulae for the Baraybar Forensic Biosample Collection sample.

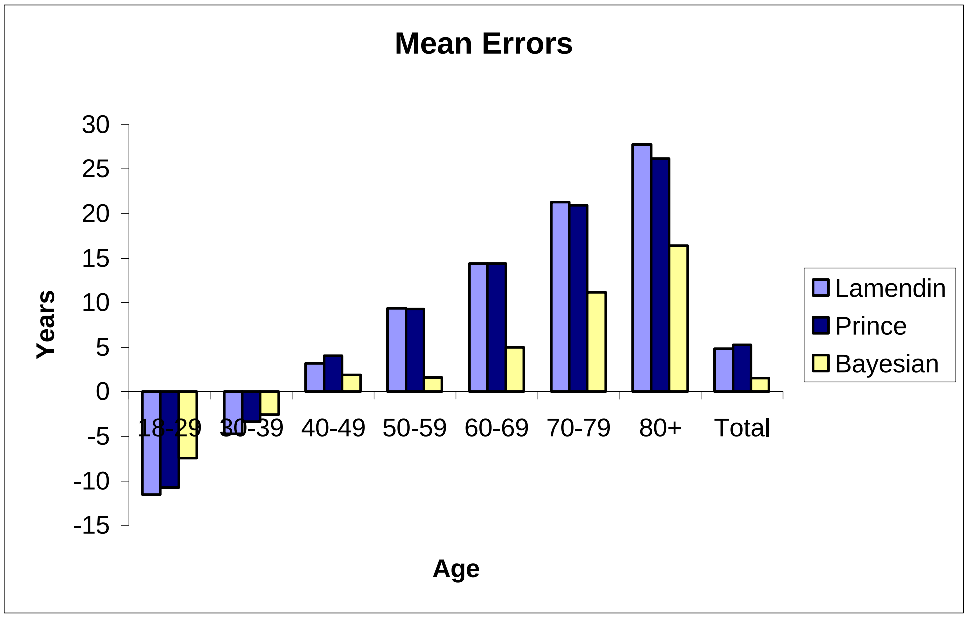

Figure 13. Comparison of mean errors among the three formulae for the Baraybar Forensic Biosample Collection sample.

formula, 23.17 years with Prince and Ubelaker's formula for white males, and 11.82 years with Prince and Ubelaker's formula for white females. Therefore, the Lamendin and Prince and Ubelaker male formulae will not produce age estimates under 25.5 and 23.2 years respectively because a tooth can have a periodontal recession and translucency of zero. Likewise, all individuals 60 years and older were underestimated in age when employing Lamendin's formula. Most 60 year olds and all individuals 70 years and older were underestimated in age when employing the appropriate formula from Prince and Ubelaker. As stated above this effect is not completely eradicated with Bayesian aging, but the effect is greatly reduced.

A paired t-test was run between the known age-at-death and the estimated ages-at-death for the Bayesian approach. The Bayesian approach produced a *t*-score of 2.5424, with 400 degrees of freedom and a *p*-value of 0.01139, thus determining that there is a significant difference between the actual ages-at-death and the estimated ages-at-death. Even though this test yielded a significant difference, two points must be considered. The first is that a *t*-test assumes that variables are measured without error, which is not so when dealing with Bayesian ages, which carry substantial standard errors. The second point, is that while the difference is significant, it is very trivial, approximately 1.5 years.

4.4 Bayesian Approach Applied to Lauchheim Cemetery Sample

Using the Baraybar Forensic Biosample Collection as a reference sample for the Lauchheim medieval cemetery sample, ages-at-death were generated (please see Appendix B for the estimated ages-at-death and the 66.67% confidence intervals). A Gompertz hazard model and a Makeham hazard model were estimated for Lauchheim using the Baraybar Forensic Biosample Collection sample as a reference sample for f(y|a), as per equation (3.2). Figure 14 represents the probability density function (pdf) for age-at death, assuming age at death is $\geq$ 17 years, from the Gompertz and Makeham hazard models for the Lauchheim sample (equation 3.2). Since the Gompertz and Makeham hazard models are so similar, only the Gompertz is utilized in further analysis. The Gompertz parameters for the Baraybar sample of 401 individuals (with age-17) are: $a3 = 0.0106$, $b3 = 0.0432$.

