J Forensic Sci, Sept. 2005, Vol. 50, No. 5
Paper ID JFS2004542
Available online at: www.astm.org

Christian Crowder,[1] M.A. and Dana Austin,[2,3] Ph.D., D-ABFA

Age Ranges of Epiphyseal Fusion in the Distal Tibia and Fibula of Contemporary Males and Females*

ABSTRACT: The range of variation in epiphyseal fusion in North American populations has not been sufficiently established. This significant oversight can lead to exclusion of persons of interest in a forensic investigation. This study evaluates epiphyseal fusion of the distal tibia and fibula in 570 European-, African-, and Mexican-American children and young adults. Radiographs of 270 females aged 9 to 17 and 300 males aged 11 to 20 were analyzed to assess the range of variation of epiphyseal fusion at each age. Results indicate that complete fusion in females occurs as early as 12 years in the distal tibia and fibula. All females demonstrated complete fusion by 16 years with no significant differences between ancestral groups. Complete fusion in males occurs as early as 14 years in both epiphyses. All males demonstrated complete fusion by 19 years. Significant differences in the earliest age of complete fusion showed that African- and Mexican-American males demonstrate complete fusion as early as 14 years in both epiphyses while European-American males do not express complete fusion until 16 years.

KEYWORDS: forensic science, forensic anthropology, age estimation, ankle, epiphyses, fusion, ancestry, tibia, fibula, x-ray

Estimating the age at death of an individual is a key element in an anthropologist's construction of an osteobiography. The age of fusion of the various epiphyses provides valuable data in estimating age at death in individuals of teenage and early adult years. Epiphyseal fusion data have been collected from various populations utilizing methods ranging from dry bone evaluation (1–3) to medical imaging (4–28). The majority of these studies were undertaken to evaluate clinical norms of skeletal development for chronological age. Anthropologists who estimate age ranges for unidentified remains are more interested in the full range of expression in skeletal maturity that can be found for each chronological age, not simply the population norm or average age. Therefore, most clinical data are inappropriate for forensic contexts. In our experience, the use of the published age ranges for the fusion of various epiphyses (29) has led to an over estimation of age in our casework.

There are several methodological factors to consider when selecting a technique for estimating the age of unknown skeletal remains. The sample size, socio-economic composition of the sample, and the geographical/ancestral composition of the reference sample are a few factors that may affect the accuracy of age estimates. Furthermore, if evidence for a secular trend of retarded or advanced skeletal maturation exists across generational lines the applicability of non-contemporary data to contemporary populations is questionable. Anthropologists frequently utilize skeletal collections, such as the Terry, Hamann-Todd, and Grant collection, to develop methods of estimating age at death (30,31). Current skeletal collections tend to over-represent elderly individuals, under-represent subadults, and inadequately sample ancestral groups other than European-Americans and African-Americans. Furthermore, these collections consist of individuals born from the early 1800's to the early 1900's. Documented secular trends in height, weight, and maturation suggest these collections may not be suitable sources to establish maturation standards to evaluate contemporary populations (32). It has been claimed that forensic anthropologists have overlooked archaeological collections that contain large numbers of subadult material when seeking sources for maturation studies (33). There are several caveats associated with using these collections. Subadults from archaeological collections may not represent normal, healthy individuals (34), are often altered morphologically by taphonomic processes, and most importantly, the exact chronological ages of these individuals are difficult or often impossible to obtain.

In contrast to difficulties encountered by examining skeletal collections, radiographic analysis provides a method of observing human tissue that can be performed quickly, accurately and non-destructively. Increasingly, forensic anthropologists are called to assist other specialists with decomposed, yet largely fleshed remains. Radiographic evaluation of such remains is essential as maceration is considered too time consuming and destructive for the predilection of many medical examiners. The need for accurate radiographic standards to estimate ages at death by anthropologists who work in the medico-legal field is of critical importance. This research utilizes the radiographic method to record the total range of variation in epiphyseal fusion of the distal tibia and fibula in males and females from three contemporary North American ancestral groups (European-American, African-American, and Mexican-American). The distal tibia and fibula were selected due to two factors: 1) Clinically, this region is commonly injured, thus frequently x-rayed providing a large sample pool; 2) in the forensic

[1] Department of Anthropology, University of Toronto, Toronto, Ontario, Canada.
[2] Tarrant County Medical Examiner's Office, Fort Worth, TX.
[3] Department of Sociology and Anthropology, University of Texas at Arlington, Arlington, TX.

