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Estimating Age at Death from Immature Human Skeletons: An Overview

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ABSTRACT: Literature on the estimation of age at death of immature human skeletons is critically reviewed. Those estimating age at death for forensic science purposes should consider all available data, but especially rely upon the most appropriate and accurate methods. Estimates should reflect the possible error resulting from the sex differences and population variability known to be associated with the growth process.

KEYWORDS: physical anthropology, musculoskeletal system, human identification

Occasionally, forensic anthropologists are asked to examine skeletal remains that are thought to represent immature humans [*1*]. Of the 174 cases submitted to my laboratory for analysis from the FBI and others since 1977, 21 (12%) were thought to represent immature humans. One of these actually represented a small dog skeleton. The remaining 20 (11%) included 10 of archeological origin, 1 from a documented relocated grave, and 9 of recent origin, with several apparently resulting from homicide.

The 20 human cases actually included 22 immature individuals. Two of these represented newborns, eleven were aged between 1 and 5 years, three between 6 and 10, four between 11 and 15, and two between 16 and 20. Thus, all age levels of immature skeletons do regularly appear as forensic science cases and all present special problems. In all cases, it is important to estimate age at death as accurately as possible to help identify the individual, as well as to help establish the general date that death occurred.

Estimating age at death of an immature skeleton consists of attempting to establish the physiological age of the skeleton and then to correlate it with chronological age. Investigators should be aware that different skeletal data sets produce estimates of varying accuracy. The following is a review of the relevant literature and recommendations to follow in estimating chronological age at death of immature human remains.

Physiological age of the immature human skeleton must be assessed from one or more of the following systems: appearance and union of epiphyses, bone size, the loss of deciduous teeth, the eruption of teeth, and dental calcification. Ideally, all of these systems should be consulted for an overall assessment of physiological age. In reality, the actual data used are influenced by the general age of the skeleton (adolescent, child, infant, or neonate), the skeletal parts present, the state of preservation of the remains, and other circumstances about the case.

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Appearance of Ossification Centers and Union of Epiphyses

As early as 1924, Stevenson [2] studied the human skeletal collection at Case Western Reserve in Ohio and documented the general timing of epiphyseal union, noting that such observations were most useful between the ages of 15 and 20. Later work by Todd and D'Errico [3], Flecker [4], Greulich and Pyle [5], Pyle and Hoerr [6], McKern and Stewart [7], and others have documented the general order and timing of both the appearance of ossification centers and the union of epiphyses. As Krogman [8] has summarized, different centers appear at ages ranging from birth to over 15 years. However, as Stewart [9] has noted, data on the appearance of ossification centers are rarely consulted in forensic science investigation since newly formed centers are fragile, easily broken, and frequently not even recovered. Even when the centers are present, most investigators prefer to estimate age from dental development or long bone length.

Data on the union of epiphyses are much more frequently used in forensic anthropology, especially for the teenage years. Standards are available for the clavicle [3], hand and wrist [5], and knee [6]. McKern and Stewart [7] provide data on the union of a variety of epiphyses in their study of young American males who died in the Korean conflict. General summaries of these and other works are provided by Krogman [8] and Stewart [9].

All of the works cited above except Stevenson [2] have documented a marked sex difference in the timing of epiphyseal union. Lewis and Garn [10] noted that in the appearance of 36 ossification centers, girls were advanced over boys by about 25%. The difference was about 19% in the timing of knee ossification. Data summarized by Krogman [8] and Stewart [9] show that union of most epiphyses occurs in females about one to two years earlier than in males. Thus, if possible, sex should be determined before estimating age from epiphyseal union. If the sex is unknown, then the estimate should be derived from both male and female data and should convey the appropriate margin of possible error.

Several problems should be noted in applying the literature on epiphyseal union to forensic science cases. Most investigators present standards showing the normal or average age of union without showing the variability. Standards such as those of Greulich and Pyle [5] and Pyle and Hoerr [6] were designed to provide clinicians and others with clearly defined definitions of average development. As such they can be useful to forensic anthropologists in estimating the most probable age at death. They do not provide data, however, on the possible range of variation around that mean. The exception is the McKern and Stewart [7] study, which documents that variation, at least in males.