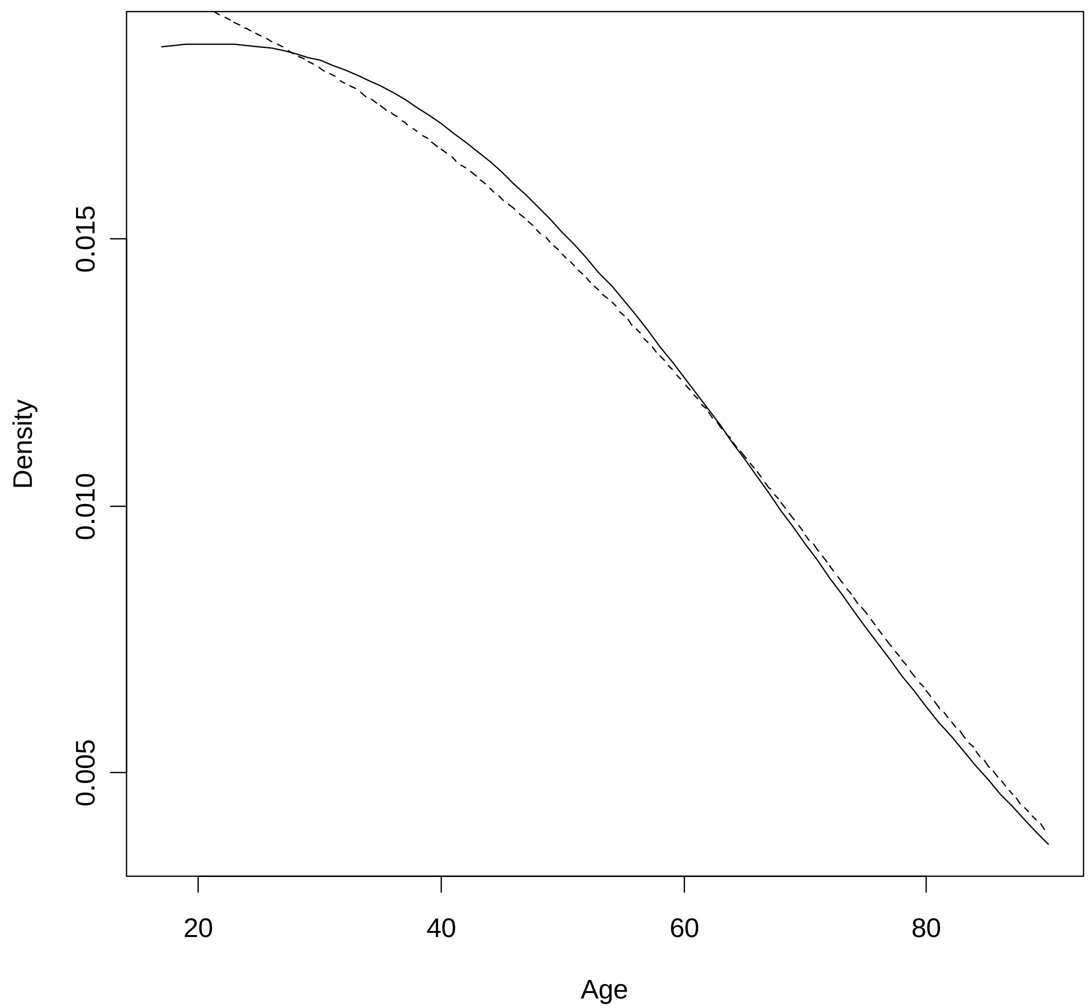

Figure 14. Gompertz (solid line) and Makeham (dashed line) pdf of age-at-death for the Lauchheim sample.

The ages-at-death generated from the Bayesian method were compared to the ages-at-death generated from the inverse calibration methods (Figure 15). Correlation coefficients of 0.89 and 0.77 were yielded between the classical calibration method and Lamendin's method and Prince and Ubelaker's, respectively. Figure 15 highlights the aging differences that occur with the two inverse calibration age estimations. Older individuals are underestimated in "age", while the younger individuals are over estimated in "age" relative to the Bayesian method when the inverse calibration methods are employed. The age-at-death distributions are depicted in Figure 16. Again, aging differences are evident from this Figure. The two inverse calibration age-at-death pdf's have regressed toward the mean, while no such effect is evident with the classical calibration age estimates. Periodontal recession was not utilized as a parameter to estimate age-at-death for the Lauchheim sample. As stated previously, the line of soft tissue attachment could not be determined on this sample and therefore the measurement was taken from the cej to the alveolar margin. Figure 17 shows that the "periodontal recession" measurement for the Lauchheim sample does not follow the trend of the modern samples. In addition, the periodontal measurements for Lauchheim show no organization, as compared to the other samples.

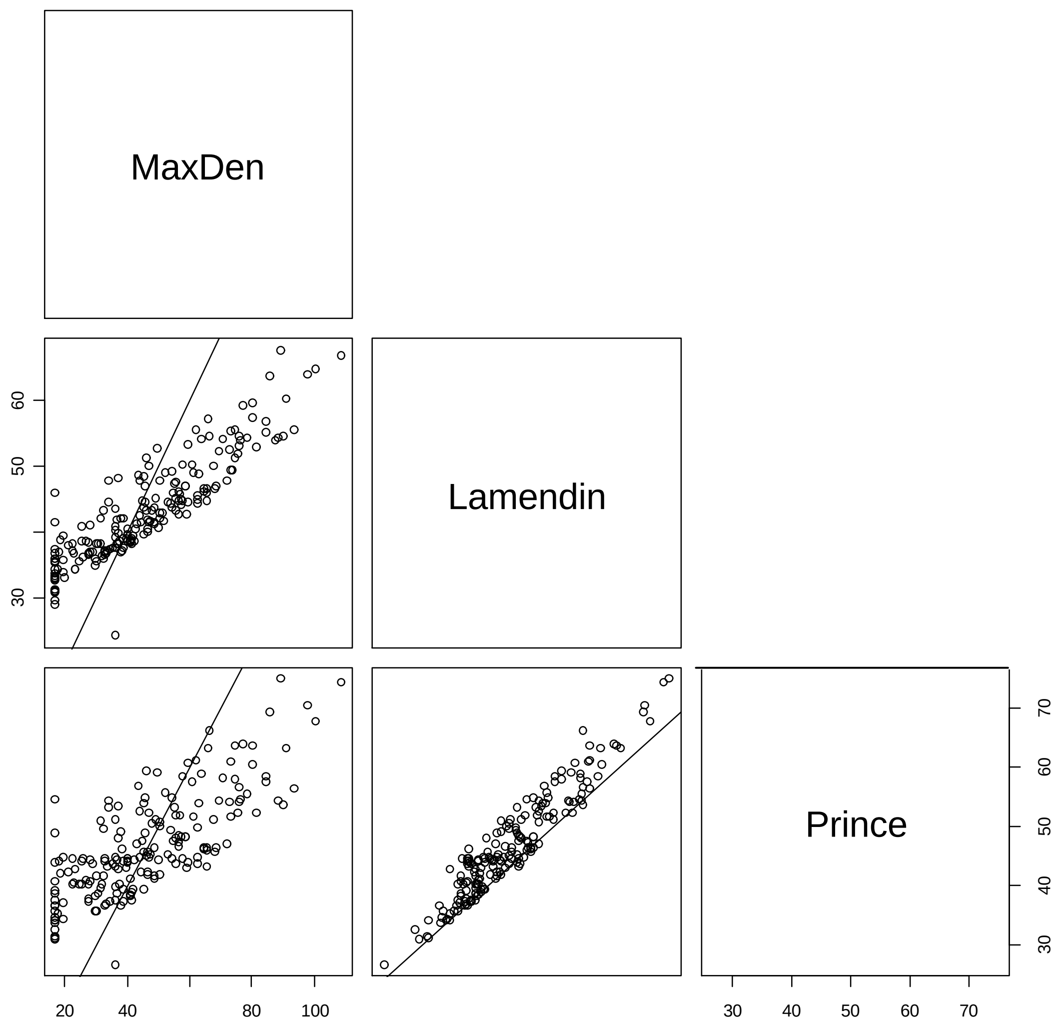

Figure 15. Correlation between the Bayesian method (MaxDen) and the two inverse calibration methods (Lamendin and Prince).

