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A Comparison of Three Dental Techniques for Estimating Age at Death in Humans.

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Abstract:

For a number of years it has been realised that age related morphological changes in the human skeleton are not the most accurate, or precise, means of estimating the age at death for an individual, and that dental changes can be used as an alternative. This paper critically examines three of the methods used for estimating human age from the dentition which have appeared in the forensic science literature, testing them against a known modern sample population. A new statistical technique to improve age estimates is described and applied to some archaeological specimens.

Keywords: Ageing Sclerotic dentine Diagenesis

A Comparison of Three Dental Techniques for Estimating Age at Death in Humans.

Introduction

In the years that have elapsed since the publication of Boquet-Appel and Masset's polemical paper (1982) various means have been employed to refine adult skeletal age at death estimates for unknown archaeological populations. New multivariate techniques which use several age related changes in the skeleton have been suggested (Workshop for European Anthropologists), but have been shown to assign inaccurate ages in recent studies by Molleson and Cox (1993) and Saunders et al. (1992). New procedures based upon probabilistic age at death have been suggested by Konigsberg and Frankenberg (1992) to bring more statistical rigour to the use of life tables by palaeodemographers and anthropologists. With this move towards improving existing age at death estimation techniques, more accurate age related macrostructural changes in teeth have recently been re-examined as an alternative to skeletally based techniques (Bang, 1993; Drusini et al., 1991). This paper tests three established dental techniques with a sample of known age individuals from a contemporary population, and recommends a modified statistical treatment for combining the various age estimates. We then apply this method to some archaeological specimens of unknown age.

Dental age estimation techniques

Gustafson (1950) first formulated observations of macrostructural changes in teeth into a workable system for adult age estimation. His method was based upon six age related changes, assigning points upon an ascending scale of 0 to 3 according to the severity of the change. These changes (see Figure 1) are:

i) attrition - the gradual wear of the enamel on the occlusal surface, as used by Brothwell (1981) as a method of ageing adult populations;

ii) secondary dentine apposition - age related build-up of dentine on the walls of the pulpal chamber;

iii) periodontitis - the irregularity in the form of the cementum and root dentine caused by ongoing repositioning of the periodontal ligament;

iv) cementum build-up, related to periodontosis, where the continuous repositioning of the tooth in the alveolar bone necessitates extra layers of cementum (Zander and Hurlezer, 1958).

v) root resorption - the gradual resorption of the root apex (a process little understood in terms of oral biology);

vi) root transparency - the tendency of root dentine in thick (300 µm) sections to appear to be transparent in transmitted light from the apex upwards (termed sclerotic dentine).

This latter change is caused by the deposition of mineralised material occluding the tubule structure of the dentine, so that the tubules have the same refractive index as the inter-tubular dentine and become transparent (Vasiliadis et al., 1983; Nalbandian et al., 1960). Again, the formation of sclerotic dentine is a little understood phenomenon, but of the six changes identified by Gustafson appears to be the most highly correlated with age forming the basis for Bang and Ramm's method of age estimation (1970).

The age changes described by Gustafson are definite observable changes, but problems revolve around quantification in the scoring system. Gustafson's system of scoring attrition is clear, with discreet scores in terms of the dental structure reached. Secondary dentine in roots without too much reactive dentine, and transparent dentine, again in roots without too much reactive sclerotic dentine, are likewise reasonably easy to judge. Cementum deposition is more difficult due to the lack of any nearby dental structure with which to compare any post eruptive cementum. However, periodontal movement and the degree of root resorption are the most subjective partly because the changes are less pronounced than the others, partly because of a lack of definite stages undergone by the change. Unhappiness with the lack of quantification in the Gustafson scheme of scoring caused Kashyap and Koteswara-Rao (1990) to devise a system based on relative measurements of each of the attributes, for instance attrition would be scored as a function of the measured width of the worn surface divided by the width of the tooth at the bottom of the crown, secondary dentine would be scored as a function of the length down the pulpal cavity occupied by secondary dentine divided by the length of the ceiling of the pulpal chamber to the apex of the root.

