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A BAYESIAN APPROACH TO THE ESTIMATION OF THE AGE OF HUMANS FROM TOOTH DEVELOPMENT AND WEAR

1. Introduction

Determination of age-at-death is an essential part of human osteoarchaeology, providing important basic information for demographic analyses, studies of palaeopathology and social identity. A considerable body of research has investigated the potential of numerous skeletal elements to produce accurate estimates of age at death. For juveniles these methods are more precise as they are based on the genetically driven process of growth and development, e.g. the fusion of bone epiphyses or tooth development. Age determination methods for adults are much less precise and based on degenerative changes to the fully developed skeleton, such as changes to joint surfaces or tooth-wear. The dentition is the most frequently used method in archaeology. Dental development during childhood is a rapidly occurring, genetically driven process that allows for precise age estimation. Once dental maturity is achieved, age estimations are based upon dental wear patterns. As with all adult ageing techniques, this is a much less precise method because wear is affected by non-age related cultural and environmental factors.

Almost all ageing methods have a common basis in their construction. The age indicator is observed in a modern *reference population* to establish its variation with age, and this information is then used to estimate the age of an archaeological *target population*. A number of studies of the past few decades have, however, demonstrated that the age distribution of the target population will be affected by the age structure of the reference population upon which an ageing method was based (e.g. Bocquet-Appel, Masset 1982, 1985, 1996; Konigsberg, Frankenberg 1994, 1997; Lucy *et al*. 1996; Aykroyd *et al*. 1997, 1999). This paper uses the principles of Bayes Theorem to minimise the statistical biases inherent in current dental ageing techniques.

2. Dental methods of ageing

2.1 *Dental development*

Tooth formation is the most accurate method of age estimation of immature skeletons (Saunders 2000). Dental development is a process that has a strong genetic component and is the developmental indicator least susceptible to environmental factors. Numerous cross sectional and longitudinal studies (mostly on North American children of European descent) have produced tooth formation standards (e.g. Moorrees *et al.* 1963a, b; Anderson *et al.* 1976). All these studies have adopted an ordinal scoring system, dividing tooth growth into a series of arbitrarily defined morphological stages. Methods tend only to vary with respect to the number of stages observed and the age ranges assigned (SAUNDERS 1992).

Despite the possibility of population differences, tests of modern standards on historically documented skeletal populations suggest that ageing by dental development produces results comparable with known age at death. SAUNDERS *et al.* (1993) tested the ANDERSON *et al.* (1976) and the MOORREES *et al.* (1963a, b) methods and found the latter to produce accurate results (usually to within one year of known age).

2.2 *Dental wear*

Observation of dental wear patterns is one of the most commonly utilised methods of ageing adult skeletal remains in archaeology. The popularity of this method arises from the high survival rate of teeth within archaeological contexts and the relative ease with which dental wear patterns can be observed and scored. As teeth wear, the enamel of the occlusal surface is progressively removed until the underlying dentine is exposed (MOLLESON, COHEN 1990). Ordinal scoring of dentine exposure on the occlusal surface of the molars based upon visual assessment is the method most frequently employed in archaeology.

The lack of a suitable known age reference population from which to age past populations is one of the main problems in dental-wear ageing. Known age populations are mostly Western with soft, processed diets resulting in slow wear rates that differ very much from archaeological populations. The problems arising from the lack of a suitable "known age" population for producing a dental wear method for ageing archaeological dentitions were in part overcome by the seminal work of MILES (1963). Miles used the dental ages of juveniles from archaeological sites to provide a "known age" group that would allow the rate of wear for a specific archaeological population to be determined. Assuming M1 erupted at 6 years, M2 at 12 years and M3 at 18 years, it was then possible to observe the wear on M1 after various functional ages (i.e. period of occlusion) up to 12 years and on M2 up to 6 years.

MILES (1963) found that M2 and M3 wore more slowly than M1, but the rate of wear of M1 was not slowed by the appearance of M2. Consequently, for a given wear stage M2 has a higher functional age than M1. MILES (1963, 2001) determined from subjective analysis that the ratio of functional ages for equivalent wear of M1: M2: M3 was 6: 6.5: 7. Some studies have reported similar wear differentials (e.g. KEISER *et al.* 1983), but others have reported equal rates of wear (e.g. NOWELL 1978). These ratios are then assumed to be fixed throughout the individual's lifetime. In order to age individuals with fully developed dentition, those who exhibited only a small amount of wear on M3 and could be not much older than the "known age" group were given estimated ages. The dentitions were seriated and ages progressively extrapolated from the known age group to the rest. Two tests of Miles method, on a skeletal population (Nowell 1978), and on an ethnographic population (Keiser *et al.* 1983), found that it produced credible results. Miles' method does, however, under-estimate the age of individuals of fifty years and over (Miles 2001).