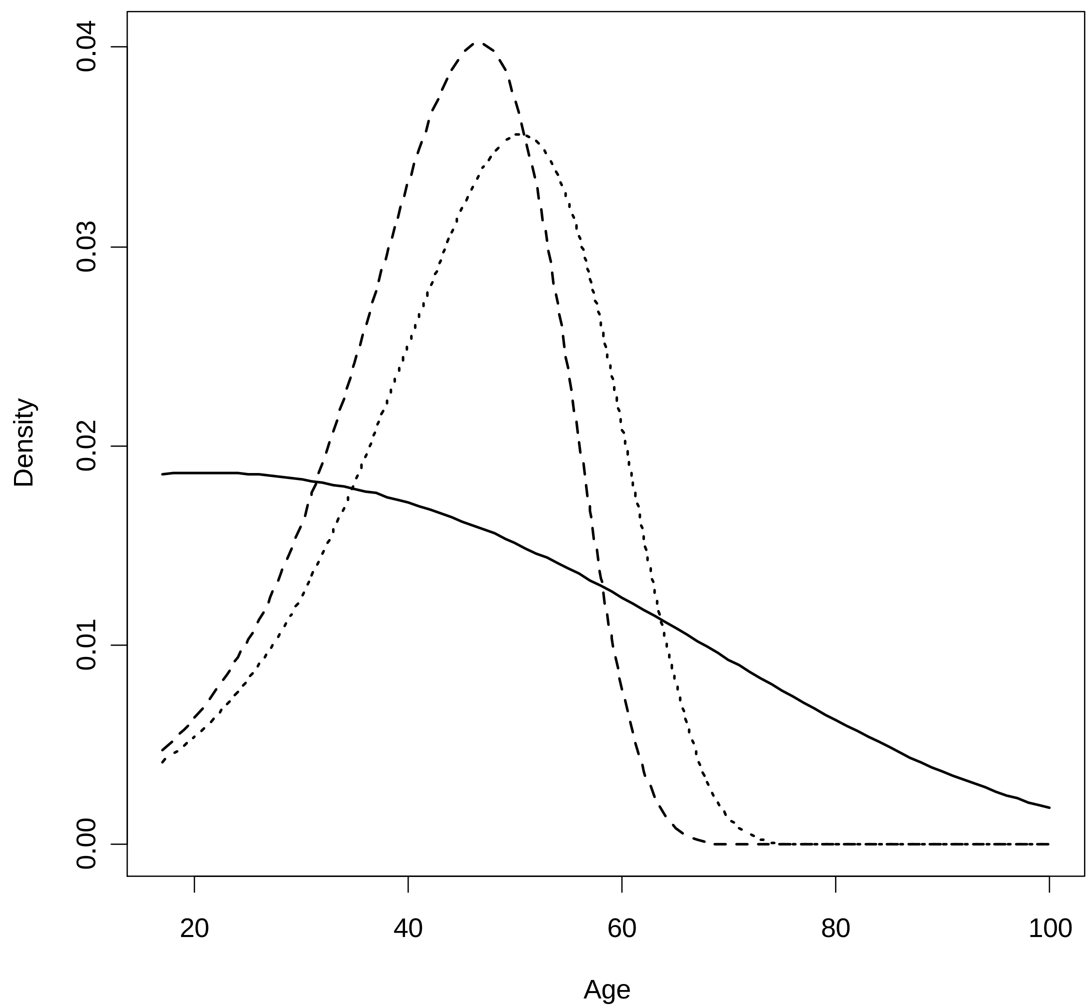

Figure 16. Comparison of the age-at-death distributions for the Bayesian method (solid line) and the two inverse calibration methods, Lamendin (dashed line) and Prince and Ubelaker (dotted line).

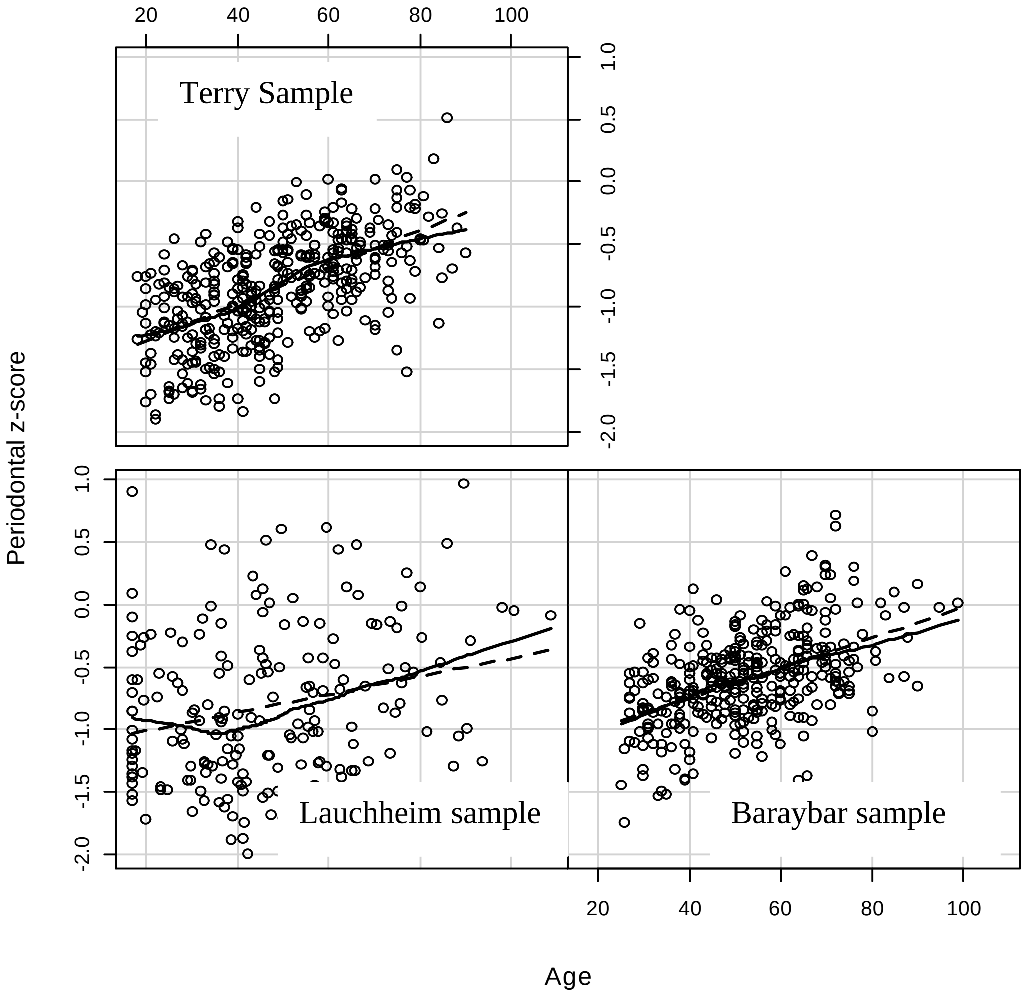

Figure 17. Periodontal recession z-scores for all three samples plotted against age. Dashed line represents the regression line and the connected line represents the Loess regression line.