Another criticism of the Gustafson points system is that some of the attributes are very poorly correlated with age. Many authors have commented on the correlation of root resorption with age (e.g. Bang and Ramm: p.29). Maples (1978) found that root resorption had by far the worst relationship with age, in fact Maples (1978) found that by using just two variables, secondary dentine formation and transparent dentine, it was possible to be nearly as accurate and precise as when using all six differences.

Gustafson (1950) summed the points allocated to each of the six age-related changes listed above and then calculated a regression line from a sample of extracted teeth of known age. He claimed a 'standard error' (see below) of about 4.5 years, but other workers have not managed to replicate this figure and further calculations based upon Gustafson's published data yield a slightly different regression line and show that a more realistic error estimation is 7.03 years (Maples and Rice, 1979).

Johanson (1971) used essentially the same age indicators as Gustafson but decided that intermediate stages of severity could be detected reliably, resulting in a system of seven ordinal stages for each of the six variables, as opposed to Gustafson's original four. Instead of Gustafson's crude summation of total points for a given individual followed by linear regression of total point score against age, Johanson used a multivariate regression against age which is stated to have yielded a standard error of 5.16 years for any given age estimation. It is worth noting at this stage that neither Johanson nor Gustafson differentiated between tooth locus in their regression analysis.

In their work, Bang and Ramm (1970) concentrated on root dentine transparency as the sole age indicator. They used 926 teeth from 265 known age individuals and regressed the average linear root dentine transparency measured in millimetres (as opposed to the ordinal measure used in the other methods) against known age at extraction for each tooth locus in the dentition. They derived two equations for each tooth type, a first order (linear equation) and a second order polynomial. The first order polynomial was recommended for use when transparent length was greater than 9mm, the second when less than 9mm. Their recorded errors were between 7 and 13 years and depended upon which tooth was under consideration.

A word of caution regarding the published error estimates of Gustafson, Johanson and Bang and Ramm may be necessary at this point. Johanson and Bang and Ramm are unspecific about their calculation of error terms. Gustafson, as noted above, was criticised for his treatment of errors by Maples and Rice (1979). The error estimate recalculated by Maples and Rice is a correct estimate of the dispersion of the data about the mean of the regression line but it does not follow that this is a correct analytical estimate of the error associated with age estimates resulting from the use of this line. According to conventional statistical theory (e.g., Miller and Miller, 1984 p. 90-96) the calculated estimated errors about a regression line should grow larger as the measurable quantity gets further from it's centroid. Maples and Rice's (1979) error estimates do not vary with predicted age (nor do Johanson's, nor Bang and

Ramm's), although to be fair to Maples and Rice they do state that this should be the case. This leads to the suspicion that the estimates of error based upon the standard deviation of the regression lines may have been incorrectly quoted in the literature. There is a clear need for either the original data to be reworked (unfortunately, only Gustafson published all the raw data), or for the regressions to be recalculated on new observations in order to re-evaluate the error terms.

Although many variations upon the basic Gustafson method for dental age at death estimation have been designed (examples being Miles, 1963, Xu et al., 1991 and Stott et al., 1982), rarely have any of these techniques been tested independently against samples of known age. An exception is the work by Burns and Maples (1976) who repeated Gustafson's work with an independent sample composed of African Americans and European Americans. Their results indicated that variables such as race, sex and class played a significant part in the ability to accurately age an individual, and that Gustafson's cited error was un-reproducible. Johanson (1971) and Bang and Ramm (1970) made no attempt to test their models; Gustafson did so, but has since been criticised by Maples and Rice (1979) for testing his model using 19 of the same individuals from which the model was itself derived. The problem is that workers in this field have always needed to base their models upon as large a sample as possible, and known-age samples within the adult age range are hard to obtain. Setting aside a reasonable number to test the model inevitably reduces the number of cases available to actually build the model, and in most cases would reduce the sample size on which the model is based to insignificant levels. There is therefore a need to test these models carefully against an independent set of data.

