J Forensic Sci, Jan. 2003, Vol. 48, No. 1
Paper ID JFS2002253_481
Available online at: www.astm.org

TECHNICAL NOTE

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Reliability and Validity of Eight Dental Age Estimation Methods for Adults*

ABSTRACT: This paper evaluates the reliability and validity of eight published dental age estimation methods for adults that may aid in victim identification. Age was calculated on 20 Caucasian teeth of known age according to the methods of Kvaal (for in situ and extracted teeth), Solheim (for in situ and sectioned teeth), Lamendin (for extracted teeth), Johanson (for sectioned teeth) and Bang (for extracted and sectioned teeth) by one independent observer. For each method, mean age error and standard error were assessed as the measures of accuracy and precision. In addition, method simplicity, requirements for tooth preparation and the equipment necessary were assessed and recommendations given for forensic use in various situations. Methods for sectioned teeth gave more reliable results when compared to methods for intact teeth.

KEYWORDS: forensic science, forensic dentistry, forensic odontology, age estimation, human identification, method validation

Age estimation may prove to be a critical part in the victim identification process. In cases of unknown bodies, age estimation becomes necessary if there is no antemortem information available and a personal profile has to be reconstructed. These cases often include bodies that are mutilated or severely decomposed either in single cases or mass graves, such as can be seen in a post-war conflict areas or disaster scenes. In addition, age estimation can be done in precious archaeological skeletal material dating back hundreds of years. In cases of living persons, age estimation may be necessary if persons cannot provide acceptable identification documents. These cases often include refugees and illegal immigrants who have arrived to a country without legal documents.

Teeth are the strongest parts in the human body and are therefore very resistant to external influences, such as extreme temperatures, explosions, and other extreme conditions, which makes them available for extensive postmortem periods. In addition, teeth are good indicators of people's age. These two facts allow us to use human teeth for age estimation in forensic work. Dental development in children follows a specific timeline of dental formation, mineralization and maturation, which over the years has been extensively studied. These studies have lead to quite accurate pediatric age estimation methods (1–3). In adults, however, the age related changes in dentition are much more diverse and thus, the variation in age estimates becomes considerably wider. Nevertheless, a number of age estimation methods have been developed for adults' teeth. The simplest age estimation method is the so-called "visual" method, which is based upon clinical experience without using formal methods. In forensic sciences, though, the use of validated and scientifically based formal methods is prerequisite and thus, mere visual estimate is simply unacceptable. Formal methods of calculation based on morphometric measurements (4–9) and amino acid racemization have also been developed. The latter method, amino acid racemization, suffers from a number of limitations: it is methodologically complex (requires special biochemistry laboratory facilities and experience), is time-consuming, and is costly and destructive. Morphometric measurements offer formal methods based on measurements of dental age-related changes, which are applied into mathematical regression models. One problem with morphometric methods is that they have not always been subsequently validated in an independent material set or formally compared to each other. One notable exception was a study in 1980 by Solheim (10). He evaluated five formal calculation methods versus visual age estimation. Solheim found that Johanson's method (5) and visual estimation were the best. The visual estimation, however, demonstrated low precision (a measure of repeatability: how much confidence one may have in the estimated result) as well as gave the highest number of unacceptable results (age error over 15 years) as compared with formal morphometric methods.

This paper updates Solheim's work by evaluating Johanson's method, the best morphometric method Solheim previously found, together with five newly developed morphometric methods. One of

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*This research has been presented in part at the Odontology Section of the AAFS 54th Annual Meeting in Atlanta, Georgia on February 11–16, 2002 and has won the 3rd Annual Emerging Forensic Scientist Award.

Received 25 July 2002; and in revised form 17 Aug. 2002; accepted 17 Aug. 2002; published 4 Dec. 2002.

these is Lamendin's method (6), which is timely because of its recent use in Orahovac, Kosovo (International Criminal Tribunal for the Former Yugoslavia investigation in 2000). The paper also evaluates Bang's intact and sectioned methods (less accurate than Johanson's method in Solheim's earlier study but easy to apply in the field) for a total of eight methods. The purpose of the study is thus to: 1) assess the accuracy and precision, 2) estimate the usability, 3) assess requirements for tooth preparation and 4) review the equipment necessary for the selected eight methods. The overall goal of the study is to provide the forensic dentist with a complete guide to select the appropriate age estimation method for a particular case.

Materials and Methods

Twenty Caucasian teeth, intact or with superficial fillings and taken from 10 females and 10 males (known age ranging from 14 to 95 years, mean age 47.5 years), were selected for this study. Two teeth were selected from each tooth group, such as upper first incisors, with the exception that molars were excluded. The reasons for teeth extractions (e.g., periodontal disease, denture, orthodontic) were provided by the dental practitioners.