CHAPTER 5

DISCUSSION

In the first chapter, seven problems associated with skeletal age-at-death estimations were discussed. Two of those issues, subjectivity of the observer and taphonomic/preservation problems, can be overcome by employing dental metric variables, as discussed above. Subjectivity of the observer is greatly reduced when measurements are used instead of phase-oriented methods. To address subjectivity of the observer and inter-observer error, an additional observer, with no prior experience with Lamendin *et al.*'s (1992) method, also measured root height, periodontal recession, and translucency of the root for the Baraybar Forensic Biosample Collection sample. A repeated measures analysis of variance (ANOVA) produced no significant difference between the two observers for root height and translucency of the root. However, a significant difference was yielded between the two observers for the periodontal recession measurements (Table 4).

Periodontal recession has yielded a low correlation with chronological age in previous studies (Maples 1978, Solheim 1992, Borrman *et al.* 1995, Foti *et al.* 2001), therefore, rendering it useless as a univariate age indicator. In addition, to being hard to observe even in modern samples, periodontal recession can also be influenced by intrinsic and extrinsic factors. Poor oral hygiene can affect both the amount of periodontal recession and the translucency. Several teeth analyzed from the Baraybar sample had such severe coronal decay that the pulp was open and then the entire root was translucent; these teeth were eliminated from the analysis. Along similar lines, several studies reviewed in Chapter 2, analyzed “reason for extraction” to determine if this category had an affect on the dental age indicators, especially periodontal recession and cementum annuli apposition. Periodontal disease was the category that received the most attention from authors, although most reported conflicting results as to its influence. Anomalous dental wear from external stimuli, such as pipes, also led to exposed pulp chambers in some extreme cases of the Baraybar sample. In the current study, periodontal recession could not be observed on the Lauchheim material, since no soft tissue remained. The distance between the cej and the alveolar margin was taken in its place. Figure 17 shows that this measurement offers very little as an age indicator. Since this measurement was not a true measure of periodontal recession, it was not utilized in the application of Bayes’ theorem to the Lauchheim sample. Translucency of the root, which has been proven to be a strong indicator of chronological age, was the only age indicator used to generate the pdf of age-at-death for Lauchheim, although periodontal recession and apical translucency were both used in the age-at-death estimates with the inverse calibrations.

Although teeth have a considerable post-mortem longevity, several researchers (Vlèek and Mrklas 1975, Marcsik *et al.* 1992, Sengupta *et al.* 1999) have stated that apical translucency was not a reliable age indicator for archaeological material. These researchers stated that soil apposition would interfere with the amount of apical translucency. In addition, Lucy *et al.* (1995) encountered preservation problems when analyzing sectioned archaeological teeth. Other researchers did not encounter problems measuring apical translucency in archaeological collections (Acsádi and Nemeskéri 1970, Maples 1978, Colonna *et al.* 1984, Drusini *et al.* 1991). The dentition of the Lauchheim material was in fair to good condition overall. Most teeth (N=201) demonstrated some amount of apical translucency, although several teeth did not (N=62). Teeth without translucency of the root (23.6%) could fall into one of two categories: they belonged to a young individual, under age 17, or taphonomic processes undermined the internal structure of the tooth. Previous research on unknown-age archaeological material compared dental age estimates with skeletal age estimates. The entire skeleton was not available for analysis when the Lauchheim material was measured, therefore, no comparisons could be made. Further research should be conducted on large, known-aged archaeological material to determine effects of taphonomic processes, without relying on estimates from different age indicators.

5.1 Advantages of Applying Bayesian Analysis to the Baraybar Sample

Comparison of the Terry and Baraybar samples by means of an ANOVA revealed that individuals acquire apical translucency at differing rates (Figure 9). The Terry Collection sample yielded higher amounts of apical translucency for any given age, when compared to the Baraybar sample. Since the samples aged differently and the Terry Collection has been questioned as an appropriate reference collection, it was not used in further analysis.

The Baraybar Forensic Biosample Collection was utilized to analyze several problems outlined in Chapter 1. The Baraybar sample was analyzed via inverse calibration, Lamendin’s formula (1992) and Prince and Ubelaker’s formulae (2002), and classical calibration, which employed Bayes’ theorem. Several advantages were evident with the Bayesian approach as compared to the inverse calibrations. Referring back to the problems outlined in Chapter 1, aging bias was decreased when Bayesian analysis was utilized. Figure 13 displays the effect of aging bias. As mentioned above, aging bias still exists with the Bayesian method, but to a much smaller degree. The largest mean errors were produced in the youngest and oldest age categories, the under 30 and over 60 age cohorts, regardless of which calibration method was applied. These mean errors were reduced when the Bayesian approach was utilized (Figure 13). This approach was able to capture more of the right-most tail of the age-at-death distribution, which encompasses the older individuals in the sample. As mentioned in the previous chapter, all individuals under 29 were overestimated in age when the inverse calibration was applied. In addition, all individuals 60 year and older were underestimated in age when Lamendin's formula was applied, while most 60 year olds and all 70 years olds were also underestimated in age with Prince and Ubelaker's formulae.

Repeatability, high accuracy, and high correlation with age are traits of a good age indicator. These features are critical when developing a biological profile, whether for forensic or paleodemographic purposes. The Bayesian analysis produced a lower overall mean error, of 1.51 years, as compared to the two inverse calibration methods for the Baraybar sample. In addition, the Bayesian method produced a higher correlation between actual age and predicted age, 0.73, as compared to the Lamendin and Prince and Ubelaker formulae, 0.67 and 0.70 respectively. Overall, the Bayesian method produced more accurate age estimates as compared to the inverse calibration.

Large age ranges associated with most phase-oriented methods are demonstrated by the large confidence intervals around the mean age-at-death for a particular phase. The Bayesian analysis utilized above produced a maximum density age that is the most probable age as well as the full posterior density for age. There are theoretical reasons why confidence intervals increase as age increases. Interpersonal variation in deterioration of skeletal elements promotes this trend. Aging methods developed on indicators that are less susceptible to individual lifestyle aid in decreasing age ranges, especially for older individuals. As mentioned previously, classical calibration will produce larger confidence intervals than those associated with inverse calibration, but the estimates will be unbiased with the classical calibration. The Bayesian analysis did produce smaller age ranges than those associated with phase-oriented methods.