While Miles' method does overcome the problem of population differences in dental wear, it has some drawbacks. Firstly, the assumption that rates of wear within a population are equal between teeth and constant throughout life may be confounded by alterations in the rate of enamel loss and secondary dentine formation as teeth wear and pathological factors (e.g. caries, ante-mortem loss). Secondly, two individuals from one population may exhibit different rates of wear due to differences in diet (possibly related to socio-economic circumstances), malocclusion, unequal susceptibility to caries, abnormal eruption ages, loss of occlusal partners, or use of the teeth as tools. In our experience, all of these factors can cause considerable variability within individuals from the same cemetery. Despite this, age determination from the dentition provides the most accurate method available for ageing adults.

2.3 *Biases in current methods*

«Nearly all methods of ageing in current use do not make proper use of the statistical nature of age estimates… age estimation from one or more skeletal traits is a process of generating the distribution of possible chronological ages... by throwing out distributional information around the mean or median age, we gain a false sense of statistical power about statements based on that age» (Konigsberg, Holman 1999, 265).

Traditional age estimation methods tend to treat ages as though they are exact, rather than a *distribution* of possible ages. Despite the relative accuracy of dental development, no ageing method can produce exact chronological ages because individuals vary in the age of attainment of a given developmental stage. Even were a skeletal marker perfectly correlated with chronological age and all variation eliminated, the use of an ordinal scoring method *still* yields a distribution of ages rather than an exact age because children enter a given developmental stage and remain there for some period of time (Konigsberg, Holman 1999).

Additionally, Bocquet-Appel and Masset (1982) argue that there is a systematic statistical bias in skeletal ageing. They demonstrate that a key problem is that the age distribution derived for the target population is partly dependent on the age distribution of the reference sample. Subsequently it was demonstrated that the use of regression analysis in producing skeletal ageing techniques was largely responsible for this "age mimicry". The majority of ageing methods are devised by regressing age on a skeletal indicator. Konigsberg and Frankenberg (1994) and Aykroyd *et al.* (1997) show that regressing age as the dependent variable on the indicator as the independent variable involves the fundamental assumption that the target population has the same age-at-death distribution as the reference population.

Konigsberg *et al.* (1994) and Aykroyd *et al.* (1997) show that one way of avoiding this is to use the classical calibration method, whereby indicator is regressed on age. Adopting this approach eliminates the systematic under and over-ageing that is a product of forward regression analysis. Unfortunately problems with this technique include the complexity of calculating inverse regression from multiple age indicators, the difficulty of determining the error range associated with a particular point, and the larger uncertainty in the ages derived (Aykroyd *et al.* 1999).

In recent years in order to address the problems discussed above, there has been a move to the use of Bayesian methods. The basis and details of Bayesian reasoning cannot be explained here, the reader is referred to Buck *et al.* (1996). For our purpose Bayes theorem may be represented by the following equation:

$$p(A|I) \propto p(I|A) \times p(A)$$

where A= age, and I= indicator (e.g. dental development stage).

Several age indicators can easily be combined if we assume that while they are conditional on age, they are independent of each other given age. This is advantageous when estimating age from multiple variables and automatically weights each indicator according to the probability distribution, eliminating the dubious process of imposing weights, or worse still, assuming that each indicator contributes equally (Lucy 1997).

In the application of Bayesian statistics to palaeodemography the choice of prior is crucial. For example, Lucy (1997) adopts a prior based on the age distribution of the reference sample, but this incorporates a bias inherent in regression analysis, and better priors can be chosen. In contrast, Chamberlain (2000) compares the adoption of a uniform prior on age and a prior based on model life tables.

3. Materials and methods

The skeletal material analysed in this study is from 10 cemeteries of Roman and Anglo-Saxon date located in the regions of Hampshire and Oxfordshire (Table 1). It forms part of a larger study investigating social identity (in particular age identity) in fourth to sixth century England through the study of archaeological funerary evidence (Gowland, forthcoming).