* Research presented orally at 2001 American Academy of Forensic Sciences' annual meeting in Seattle and 2001 Canadian Association of Physical Anthropologists' annual meeting in Winnipeg, Manitoba, CA. Funding is sponsored by Lucas Grant.
Received 23 Dec. 2004; and in revised form 23 March 2005; accepted 27 March 2005; published 3 Aug. 2005.

context, the distal tibia and/or fibula are often preserved by clothing and shoes, particularly in cases of fatal fire incidents and aviation disasters.

Materials and Methods

The sample consists of 10 individuals from each selected age and ancestral group, for a total of 270 females aged 9 through 17 and 300 males aged 11 through 20 (Table 1). Upper and lower age limits for the sample were derived from an extensive review of the literature and were refined during the data gathering process. The authors' goal was to review radiographs two years before earliest fusion through two years after latest fusion to conclusively exclude outliers. Three ancestral categories: European-American (EA), African-American (AA), and Mexican-American (MA), were studied as these groups were predominantly available. Radiographs were obtained from Cook Children's Medical Center, Plaza Medical Center, and John Peter Smith Hospital in Fort Worth, Texas with the permission of each hospital's internal review board. To ensure a contemporary sample, all subjects were born between 1969 and 1991.

Radiographs of the distal tibia and fibula were selected through each hospital's computer system by recognizing diagnosis and/or procedure codes associated with the lower leg, ankle and foot. To perform adequate analyses of the epiphyseal junctions, two of three radiographic views (A-P, lateral, and oblique) were required. Each patient's radiographs were viewed by one of the authors (C.C.) using standard hospital light boxes and magnifying lenses, with the exception of digitized images taken in 2000 that were available on the hospital's computer from Cook Children's Medical Center. Prior knowledge of sex, age, and ancestry was avoided. Subjects were excluded from the study if they had fractures or dislocations involving the growth plate, medical fixatives (i.e., surgical implants or casts) near the diaphyseo-epiphyseal junction, or a medical history of chronic disease that could significantly alter skeletal development. Furthermore, subjects exhibiting radiographic evidence of episodic disruptions (i.e., Harris lines) caused by malnutrition or disease were removed from the study. The following information was recorded for each subject:

1. The date of birth and date of radiograph.
2. Sex, as reported on the radiograph.

TABLE 1—*Age, sex, and ancestry distribution of the sample.*

	EA*		AA†		MA‡		
Age	Male	Female	Male	Female	Male	Female	N
9	—	10	—	10	—	10	30
10	—	10	—	10	—	10	30
11	10	10	10	10	10	10	60
12	10	10	10	10	10	10	60
13	10	10	10	10	10	10	60
14	10	10	10	10	10	10	60
15	10	10	10	10	10	10	60
16	10	10	10	10	10	10	60
17	10	10	10	10	10	10	60
18	10	—	10	—	10	—	30
19	10	—	10	—	10	—	30
20	10	—	10	—	10	—	30
N	100	90	100	90	100	90	570

* European-American.
† African-American.
‡ Mexican-American.

FIG. 1—*Stage one, no fusion: Absence of bony bridging between the diaphysis and epiphysis.*

3. Ancestry, reported by either self/family or visual evaluation by hospital staff.
4. Stage of fusion for each epiphysis. Stages 1, 2, 3, and 4 are described below.

Stage one, no fusion: Absence of bony bridging between the diaphysis and the epiphysis (Fig. 1). The epiphyses are separated from the diaphyses of the distal tibia and fibula by cartilaginous plates. During this stage the epiphyses are small and may appear oddly shaped, meaning that they have not yet fully ossified. Near the end of stage one the epiphyses have usually obtained their mature shape and the margins of the diaphyseo-epiphyseal junction begin to thicken.

Stage two, unclear: Relationship of the epiphysis and the diaphysis is not discernable (Fig. 2). The epiphyses begin to form a cap-like shape and the metaphysis becomes severely narrowed. The osseous margins may cause a shadowed or fuzzy appearance due to the epiphysis overlapping the diaphysis in the radiograph. The thickening of the diaphyseo-epiphyseal margins are more noted in this stage. This phenomenon is referred to as subchondral thickening, which is a prelude to epiphyseal fusion (35). In this stage fusion may begin in the middle of the bone, but it cannot be determined radiographically with any certainty. It is important to realize that categorizing a growth center into stage two is dependant on the researcher's inability to confidently determine if the epiphyseal center is open or if fusion has begun.