Acquisition of apical translucency may be related to a myriad of individual lifestyle variables. Mastication and heavy loading forces may increase the amount of translucency associated with an individual or a population. This may be one of the factors associated with the variation in acquirement of translucency between the Terry and Baraybar samples. Other dental methods, such as cementum annuli counts and aspartic acid racemization seem to offer promising results for age-at-death estimates, but require destructive analyses. Both of these dental methods have produced very high correlations with age, very accurate age estimates, and small age ranges.

5.2 Comparison of Age-at-death Estimations for the Lauchheim Medieval Cemetery

The previous chapter analyzed two known-aged samples to determine applicability as a reference sample for the unknown-age skeletons from the Lauchheim medieval cemetery. Since the Baraybar Forensic Biosample Collection sample is geographically close to Lauchheim, comprised of a large sample, and is free of sampling issues associated with the Terry Collection, it was thought to be a more appropriate reference sample for Lauchheim. Although no chronological ages were available for the Lauchheim sample, comparisons were made between the Bayesian age estimations and the inverse calibration estimations. The Prince and Ubelaker formulae consistently aged individuals older than the Lamendin and Bayesian methods. Several reasons could account for this trend. The inverse calibration age estimates included the apical translucency measurement as well as the "periodontal recession" measurement. As mentioned above, this "periodontal recession" measurement was not a true measure of that feature. Aside from difference of the measurement, population variation may also contribute to the observed trend. Prince and Ubelaker's formulae are based on the Terry Collection, which was thought to be a less appropriate reference sample for Lauchheim. A final point to consider is that root height is also incorporated into the Prince and Ubelaker formulae. Additional variables will increase the age estimate because more factors are added into the formulae.

The pdf's of age-at-death of the three samples are depicted in Figure 16. The two inverse calibration methods have very similar distributions, with highest densities between 45 and 50 years. The Bayesian approach produces a much wider and more encompassing distribution. Age estimates using this approach, range from 17-108.6 years, while the inverse calibrations produces a much smaller age range, 27.24-67.72 years with Lamendin's formula, and 28.76-74.99 years with Prince and Ubelaker's formulae. As mentioned above, the inverse calibration methods regress toward the mean, an effect that is nearly absent with the Bayesian age estimations.

Another problem discussed in Chapter 1 was age mimicry, where the target sample mimics the age-at-death distribution of the reference sample. The age-at-death distribution of the Baraybar sample (Figure 7) is not reflected in the pdf of age-at-death of the Lauchheim sample (Figure 16). This effect is one of the biggest advantages of using classical calibration, when an appropriate reference sample is available.

Although cementum annuli counts and aspartic acid racemization seem promising aging techniques, both methods encounter problems when applied to archaeological or exposed material. Cementum annuli counts were also obtained for the Lauchheim material by U. Wittwer-Backofen. She reported several problems with analysis of the material, which included wavy lines, focusing issues, and repeatability problems (Wittwer-Backofen, personal communication). Masters (1986) analyzed a very small sample (6 teeth) to assess postmortem changes in aspartic acid racemization and also reported problems with one tooth which experienced long exposure to different climatic changes. Despite these issues and the destructive nature of the types of analyses, further research may prove promising with these two methods of age estimation.

5.3 Summary

The classical calibration age-at-death estimates produced a lower overall mean error and higher correlation with actual age as compared to the inverse calibration methods for the Baraybar Forensic Biosample Collection. In addition, the classical calibration approach reduced aging bias, age mimicry, and the age ranges associated with the most probable age. The Baraybar Forensic Biosample Collection sample was used as a reference sample for the Lauchheim material. Although periodontal recession was not utilized with the classical calibration of Lauchheim, apical translucency proved to be a robust univariate age indicator.

CHAPTER 6

CONCLUSIONS

Following a Rostock compliant analysis, several problems outlined in Chapter 1 were addressed with this research. Age mimicry, aging bias, and age ranges were reduced following this protocol. Proper application of statistical methods, where the dependent variable, the amount of apical translucency divided by the root height (y), is regressed on the independent variable, age (x) followed by solving for age was applied to the Baraybar Forensic Biosample Collection and the Lauchheim samples. This Bayesian approach offered the most appropriate statistical analysis for the estimation of age-at-death with the current samples.

The current research supports previous authors' results concluding that periodontal recession cannot be used as an age indicator for archaeological samples. In addition, this feature should not be used in isolation to estimate age-at-death for contemporary populations and offers little insight into aging processes. Although periodontal recession could not be measured on the archaeological sample, apical translucency could be assessed for most individuals. Since apical translucency is highly correlated with chronological age, it can be used as a univariate paleodemographic age indicator. Paleodemographic samples are inherently biased because they "represent a distorted portion of a once-living population" (Kemkes-Grottenthaler 2002). Taphonomic processes affect all aging methods, whether they are phase-oriented or measurements of continuous variables. Such processes can lead to missing and/or misinterpreted data. Although several dental methods, such as cementum annuli apposition, aspartic acid racemization, and apical translucency, yield promising advances in estimating age-at-death, postmortem events may hinder estimations. Previous research illustrates the need for continued research and development of techniques to counter problems pertaining to taphonomic processes.

As noted by several authors, all available skeletal age indicators should be assessed when possible. There are several important advantages to multiple-trait age estimates. A more robust age estimate can be derived when multiple indicators corroborate an age range. In addition, interpersonal variation can be better understood when multiple indicators are analyzed. Focusing on only one or two age indicators will offer only a minimum understanding of the actual aging process.

From this research, the importance of proper statistical modeling and choosing an appropriate age indicator is evident. Future research should include analysis of large, known-aged archaeological material to assess effects of taphonomic processes on acquisition of translucency of the root. In addition, analysis of known-aged historical material will further enable comparison among statistical methodologies. As technological, methodological, and statistical advances add to the resources physical anthropologists employ to estimate age-at-death from skeletal indicators, we will continually refine and improve techniques to more accurately establish a biological profile from skeletal remains.