Experimental methods

A sample of 53 teeth from 33 individuals were obtained from the Oral Surgery Department, St. Luke's Hospital, Bradford. Many of the teeth available were extracted from individuals at the lower end of the adult age range (i.e., at or below the bottom of the age range over which the three age estimation methods are applicable). It was therefore decided to use a sub-sample which comprised all those individuals who were aged 30 and above plus a randomly selected sample of teeth from younger individuals, to give as even an age distribution as possible across the whole sample. The sample used comprised 24 teeth from 17 individuals, which yielded a total of 35 root sections since for multi-rooted teeth each root was sectioned separately. A full list of the samples used is given in Appendix 1.

The teeth were soaked in 20% methanal (formaldehyde) for 24 hours, washed in water, then soaked in 30% methanol for 24 hours and embedded in a silica mounting rubber. 300µm longitudinal sections were then taken from the centre of each tooth root using a Malvern Instruments Microslice II annular saw. The sections were placed onto conventional microscope slides and observed under a low power binocular microscope. Observations were made of each of the six ordinal Gustafson age estimation criteria by one of the authors (DL), but scored using Johanson's finer scale, and transparent dentine was also measured according to the method described by Bang and Ramm (1970). Ages were then calculated using the Maples and Rice (1979) revised version of Gustafson's regression line, Johanson's multiple regression line, and Bang and Ramm's regression lines. The basic data, the age estimates and the estimate of the associated standard errors as recommended by the appropriate authors are presented in Appendix 1.

Results: estimations from each separate tooth root

In the first instance each of the 35 roots was treated as if it represented a separate individual. This allowed us to assess the variability of age estimates obtained from different teeth within the same dentition, before going on to combine the age estimates for each individual within the sample. The ages predicted using the formulae given by Gustafson (1950), Johanson (1971) and Bang and Ramm (1970) were separately plotted against the chronological age of the donor at extraction (the 'known age'). To assess how well each of the methods worked two measures were considered. First was the accuracy of the estimation, defined as how closely the predicted ages corresponded to the known ages. This was measured by the statistic of average absolute deviation (referred to as 'average deviation'), which is the average of the difference in years between the estimated age and the known age (irrespective of sign) across the whole sample. Average deviation was selected in preference to standard deviation because it gives a direct estimate of the average difference between 'true' and predicted age. The second important quantity was the extent to which the quoted 'standard error' derived from the appropriate model corresponded to the real errors, which could easily be calculated since we knew independently the age at extraction for each tooth. This was measured by noting the percentage of estimated ages which fell within one quoted error of the known age and comparing this figure to the theoretical value of 68% (assuming that the 'standard errors' quoted by the original authors correspond to a one standard deviation confidence interval of the estimate - an assumption which, as noted above, may not be strictly correct).

Figures 2, 3 and 4 compare the known ages of the teeth against those estimated by each of the three techniques. The 1:1 line superimposed is the line upon which all points should fall were the techniques able to estimate age with 100% accuracy. The area above the line is an area of over-estimation, where the technique has derived an age which is greater than the real age; below the line is the area of under-estimation, where the estimated age is less than the real age. Table 1 summarises the information on average deviation, quoted error and percentage of estimations falling within the quoted error limits contained in Figures 2, 3 and 4 and Appendix 1.

Discussion

Table 1 shows that both Gustafson's and Johanson's techniques give the expected figure of about 68% of estimations falling within one standard error of the true value. Johanson's slightly more sophisticated treatment of Gustafson's ageing traits does seem to produce a slight improvement in accuracy and precision, as demonstrated by a mean average deviation of 4.5 years (i.e., the mean value of the average deviation across all 35 samples) and a quoted standard error of 5.16 years, compared to 5.03 years and 7.0 years respectively for Gustafson's method. Bang and Ramm's method seems to produce a noticably poorer average deviation of 5.15 years, with the quoted standard error being dependent upon tooth type (but not estimated age, as discussed). However, in this case 88% of the estimated ages fall within one quoted error of the true value, suggesting that Bang and Ramm may have been conservative with their error estimations.