An impression of the population variation in the timing of epiphyseal union can be gained from comparing the data of various investigators. Such a comparison by Stewart [9] revealed differences of two years or more for most of the major epiphyses. Stewart also noted that gross inspection of union in bones generally yields slightly higher estimates than does radiographic assessment.

An important contribution of the McKern and Stewart [7] study is the data provided on the relative timing of the different stages of epiphyseal union. These data clearly show that at least several years normally elapse between beginning and final closure of an epiphysis and emphasize the importance of defining the exact stage of union for each epiphysis, rather than a simple score of "united" or "ununited." The study also shows that not all epiphyses are of equal value in estimating age. The best indicators are from the proximal humerus, medial epicondyle, distal radius, femoral head, distal femur, iliac crest, medial clavicle, sacrum 3/4 joint, and the lateral sacral joints. They also recommend that the total pattern of skeletal maturation be considered and provide a useful system for doing so.

In summary, estimates of age from epiphyseal union should consider three factors: the exact stage of union of each epiphysis available; the sex of the individual; and the range of variation in the literature for the timing of union and possible differences between gross examination and radiographic methods. This last point is especially relevant since many forensic anthropologists may lack radiographic experience, and at many sites, lines may persist radiographically that mimic incomplete union.

Dental Formation and Eruption

Numerous studies have documented the independence and variability of skeletal and dental aging. In general, bone development and dental calcification are more highly correlated with chronological age than is dental eruption [*11*]. Dental calcification and skeletal development are more correlated with each other than either is with dental eruption [*11,12*]. Steggerda [*13*] found a low correlation between body size and dental eruption, and Meredith [*14*] found a low correlation between long bone growth and dental eruption. In an analysis of variance of different maturational systems with age, Lewis and Garn [*10*] found that long bone ossification showed the greatest variability, followed closely by hand bone ossification, deciduous tooth eruption, and then permanent tooth eruption. Less variability was found in cusp calcification, complete crown formation, menarche, and apical closure. Research indicates that dental eruption is more effected by nutritional stress [*15,16*], disease [*17*], population variation [*18*], and premature loss of teeth [*19,20*]. Fanning [*21*] argued that premature loss of deciduous teeth causes premature eruption of permanent teeth, but does not affect formation. In short, numerous studies argue strongly that dental calcification, including both crown and root formation, provides the best means to estimate age at death from the immature skeleton. Dental formation has a strong genetic component, much less influenced by environmental factors than are other maturational systems [*22*].

A growing literature on dental calcification provides considerable data to use in estimating age at death. Kraus [*23*], Christiansen and Kraus [*24*], and Lunt and Law [*25*] offer data on calcification of the deciduous dentition, and Nolla [*26*] offers the same for permanent teeth. Fanning's work [*27*] provides additional data on permanent teeth, showing that sex differences increase with age and are greatest in the mandibular canine. She also noted that emergence of most teeth occurs when the roots are between 67 and 100% formed. Garn et al. [*28*] documented the great variability in formation time of the third molar and also the lack of a sex difference in the development of that tooth. Gilster et al. [*29*] provide data on calcification of the mandibular second primary molars, noting that females are advanced over males and that blacks are advanced over whites. Garn et al.'s study [*30*] of 255 Ohio whites showed that variability of tooth formation was about three times that previously believed. All of these works provide important data and perspective useful to us in estimating age at death forensically.

In my opinion, the best single standards for estimating age from dental development are those of Moorrees et al. [*31,32*]. In 2 articles based on their study of 48 males and 51 females in the Fels Ohio series, they present both means and variation around the means for 14 clearly defined stages of crown and root formation of the permanent maxillary incisors, 8 mandibular teeth, and 3 deciduous teeth. Data are presented separately for males and females. Such separation is appropriate since Garn et al. [*33*], Demisch and Wartmann [*34*], Lewis and Garn [*10*], and others have shown that girls are advanced in both calcification and eruption over boys by a factor of between 3 and 6%, that the difference increases with advancing age, and that it varies with individual teeth.

Data on tooth emergence are presented by Gron [*35*], Hurme [*17*], Meredith [*36,37*], Orner [*38*], and Robinow et al. [*39*]. These studies present conflicting data on the eruption timing differences between boys and girls, but do provide information on the mean eruption time of each tooth and the variability involved.