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APPENDICES

APPENDIX A: Estimated and actual ages-at-death for the Baraybar Forensic Biosample Collection sample.

case	actual age	estimated age
1	65	62.32318
2	65	69.74039
3	34	32.99196
4	21	30.07513
5	79	57.54283
6	62	63.85226
7	51	45.59182
8	56	57.84312
9	74	65.67903
10	64	61.16787
11	77	27.64545
12	40	39.74976
13	42	31.92918
14	31	47.80225
15	21	34.06639
16	43	48.17784
17	40	64.80407
18	40	34.56899
19	43	38.38423
20	41	32.39080
21	25	30.07385
22	30	36.78592
23	48	73.74282
24	33	37.83223
25	47	39.99709
26	36	35.02024
27	45	37.33369
28	35	29.23638
29	27	26.23688
30	33	23.71808
31	51	58.30670
32	55	60.23045
33	66	48.77404
34	42	35.49416
35	45	39.42533
36	20	21.77261
37	51	38.31229
38	53	50.21183
39	29	28.05326

case	actual age	estimated age
40	46	38.65655
41	79	72.99211
42	36	30.23932
43	85	54.87169
44	24	61.93788
45	45	39.39661
46	38	39.66393
47	56	36.22892
48	56	38.79723
49	23	36.54324
50	30	20.91839
51	59	62.30761
52	87	49.72171
53	71	80.78336
54	55	65.49966
55	80	72.21868
56	84	42.37915
57	57	64.42494
58	59	59.84322
59	66	58.91507
60	22	33.81472
61	42	39.08258
62	33	31.28443
63	35	33.47791
64	33	41.23958
65	63	72.44240
66	26	24.69945
67	22	28.67212
68	30	66.56840
69	64	49.22904
70	78	76.93522
71	37	35.64834
72	74	71.89368
73	32	39.24769
74	51	59.19667
75	27	37.02549
76	25	26.45550
77	61	60.26493
78	35	41.44345
79	34	28.53664
80	73	43.10366
81	22	28.35627
82	49	48.60196
83	54	47.21073

case	actual age	estimated age
84	26	40.33637
85	59	71.93584
86	61	61.73321
87	55	69.81704
88	66	66.36070
89	20	39.83566
90	55	44.84513
91	41	38.46495
92	74	43.85025
93	72	68.93247
94	62	61.65768
95	32	29.26258
96	39	30.67554
97	26	18.05698
98	49	49.81672
99	63	64.95962
100	63	47.62207
101	42	42.44449
102	41	40.16656
103	24	34.82292
104	25	27.52178
105	48	47.19396
106	72	69.93003
107	55	39.23449
108	39	52.76551
109	31	23.62740
110	31	22.82081
111	47	37.31926
112	41	46.04067
113	28	39.41908
114	46	36.62201
115	41	45.11316
116	35	40.37189
117	54	38.88377
118	62	60.46534
119	24	37.68606
120	64	58.22148
121	31	37.07799
122	59	57.11936
123	42	44.29703
124	61	54.28075
125	39	38.01132
126	24	32.99435
127	63	68.95575

case	actual age	estimated age
128	33	49.14821
129	18	27.80141
130	73	61.13634
131	59	49.71596
132	49	46.27494
133	41	33.49976
134	33	41.58382
135	41	41.77975
136	41	24.74318
137	47	45.72226
138	70	70.96801
139	39	36.58394
140	54	53.47945
141	55	64.97769
142	18	43.81790
143	51	41.32272
144	75	76.58564
145	44	60.68421
146	49	43.94774
147	32	32.09065
148	26	18.00007
149	20	22.82802
150	59	41.60675
151	21	39.59393
152	43	37.79572
153	55	44.37287
154	49	48.21425
155	35	46.42392
156	57	45.69092
157	47	43.05256
158	47	35.11968
159	62	55.27352
160	62	37.50515
161	64	56.47345
162	70	56.15955
163	41	47.40955
164	26	31.19067
165	65	63.10844
166	45	54.92809
167	30	41.29812
168	43	44.79452
169	82	65.66141
170	75	64.48806
171	65	50.77443

case	actual age	estimated age
172	60	62.08674
173	29	25.76419
174	70	34.16746
175	49	26.38183
176	84	51.46633
177	83	86.27698
178	65	58.54297
179	68	40.09452
180	70	59.85998
181	36	30.78069
182	88	56.90480
183	39	34.37223
184	29	40.20127
185	64	66.67134
186	24	28.58988
187	45	52.08262
188	50	56.76254
189	63	49.48032
190	59	61.65515
191	36	63.41639
192	80	79.40319
193	54	65.82131
194	77	74.82337
195	73	59.92525
196	64	54.13800
197	54	47.07826
198	28	36.41109
199	34	32.15595
200	61	68.63290
201	57	47.17345
202	70	78.99517
203	43	33.23197
204	43	38.14289
205	24	45.77507
206	46	32.03920
207	48	37.59476
208	32	24.09362
209	73	62.13525
210	77	54.74473
211	79	66.51854
212	67	66.72398
213	75	66.98188
214	61	54.68932
215	65	54.82553

case	actual age	estimated age
216	61	71.57328
217	49	42.38267
218	22	20.97667
219	35	46.72355
220	69	47.90145
221	67	48.27377
222	62	63.37172
223	50	69.82909
224	29	23.35410
225	31	39.60073
226	34	43.85690
227	35	59.34605
228	56	53.77261
229	56	59.22011
230	41	45.40071
231	50	50.20492
232	20	18.00007
233	20	24.43383
234	81	72.56200
235	42	38.26248
236	37	40.04384
237	29	40.48819
238	29	32.81903
239	44	46.73587
240	67	59.12200
241	46	48.63039
242	60	71.78931
243	53	66.93352
244	60	63.84666
245	38	51.16803
246	39	56.52624
247	67	19.32665
248	70	68.23045
249	56	61.80738
250	28	18.06916
251	31	34.15780
252	78	78.83427
253	64	60.13881
254	52	43.77447
255	70	54.03328
256	61	64.63499
257	60	53.86135
258	39	41.69528
259	27	41.02317

case	actual age	estimated age
260	40	70.06897
261	60	71.34385
262	40	51.01942
263	35	29.88856
264	30	36.36108
265	57	45.16148
266	43	50.85641
267	50	56.28086
268	23	34.60838
269	28	28.34538
270	45	39.92788
271	55	48.87980
272	60	45.00701
273	28	28.65749
274	36	22.26993
275	20	40.02066
276	30	28.30917
277	53	45.46729
278	22	23.77990
279	28	47.49176
280	50	53.83910
281	69	54.24017
282	42	44.23275
283	86	88.09236
284	39	45.63862
285	25	22.25765
286	43	33.59613
287	35	38.41005
288	64	62.36110
289	66	55.07677
290	52	82.98379
291	78	75.49894
292	61	69.50622
293	21	22.84749
294	51	46.24351
295	75	57.19872
296	33	26.31326
297	44	44.51977
298	26	47.03493
299	85	71.87436
300	81	82.73161
301	47	59.73186
302	90	72.42226
303	44	49.43401

