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Mandibular Morphology as an Indicator of Human Subadult Age: Interlandmark Approaches*

ABSTRACT: The dentition is widely recognized as the set of developmental markers that appear to show the least variability against chronological age; these markers are thus widely used in forensic anthropological investigations. As a possible alternative, we investigate here the potential of mandibular morphology as a developmental marker for estimating age at death in subadults. The sample analyzed comprises 79 known age and sex subadult individuals of South African Bantu and African American origin. Linear measurements of ramus height were obtained from the mathematical conversion of three-dimensional landmark data. A series of regression analyses were then performed to predict age by using the measurement of ramus height; results were cross-validated using a jackknife procedure. Our results show that ramus height can be used to predict age in the subadult skeleton with accuracy, closely approaching that of standards based on the dentition (standard error rates are between ±1.1 years and ±2.4 years).

KEYWORDS: forensic science, forensic anthropology, subadult, mandible, age assessment, morphological variation

Age estimation from human skeletal remains is a well established practice in physical anthropology and is one of the four key biological characteristics important in forensic identification (1). Age related changes have been documented for almost every part of the human skeleton—e.g., cranial sutures (2,3); dentition (4–8); hand (9); ribs (10); os coxae (11–14); and foot (15)—with the selection of an appropriate technique being inherently dependant upon skeletal preservation and the efficacy of the available standards. While a significant proportion of forensic investigations involve diagnosis of age in the deceased, there has been a steady increase in the importance of determining the age of living individuals, mostly to ascertain whether a person of interest has reached the age of criminal responsibility (16).

When developing or applying age estimation standards, due consideration must be given to the effects of nutritional deficiencies or other environmental insults, and the degree of variability among individuals of a given age, both within and between different populations (17). With regard to dental development standards, it has been shown that emergence times of the deciduous dentition are relatively similar across different populations. Further, most childhood illnesses, and slight to moderate nutritional deficiencies, do not appear to disrupt the sequence and timing of eruption (18). This is perhaps due to tooth development being under strict genetic control and thus being less susceptible to environmental insults (17,19,20).

An inherent limitation of dental development standards, however, is that reliability of age estimation is not uniform from birth to adulthood; at around 14 years of age most of the teeth are fully developed and age estimation becomes increasingly difficult (21). The third molars are generally the only teeth still developing at this stage (22), however they are characterized by a higher incidence of congenital absence, and are also particularly variable in crown and root morphology and sequence of formation and eruption (23,24). Even so, dental development and eruption is still recognized as the set of developmental markers that appear to show the least variability against chronological age (17); accordingly, these markers are widely used in forensic anthropological investigations.

From a developmental and functional perspective there is good reasoning to suggest that the mandible would be a suitable bone for estimating age. The mandible accommodates the lower dentition, and also provides attachment for the muscles of mastication (*temporalis* and *masseter* amongst others), thus mandibular growth would be expected to be closely integrated with dental development (see Ref. 25). This, and the premise that the dentition is less affected by nutritional variation and other insults than other skeletal tissues (26), would imply that mandibular morphology could be a useful element for forensic skeletal-age assessment.

In a recent study, Norris (27) attempted to determine whether an infant sample (near birth to 2 years of age) could be aged using mandibular measurements. It was found that the only mandibular dimension that could statistically differentiate between the age groups (demarcated at 6-month intervals) was ramus height. Norris established that there are age related morphological differences in the infantile mandible, but no age prediction standards (coefficients, standard error estimates, and cross-validations) were presented.

This paper is part of a series of studies designed to apply morphometric methods for the analyses of three-dimensional anatomical landmarks to problems in forensic anthropology. We previously investigated sexual dimorphism and population variation in both the subadult (28) and adult mandible (29,30). This is the next paper in the series; an investigation into whether the simple interlandmark measurement of ramus height can be used to accurately estimate age in the subadult skeleton.

We have outlined evidence suggesting that subadult mandibular morphology has the potential to be used for forensic age estimation

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(see above), but there are some questions that require further clarification: (i) determining the standard error of age estimation using the measurement of ramus height; (ii) determining whether age estimations are accurate beyond the first few years of life; (iii) determining whether age estimation using mandibular morphology is sex and/or population specific.

Material and Methods

Material

This study examined the mandibles of 79 subadult individuals drawn from two populations: South African Bantu-speaking (*R.A. Dart Collection of Human Skeletons*); and African American (*Hamann-Todd Osteological Collection*). The composition of the mandible series is summarily described in Table 1. The entire sample comprises "known individuals" prepared from anatomical dissecting room samples; consequently the sex and a statement of age is documented for each individual (31,32).