Eight dental age estimation methods were chosen for this study according to the rationale described above:

1. Johanson's method for sectioned teeth (5). Six variables were chosen and seven assessment scores given in the Johanson's method. The variables included: attrition (A), secondary dentin (S), periodontal recession (P), cementum apposition (C), root resorption (R) and root translucency (T). One formula was computed for all types of teeth:

$$\text{Age} = 11.02 + 5.14A + 2.3S + 4.14P + 3.71C + 5.57R + 8.98T$$

2. Kvaal and Solheim's (9) first formula for extracted teeth. The following variables were measured in their formulas:

   - Length of the apical translucent zone (measured in mm, according to Bang's method (4).
   - Extent of the periodontal retraction measured on the mesial root surface (mm).
   - Ratios between the width of the pulp and root at the cemento-enamel (CE) junction and at the midroot level measured on dental radiographs.
   - Ratio between the length of the pulp and root measured on dental radiographs. The authors had calculated five separate formulas, one for each tooth group (such as upper first incisors), except for molar teeth.

3. Kvaal and Solheim's (9) second formula for in situ teeth. The formula includes all the variables above except for the length of the apical translucent zone of the root. Again, each tooth group has a separate formula.
4. Solheim's method for in situ teeth (9). The formulas included eight variables: two color estimates, two periodontal recession measures, two attrition measures, crown length and sex. Separate formulas were created for each type of tooth.
5. Solheim's method for sectioned teeth (7). Solheim used 14 different variables and had separate formulas for each type of tooth.
6. Lamendin's method for extracted teeth (6). The formula includes three variables: the height of periodontal attachment from the CE junction (P), the root translucency (T) and the height of the root (H). Only one formula was computed for all types of teeth. Age = (0.18 × P) + (0.24 × T) + 25.53.
7. Bang's method for extracted teeth. Bang and Ramm (4) created a method that is solely based on the length of apical translucency zone. Two separate formulas were computed; one if the translucency was less than 9 mm and another if it was more than 9 mm. Every individual tooth had its own formula.
8. Bang's method for sectioned teeth (4). Bang used only one variable, translucency, but computed separate formulas for each individual tooth.

In order to ensure independent and unbiased results, the observer was blind to the actual age of the 20 subject teeth during the analyses (all labels containing information about the subject teeth were covered up prior to taking the appropriate measurements as well as applying the age estimation formulas).

Firstly, all of the 20 teeth were X-rayed and measurements were taken from the radiographs according to the two Kvaal's methods (9). Secondly, all the remaining measurements were taken and age calculated according to the five intact methods (4,6,9). Thirdly, the 20 subject teeth were sectioned using half-tooth technique (11) so that the distal side of a tooth was drilled away exposing mid-pulpal area. Finally, measurements were taken and age calculated according to the three sectioned methods (4,5,7).

Results

Method accuracy is a measure of reliability: how close a result comes to the true value. Method precision is a measure of repeatability: how much confidence one may have in the estimated result (12). These two measures were therefore assessed as key outcomes. Method accuracy was determined using statistical measures of central tendency, namely, the means of the Age Errors for each method. Method precision was described by the standard error (SE) of the mean. These results are shown in Fig. 1.

The next analysis compared the mean Age Errors in order to determine whether or not the methods' accuracy differed significantly. An ANOVA and Fisher's PLSD post-hoc analysis (*t*-tests) were used to compare the mean Age Errors for each of the 28 possible pairs of methods (e.g., Bang intact versus Lamendin). Given the present data, Fisher's method indicated that the critical significant difference needed in the present analysis to distinguish two

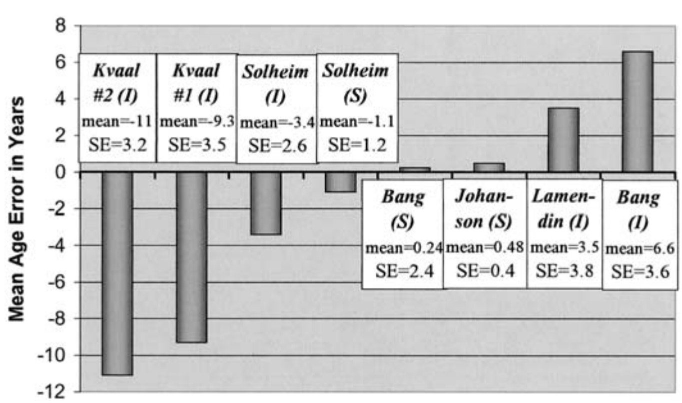

FIG. 1—*The mean Age Error and its standard error (SE) associated with the five intact and three sectioned methods.* (I) = *method for intact teeth; (S) = method for sectioned teeth.*

TABLE 1—*Criteria for selecting an age estimation method in forensic odontology.*

Method	Accuracy (mean Age Error)*	Precision (Standard Error)*	Usability†	Tooth Preparation	Measuring Equipment‡
Kvaal 1	Low	Low	Moderate	Extraction	Dental X-ray Stereomicroscope
Kvaal 2	Low	Low	Moderate	None	Dental X-ray Stereomicroscope
Bang's Int	Moderate	Low	High	Extraction	Standard
Solheim's Int	High	Moderate	Moderate	None	Stereomicroscope Truebite© color scale
Lamendin Int	High	Low	High	Extraction	Standard
Bang's Sect	High	Moderate	Moderate	Sectioning	Standard
Solheim's Sect	High	High	Moderate	Sectioning	Stereomicroscope Truebite© color scale
Johanson Sect	High	High	High	Sectioning	Stereomicroscope