In estimating age at death from the dentition, I recommend consultation with Moorrees et al. [*31,32*] and other publications and heavy reliance on the calcification standards. If eruption standards are used, investigators should be aware that definitions of eruption in the literature vary from emergence through the alveolus or the gingival tissues or both to reaching the occlusal plane.

Some attention must be provided here to the much used Schour and Massler dental chart published by the American Dental Association [40]. The chart does have visual convenience over the studies cited above and presents data on all teeth. As Lunt and Law [25] point out, the chart was developed from the 1933 study by Logan and Kronfeld [41] on 25 diseased Ohio children ranging in age from birth to 15 years. The chart combines the sexes and suggests that variation does not exceed nine months for each of 19 stages of development. Researchers should be aware that differences exist between the original chart published in 1941 [42] and the larger version published in 1944 and distributed by the American Dental Association [40]. Some of the differences could affect individual age estimates by as much as 2 years [43].

The impact of the use of different standards on age estimation can be seen in Fig. 1, taken from a cross-sectional growth study published by Merchant and Ubelaker [44]. The chart plots femoral growth curves of protohistoric Arikara Indians derived from ages estimated from the dental calcification of archeologically recovered skeletons. The thicker solid line results from ages estimated using Moorrees et al. [31,32], and the lower dashed line was

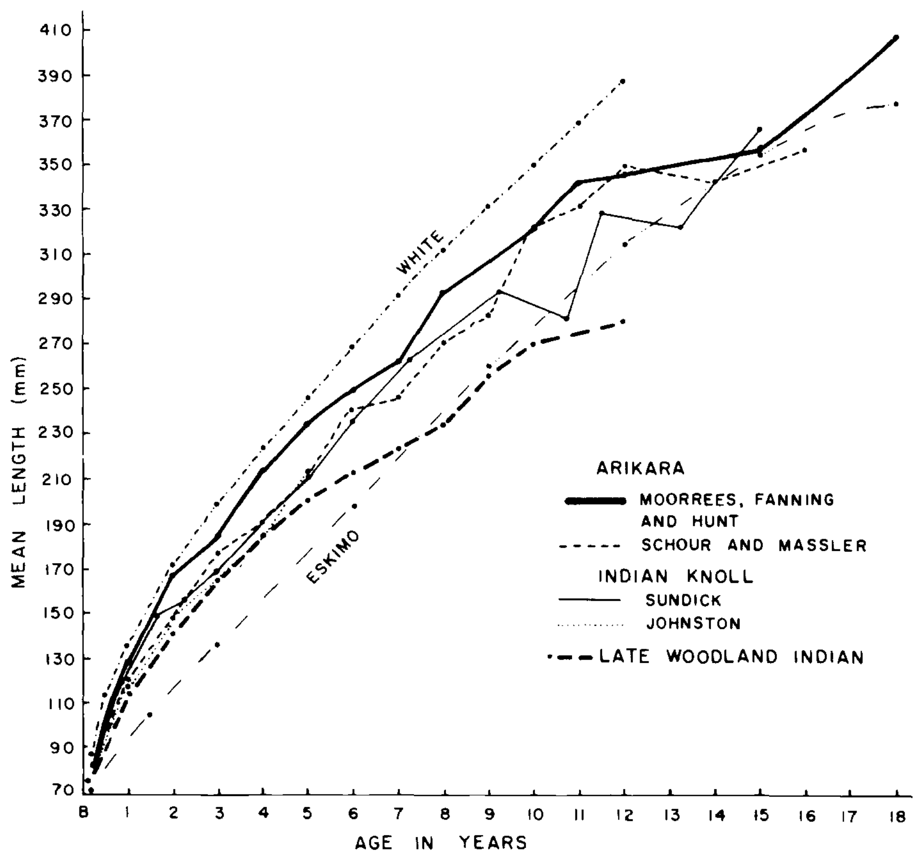

FIG. 1—*Comparison of cross-sectional femoral growth curves of modern whites, Eskimos, and Arikara, Indian Knoll, and Late Woodland Indians. From Merchant and Ubelaker, p. 69* [44].

produced using ages derived from the 1944 Schour and Massler chart [*40*]. In the Arikara study, the Schour and Massler chart consistently gave higher age estimates than did the Moorrees et al. data.