Methods

The linear (interlandmark) measurements used in the present study were abstracted from a data set of 38 variables recorded in three-dimensions using a *Microscribe G2X* portable digitizer running *Inscribe-32* software (Immersion Corporation, San Jose, CA). The measurement of ramus height was acquired using a mathematical conversion of the three-dimensional landmark coordinates (*condylion superior*—the most superior point on the mandibular condyle; and *gonion*—the most lateral external point of junction of the horizontal and ascending rami of the lower jaw—see Fig. 1).

The conversion formula applied is a simple extension in three dimensions of the standard theorem of Pythagoras: $\sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2 + (z_1 - z_2)^2}$, where $x_1 - x_2$ is the x coordinate difference between any two landmarks, and x, y, and z are the three-dimensional landmark coordinates. We have previously established that mathematically transformed three-dimensional coordinates are amenable to the abstraction of linear measurements statistically comparable to those taken using standard anthropological techniques (see Ref. 33).

A series of regression analyses were performed to test whether it is possible to estimate age using the linear measurement of ramus height. Accuracy of the regression models was estimated, using standard errors of the estimate (the standard deviation of the residuals). In a few cases, the age predicted by the regression was negative; as this is an unrealistic result, these individuals were classified as belonging to the first year of age. Regression models were cross-validated using a jackknife procedure; each specimen was removed and regression coefficients were estimated, which are then used to predict the age of the excluded specimen, thus providing the predicted age of a specimen which had not been used to estimate the original regression parameters. The percentages of individuals classified in the correct age category, or in those corresponding years (± 1, 2…) relative to the observed age, were then computed. Statistical analyses were performed using the following software: *SPSS 11.5.0* (34); *NTSYS-pc 2.2f* (35); and *TPSSmall 1.20* (36).

TABLE 1—*The composition of the skeletal material used in the present study.*

Stated age range (years)	South African Bantu		African American	
1–10 years	10 ♂	9 ♀	13 ♂	11 ♀
11–17 years	15 ♂	8 ♀	5 ♂	8 ♀

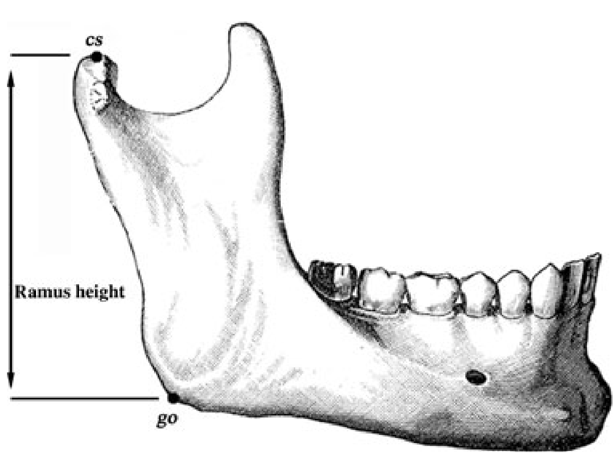

FIG. 1—*Lateral view of the mandible showing the measurement of ramus height.*

Results

Our initial analyses involved using linear regression models to assess the degree of sexual dimorphism present in the subadult mandible; tests of common slopes and homogeneity of intercept were nonsignificant ($p > 0.05$), thus demonstrating negligible dimorphism in the sample. Morphological variation within populations tends to increase with age; ontogenetic trajectories of males and females may thus diverge. In a recent study that utilized much of the same material analyzed here, however, we demonstrated no appreciable dimorphism until approximately 15 years of age (28). So, in relation to the present study, we can justify pooling sexes, which allows us to increase sample size and estimate regression coefficients in a relatively homogenous sample.

To fully explore the age prediction potential of subadult mandibular morphology, the following pooled sex sub-samples were analyzed: (i) all individuals; (ii) all children (≤10 years of age—generally assumed to be prepubertal); (iii) all individuals according to population; and (iv) all children according to population.

Using the linear measurement of ramus height, standard errors of estimates in the total sample is 2.3 years in the South African Bantu, and 2.4 years in the African American and pooled samples (Table 2). Standard errors of estimates in the sample consisting of children are 1.1 years in the South African Bantu, and 1.4 years in the African American and pooled samples (Table 2). It is clearly apparent that excluding adolescents (individuals older than 10 years of age) consistently reduced errors. The next step was to formulate a set of standards for predicting the age of subadults. As our analyses of separate samples did not confer any appreciable improvement in prediction accuracy, we built the regression models using

TABLE 2—*Standard error (in years) of regression estimates using ramus height.*

Population	Total sample*	Children†
Pooled	2.4	1.4
African American	2.4	1.4
South African Bantu	2.3	1.1

*Stated age range 1–17 years.
†Stated age range ≤10 years.