Site	**County**	**Period**	**No. Individuals**	**Reference**
Abingdon	Oxfordshire	Early Saxon	129	LEEDS, HARDEN 1936
Alton	Wiltshire	Early Saxon	50	EVISON 1988
Berinsfield	Oxfordshire	Early Saxon	119	BOYLE *et al.* 1995
Cassington	Oxfordshire	Late Roman	63	MUSGROVE (unpublished)
Lankhills	Wiltshire	Late Roman	486	CLARKE 1979
Portway	Wiltshire	Early Saxon	71	COOK, DACRE 1985
Queensford Farm	Oxfordshire	Late / Sub Roman	164	HARMAN *et al.* 1979; CHAMBERS 1987
Victoria Road	Wiltshire	Late Roman	134	REECE (unpublished)
Winnall II	Wiltshire	Mid-Saxon	48	MEANEY, HAWKES 1970
Worthy Park	Wiltshire	Early Saxon	109	HAWKES, GRAINGER (unpublished)

Table 1 – Sites used in this study. There may be some discrepancy between number of individuals here and previous reports as a result of skeletons having been misplaced, the presence of skeletons not previously recorded, or (as in the case of Cassington) the incompleteness of notes and reburial of some of the material.

For immature skeletons, the developmental stage of each observable tooth was recorded using the charts of MOORREES *et al.* (1963a, b). The jaws were not radiographed and the developmental stage could only be observed where teeth could easily be removed, were free of the jaw, or where the jaw was damaged. Fortunately these conditions applied in the majority of cases. Where the developmental stage could not be observed, but the tooth was present, the eruption status was noted as unerupted, just erupting (just emerged through the alveolar crest), partially erupted (fully emerged from the alveolar crest, but not fully occluded), or erupted.

Molar wear was recorded for upper and lower molars by shading a diagram on a recording form. In those dentitions with complete loss of occlusal enamel, the quantity and appearance of the remaining crown was noted and measured using sliding callipers. The absence of a tooth was recorded as due to post-mortem loss, missing jaw, ante-mortem loss, or congenital absence. Subsequently each molar was assigned a wear stage according to the thresholds shown in Fig. 1. These stages are similar to BROTHWELL's (1981) with only our later attritional stages demonstrating any significant departure. Our scoring system covers wear after the loss of occlusal enamel in more detail than Brothwell's, as his last stage represents two to five times the duration of any of the preceding stages (MOLLESON, COHEN 1990). Where ante-mortem loss of teeth or congenital absence of molars were in evidence, the method described below was not used to determine the age of the individual. Such factors are likely to alter attritional stresses within the jaw and change the correlation with age.

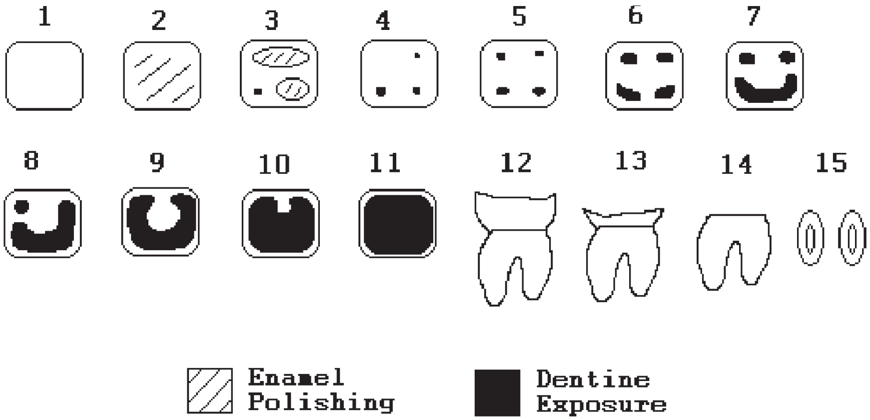

Fig. 1 – Wear thresholds used to define wear stages in this work.

Fig. 2 – Mean development stage thresholds and population variation of permanent molars, 95% confidence intervals for lognormal distribution of MOORREES *et al.* 1963b (upper line) and a logistic approximation to that distribution (lower line).

The MOORREES *et al.* (1963a, b) known age dental development data was chosen as our reference sample for ageing juveniles. The data were degraphed to obtain mean ages of transition, and then, as it is not possible to sex juvenile skeletal material, male and female data were averaged. This slightly extends the degree of variation for each stage of development, however, sexual differences in tooth development are minor and represent an insignificant source of error.