Seemingly, therefore, within the constraints of this particular sample, Johanson's technique offers a small advantage in terms of both accuracy and precision when measurements from a single root are taken as representing one individual.

Multiple estimations from the same individual

The limitation of the above observation is that we have assumed each individual is represented by measurements from a single root section, not taking into account the fact that several roots may be from the same tooth, or that several different teeth may be from the same individual. The maximum differences in the estimated age from multiple roots of the same tooth are 11.4 years using Gustafson's method, 16.7 by Johanson and 12.9 by Bang and

Ramm. The maximum differences in the age estimates for the same individual using multiple teeth are 13.7, 19.5 and 13.8 years respectively (in all cases the maximum differences are recorded in the same individual, number A020 in Appendix 1). Interestingly, this indicates that the range of estimated ages for the same individual is only slightly greater from multiple teeth than from multiple roots of the same tooth, which suggests that tooth roots and not individual teeth can be regarded as sources of independent age estimates for the same person. Given the potential age range represented by these maximum observed differences, it is clearly important to pool the estimates if it is definitely known that several teeth are from the same individual in order to derive the best estimate for that individual's age. Methods for doing this are given in the original publications; Gustafson (1950) uses Equation 1, which is also applicable to Johanson's method, whilst Bang and Ramm (1970) advocate Equation 2, as follows:

Equation 1.

$$Age_{(mean)} = \Sigma \frac{age_i}{N} \qquad \text{where: } SE = \frac{SE_i}{\sqrt{N}}$$

Equation 2.

$$Age_{(mean)} = \Sigma \frac{age_i}{N} \qquad \text{where: } SE = \frac{1}{N} \times \sqrt{\Sigma (SE_i)^2 + 85N(N-1)}$$

where:
Age(mean) = new estimate of age based upon multiple independent estimations
age_i = individual age estimate
N = number of independent individual age estimates
SE = new error estimate based upon multiple estimations
SE_i = individual error estimates

As all error estimations based upon Gustafson's method have the same quoted standard error, the first equation may be taken as correct and also equally applicable to estimates made using Johanson's (1971) method. The calculation of the standard error of the pooled estimate using the equation cited by Bang and Ramm fails to take account of the fact that these errors represent a probabilistic dispersion about a mean value where the errors are assumed to be normally distributed around their mean, and each error can be different. Bang and Ramm's equation simply finds a mean point between all the individual age estimates, not the mean point of the probability distribution. An alternative method is offered by Ward and Wilson (1978), originally given in the context of combining radiocarbon dates. For normal distributions where the standard deviations are different and all measurements are nominally of the same quantity, they derive a pooled mean and an associated error term, given here as Equation 3:

Equation 3.

$$\text{Age}_{(\text{mean})} = \frac{\sum \frac{\text{age}}{SE_i^2}}{\sum \frac{1}{SE_i^2}} \qquad : \text{where } SE = \sqrt{\frac{1}{\sum \frac{1}{SE_i^2}}}$$

Where the symbols have the same meanings as for Equations 1 and 2.

New pooled age estimates, this time for individuals rather than each of their tooth roots, were therefore calculated using Equation 1 for Gustafson's and Johanson's methods, and Equation 2 for Bang and Ramm's. In addition, a new combination was devised which consisted of Bang and Ramm's root transparency plus a revised Gustafson model. Since root dentine transparency is a relatively easily produced continuous measurement and is said to be more highly correlated with age than any other single attribute (Maples, 1978), it was felt that there might be some advantage in combining Bang and Ramm's quantitative measurement of root translucency with the other five ordinal observations in a new version of Gustafson's method. However, since Gustafson's and Johanson's original models both use an estimate of the degree of root dentine transparency it would be inappropriate to use a Gustafson (or Johanson) age estimate coupled with an independent Bang and Ramm estimate as this would mean that transparency would appear twice. A new linear regression was therefore calculated from Gustafson's (1950) published data which excluded the transparency. A pooled mean age estimate for each individual was then produced by combining this with an estimate obtained using the procedure of Bang and Ramm via Equation 3.

