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A Radiographic Database for Estimating Biological Parameters in Modern Subadults

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ABSTRACT

Current techniques in forensic anthropology for estimating age at death in fetuses, infants, and children are of questionable validity due to a lack of data from modern and diverse groups and a lack of appropriate statistical methods. Age estimation in subadults has been based on data from clinical studies undertaken to assess if children of known age showed normal growth. The application of these clinical data for forensic use is problematic, however: in forensic analysis the actual age is to be estimated from known (measured) bone lengths. Radiographs obtained from Medical Examiner's and Coroner's Offices (MECOs) provide anthropologists with a means of assembling large amounts of data from modern subadults with known age, sex, ancestry, date of birth, and other demographic information. Such a radiographic database fills a void for data from subadults, data not contained in the well-known Forensic Data Bank at the University of Tennessee. This grant award established a database of digital radiographs and demographic data from modern American subadults.

In all research involving growth, it is essential to obtain large samples when divided by age, ancestry/ethnicity, and sex, and not merely a large sample in total. A radiographic sample derived from a morgue population of subadults is essentially the only modern source that can provide enough radiographic and demographic information, especially for the very young. Full-body radiographs are rarely taken in a clinical context, but extensive and often full-body radiographs are routinely collected by medical examiners and coroners during postmortem examination of fetuses, infants, children, and many subadults. Clinical radiographs, however, provide samples from ages that are poorly represented in MECOs. During the course of the grant, it was recognized that additional data sources data were required because MECOs have

very few cases involving children between five and 14 years of age. Basic information to be gleaned from radiographs includes appearance and fusion of epiphyses and long bone lengths. Because the process of radiography involves magnification and distortion of actual bone shape, any study incorporating measurements from radiographs must compensate for those effects.

Twenty offices were visited during the course of the grant. Information regarding age, sex, stature, ancestry, birth date, anthropometric data such as stature or crown-heel length, weight, and manner of death were recorded when available. Clinical radiographs were obtained from two locations. A total of 44,220 radiographic images were assembled from 9,709 different individuals, almost 4,000 of which were x-rayed on multiple occasions at the clinical offices. Of the 9,709 individuals, 4,061 are females, 5,610 are males, and 38 are of unrecorded sex. All major ethnic groups and ancestries in the US are reasonably well represented.

The radiographic collection has tremendous potential for research in age, sex, and ancestry estimation methods, trauma analysis, and bone healing rates, and the database is expected to grow further. Four Master's students at Mercyhurst have utilized the radiographic scans in their thesis work so far and their results confirm and better illustrate that children today are taller for a given age and are maturing faster skeletally than the currently used forensic and clinical standards suggest.

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Description of the problem

Current techniques in forensic anthropology for estimating age at death in fetuses, infants, and children are of questionable validity due to a lack of data from modern and diverse groups and a lack of optimal statistical methods. Age estimation in subadults has been based on data from clinical studies undertaken over 80 years ago to assess if children of known age showed normal growth. Skeletal collections of subadults are quite rare (Shapiro and Richtsmeier 1997), and other sources for subadult data are needed. Radiographs obtained from Medical Examiner's and Coroner's Offices (MECOs) would provide anthropologists with a means of assembling large amounts of data from modern subadults with known age, sex, ancestry, date of birth, and other demographic information. Such a radiographic database fills a void for data from subadults, data not contained in the well-known Forensic Data Bank at the University of Tennessee. A database of digital radiographs and demographic data from modern American subadults is sorely needed to provide the best means of forensic age estimation in subadults.

Whether explicitly acknowledged or not, nearly all available data concerning skeletal growth and development in the US have come from growth studies started in the later 1920's or early 1930's, such as the Fels study, which started in 1929 (Roche 1992). Applying Fels data to modern age estimation is inherently problematic: Growth data were collected to derive the “normal” development and growth of bones in children of known age, but forensic anthropologists utilize known bone lengths or the appearance of epiphyses to estimate age. Forensic anthropologists have navigated through published data often limited to medians, minimums, and maximums of bone lengths for known ages and guesstimate a probable age through extrapolation and “eyeballing”. As a result, statistical approaches have been impossible or very limited. Furthermore, today's children from many groups are maturing and getting taller at earlier ages, showing what are known as secular trends. Age estimation in subadults usually involves dental development, appearance and fusion of epiphyses, or long bone lengths, and all three show a secular trend. Also, most American growth and development studies involved children exclusively of European descent in the US, such as the Fels Longitudinal Study, and there is abundant evidence that other groups grow and develop differently.