* The smaller the Age Error and Standard Error the higher the method's Accuracy and Precision.
† "Usability'' relates to the minimum number of measurements and formulas required per method.
‡ "Standard equipment" includes a measuring caliper and a constant light source.

methods from one another was at least 7.922 years. The results of the analysis showed that the Kvaal's in situ and extracted methods were significantly different from all other methods they were paired with (p values ranging from 0.0001 to 0.0498 and mean Age Error differences exceeding 7.922 years), except when tested in comparison with Solheim's intact method ($p = 0.1587$, mean Age Error difference $= -5.680$ years). The present data also showed that among the remaining methods accuracy did not significantly differ ($p =$ NS, Age Error difference $>$7.922 years) when compared pairwise, with the exception of Bang's intact method versus Solheim's intact method ($p = 0.0132$, Age Error difference $=$ 10.055 years).

Method's accuracy and precision are the most important criteria when selecting a forensic method. In addition to the accuracy and precision, the authors also assessed the methods' simplicity ("usability"), requirements for tooth preparation and special equipment, such as X-ray machine or stereomicroscope. These factors are summarized in Table 1.

Discussion

When performing age estimation, accuracy and precision are of utmost importance. As Fig. 1 graphically demonstrates, the present data indicate that the sectioned methods have a trend (albeit nonsignificant by an ANOVA done on method type, sectioned versus intact) towards higher accuracy and precision (mean $= -0.139$, SE $= 1.631$) as compared with intact methods (mean $= -2.682$, SE $=$ 0.902). This trend might be because direct measurements on sectioned teeth, such as the amount of secondary dentin, are more precise than measurements taken on intact teeth or indirectly from dental radiographs. A larger sample size might have resulted in a statistically significant ANOVA result.

The ANOVA and Fisher's PLSD *t*-testing data show the two Kvaal methods both significantly underestimated true age (Fig. 1). They also exhibited high variability and low precision in the present materials. Kvaal's original data gave significantly better regression coefficients (0.9) for the maxillary premolar teeth (9). The relatively small size of the present study (20 teeth) did not permit a subgroup analysis by tooth type, which might have given better results for the Kvaal methods if used for maxillary premolar teeth. Therefore, dentists who are analyzing upper premolar teeth may wish to choose Kvaal's method.

Another reason to select Kvaal's second method, or Solheim's intact method, is that only these two are applicable to the study of teeth in situ in living adult persons of unknown age, such as war refugees or immigrants without legal documents. On the other hand, if extracted teeth are available, the data indicate that the forensic scientist can choose a more accurate method. For example, one might choose either Solheim's sectioned method or Johanson's sectioned method in this case. Both offer high accuracy (low mean Age Error) and high precision (high reproducibility and a narrow confidence limit). Fieldwork also imposes unique limitations. In the case of mass fieldwork in primitive conditions, such as a mass grave or battlefield, Lamendin's or Bang's intact method would have an advantage in not requiring a stereomicroscope, a special color scale nor tooth sectioning. In addition, sometimes one must perform age estimates on materials in precious anthropological collections. In these cases there may be restrictions on sectioning or the use of other destructive methods. In these situations, high quality measuring equipment is likely to be available, and one might then reasonably select Solheim's intact method.

In all cases, the forensic scientist must remember the inherent imprecision and variability associated with age estimation measurements. Each age estimation method is based on a linear regression with associated confidence intervals. However, the formula only yields the predicted "population mean," in essence, the expected value for repeated measurements on similarly aged teeth in a population. For an individual tooth, often the focus of a forensic investigation, one must remember to include the method's standard deviation or confidence interval (plus or minus 1.96 SE) as part of the age estimate, e.g., "the tooth is predicted to be 42 years old by Bang's sectioned method, with an expected standard deviation of 10.87 years (SE $=$ 2.43)."

In conclusion, each dental age estimation method presented provides a different combination of accuracy, precision, procedure, and requires different equipment. Forensic odontologists should evaluate each age estimation case and, in addition to their visual age assessment, choose one or more methods that would best serve their particular case, keeping in mind that accuracy and precision are the main requirements. Finally, it is important not only to generate methods for age estimation but also to test their reliability using independent data and examiners.

Acknowledgments

The authors would especially like to thank Dr. Tore Solheim of University of Oslo, Department of Oral Pathology, Section for

Forensic Odontology for providing the tooth specimens, laboratory equipment, and consultation for this project. Dr. Seppo Sarna, Ph.D. of the University of Helsinki, Department of Public Health, is kindly acknowledged for statistical consultation. The Research Council of Norway (grant number: EJ/hsm IS OE00-67) and Estonian Science Foundation (grant number: 4374) provided funding for this research.

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