TABLE 3—*Regressions of age onto ramus height in the pooled sample (combined South African Bantu and African American).*

	Coefficients					Goodness of fit			
Sample	Coefficient	Score	SE	t	p-value	R^2	df	F	p-value
Model 1—total*	Intercept	−13.3	1.2	−11.255	6.2×10^{-18}	0.834	1, 77	385.578	1.0×10^{-31}
	Slope	0.535	0.027	19.636	1.0×10^{-31}				
Model 2—children†	Intercept	−7.1	0.9	−7.616	2.3×10^{-9}	0.794	1, 41	157.753	1.2×10^{-15}
	Slope	0.325	0.026	12.560	1.2×10^{-15}				

Two separate models are presented; (Model 1) total sample and (Model 2) children only.
*Stated age range 1–17 years.
†Stated age range ≤10 years.

the pooled populations: Model 1—total sample; and Model 2—children separately.

Regression coefficients and estimates of the goodness of fit of the regression of age onto ramus height are shown in Table 3. Regression lines and 95% confidence intervals for predictions are shown in Fig. 2. Consistently with the differences in standard errors shown in Table 2, prediction intervals were clearly larger for the regression including both children and adolescents. Jackknife cross-validation for the age predictions based on ramus height was performed for both the total sample and children separately. The percentages of individuals whose age was predicted correctly or with an error of ±1, 2… years are shown in Table 4. Age was predicted with an error smaller than 2 years in <70% of subadults when adolescents were included (Model 1); however, this percentage rose to better than 90% when the children were analyzed independently (Model 2).

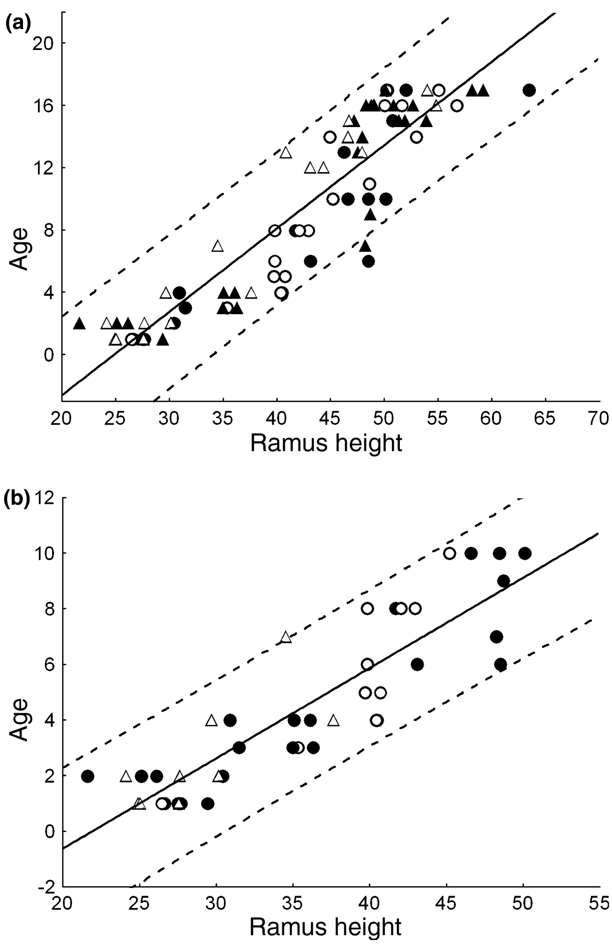

FIG. 2—*Linear regressions of age onto mandible height with 95% prediction bands and different symbols for populations and sexes. (a) Total sample; (b) children only (≤10 years of age). Key: shaded = male; open = female; ●African American; ▲South African Bantu.*

TABLE 4—*Jackknife cross-validation of predictions based on regressions of age onto ramus height in the pooled samples (both populations), including the total sample (Model 1) or only children (Model 2).*

Sample	Correct Year ±	Frequency	%	Cumulative %
Total*	0	7	8.9	8.9
	1	28	35.4	44.3
	2	17	21.5	65.8
	3	15	19.0	84.8
	4	9	11.4	96.2
	5	1	1.3	97.5
	6	1	1.3	98.7
	7	1	1.3	100
Children†	0	8	18.6	18.6
	1	21	48.8	67.4
	2	11	25.6	93.0
	3	3	7.0	100.0

*Stated age range 1–17 years.
†Stated age range ≤10 years.

