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New Formulae for Estimating Age-at-Death in the Balkans Utilizing Lamendin's Dental Technique and Bayesian Analysis*

ABSTRACT: The present study analyzed apical translucency and periodontal recession on single-rooted teeth in order to generate age-at-death estimations using two inverse calibration methods and one Bayesian method. 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 problems associated with adult skeletal age-at-death estimations. The Bayesian estimates produced a lower overall mean error, a higher correlation with actual age, reduced aging bias, reduced age mimicry, and reduced the age ranges associated with the most probable age as compared to the inverse calibration methods for this sample. This research concluded that periodontal recession cannot be used as a univariate age indicator, due to its low correlation with chronological age. 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 sample.

KEYWORDS: forensic science, forensic anthropology, metric dental aging, Bayes' theorem, Lamendin, translucency, age-at-death

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 (1–20). Differences can be attributed to socioeconomic status, cultural differences, genetic differences, differences in behavior, environmental factors, diet, and disease (16,21).

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 (3,8,22–30), the sternal ends of ribs (7,31–34), the auricular surface of the os coxae (21,35), cranial suture closure (3,35–39), dental attrition (35,40–56), radiology of the proximal femur, and clavicle (57). 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: (i) the subjectivity of the observer leads to problems with inter- and intra-observer error; (ii) 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); (iii) stages often overlap one another; (iv) preservation problems may lead to missing data; (v) bias in overestimating age in younger individuals while underestimating age in older individuals occurs quite frequently; (vi) age mimicry occurs when appropriate reference samples are not utilized and thus increases error estimates; and (vii) improper theoretical and statistical methodologies have often been used to derive age-at-death estimates. The latter three of these will be discussed in further detail below.

A multitude of authors have reported bias in age estimates, which is often referred to as "attraction of the middle" (10,14–17,58–64). 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 (63). This problem is partially attributed to statistical methodologies where inverse calibration is utilized (65). 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, the amount of apical translucency (y), 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 (10,13–16,59,64,66–83). As Konigsberg and Frankenberg (10) point out, this problem has been well known and managed in the fisheries literature (84–89). Bocquet-Appel and Masset (59) 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

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reference sample. Although Bocquet-Appel and Masset stated that this problem, along with aging bias and low correlation between age indicators and chronological age could not be overcome, several researchers (10,14–16,64,68,73,77,79–81,90–98) have provided adequate and ample solutions to the problems reported by Bocquet-Appel and Masset. Using appropriate reference samples and statistical methodologies, as addressed below, can eliminate age mimicry.

The last issue focuses on improper theoretical framework and statistical methodology used to estimate age-at-death. 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 (10,13–15,78,99). The probability density function for the entire target sample is necessary, because every skeleton has its own degree of error (14). 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.

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 into 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.

Several problems associated with age-at-death estimates can be minimized with application of appropriate statistical methods. Most aging methods rely on linear regression or multiple regression analysis (65). 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 (95). Typically in physical anthropology inverse calibration is utilized, where the reference sample age-at-death distribution is usually used as a prior distribution for age. This type of theoretical framework is inappropriate unless the target sample has a similar age-at-death distribution as the reference sample. 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 (65). Confidence intervals will be larger with classical calibration as compared to inverse calibration, but the results will be unbiased. In addition, Konigsberg et al. (65) 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 stature estimated by Geissmann, (100) was not included in that interval. On the contrary, classical calibration captured Lucy's estimated stature provided by Geissmann (100). 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.

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 (15,16). 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 interment 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 (9,10,13,17–20,101,102).

Although the following research will pertain to just two age indicators from 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 (16). 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 (16). Each age indicator and method has its own degree of error (14), 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 (14). In addition, several authors (14,16,30,60,74,103–107) have recommended that multiple trait methods offer a more precise and complete estimate of age-at-death.

The purpose of this research was twofold: (i) to establish the applicability of utilizing Lamendin's method in the Balkans, and (ii) to establish new age parameters calculated specifically from a Balkan reference sample in order to generate Bayesian derived age-at-death estimates.

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. In addition, dental remains are often the only elements recovered from forensic scenes and archaeological sites (108–110).

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 (35,41–56,111–116), secondary dentin deposits (117–123), cementum apposition (83,107,124–135), apical translucency (109,136–148), periodontal recession (149,150), root resorption (40,150), acid racemization (151–163), color change of the root (150,164–167), or a combination of several of these indicators (17,40,104,168–173).