case	actual age	estimated age
304	38	44.18307
305	68	60.13547
306	65	56.77371
307	70	60.21185
308	50	55.21240
309	40	39.93554
310	25	22.49764
311	52	65.50062
312	57	41.25346
313	44	49.88436
314	39	44.21819
315	30	40.42196
316	45	55.46094
317	61	53.22202
318	78	65.87237
319	73	63.67669
320	65	54.03369
321	45	31.53647
322	28	28.70327
323	24	35.64928
324	64	57.77667
325	40	18.66352
326	40	40.72331
327	27	44.75902
328	73	60.39388
329	39	35.95561
330	70	38.90233
331	58	41.64272
332	26	31.44622
333	64	60.77813
334	35	43.86450
335	44	56.82783
336	63	64.10807
337	28	24.08276
338	48	41.69424
339	41	37.69462
340	65	70.89961
341	75	69.51020
342	20	35.81816
343	49	28.20611
344	30	39.12755
345	49	55.99803
346	35	26.99157
347	38	30.86887

case	actual age	estimated age
348	33	22.73332
349	61	54.55538
350	50	44.81647
351	47	47.47762
352	75	74.64479
353	25	33.17689
354	66	53.30214
355	47	45.25580
356	46	40.58527
357	51	59.63979
358	48	53.74896
359	54	35.07662
360	21	40.10629
361	45	28.12783
362	45	33.92539
363	59	59.71476
364	63	62.69645
365	42	37.21405
366	42	34.46179
367	32	33.43277
368	19	31.02556
369	61	68.49028
370	37	29.53753
371	35	36.68077
372	32	43.84773
373	57	55.28323
374	25	20.32877
375	30	25.96278
376	35	50.15367
377	45	31.51329
378	42	55.96365
379	55	48.85556
380	76	54.03676
381	43	34.91441
382	54	58.30551
383	32	20.10895
384	49	35.16244
385	59	38.92162
386	65	61.37046
387	54	46.38692
388	58	49.71538
389	30	18.05353
390	56	56.66687
391	48	56.70071

case	actual age	estimated age
392	48	27.47523
393	40	49.65365
394	50	56.32978
395	53	46.77054
396	49	29.14598
397	33	31.85031
398	41	31.57497
399	58	54.89900
400	52	51.35435
401	33	31.92795

APPENDIX B: Bayesian estimated ages-at-death for the Lauchheim Medieval Cemetery

Burial	Low	MaxDen	Hi
WS_LH_1063	23.26042	29.97468	36.6576
WS_LH_0494	52.48897	59.44059	66.362
WS_LH_0015	17	17.85139	24.499
WS_LH_0531	30.75954	37.79114	44.7903
WS_LH_0183	17	17.00006	23.7582
WS_LH_0613	21.08692	27.45405	33.7924
WS_LH_0808	17	17.00006	20.9832
WS_LH_0093	29.2952	36.31406	43.3003
WS_LH_0508	36.0639	43.09255	50.0897
WS_LH_0525	17	19.51897	25.382
WS_LH_0618	33.12444	40.16035	47.1643
WS_LH_0502	67.86401	74.73256	81.5682
WS_LH_1280	17	17.00006	23.6683
WS_LH_0507	46.24273	53.22524	60.1775
WS_LH_0559	68.67225	75.53605	82.3668
WS_LH_0570	77.98829	84.7944	91.5637
WS_LH_0499	17	17.00006	19.6555
WS_LH_0972	17.39818	22.53419	27.6505
WS_LH_0132	41.93925	48.9423	55.9147
WS_LH_0388	40.95927	47.9669	54.9438
WS_LH_0099	29.08358	36.09963	43.083
WS_LH_0814	49.76025	56.7255	63.6606
WS_LH_0401	17	17.00006	23.2638
WS_LH_0477	21.3702	27.79503	34.1906
WS_LH_0080	51.84768	58.80253	65.7272
WS_LH_0591	51.82758	58.78253	65.7073
WS_LH_0670	17	17.00006	22.4344
WS_LH_0066	17	17.00006	22.344
WS_LH_1157	48.04926	55.02295	61.9665
WS_LH_0193	61.0366	67.9435	74.8192
WS_LH_0839	39.15263	46.16848	53.1534
WS_LH_0633	20.51789	26.7556	32.9655
WS_LH_0483	69.34873	76.20857	83.0351

Burial	Low	MaxDen	Hi
WS_LH_0663	17	18.07677	24.6119
WS_LH_0428	56.12487	63.05786	69.9603
WS_LH_0186	66.22559	73.10357	79.9492
WS_LH_0542	17.48887	22.66718	27.8255
WS_LH_0925	19.63085	25.62712	31.5974
WS_LH_0523	38.25398	45.27379	52.2625
WS_LH_0204	71.8586	78.70336	85.5139
WS_LH_0457	17	21.08314	26.3131
WS_LH_0133	42.42512	49.42587	56.3961
WS_LH_0447	69.76436	76.62172	83.4456
WS_LH_0708	30.81484	37.84673	44.8462
WS_LH_0084	29.63622	36.65905	43.6493
WS_LH_0520	54.57537	61.51636	68.427
WS_LH_0380	77.67256	84.48074	91.2522
WS_LH_0673	48.87083	55.84049	62.78
WS_LH_0810	48.3801	55.35218	62.2941
WS_LH_0215	17	17.00006	20.3608
WS_LH_0405	38.65812	45.67617	52.6632
WS_LH_0463	62.58313	69.48157	76.3485
WS_LH_0054	69.09572	75.95705	82.7851
WS_LH_0897	37.78924	44.81102	51.8017
WS_LH_0917	17	18.79166	24.9832
WS_LH_0452	21.66603	28.14665	34.5976
WS_LH_0625	84.47163	91.23363	97.9552
WS_LH_0087	53.98851	60.93251	67.8462
WS_LH_0632	17	19.43936	25.3373
WS_LH_0846	17	17.00006	20.9116
WS_LH_1008	24.62609	31.46976	38.2813
WS_LH_0904	29.41546	36.43582	43.4235
WS_LH_0522	19.48257	25.43331	31.3584
WS_LH_0322	73.72596	80.55924	87.3576
WS_LH_0615	68.03627	74.85383	81.6389
WS_LH_0553	63.75647	70.6484	77.5086
WS_LH_0327	43.38194	50.37816	57.3439
WS_LH_0389	51.12813	58.08658	65.0149
WS_LH_0497	47.49527	54.47167	61.4179
WS_LH_0617	66.68038	73.55575	80.3986