Stage three, partial fusion: Slight to nearly complete fusion of the diaphyseo-epiphyseal junction. At this stage, the epiphyses are fully ossified and have reached their mature shape. Epiphyseal fusion occurs first internally in the center of the junction, then expands towards the outer margins. Close observation and clear radiographs are essential to correctly assess this stage. At the onset of stage three, the diaphyseo-epiphyseal junction may appear hazy in the radiograph. It is important to look for centrally located small areas of fusion where the bone matrix will be continuous from the diaphysis to the epiphysis (Fig. 3*a*). Toward the end of this stage it is important to give attention to the extreme outer edges of the

FIG. 2—*Stage two, unclear: Relationship of the diaphysis and epiphysis is not discernable from stage one and early stage three. The radiographic image has been inversed to clarify the open lateral borders. Note as you follow the open lateral borders of the tibia towards the center of the bone the diaphyseo-epiphyseal margins overlap considerably.*

diaphyseo-epiphyseal junction where a diminutive v-shaped gap may indicate an incomplete fusion (Fig. 3*b*).

Stage four, complete fusion: Epiphysis is completely fused to the diaphysis (Fig. 4*a*, 4*b*). The diaphyseo-epiphyseal junction now appears as an epiphyseal line or scar, which may remain visible up to six months after fusion in the distal tibia and fibula (36,37). To correctly assess this stage the peripheral margins of the bones must be carefully observed to ensure there are no gaps. The lateral view of the ankle provides excellent visualization of the anterior and posterior margins of the tibia, while the oblique view provides the optimal view of the medial margin. In the oblique view, the distal fibula can sometimes appear to have an angled opening at the point where the interosseous ligament attaches just above the articular surface of the lateral malleolus. This attachment overlaps with the epiphyseal line causing a small to large groove superior to the articular margin, which can give the appearance of incomplete fusion in a cursory examination.

FIG. 4—*Stage four, complete fusion: Epiphysis is completely fused to the diaphysis. Note the epiphyseal line or scar, which should be carefully examined for small gaps.*

Results

The complete range of epiphyseal fusion recorded in this study is presented in Table 2. The data sets for stage one and four were truncated for statistical analysis. These original data sets included female subjects in the 9–10 and 16–17 age ranges and male subjects in the 11–12 and 19–20 age ranges that were reviewed to conclusively exclude outliers before the earliest and after the latest documented ages of partial fusion. Their inclusion in analyses of variance could mask subtle differences in the means within the aforementioned stages.

Females

As indicated in Table 2, the latest age of no fusion (stage one) for the distal tibia was 12 and the earliest age of partial fusion (stage three) was 11 years. The latest age of partial fusion for all ancestral groups was 15 years. One EA female and several MA females showed complete fusion of the distal tibia at age 12, while no AA females showed complete fusion until 13 years of age. By age 16 all

FIG. 3—*Stage three, partial fusion: Partial to nearly complete fusion of the diaphyseo-epiphyseal junction. The fibula demonstrates early partial fusion and the tibia demonstrates nearly complete fusion (a). The inversed radiographic image extenuates the small gap on the distal tibia (b).*

TABLE 2—*Age ranges for the stages of epiphyseal fusion of the distal tibia and fibula in females and males.*

Group	Bone	Stage 1	Stage 2	Stage 3	Stage 4
		Females			
EA	Dist. Tibia	<13	10–13	11–15	>11
	Dist. Fibula	<14	11–14	12–15	>11
AA	Dist. Tibia	<13	10–13	11–15	>12
	Dist. Fibula	<13	11–13	11–15	>12
MA	Dist. Tibia	<13	10–13	11–15	>11
	Dist. Fibula	<13	11–13	12–15	>11
Pooled	Dist. Tibia	<13	10–13	11–15	>11
	Dist. Fibula	<14	11–14	11–15	>11
		Males			
EA	Dist. Tibia	<15	12–16	13–17	>15
	Dist. Fibula	<17	13–16	14–17	>15
AA	Dist. Tibia	<15	13–15	13–18	>13
	Dist. Fibula	<16	13–15	14–18	>13
MA	Dist. Tibia	<15	13–15	12–17	>13
	Dist. Fibula	<15	13–15	12–17	>13
Pooled	Dist. Tibia	<15	12–16	12–18	>13
	Dist. Fibula	<16	13–16	12–18	>13

the female subjects, regardless of ancestry, demonstrated complete fusion of the distal tibia. There were no significant differences ($\alpha = 0.05$) in mean ages between ancestral groups at any of the stages.