Discussion

Age estimation is an important element of any forensic anthropological investigation and is one of the primary sources of data for establishing the identity of unknown remains. In this study, we used a documented sample to assess the potential of mandibular morphology, specifically the linear measurement of ramus height, as a developmental marker for estimating age at death in subadult human skeletal remains.

In evaluating the efficiency of ramus height for subadult age estimation, we found that in the pooled population sample, standard error rates were higher for the total sample (Model 1: ±2.4 years) compared with the children only (Model 2: ± 1.4 years); there was generally little improvement in prediction accuracy in treating the populations separately. Ubelaker (6) reported a similar difference in prediction accuracy between younger and older subadults, and stated "Dental development provides the most accurate results, especially between birth and 10 years..." (p. 63). This may be related to an expectation that variation in remodeling of the mandible due to masticatory strain (e.g., chewing and cultural activity) increases with age, and thus would be practically nonexistent in infants prior to the eruption of the deciduous dentition (see Refs. 37–39). It is interesting to note that a recent study by Maber et al. (40) reported no difference between age prediction accuracy in younger compared with older children.

There are many dental development aging standards available in the literature (e.g., Refs. 4–7); however not all list standard error rates. Ubelaker's (6) standards, utilizing composite visual images of dental development stages keyed to chronological age, are perhaps most familiar to the forensic anthropologist, increasingly so since their reproduction in 1994 (41). Those standards are suitable for individuals aged 5 months *in utero* through to 35 years; standard error rates range from ±2 months to 3 years. In their assessment of dental age versus real age, Reppien et al. (42) concluded that "In cases with a developing dentition the estimated age range can be narrowed to 2–4 years. Depending on the degree of development, the dentition of a small child can be estimated within a range of 2 years and for the subadults a range of 4 years is more appropriate" (p. 87).

This study established that the linear measurement of ramus height can be used to predict age with accuracy comparable to, or closely approaching that of, standards based on the dentition. This is not an unrealistic expectation; mandibular growth would be expected to be closely integrated with dental development, largely because this bone serves to accommodate the lower dentition and also provides attachment for the muscles of mastication (25). Also, the mandible undergoes the greatest size increase of all the facial bones; the ramus specifically has been shown to be associated with the greatest morphologic changes in size and remodeling during growth (43,44; and for ontogeny of facial development see Ref. 45,46). A further practical advantage of using a direct linear measurement, as opposed to standards based on visual stages keyed to chronological age, is better intra- and inter-observer accordance; metric methods introduce less subjectivism into the final age determination compared with visual scoring systems.

Selecting appropriate techniques for forensic age estimation is inherently dependant upon skeletal preservation and the efficacy of the available standards. In recovering human skeletal remains, the preservation of individual elements can be highly variable, thus not all bones are suitable for forensic analysis. The structural density of the mandible (gm/cm^3) is relatively high (because of a particularly dense layer of compact bone) compared with other more porous and less dense bones (e.g., vertebrae, ribs, sternum) (47,48). The mandible is thus often recovered largely intact, and dental development standards are used to estimate age; if however, the tissue surrounding a tooth (or tooth bud) has decayed, there is a higher probability that some or all of the dentition may not be recovered. In this situation, we suggest that the standards outlined in this study offer a practical alternative; they are accurate and not contingent on the recovery of the dentition.

Conclusions

This study affirms that subadult mandibular morphology can be used to predict age with a high degree of expected accuracy. We have outlined a set of age-prediction standards using the linear measurement of ramus height, suitable for children (≤10 years of age) or subadults (1–17 years of age); standard error rates are ±1.4 and ±2.4 years, respectively. We found only negligible difference in prediction accuracy when the material was analyzed according to the two populations and/or sex. These new standards thus have obvious benefits to the forensic community; they are quick and simple to apply and are capable of predicting age in the subadult skeleton with accuracy closely approaching that of standards based on the dentition.

While the standards we have outlined here are based on South African Bantu-speaking and African American individuals, the applicability of these statistics for use in other populations needs to be assessed. Also, the effectiveness of other mandibular measurements for age prediction is yet to be investigated. To this end, we are currently in the process of assembling additional subadult individuals, to facilitate a comprehensive analysis of the age prediction potential of various mandibular dimensions in a range of populations. This future research will also involve assessing the effectiveness of geometric morphometric data, specifically three-dimensional multivariate descriptors of size and shape, for subadult age estimation.

Disclaimer

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