Burial	Low	MaxDen	Hi
WS_LH_0518	102.078	108.7	115.268
WS_LH_0269	38.66609	45.68411	52.6711
WS_LH_0061	25.42416	32.32142	39.1862
WS_LH_1202	45.37258	52.35927	59.3157
WS_LH_1065	94.02285	100.7129	107.356
WS_LH_0456	91.43017	98.14063	104.806
WS_LH_0538	29.48843	36.50964	43.4982
WS_LH_0818	27.23813	34.21435	41.1579
WS_LH_1205	39.91905	46.93145	53.913
WS_LH_0503	59.76325	66.67702	73.5598
WS_LH_0057	17	17.00006	23.8161
WS_LH_0372	36.91009	43.9355	50.9296
WS_LH_0788	38.42816	45.44721	52.4352
WS_LH_0114	73.42951	80.26464	87.0649
WS_LH_0009	57.09323	64.02116	70.9185
WS_LH_0866	52.637	59.58787	66.5085
WS_LH_0396	36.48722	43.51428	50.51
WS_LH_0045	70.27384	77.12815	83.9489
WS_LH_0284	55.12196	62.06015	68.9679
WS_LH_0533	29.98356	37.00975	44.0034
WS_LH_0002	59.25567	66.17216	73.0577
WS_LH_0036	27.29761	34.27563	41.2209
WS_LH_0451	79.05642	85.85553	92.6172
WS_LH_0662	39.41055	46.42526	53.409
WS_LH_0845	42.57339	49.57344	56.543
WS_LH_0438	17	17.00006	22.737
WS_LH_0027	82.8526	89.62596	96.3599
415	44.38516	51.3766	58.3377
516	66.94545	73.81933	80.6606
543	17	17.00006	20.446
543	17.80864	23.13116	28.4327
753	44.65041	51.64056	58.6004
758	35.57515	42.6055	49.6043
1180 I	17	19.77659	25.5284
1191	17	17.00006	20.3913
1192	50.66509	57.62586	64.5564
1218	80.8003	87.58772	94.3368

Burial	Low	MaxDen	Hi
16	19.70433	25.72258	31.7147
74	33.04285	40.07886	47.0828
260	23.74727	30.51391	37.2489
7	40.50265	47.51239	54.4913
316	32.67188	39.70801	46.712
319	55.67142	62.6068	69.5117
350	50.63383	57.59476	64.5255
300	23.50738	30.24913	36.9594
402	29.93696	36.96273	43.9559
405	48.74173	55.71203	62.6521
407 I	66.65992	73.53541	80.3784
418	25.24761	32.13419	38.9884
447	52.08184	59.03551	65.959
460	36.94965	43.9749	50.9688
481	50.09505	57.05865	63.9921
503	17.7399	23.03207	28.3035
523 I	86.77826	93.52367	100.227
600	61.75368	68.65669	75.5283
612	25.87189	32.79354	39.6826
616	21.7719	28.27144	34.7412
625	49.52182	56.48828	63.4245
632	83.52107	90.28977	97.0186
632	17	17.00006	18.6576
653	43.57422	50.56952	57.5344
662	57.95487	64.87826	71.771
695	39.58081	46.59473	53.5778
818	30.09629	37.12342	44.118
820	22.43281	29.03884	35.6142
846	28.25729	35.25925	42.2285
861	33.252	40.2878	47.2917
939	23.05353	29.74309	36.4014
1006	58.08023	65.00299	71.895
1018	42.92092	49.91933	56.8872
1065	31.5792	38.614	45.6165
1065	33.17819	40.21406	47.218
47	34.22817	41.26235	48.2648
276	17.90885	23.27496	28.6198

Burial	Low	MaxDen	Hi
464	55.58504	62.52084	69.4262
478	47.1154	54.09366	61.0417
667	25.67649	32.58795	39.4669
743	35.24988	42.28129	49.2811
277	17	17.00006	20.7127
934	81.87701	88.6571	95.3983
985	58.60947	65.52942	72.4185
416	26.68802	33.64546	40.5702
569 I	18.83588	24.56845	30.277
803	39.78245	46.79547	53.7776
630	58.65044	65.57018	72.4591
644	55.85663	62.791	69.6949
755	49.819	56.78396	63.7188
904	25.80603	32.72432	39.6101
970	40.15139	47.16272	54.1432
236	34.62583	41.65907	48.6605
305	21.38615	27.81409	34.2127
314	74.62369	81.45137	88.2437
314	61.1594	68.06563	74.9406
320	17	17.00006	23.5557
361	58.9607	65.87876	72.766
370	34.27578	41.30985	48.3122
410	33.99069	41.02538	48.0282
438	29.78915	36.81353	43.8053
440	47.52918	54.50542	61.4515
477	34.94813	41.98046	48.9811
488	26.44191	33.38964	40.3047
507	65.14063	72.02479	78.8768
541	48.55412	55.52534	62.4664
585	17	17.00006	18.837
610	41.96229	48.96523	55.9376
638	17	17.00006	22.7313
652	29.39199	36.41208	43.3995
660	33.91591	40.95076	47.9537
712	30.96842	38.00105	45.0013
754	29.15103	36.168	43.1524
779	31.70644	38.74155	45.7444

Burial	Low	MaxDen	Hi
977	43.5721	50.56742	57.5323
1057	41.75549	48.75938	55.7327
1217	23.4812	30.22013	36.9276
1233	37.66942	44.69172	51.6828
1247	38.40771	45.42685	52.4149
845	31.78334	38.81861	45.8216
537	39.57229	46.58625	53.5693
778	31.84197	38.87736	45.8805
1012	27.65972	34.64791	41.6034
1242	17	19.31244	25.2666
1271	17	17.00006	20.3918
535	26.11361	33.04697	39.9477
419	17	17.00006	23.8384
349	24.79386	31.64997	38.4739
614	50.99808	57.95718	64.8861
1004	17	17.00006	19.8229

VITA

Debra Ann Prince was born in Wilmington, DE on February 2, 1974. She was raised in Wilmington, DE and attended St. John the Beloved and Ursuline Academy grade schools. She graduated from Ursuline Academy High School in 1992. From there, she attended James Madison University on an athletic scholarship, where she double majored in Anthropology and Psychology. She received a B.S. in each in 1996. She received her M.A. in anthropology in 1999 from the George Washington University and her Ph.D. in anthropology in 2004 from the University of Tennessee, Knoxville.

Debbi is currently a contract archaeologist at the Tennessee Valley Authority and hopes to pursue a career in teaching and research in physical anthropology.