The latest age of no fusion for the distal fibula was 13 years for EA and 12 years for AA and MA. The earliest age of partial fusion was 11 years for AA and 12 years for EA and MA. The latest age of partial fusion was 15 years for all ancestral groups. Both EA and MA females demonstrated complete fusion as early as age 12 while AA females did not show complete fusion until 13 years of age. By age 16, all of the female subjects regardless of ancestry showed complete fusion of the distal fibula. There were no significant differences in mean ages at any of the stages.

Males

It is evident from Table 2 that males exhibit more age variation within the stages of fusion between ancestral categories compared to the females. The latest age of no fusion for the distal tibia was 14 years for all ancestral groups. The earliest age of partial fusion was 13 years for EA and AA and 12 years for MA. The latest age of partial fusion was 17 years for EA and MA and 18 years for AA. The variation in the mean ages within the first three stages was not statistically significant, but the mean ages of stage four were significantly different ($\alpha = .05$, $p = .015$). The Scheffé method for testing post hoc comparisons indicated that the mean age at stage four fusion for the EA sample is significantly different from the mean ages of the AA and MA samples. AA and MA males exhibited complete fusion at age 14 while EA males did not demonstrate this stage of fusion until 16 years or age. By age 18 all EA and MA males showed complete fusion of the distal tibia, while none of the AA males demonstrated complete distal tibia fusion until 19 years of age.

The latest age of no fusion for the distal fibula was 16 years for EA, 15 years for AA, and 14 years for MA. The earliest age of partial fusion was 14 years for AA and EA males and 12 years for MA males. The latest age of partial fusion was 17 for MA and EA males and 18 for AA males. The variations in age between groups within the first three stages were not statistically significant, but the results of stage four were significantly different ($\alpha = .05$, $p = .020$). The Scheffé test indicates the EA sample is significantly different from the mean ages of the AA and MA samples. As with the distal tibia, AA and MA males demonstrated earlier complete fusion of the distal fibula than EA males. AA and MA males exhibited complete fusion at age 14 while EA males did not demonstrate this stage of fusion until 16 years or age. By age 18 all EA and MA males showed complete fusion of the distal fibula, while all AA males did not demonstrate this until 19 years of age.

Discussion and Conclusions

As the field of forensic anthropology develops and evolves separately from its parent discipline, physical anthropology, there are increasing needs for large, contemporary samples to develop more accurate methods of age estimation for forensic practice (38). A forensic skeletal collection large enough to confidently reflect the range of variation in epiphyseal fusion would be difficult to obtain; however, clinical radiographs are highly accessible. The dearth of modern juvenile skeletal collections also renders this modality a desirable research tool. Radiographic assessment of age at death is a practical method that can provide a comparable technique to gross morphological observation when maceration is unadvisable, yet there are some issues to consider in using a radiographic data set. The first involves the integrity of the x-ray and the experience of the radiographer (39,40). The film type utilized, developing techniques, and age and condition of the equipment affect the integrity of the x-ray, any of which may produce artifacts on the film. Although radiographic positions and exposure variables are standardized, the biological variability in tissue thickness and bone density requires a certain level of experience to obtain an optimal film series. As hospitals move toward digital x-rays, these considerations carry less weight. Digital images may be manipulated and corrected through computer imaging software. The second issue involves the experience of the observer in interpreting radiographic films. Because of the two dimensional nature of the radiograph, which causes overlap from surrounding structures, the observer could incorrectly assess the stage of fusion unless multiple radiographic views are utilized. Although the ankle is a fairly simple anatomical structure with little overlay from surrounding tissues, this research utilized two or three radiographic views. Other more complex areas that exhibit multiple areas of superimposition may require additional radiographic positions than used for this research.