An additional problem to consider is the application of these standards, mostly based on U.S. white populations to American Indians, blacks, Orientals, and others that may appear as forensic science cases. Gilster et al. [*29*] found that at least the mandibular second primary molar formed earlier in blacks than in whites. Numerous other studies document that tooth eruption is earlier in a variety of nonwhite populations. These include Japanese [*18*], Navajo and Maya Indians [*45*], Aleuts [*46*], Eskimo [*47*], and the Apache and Pima Indians [*48*]. In an important radiographic study of 236 Indian and 149 Inuit children on Canadian Reserves, Trodden [*49*] showed that in both Indian and Inuit samples, female teeth calcified and erupted earlier than males and that males and females of both the Indian and Inuit samples calcified and erupted earlier than whites. Ubelaker [*50*] summarized these works into a Schour- and Massler-type chart that can be used for American Indian remains or other nonwhite dentitions. The chart assumes that the earlier eruption and calcification documented for some teeth can be extended to all teeth. The chart of course does not substitute for the individual publications themselves. Jantz and Owsley [*51*] present data derived from archeological specimens showing that the Arikara conform to that pattern, but that the timing of individual teeth may vary considerably from that predicted by the Moorrees et al. standards.

Bone Size

In the absence of the dentition, age at death of children and infants can be estimated from bone size. This approach is especially useful for very young infants or fetal material when the incompletely calcified teeth are easily lost or broken. Numerous publications are available showing the correlation of perinatal age with the fetal measurements of crown-rump length and crown-heel length [*52–57*]. Note in consulting these formulae that Scammon and Calkins [*58*] found greater measurement error in crown-rump length than in crown-heel length. Standards for estimating fetal length and subsequently perinatal age from individual bones are provided by Olivier and Pineau [*59*] and Fazekas and Kosa [*60*]. In addition, Scheuer et al. [*61*] provide regressions for estimating perinatal age directly from limb bone length. The Scheuer et al. study focuses on the femur, tibia, humerus, radius, and ulna of English samples and yields regressions with standard errors as low as 1.24 weeks for the humerus, sexes combined. Their application of their regressions and others from the literature to different bones of 4 ancient European fetal skeletons produced within skeleton estimates that varied by as much as 13 weeks.

The Fazekas and Kosa [*60*] book deserves special attention since it is based on a very large sample of 138 foetal skeletons ranging in age from the third to the twelfth lunar month. Their publication presents regressions and tabular data for 67 measurements of 37 bones, including not only the major bones of the skeleton but also the inferior concha, vomer, and auditory ossicles. Measurements of each bone are well-defined, and the authors claim that error never exceeds one half of a lunar month. Correlation coefficients are highest for maxilla height (0.9998), tibia length (0.9988), frontal width (0.9988), mandible length (0.9986), and femur length and temporal height (0.9985). Values were lowest for incus length (0.617), stapes length (0.688), and incus width (0.781).

To test the utility of their data on forensic science cases, I applied their regressions to as many bones as possible from 2 archeologically recovered fetal skeletons from the protohistoric Mobridge site (39WW1) of South Dakota and 4 fetal skeletons from the Smithsonian fetal collections (Table 1). This fetal collection was assembled in the early 1900s and contains over 300 skeletons collected from hospitals in the Washington, DC area. Many of them are of known or at least estimated gestational age and have crown-rump lengths or total

TABLE 1—*Age at death of museum specimens estimated using regression equations of Fazekas and Kosa* [60].

S.I. Catalogue Number	Known Age	Number of Measurements	Age Estimate, fetal months	Age Range, fetal months
382 986 S. Dakota	?	26	10	8.5–10+
382 924 S. Dakota	?	16	10	8.5–10+
255 286 male	newborn	67	9.5	7.0–10+
255 286 female	newborn	62	10	7.0–10+
299 226 male	7 fetal mos.	58	7.5	4.5–10
299 230 female	newborn	61	7.0	4.5–10

lengths or both available. Note that between 58 and 67 of the measurements were taken on the dissection room specimens and only 16 and 26 on the archeological specimens. This directly results from the poorer preservation of the archeological specimens and perhaps indicates a limitation in application to the typically poorly preserved forensic science case. Note also that the average estimate for the skeleton compares well with known age in the 4 dissection-room cases. The total age range, however, greatly exceeds the one half of a lunar month accuracy stated by Fazekas and Kosa [*60*]. Obviously, the error increases when the method is applied outside of its original sample. In using the method, I would recommend relying mostly on the long bone measurements and averaging estimates from at least several bones. Researchers should also be cognizant of varying definitions of fetal age in the literature, but note that most refer to "lunar months," computed from the onset of the last menstrual period and calculated on a 28-day monthly interval.