Moorrees *et al.* report that their data for cumulative percentages of children having attained or passed a particular stage fitted a cumulative log-normal distribution with a standard deviation of 0.042 $\log_{10}$ conceptional age units. For each threshold in Fig. 2, the top line represents a 95% confidence interval for the Moorrees *et al.* log-normal distribution of ages of transition. We have approximated this with a logistic distribution (95% CI represented by the bottom line) as this:

a) has heavier tails and helps counter the problem of underestimating uncertainty by assuming all of an individual's teeth development stages are independent conditional on age;

b) is computationally more stable.

3.1 *Mathematical/Statistical model*

As tooth development and wear are recorded as ordinal stages with thresholds, we adopt a common model for the probability that a tooth is in a particular stage.

If Q_{jk} is the probability of tooth *j* having passed the threshold for the end of stage *k* ($k = 1,2,\ldots N_j-1$, where N_j is the number of stages for tooth *j*), then:

$$\text{logit}\,(Q_{jk}) = \delta \times (\ln(\theta) - \ln(\gamma_{jk}))$$

where θ is the individual's age, γ_{jk} is the mean threshold age for the population, both expressed as years from conception and δ is the discriminability. If $p(k_j \mid \theta)$ is the probability of tooth *j* being in stage *k* at age θ, then:

$$p(1_j \mid \theta) = 1 - Q_{j1}$$

$$p(k_j \mid \theta) = Q_{jk-1} - Q_{jk} \text{ for } 2 \leq k \leq N_j-1$$

$$p(N_j \mid \theta) = Q_{jN_j-1}$$

By specifying a joint likelihood for the data we are able to provide a full probability model for all observable and unobservable quantities (Lunn *et al.* 2000). If we assume that the development stages of all the teeth are independent then:

$$p(\mathrm{k} \mid \theta) = \prod_j p(k_j \mid \theta)$$

where **k** is the vector of observed stages. In order to make inferences about age we use Bayes' theorem to construct the posterior distribution from the observed data.

$$p(\theta \mid \mathbf{k}) \propto p(\mathbf{k} \mid \theta) \times p(\theta)$$

3.2 *Dental development*

For dental development we take d = 1.6 ×10.34, where 10.34 = 1/ $\ln(10^{0.042})$ equivalent to Moorrees *et al.*'s 0.042 $\log_{10}$ conceptional age units and 1.6 adjusts the 95% spread of the log-logistic to be similar to (but slightly greater than) the log-normal distribution.

Moorrees *et al.* (1963a, b) give no indication whether development stages are correlated, but Konigsberg and Holman's (1999) data on covariance of eruption ages show for the most part, weak correlations between different teeth, suggesting that the assumption of independence leads to a small under-estimation of uncertainty.

Because the joint posterior distribution $p(\theta \mid \mathbf{k})$ requires complex numerical integration we use a Markov-Chain Monte Carlo (MCMC) method for its evaluation using the WinBUGS program (Spiegelhalter *et al.* 2000; Lunn *et al.* 2000).

A uniform prior has been adopted in this study, however, a model prior obtained from an appropriate model life table, or from ages estimated from the population using other techniques may be more appropriate.

3.2 *Toothwear*

We use the same generic model for tooth-wear that was used for development:

$$\mathrm{logit}(Q_{jk}) = \delta \times [\ln(\theta) - \ln(\gamma_{jk})]$$

We adopt a model analogous to Miles (1963) and relate M1, M2 and M3 thresholds via functional ages using the following formula:

$$\gamma_{jk} = \gamma_{j1} + \alpha_j \times (\gamma_{\mathrm{M1},k} - \gamma_{\mathrm{M1},1})$$

where j = M2, M3, α_j allows for wear differentials and $\gamma_{j,1}$ is the eruption age of the tooth.

Wear thresholds for those individuals ageable from their dental development were compared; Romano-British versus Anglo-Saxon, and Oxfordshire versus Hampshire, but no significant differences were found. All of the available data was, therefore, pooled in order to obtain a large amount of "known age" information concerning molar wear.

Wear thresholds 1 to 5 were calculated using regression on those individuals with incomplete dental development. The mean values for thresholds so estimated are then treated as "known" in a second regression based on all individuals with at least one tooth in wear stages 1-5, thus estimating thresholds 6-12. Finally, a third similar regression gave ages of thresholds 13-15, and thus ages for all individuals.