Past research documenting the timing of epiphyseal fusion, both gross and radiographic, has either not focused on establishing the range of epiphyseal fusion or has not devoted sufficient efforts to establish the complete range of variation. Documenting the complete range of variation is the key to developing non-exclusive age ranges for estimating the age of unidentified human remains. Medical texts continue to print standard ages of epiphyseal fusion that are outdated, incorrect, or oversimplified. Another issue is the applicability of prior age standards from non-contemporary, non-North American studies on individuals that are geographically and temporally outside the reference samples (41,42). In American populations, a secular trend in growth and development resulting in an increase in height, weight, and earlier maturation has been observed (43–50). This trend indicates an earlier achievement of the body mass necessary to stimulate sexual maturation, as onset of pubertal maturation is associated with greater height, weight, body mass index, and skin-fold measurements in pubescent females (49). Studies indicate that modern teenaged females are evidencing a secular trend toward earlier sexual maturation with an average age for the onset of puberty between 8 and 9 years for African American females and 10 years for European-American females (45,49,50). According to these studies, females are developing six months to

TABLE 3—*Comparison of age ranges from this study with various authors that evaluated fusion of the distal tibia and fibula.*

Epiphyseal Fusion Study			Distal Tibia				Distal Fibula			
			Earliest Age of Fusion		100% of Sampled Fused		Earliest Age of Fusion		100% of Sampled Fused	
Author	Sample	N*	Males	Females	Males	Females	Males	Females	Males	Females
Stevenson [9]	American	110	—	—	18	—	—	—	18	—
Davis & Parson [10]	N/A	IND	16	16	19	19	17	17	19	19
Paterson [11]	English	IND	—	—	18	16	—	—	18	16
Galstaun [15]	Indian	N/A	14	13	18	17	14	13	—	—
Basu [17]	South Asian	130	—	13 1/2	—	—	—	14	—	—
Flecker [4]	Australian	IND	14y 9m	13	19	17	15y 8m	14y 10m	19	17
McKern & Stewart [1]	American	152	—	—	20	—	—	—	20	—
Hoerr et al. [8][†]	American	3000+	15.3	13.3	18	15.2	15.3	13	18	15.2
Bass [54]	N/A	N/A	14–16	11–13	20	17	14–15	11–12	20	17
Pfau & Sciulli [26][‡]	American	183	≈16	≈14.5	—	—	≈16.5	≈13	—	—
Banerjee & Agarwal [28]	Indian	180	14	14	18	17	14	14	18	17
Present Study[‡]	American	570	14	12	19	16	14	12	19	16

[*] Sample size field consist of one of the following: 1) actual number of individuals, 2) IND = indeterminate due to confusion between films examined vs. number of individuals or epiphyseal centers they represent, 3) N/A = not available in the literature.

[†] Ages for earliest fusion are derived from taking one standard deviation from the mean.

[‡] Ancestral groups combined for each sex providing a comprehensive age range.

one year earlier than girls from earlier studies. Causes of this trend have been attributed to new migrations introducing more genetic admixture, improved nutrition, medicine, and hygiene, and the effects of a more sedentary lifestyle rich with fatty foods (43,47). It has even been suggested that certain plastics and insecticides may provide a source for increased estrogen in the environment (51,52), which may inhibit chondroblast proliferation causing growth cessation and then active fusion of the growth plate (53). Due to the secular trend in growth and development, one should be cautious in applying older data to contemporary populations.

Given the trend toward earlier sexual maturation, a secular trend in earlier skeletal development for both sexes should be evident by comparing this research to prior studies that report the earliest age of fusion (Table 3). It is difficult to ascertain if age differences between the studies listed in Table 3 and this research are caused by temporal or spatial population differences or are simply the result of incomplete data sets and/or inadequate age ranges. In combining ancestral groups, our study indicates that complete fusion of the distal tibia and fibula occurs by age 16 in females and 19 in males, while the majority of sources report this occurring by age 17 in females and age 18 in males. The earliest age of fusion of the distal tibia and fibula occurs by age 14 in males and age 12 in females. These ages are largely reported as 15 to 16 in males and 13 to 14 in females. The female data from our study indicates earlier fusion of the distal tibia and fibula than reported in the literature with the exception of ages reported by Bass (54). While Bass' age ranges are similar to our results, there is no indication as to the sample size or the population from which the sample was derived.