Anyone attempting to estimate if a skeleton represents a fetus or a newborn should realize that size at birth also varies both within and among populations, and can be influenced by dietery and disease factors. In low socioeconomic groups, Lechtig et al. [*62*] found that nutrition can have a strong effect on the frequency of low-birth-weight infants, although Bagchi and Bose [*63*] suggest that dietary problems must be extreme to effect obstetrical performance. Ebbs et al. [*64*] suggest that poor diet in pregnant women can lead to a higher incidence of miscarriage, stillbirths, premature births, and minor complications that collectively could produce smaller birth size. Smith [*65*] notes that generalized undernutrition in urban Holland around 1945 produced infants of smaller than normal birth weight and length. Venkatachalam [*66*] found similar effects of dietary deficiencies of calorie-protein and vitamin B complex in South India. Antonov [*67*] noted that widespread hunger during the siege of Leningrad in 1942 resulted in an increase of the rate of stillborns, premature births, smaller birth size, and infant morbidity and mortality. Laga et al. [*68*] report generally lower placental mass, correlated with smaller birth size among low-class Guatemala populations, presumably with nutritional problems. Commey and Fitzhardinge [*69*] further suggest that small-for-gestational-age infants continue to show growth retardation after birth.

Several publications are available that allow for the estimation of age at death of older infants and children from bone size. Anderson and Green [*70*], Ghantus [*71*], Hoffman [*72*], and Maresh [*73,74*] all offer data on long bone growth derived from radiographs of contemporary U.S. white samples. All but the Ghantus study represent longitudinal studies and present somewhat conflicting reports of the degree of sexual dimorphism. Comparative data on American Indian and Eskimo populations are provided by Jantz and Owsley [*75*], Johnston [*76*], Merchant and Ubelaker [*44*], Perzigian [*77*], Stewart [*78*], Sundick [*79*], and Walker [*80*].

An impression of the population variability involved in long bone growth is revealed in Fig. 1 from Merchant and Ubelaker [*44*]. The figure plots cross-sectional growth curves for the Arikara, Indian Knoll, Late Woodland Indian, Eskimo, and modern white populations. Generally, the Indian curves fit between the Eskimo and white extremes.

TABLE 2—*Range of ages at death estimated for six femoral lengths using eleven different published growth standards.*

Femur Length, cm	Mean Age Estimate, years	Range of Age Estimates, years	Years Within Range
19	3.8	2.0-5.5	3.5
24	5.8	3.5-8.0	4.5
28	8.3	5.5-11.0	5.5
32	9.3	6.0-12.5	6.5
35	11.2	7.8-14.5	6.7
38	13.8	9.5-18+	8.5

To assess the impact of this variability on a possible individual forensic science case, I estimated age at death of six femur lengths ranging from 19 to 38 cm using eleven different standards. The standards were Maresh [*73*] boys, Maresh [*73*] girls, Anderson and Green [*70*] boys, Anderson and Green [*70*] girls, Hoffman [*72*], Stewart [*78*] Eskimo, Walker [*80*] Late Woodland Indians, Merchant and Ubelaker [*44*] Arikara Indians derived from the Schour and Massler standard, Merchant and Ubelaker [*44*] Arikara Indians derived from Moorrees et al. standard, Johnston [*76*], and Sundick [*79*]. As Table 2 shows, the variability of the estimates is considerable and increases dramatically with the size of the bone. Obviously, an estimate of age from a forensic science specimen of unknown racial affiliation must consider this variability. If racial affiliation is known, then the accuracy is greatly increased.

Conclusion

A variety of methodological approaches and a sizeable literature are available to assist forensic science experts in estimating age at death of immature skeletons. I recommend that all age indicators be consulted, but that special emphasis be given to dental formation and other processes that show the highest correlation with chronological age at death. Any final estimate should express the known variability in the aging process, especially if the sex and population affinity of the individual are unknown.

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