Lamendin's method (171) is preferable for application in the Balkans compared to other methods because it offers a quick, simple and reliable, nondestructive technique employing dental microstructure and is based on a European reference sample. With most other dental methods, thin sections of teeth and a vast knowledge of dental histology are 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.

Lamendin et al. analyzed 306 single-rooted teeth extracted from 208 oral surgery patients. The sample consisted of 135 males, 73 females, of which 198 had a European Ancestry (French), 10 an African Ancestry, and the sample ranged in age from 22 to 90 years. The researchers also tested their method on 45 teeth from 24 forensic cases. The forensic sample contained individuals only from the 30–69-year-old age cohorts, 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 and the cementoenamel junction (cej); periodontal regression, the maximum distance from the cej to the line of soft tissue attachment; and translucency of the root, measured from the apex of the root toward the cej and enhanced with the aid of a light-box. This translucency should not be confused with sclerotic dentin found in the crown, which is a result of pathological conditions. In addition, this physiological feature does not appear before age 17 and is the result of the hydroxyapatite crystals depositing in the dentin tubuli.

From multiple regression analysis, Lamendin et al. (171) 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 periodontal regression measurement × 100/RH. These researchers produced a mean error of ±10 years on their working sample and ±8.4 years on their forensic control sample.

In order to assess the accuracy of Lamendin's method, Prince and Ubelaker (17) analyzed 400 single-rooted teeth, extracted from 359 individuals from the Terry Collection, housed at the Smithsonian's National Museum of Natural History. The sample ranged in age-at-death from 25 to 99 years, with a mean age of 52.67 years and a standard deviation of 14.95 years. The sample consisted of 94 black females (age 25–99 years, mean 52.10, standard deviation 17.36), 72 white females (age 27–90 years, mean 56.95, standard deviation 14.11), 98 black males (age 26–76 years, mean 47.76, standard deviation 12.96), and 95 white males (age 27–85 years, mean 53.88, standard deviation 13.72). 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 Lamendin's method, Prince and Ubelaker (17) divided the sample into age cohorts. Lamendin's method yielded the most accurate age estimates for the 30–69-year-old age groups, which is consistent with Lamendin's original 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 trend with inverse regression techniques of the attraction to the middle, where older individuals were underestimated in age, while younger individuals were overestimated in age. An R^2 of 0.49 was obtained with a p-value <0.001.

Even though Lamendin's method and formula produced low overall mean errors for the Terry Collection, new formulae separating individuals by sex and ancestry and including RH were created, which significantly lowered the mean errors further.

Previous Dental Research in the Balkans

Lamendin's method and formula (171) and Prince and Ubelaker's formula for white males (17) were evaluated by Sarajlić et al. (174). 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 eight 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 (171), Sarajlić et al. (174) yielded 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, Sarajlić et al. (174) found that with both Lamendin's formula and Prince and Ubelaker's formula, that younger individuals were overestimated in age, while older individuals were underestimated in age. Maxillary central incisors produced the lowest mean error, consistent with results of Lamendin (171) and Prince and Ubelaker (17).

Sarajlić et al. (174) concluded that Lamendin's method and Prince and Ubelaker's modified formula are both suitable for use in a Bosnian population.

Materials and Methods

Sample

The sample consists of 401 single-rooted teeth of known age and sex from individuals identified from Kosovo. Identifications were considered presumptive or positive identifications based on forensic work conducted by the International Criminal Tribunal for the Former Yugoslavia (ICTY) (see Kimmerle et al. [175] for further discussion of the validity of these identifications). Permission for this research was given to the University of Tennessee, Knoxville by the ICTY with the expressed goal of sharing data and results that would aid agencies working on human identification in the former Yugoslavia and other areas of the world. Only one tooth per individual was available for analysis, which consisted of a maxillary or mandibular incisor, canine, or premolar. The authors of this paper could not dictate which tooth type was utilized as the teeth were obtained and provided by ICTY to the University of Tennessee.

The sample consists of 359 males, ranging in age-at-death from 18 to 90 years, with a mean age-at-death of 48.16 years and a standard deviation of 16.63 years, and 42 females, ranging in age-at-death from 19 to 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.

Measurements

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 using Bayesian analysis in the R statistical package (176–179, http://www.r-project.org/) with code written by the second author.

The first author, who possesses considerable experience with Lamendin's method, took the three measurements from each tooth: RH, periodontal regression, and translucency of the root. All measurements were recorded in millimeters and taken from the labial surface. All observations were taken blindly. To assess repeatability and inter-observer error, three additional observers with no prior experience with Lamendin's method took the three measurements from the Kosovar dental material following the procedures outlined above (see Kimmerele et al. [180] for those results and further discussion of the inter-observer errors).