Studies that sampled American populations, such as Stevenson (9), McKern and Stewart (1), and Pfau and Sciulli (26) should provide the most acceptable comparison to our results; however, these studies have inadequate sample sizes to extrapolate valid ranges of epiphyseal fusion from their data sets. Stevenson's (9) study has no White males or females in the 15 to 17 year age range. Furthermore, his entire sample for the 15 to 19 year age range for males and females from two ancestral groups consisted of only 20 individuals. The sample evaluated by McKern and Stewart (1) consists of males only and does not contain subjects younger than 17 years of age. Pfau and Sciulli (26) evaluated only 37 White males, 12 White females, 24 Black males, and 2 Black females within a large age range from 12 to 20 years indicating that some ages are represented by one individual or none at all. The final American study listed in Table 3 performed by Hoerr and colleagues (8) was modeled after the Greulich and Pyle (6) and Tanner and colleagues' (25) studies in that it determines the clinical norms for epiphyseal development and maturation and not the total range of variation in epiphyseal fusion. Their radiographic sample was hand selected from over 5000 children that fit into specific developmental criteria from various growth studies performed during the early to mid twentieth century. One hundred films were chosen from both males and females at each age that "did not differ chronologically among themselves by more than two percent" (8,pg. 50). The mean ages of fusion accompanied by one standard deviation produce age ranges that are similar to the results from this study. A direct comparison of Hoerr and colleagues study with this research is not possible due to the differences in research design; however, the mean ages indicate that a secular trend in earlier skeletal development is not overtly prevalent.

The non-North American research, namely the South Asian studies (15,17,27,28) and Flecker's (4) study of Australian hospital patients, produce earliest ages of fusion that are similar to those from this research. The validity of the chronological ages reported in the South Asian studies are questionable because birth records from these regions are often inaccurate or nonexistent, necessitating dates of birth and chronological ages for some subjects to be determined through horoscopes (17,28). Therefore, Flecker's (4) research is the only non-North American study that produces reliable ages of earliest fusion similar to ours. As with Hoerr and colleagues' study (8), Flecker's (4) data do not provide for a direct association to our research; but his documentation of the complete range of epiphyseal fusion allows for interesting comparisons. While our data exhibit the earliest ages of fusion for females, it is only one year less than those ages reported by Flecker (4) from data published 62 years ago! While the proposed secular trend in skeletal maturation may be a North American phenomenon, comparisons made between prior studies and this research demonstrate the importance of adequate sample sizes and age ranges.

This study establishes the range of variation for epiphyseal fusion of the distal tibia and fibula in modern American populations using a balanced age and sex distribution within three ancestral groups. The data from this study help to modify the incomplete or imprecise data that has been collected through the years and repeatedly published as standards of epiphyseal fusion. For the forensic anthropologist, an incorrect assessment of age due to the utilization of incomplete maturation standards could hinder the identification process and alter law enforcement investigations. Prior to this study research documenting the timing of epiphyseal fusion of the distal tibia and fibula for Mexican-Americans was nonexistent in the literature. The results of this analysis will prove particularly valuable in the south and southwestern United States given the growing Mexican-American population in these areas and the increasing number of unidentified remains associated with illegal border crossings.

Acknowledgments

We thank the staff of Cook Children's Medical Center, Plaza Medical Center, and John Peter Smith Hospital for access to their radiographic images and facilities. Special thanks to Shelly Smith for her help with this research and Tracy Rogers for her comments regarding the manuscript.

References

1. McKern TW, Stewart TD. Skeletal changes in young American males. Analyzed from the standpoint of age identification. Environmental Protection Research Division (U.S. Army Quartermaster Research and Development Command), Technical Report EP–45. Natick, Massachusetts: US Army, 1957.
2. Webb PA, Suchey JM. Epiphyseal union of the anterior iliac crest and medial clavicle in a modern multiracial sample of American males and females. Am J Phys Anthropol 1985;68:457–66. [PubMed]
3. Albert AM, Maples WR. Stages of epiphyseal union for thoracic and lumbar vertebral centra as a method of age determination for teenage and young adult skeletons. J Forensic Sci 1995;40(4):623–33. [PubMed]
4. Flecker H. Time of appearance and fusion of ossification centers as observed by roentogenographic methods. Am J Roentgen 1942;47:95–159.
5. Lurie LA, Levy S, Lurie M. Determination of bone age in children: A method based on a study of 1,129 White children. J Pediatrics 1943;23(2):131–40.
6. Greulich W, Pyle S. Radiographic atlas of skeletal development of the hand and wrist. Stanford, California: Stanford University Press, 1950.
7. Pyle SI , Hoerr NL, A Radiographic Standard of Reference for the Growing Knee. 2nd edition. Springfield: Charles C. Thomas, 1955.
8. Hoerr NL, Pyle SI, Francis LC. Radiographic atlas of skeletal development of the foot and ankle: A standard of reference. Springfield, IL: Charles C. Thomas, 1962.