The pooled age estimates obtained by each of these four methods for the 17 individuals in the test sample are given in Appendix 2. The results are plotted against known age (see Figures 5, 6, 7 and 8) and the data are summarised in Table 2. The average error on the estimate cited in Table 2 for each method is the average of the calculated standard errors for each individual in the sample. The reason for the range observed in these calculated error values is that the estimated error for any individual is dependent on the number of roots available from that individual.

Discussion

Clearly, from Table 2, the use of estimates based upon two or more roots brings considerable advantages in terms of an increased confidence through repeated observation, which is reflected in the decrease in the calculated estimates of error. Gustafson's method now gives an average deviation of 3.77 years, representing a decrease of nearly one and a half years from the previous calculations, whilst still keeping 70% of the estimates within the calculated (one standard deviation) error of between 4 and 7 years (average 5.34 years). Problems arise when estimates based upon multiple roots using Johanson's method are examined. Although the calculated estimate of error has come down from 5.16 years for estimates based upon a single root to between 3 and 5.16 years (this figure being dependent on the number of roots from which the estimate is made) with an average of 3.92 years for the whole sample, only 53% of the estimates fit within this supposedly one standard deviation error term, suggesting that the predicted error is underestimated. Combined with this, the mean average deviation is slightly higher, at 4.15 years. This means that in this instance the use of Johanson's method for combining two or more roots has proved less reliable than the other methods, giving an apparently unrealistic error associated with the estimated age. Similarly, the use of Bang and Ramm's method for combining age estimates leads to an average calculated estimate of error of 10.38 years (best 7 years, worst 15 years) which is unrealistically large when compared to the calculated mean average deviation of 4.01 years. This discrepancy is now reflected in the fact that 94% of estimates fall within one standard error, suggesting that the predicted error is overestimated. The use of pooled mean estimates (i.e., our novel combination of a modified Johanson measure with Bang and Ramm's method, as described above) leads to the smallest mean average deviation of 3.42 years and, with the exception of the (possibly underestimated) standard error derived from Johanson's method, the smallest calculated average estimate of error of 4.61 years. We again find, however, that 82% of the estimates fall within this standard error, suggesting that our predicted average error is still too large. We observe, however, that given the sample size of seventeen individuals, it would be unwise to draw too many conclusions about the accuracy of the error term from the number of age estimates which fall within a one standard deviation band around the true age.

The pooled mean estimate method of treating data from tooth sections when applied to multiple roots appears to be the most accurate, precise and robust method for estimating age, when compared with the other models of dental age prediction already in the literature. This is probably because it combines the best features of the Johanson method (which, with the half point scoring system, represents an improvement over the original procedure proposed by Gustafson) with the maximum exploitation of the sensitivity of the measurement of root dentine transparency offered by Bang and Ramm. We therefore recommend this new combination as the best method yet available for deriving an estimated age from the observations described here.

Application to archaeological specimens

In order to test the applicability of our new method to archaeological specimens, teeth from four skeletons from the Medieval Hospital cemetery at Chichester (Lee and Magilton, 1989; Magilton and Lee, 1989) were sectioned (one molar and one incisor from each skeleton). Initial age estimations were based on changes in the pubic symphysis, late epiphyseal closure, erruption of the third molar, changes in the sternal rib ends and dental wear, all these methods of age estimation are described in Bass (1987). 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 (Figure 10), and displayed a pinkish tinge throughout the dentine. These phenomena clearly require further investigation. Although some similar diagenetic changes have been observed previously in dentine from other archaeological contexts (e.g., Beeley and Lunt 1980; Lunt and Beeley, 1981: Bell et. al., 1991) none have noted such an extensive pinkish tinge throughout the dentine. It is not thought that the pink dentine observed here is related to pink dentine seen in forensic cases of violent death (Van Wyk, 1987).