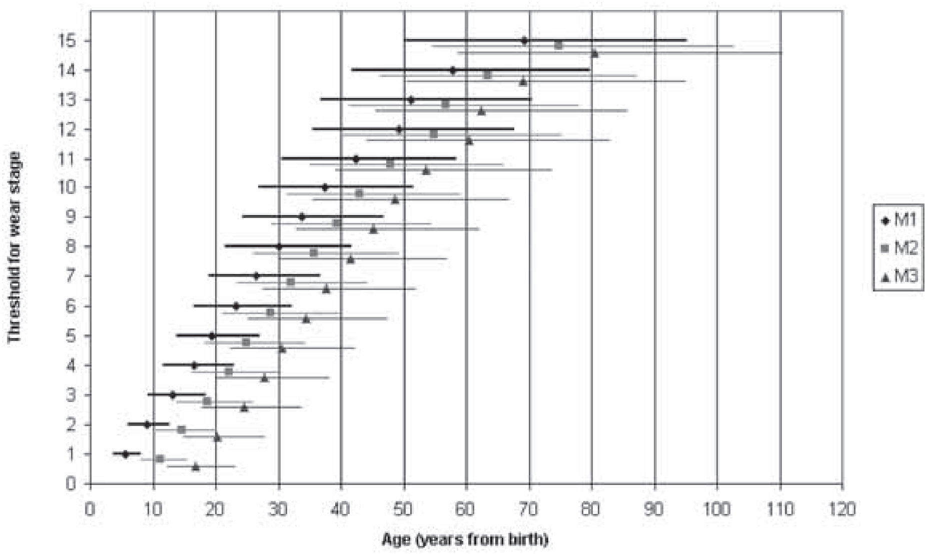

Fig. 3 – Posterior means and population variation for wear stage thresholds as 95% confidence intervals of a logistic distribution.

Threshold		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
no differences $\delta = 11.6$	M1	5.5	9.0	13	16	19	23	26	30	34	37	42	49	51	58	69
	M2	11	14	19	22	25	29	32	36	39	43	48	55	57	63	75
	M3	16	20	24	28	31	34	38	41	45	49	54	60	62	69	80
Miles differences $\delta = 11.0$	M1	5.6	8.9	13	17	20	24	27	32	36	40	46	54	56	65	79
	M2	11	14	19	23	26	31	35	39	44	48	55	63	66	75	90
	M3	16	20	26	30	33	38	42	47	52	57	64	73	75	85	102

Table 2 – Posterior means for each wear threshold of each molar (in years from birth) and discriminabilities, assuming no differential wear rate, and the differential obtained by MILES (1963).

4. RESULTS

Posterior confidence ranges have been obtained for each threshold of each molar and these are shown in Fig. 3 and Table 2. A comparison between the thresholds obtained when equal rates of wear, or Miles rates of wear ($\alpha_1=6.5/7$, $\alpha_2= 7/6$) is shown in Table 2. A broader age range for each stage and slightly older ages result from the use of a wear differential similar to that of Miles. There was an approximate correlation between the ages of individuals obtained from this method and those from examination of the pubic symphysis and auricular surface.