9. Stevenson P. Age order of epiphyseal union in Man. Am J Phys Anthropol 1924;7:53–92.
10. Davis DA, Parsons FG. The age order of the appearance and union of the normal epiphyses as seen by x-rays. J Anatomy 1927;62:58–71.
11. Paterson RS. A radiological investigation of the epiphyses of the long bones. Anat London 1929;64:28–46.
12. Todd TW. The anatomical features of epiphyseal union. Child Devol 1930;1(2):186–194.
13. Stewart TD. Sequence of epiphyseal union, third molar eruption and suture closure in Eskimos and American Indians. Am J Phys Anthropol 1934;XIX:433–52.
14. Pillai MJS. The study of epiphyseal union for determining the age of South Indians Ind J Med Res 1936;23(4):1015–7.
15. Galstaun G. A study of ossification as observed in Indian subjects. Ind Jour Med Res 1937;25:267–323.
16. Todd TW. Atlas of skeletal maturation (hand). St. Louis: The C.V. Mosby Co., 1937.
17. Basu SK. Medico-legal aspects of the determination of age of Bengale girls. Ind Med Rec 1938;58:97–100.
18. Pyle SI, Sontag LW. Variability in onset of ossification in epiphyses and short bones of the extremities. Am J Roentgenol & Radium Therapy 1943;49:795–8.
19. Acheson RM. A method of assessing skeletal maturity from radiographs: A report from the Oxford child health survey. J Anatomy 1954;88:498–508.
20. Aggarwal ML, Pathak IC. Roentgenologic study of eiphyseal union in Punjabi girls for determination of age. Ind J Med Res 1957;45(2):283–9.
21. Narayan D, Bajaj ID. Ages of epiphyseal union in long bones of inferior extremity in U.P. subjects. Ind J Med Res 1957;45(4):645–9.
22. Hansman CF, Maresh MM. A longitudinal study of skeletal maturation. Am J Dis Child 1961;101:305–61. [PubMed]
23. Liliequest B, Lundberg M. Skeletal and tooth development, a methodological study. Acta Rad 1971;11(2):97–111.
24. Spencer RP, Sami S, Karimeddini M, Sziklas J, Rosenberg R. A role of bone scans in assessment of skeletal age. Int J Nucl Med Biol 1981;8:33–8. [PubMed]
25. Tanner JM, Whitehouse RH, Cameron N, Marshall WA, Healy MJR, Goldstein H. Assessment of skeletal maturity and prediction of adult height (TW2 method). New York: Academic Press, Haracount Brace Jovanevich, 1983.
26. Pfau R, Scilli P. A method for establishing the age of subadults. J Forensic Sci 1993;39(1):165–76.
27. Sahni D, Jit I. Time of fusion of epiphyses at the elbow and wrist joints in girls of Northwest India. Forensic Sci Intl 1995;74:47–55.
28. Banerjee KK, Agarwal BBL. Estimation of age from epiphyseal union at the wrist and ankle joints in the capital city of India. Forensic Sci Intl 1998;98:31–9.
29. Scheur L, Black S. Developmental juvenile osteology. London: Academic Press, 2002.
30. Bedford M, Russell K, Lovejoy C, Meindl R, Simpson S, Stewart-Macadan P. Test of multifactorial aging method using skeletons with known ages-at-death from the Grant collection. Am J Phys Anthropol 1993;91:287–97. [PubMed]
31. Galera V, Ubelaker D, and Hayek L. Comparison of macroscopic cranial methods of age estimation applied to skeletons from the Terry collection. J Forensic Sci 1998;43:933–9. [PubMed]
32. Loder RT, Estle DT, Morrison K, Eggleston D, Fish DN, Greenfield ML, Guire KE. Applicability of the Greulich and Pyle skeletal age standards to Black and White children of today. Am J Dis Child 1993;147(7):1329–33. [PubMed]
33. Sundick R. Age and sex determination of subadult skeletons. J Forensic Sci 1977;22:141–4. [PubMed]
34. Steyn M. and Henneberg M. Skeletal growth of children from the Iron Age site at K2 (South Africa). Am J Phys Anthropol 1996;100:389–96. [PubMed]
35. Ogden JA, McCarthy SM. Radiology of postnatal skeletal development: VIII. Distal tibia and fibula. Skeletal Radiol 1983;10:209–20.