For the single sample which displayed intact internal macrostructure the full range of age observations could be made (Figure 9), and Table 3 shows the estimate of the pooled mean age using our procedure described above. In this case, the scatter between individual teeth is small, and the pooled age of 46.7 ± 4.0 years is consistent with the age estimated from the skeletal evidence (35+). For the three individuals with poor internal macrostructure age estimates were made solely on the basis of the modified Gustafson model (i.e., omitting the score for root dentine transparency). These estimated ages are presented in Table 4. In each case, the pooled mean age predicted from dental observations is close to that derived skeletally (40.1 ± 4.3 compared to 30-40, 48.0 ± 4.3 and 50+, 44.0 ± 4.3 and 35+). Clearly, the improvement offered by our method applied to dental observations is the provision of a statistically valid age range for each individual, rather than the broad undifferentiated age category (or, more often, simply a lower limit) provided by skeletal methods.

Conclusions

Existing dental methods of age estimation can be combined to produce relatively accurate ages for a skeletal population. The most robust of these is given when both Gustafson's (1950) technique, modified to ignore transparency, and Bang and Ramm's (1970) method are used in combination with the statistical treatment outlined above. Our tests suggest that this can be done to give a standard error of approximately ±4 years at the 68% confidence level. 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.

Despite the small size of the modern population used here there is no reason to suppose that this test of dental ageing techniques gives anything other than reproducible errors when used with modern North European populations. The populations from which Gustafson (1950), Johanson (1971) and Bang and Ramm (1970) derived their models were Scandinavian; the modern population for this study came from northern England. However, the assumption that past populations, and ethnically different modern populations, will show the same age related traits occurring at the same rate is problematic. Although the question is potentially resolvable in the latter case, for past populations the reliability of any of the above age estimation methods must always be in doubt. In fact, the balance of expectation would be that some at least of the traits used in the Gustafson method must have developed at different rates in past populations. An obvious example is the rate of attrition of the occlusal surfaces of teeth, which would be expected to be faster in cultures without fine ground flour. It is also likely, however, that similar problems relating to skeletal development in the past must also call into question the reliability of skeletally-based age estimates.

Although the uniformitarian assumption will always be a problem for those working with past behaviour, difficulties of a more immediate, physical nature are encountered when applying this method to archaeological specimens. There is a clear need to section a larger sample of archaeological teeth in order to determine whether the dentine modifications noted here and also by Bell et al. (1991) are common. If so, such degradation may undermine to some extent the densitometric work of Drusini et. al. (1991) who observed unsectioned teeth against a powerful light, and estimated the degree of transparent dentine using computer aided image analysis in order to derive an age for the individual from which the teeth had come.

Additional advantages of dentally-based age estimation techniques are that they cover the whole adult age range, whereas, with the exception of the aricular surface method (Lovejoy et. al., 1985), most skeletal methods have an upper age limit of 45 years. Above this age it appears that degenerative skeletal change becomes less dependent on chronological age and more influenced by pathological change. The dentally based methods also have errors which are continuously distributed, and can be assumed to be normal. This makes them eminently suited to the probabilistic methods of estimating population age structure such as those outlined by Konigsberg and Frankenberg (1992). We propose to explore the use of dental age estimates using these techniques. On the other hand, the need to destroy potentially valuable archaeological material might deter more widescale implementation of these methods by biological anthropologists. The probability of finding teeth with extensive diagenetic alteration may also be a factor if it proves to be a common phenomenon. We believe, given the evidence and techniques outlined above, that dentally based adult age at death estimation offers significant advantages over skeletally based age estimation methods, and that the potential advantages are most pronounced in the case of individuals aged more than 50. It is apparent that armed with these techniques palaeodemographers can go a long way towards a fuller reply to the criticisms of Bouquet-Appel and Masset (1982), biological anthropologists can begin to have a more complete understanding of observed age related skeletal changes.