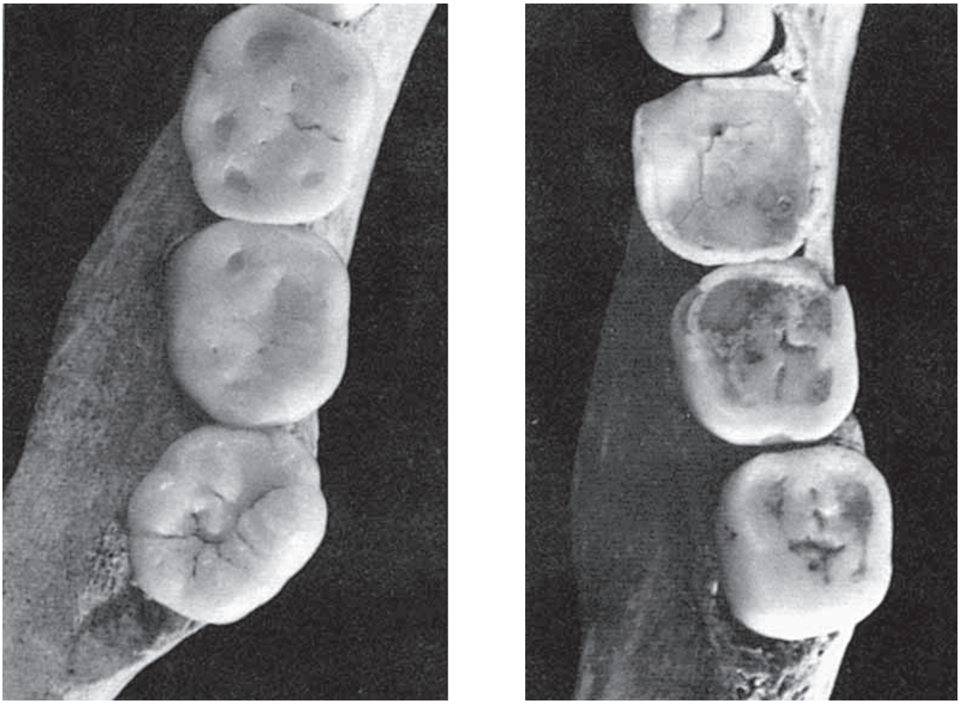

Fig. 4 – Wear on archaeological tooth specimens (from CHAMBERLAIN 1994, figure 9 p. 18, used by permission, © ANDREW CHAMBERLAIN). See text for discussion of age estimates. On the left teeth conventionally aged at about 18 years, on the right at 40-50 years.

A comparison between the ages estimated using this method with those using the Miles method provides encouraging results. For example, the teeth in Fig. 4, aged using conventional techniques, are assigned ages of 18 years and 40-50 years (CHAMBERLAIN 1994). Using our new method provides 95% confidence ranges of 18-22 and 43-54 years respectively (for equal wear rates) or 17-21 and 48-61 years (using Miles' wear differential).

5. CONCLUSIONS

Our method for ageing juveniles overcomes a number of problems with previous applications of dental standards to archaeological populations:

a) It does not assign the threshold or mean age associated with the developmental stage, and treat these as exact ages, rather it takes into account the distribution of ages.

b) The ages obtained are independent of the age structure of the reference sample.

c) Rather than averaging the mean ages from a number of different teeth, this method automatically derives an age from the distribution data of all available teeth. It therefore takes into account the fact that some teeth may produce more precise ages than others, allows for missing teeth, and produces appropriate confidence limits.

Our Bayesian version of Miles' Method gives an estimate of age that accounts for much more of the uncertainty in age determination. Notably we can estimate population-specific eruption ages, and wear threshold ages. Our method produces older ages than traditional methods for those individuals showing heavy degrees of wear and as we know that Miles' method underages older individuals this outcome seems more satisfactory. This method also allows consideration to be made of the increasing variability of wear with age, automatically producing broader confidence limits so that while the final age may not necessarily be more precise, it is likely to be a more realistic estimate of age at death. Although there remain problems with congenital absence of M3 and ante-mortem tooth loss, we have no problem handling individuals with missing teeth; their ages typically have broader confidence limits, involving as they do a greater degree of uncertainty than individuals with a full dentition.

Age estimates with full probability distributions allow us to construct further regressions of other parameters on age. For example, we have obtained age-growth curves for long bones from our dentally aged juveniles and used these to make population comparisons of growth. This has allowed us to age juveniles lacking any surviving teeth.

In the future we intend to develop more detailed comparisons with other ageing methods and, where fully probabilistic age estimates are available, to combine age estimates from different methods to increase the precision of the final age estimate. Tooth-wear ageing is also applied to the estimation of age-at-death of animals, and we intend to extend our methodology to species with appropriate data.

Finally we note that palaeodemographers are interested in population age distributions, which have to be assumed in the form of a prior in our analyses. However it should be possible to generalise our method to a hierarchical statistical model that considers a multiplicity of age structures, via a hyperprior on the age structure of the population.

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ABSTRACT

Examination of dental development is considered to be an accurate method of ageing non-adults, but ageing adults from dental wear is much less accurate. Miles' method is generally accepted to be the best way we have to derive estimates of tooth-wear ages because it takes into account population variability in wear-rates. Here we develop a Bayesian approach to ageing from dental development and tooth-wear, using a latent trait model and logistic regression to estimate the ages of individuals whose tooth devel-

opment and/or wear has been scored on ordinal scales. In addition to the original methods this: (a) accounts for uncertainties in tooth development; (b) incorporates in a natural fashion individuals with teeth missing post-mortem. Numerical integrations were performed using Markov-Chain Monte-Carlo techniques and WinBUGS software.