36. Todd TW. Comparative youth: The physical aspect. Child Devol 1930;1(2):79–89.
37. Todd TW. The anatomical features of epiphyseal union. Child Devol 1930;1(2):186–94.
38. Ritz-Timme S, Cattaneo C, Collins MJ, Waite ER, Schütz HW, Kaatsch HJ, Borrman HI. Age estimation: The state of the art in relation to the specific demands of forensic practise. Int J Legal Med 2000;113:129–36. [PubMed]
39. Berlin L. The importance of proper radiographic positioning and technique. Am J Roentgen 1996;166(4):769–71.
40. Riddick L. Identification of the dead. In: Brogdon BG, editor. Forensic radiology. New York: Library of Congress, CRC Press. 1998; 55–61.
41. Garn SM, Silverman FN, Rohman CG. A rational approach to the assessment of skeletal maturation. Ann Radiol 1964;7:297–307.
42. Lampl M, Johnston F. Problems in the aging of skeletal juveniles: Perspectives from maturation assessments of living children. Am J Phys Anthropol 1996;101:345–55. [PubMed]
43. Ousley SD, Jantz RL. The forensic data bank: Documenting skeletal trends in the United States. In: Reichs KJ, editor. Forensic osteology: Advances in the identification of human remains. 2nd ed. Springfield, Illinois: Charles C. Thomas. 1999:454–8.
44. Meadows MA, Jantz RL. Allometric secular change in the long bones from the 1800s to the present. J Forensic Sci 1995;40(5):762–7. [PubMed]
45. Herman-Giddens ME, Slora EJ, Wasserman RC, Bourdony CJ, Bhapkar MV, Koch GG, Hasemeier CM. Secondary sexual characteristics and menses in young girls seen in office practice: a study from the pediatric research in office settings network. Ped 1997;99(4):505–12.
46. Meredith HV. Findings from Asia, Australia, Europe, and North America on secular change in mean height of children, youths, and young adults. Am J Phys Anthropol 1976;44:315–26. [PubMed]
47. Malina RM, Zavaleta AN. Secular trend in the stature and weight of Mexican-American children in Texas between 1930 and 1970. Am J Phys Anthropol 1980;52:453–61. [PubMed]
48. Katzmarzyk PT, Leonard WR. Climatic influences on human body size and proportions: Ecological adaptations and secular trends. Am J Phys Anthropol 1998;106:483–503. [PubMed]
49. Morrison JA, Barton B, Biro FM, Sprecher DL, Falkner F, Obarzanek E. Sexual maturation and obesity in 9- and 10-year-old black and white girls: the National Heart, Lung, and Blood Institute growth and health study. J Ped 1994;124:889–95.
50. Britton JA, Wolff MS, Lapinski R, Forman J, Hochman S, Kabat G, Godbold J, Larson S, Berkowitz G. Characteristics of pubertal development in a milt-ethic population of nine-year-old girls. AEP 2004;14(3):179–87. [PubMed]
51. Krstevska-Konstantinova M, Charlier C, Craen M, Heinrichs C, Beaufort C, Plomteux G, Bourguignon JP. Sexual precocity after immigration from developing countries to Belgium: evidence of previous exposure to organochlorine pesticides. Hum Reprod 2001; 16(5):1020–6. [PubMed]
52. Golub MS, Hogrefe CE, Germann SL, Lasely BL, Natarajan K, Tarantal AF. Effects of exogenous estrogenic agents on pubertal growth and reproductive system maturation in female rhesus monkeys. Toxicol Sci 2003;74:103–13. [PubMed]
53. Parfitt AM. Misconceptions (1): Epiphyseal fusion causes cessation of growth. Bone 2002;30(2):337–9. [PubMed]
54. Bass WM. Human Osteology. 4th ed. A laboratory and field manual of the human skeleton. Columbia, Missouri: Archaeological Society, 1987.

Additional information and reprint requests:
Dana Austin, Ph.D., D-ABFA
Office of the Chief Medical Examiner and Forensic Laboratories
200 Feliks Gwozdz Place
Fort Worth, Texas 76104-4919