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 (181). Observed dental information (translucency and periodontal regression) is denoted as *D*. 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 conditional on the individual being exact age *A*, although 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 equal to the product of the prior probability and the likelihood divided by the integral across age of this product, and Bayes' theorem can be written as:

$$f(A|D) = \frac{f(D|A)f(A)}{\int f(D|A)f(A)\mathrm{d}A} \tag{1.1}$$

In equation (1.1), *f*(*D*|*A*) is estimated by the regression of the observed dental data (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:

$$\ln \mathrm{LK}(\theta|y) = \sum_{i=1}^{m} \ln\left(\int_{17}^{120} f(y_i|a)f(a-17|\theta)\mathrm{d}a\right) \tag{1.2}$$

In equation (1.2), θ 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 (1.2) 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 θ gives the most likely set of Gompertz parameters, which are in turn used in equation (1.1) to generate *f*(*A*).

This approach has been employed in forensic applications to estimate age (63,64,181,182), stature (18,65), sex (183), and ancestry (184). 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 (Eq. [1.1]). When an appropriate reference sample is not available, as in paleodemography, then MLE (Eq. [1.2]) should be utilized. These approaches offer the best estimates in forensic anthropology and paleodemographic analysis.

Results

Applying Bayes' theorem, equation (1.1) to the Kosovar dental data, a mean error of 1.51 years was produced with an absolute mean error of 9.01. As with the previous research mentioned above, the sample was broken into age cohorts (Table 1, Fig. 1). 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 (Fig. 2). To assess the accuracy of the Bayesian approach, the mean absolute mean errors were compared to Lamendin's inverse calibration formula and Prince and Ubelaker's inverse calibration formulae for white males and females (Fig. 3).

TABLE 1—*Mean absolute error (years) using Bayes' theorem.*

Age Interval (Years)	<20	20–29	30–39	40–49	50–59	60–69	70–79	80–90	Total
Number of teeth	3	58	72	88	65	63	38	14	401
Mean absolute error	15.88	8.88	7.69	7.69	8.63	8.29	12.30	17.40	9.01

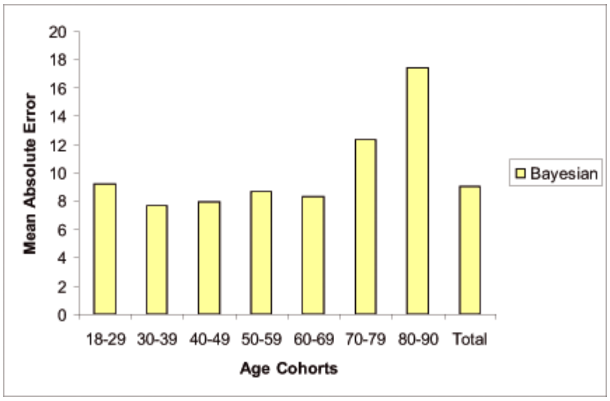

FIG. 1—*Mean absolute error for the Kosovar dental data.*

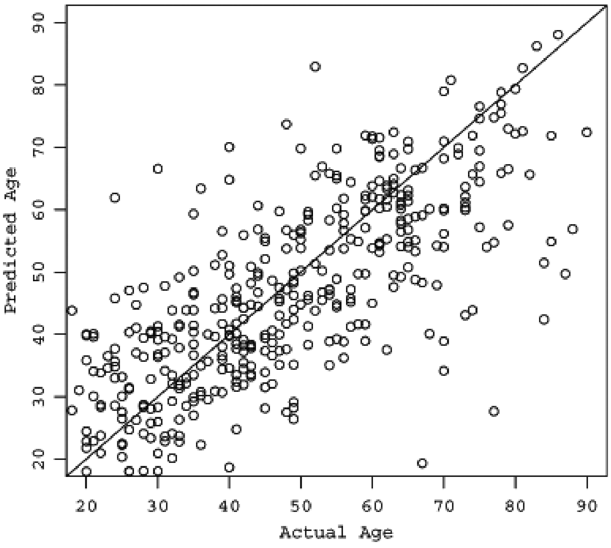

FIG. 2—*Actual age versus estimated age-at-death for the Kosovar dental data.*

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 (Fig. 4). As mentioned above, traditional multiple regression (inverse calibration) 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. 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 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.