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Figure 1. Diagram depicting two examples of Gustafson's points system for sections through teeth, one from an individual aged 35, the other from an individual aged 61.

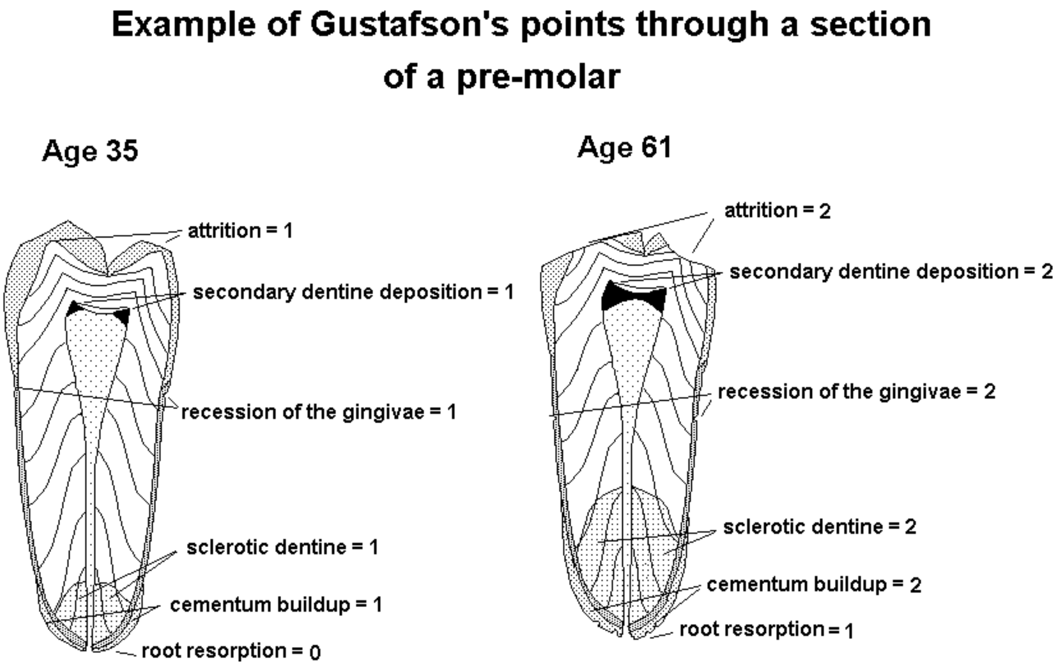

Figure 2. Plot of estimated ages derived from Gustafson's method against known ages for 35 roots from 17 individuals.

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Figure 3. Plot of estimated ages derived from Johanson's method against known ages for 35 roots from 17 individuals.

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Figure 4. Plot of estimated ages derived from Bang and Ramm's method against known ages for 35 roots from 17 individuals.

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Figure 5. Plot of estimated ages derived from all available roots for a given individual and using Gustafson's method.

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Figure 6. Plot of estimated ages derived from all available roots for a given individual using Johanson's method.

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Figure 7. Plot of estimated ages derived from all available roots for a given individual and using Bang and Ramm's method.

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Figure 8. Plot of estimated ages derived from all available roots for a given individual and using pooled mean averages for estimates from the modified Gustafson technique and Bang and Ramm's method.

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Figure 9. Section from a tooth from Medieval Chichester unaffected by diagenetic change; A= attrition, P = peridontosis, C = cementum buildup, T = transparency, R = root resorption, S = secondary dentine apposition.

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Figure 10. Section from a tooth from Medieval Chichester showing extensive diagenetic change; DD indicates area of diagenetic change.

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