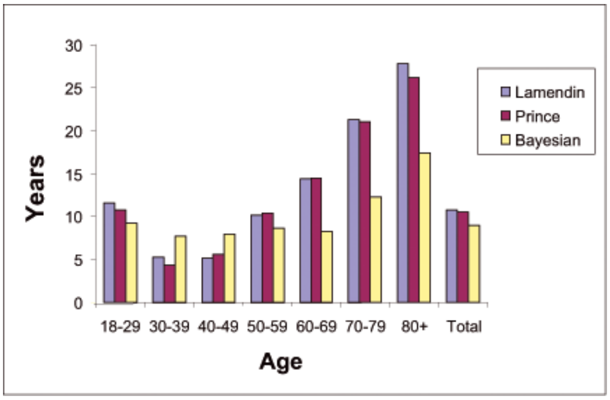

FIG. 3—*Comparison of mean absolute errors among the three formulae.*

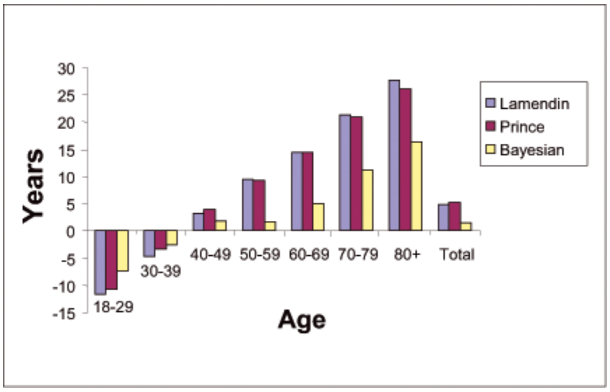

FIG. 4—*Comparison of mean errors among the three formulae.*

Discussion

This research analyzed several problems associated with estimating age-at-death. The effects of two of these issues, subjectivity of the observer and taphonomic⁄preservation problems, can be decreased by employing dental metric variables. Subjectivity of the observer is greatly reduced when measurements are used instead of phase-oriented methods. Dental remains can withstand harsh postmortem environments, therefore making them practical age indicators. But even though dental remains have a considerable postmortem longevity, the age indicator selected must be a good indicator of age. 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. Translucency of the root has proven to be a robust age indicator and employable as a univariate age indicator for forensic applications. However, several researchers (109,145,185,186) have stated that apical translucency was not a reliable age indicator for archaeological material. These researchers stated that soil apposition interfered with the amount of apical translucency. In addition, Lucy et al. (187) encountered preservation problems when analyzing sectioned archaeological teeth. Other researchers did not encounter problems measuring apical translucency in archaeological collections (108,138,188).

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. 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.

Periodontal recession has yielded a low correlation with chronological age in previous studies (108,149,150,189), 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. The current authors stress that periodontal recession cannot be observed in archaeological material and therefore should not be considered in application for archaeological samples; this has also been cautioned by other authors (185,186).

Poor oral hygiene can affect both the amount of periodontal recession and the translucency. Several teeth analyzed from the Kosovar dental 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. Anomalous dental wear from external stimuli, such as pipes, also led to exposed pulp chambers in some extreme cases of the Kosovar dental sample.

In the present study, the sample was analyzed via inverse calibration, Lamendin's formula (171) and Prince and Ubelaker's formulae (17), 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 above, aging bias was decreased when Bayesian analysis was utilized. Figure 4 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 (Fig. 3). 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 previously, all individuals under 29 were overestimated in age when the inverse calibration was applied. In addition, all individuals 60 years and older were underestimated in age when Lamendin's formula was applied, while most 60 year olds and all 70 year olds were also underestimated in age with Prince and Ubelaker's formulae.

The Bayesian analysis produced a lower overall mean error, of 1.51 years, as compared to the two inverse calibration methods (4.85 years for Lamendin's and 5.27 years for Prince and Ubelaker) for the Kosovar dental 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.

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 sample analyzed. In addition, the classical calibration approach reduced aging bias, age mimicry, and the age ranges associated with the most probable age.

Conclusions

Following analytical guidelines set forth by anthropologists and paleodemographers deemed the "Rostock Manifesto" (15), the current research addressed several problems outlined above. 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 sample. This Bayesian approach offered the most appropriate statistical analysis for the estimation of age-at-death with the current sample.

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 (109,144,145,185–187).

As noted by several authors, all available skeletal age indicators should be assessed when possible (14,16,17,30,60,74,103–107). 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, archaeologically recovered material to assess effects of taphonomic processes on acquisition of translucency of the root. 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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