Publications by Garn et al. (1967) and Graham (1972) outlined problems of using antiquated samples to establish contemporary growth standards, qualifying variability in growth, and the statistical methods used to derive standards. To the best of their abilities, Garn et al. (1967), made up for the deficiencies they acknowledged. Though their data came from the Fels study, they provided essential information that has been rarely given, such as 5th and 95th percentiles for the age of epiphyseal appearance. Forty years later, none of the problems Garn and Graham mentioned have been solved. Nearly all current methods of estimating age from bone observations have at least one shortcoming related to the age of the sample, sample composition, or summary statistics. One of the most recent publications dealing with forensic age estimation is *Juvenile Osteology: A Laboratory and Field Manual*, by Schaefer, Black, and Scheuer (2009), in which they cite Maresh (1970) for bone length standards. Maresh's 1970 study, the most often cited reference in the forensic literature, was based on data collected on children from the Denver area as part of the Child Research Council longitudinal study, which started in 1935 ***. Due to secular trends, Maresh's data are out of date. More specifically, in a comparison between Maresh's (1970) stature medians and World Health Organization (WHO) standards, Maresh's girls after four and boys after six years of age start showing progressively greater stature deficits (Schillaci 2012).

More recently, despite clear indications of secular changes, *Brogden's Forensic Radiology* (Brogdon 2010), presented a revised developmental chart that was reproduced from Girdany and Golden (1952), which for the most part merely repeated the fusion ages and figures from Camp and Cilley (1931). Brodgdon's very useful Table 8.1, which shows 5th and 95th percentiles for bone element appearance, is a reproduction of a table in Graham (1972), which repeated the valuable percentiles from Garn et al (1967). Unfortunately, the ages in Brogdon's table contradict the ages in his figure.

The lack of appropriate methods has rarely been acknowledged in the forensic literature, though Ubelaker (1987:1255) is an exception. Modern data are also lacking, with few relatively recent growth and development estimation and validation studies. For example, Warren (1999) published a recent and rare study with estimation equations for crown-rump length (CRL) that tested age estimation methods from Fazekas and Kosa (1978). More recently, Crowder and Austin (2005) evaluated a large sample of radiographic data to update epiphyseal union in the ankle area in modern groups and found significant differences by ethnicity, though their statistical methods were limited. Differences in hand-wrist maturity by age were also noted in a large sample of African-Americans, Euro-Americans, Asian-Americans, and Hispanic Americans, though the approach was strictly clinical (Zhang et al. 2009). Most recently, Ubelaker (2010) listed "numerous" references regarding studies of the appearance of ossification centers but the most recent publication he listed was published in 1982, for fetal bone development (Ubelaker 2010:179).

The few studies that have utilized better statistical methods for age estimation in subadults have not been conducted using modern samples, or if so, are very limited in their application so far, though they show great promise. Black et al. (1980) applied linear and logistic regression to fetal long bone data, but the data were not from a modern cohort. Transition analysis is a sophisticated approach that models times that specific changes from one phase to another occur, such as from a separate epiphysis to a partially fused one (Boldsen 2002). Passalacqua (2011) used transition analysis to derive the 95% prediction interval for age based on the fusion of the calcaneal epiphysis, but his sample came from Americans born predominantly in the 19th century. Methods for automatic computerized analysis of radiographic images, including "BoneXpert" (*http://www.bonexpert.com/home*), have also been developed, predominantly for the hand, to calculate bone developmental "age", and the results can be used to estimate chronological age (Giordano 2009; van Rijn et al. 2009; Thodberg 2009; Zhang 2007). All researchers recognize that any system in use will have to compensate for genetic and environmental differences in different groups, which influence growth and development, and therefore age estimation.

Collecting cross-sectional data is a fast way to compile large amounts of data on growth and solves several problems inherent with longitudinal data. The classic growth studies used longitudinal data sampling, and, though expensive, provided very good sources for establishing age standards and is ideal for estimating growth acceleration rates in individuals. However, longitudinal data are not as useful as cross-sectional data for age estimation. Children in the classic longitudinal growth studies were measured near their birthdays, as in most longitudinal studies, which causes data "heaping", with far greater numbers of observations near birthdays. Interpolation was used to estimate ages at specific events, such as the appearance of an epiphysis, from the heaped data, rather than from more evenly distributed ages. Longitudinal data have another problem, that of autocorrelation: because the children were measured repeatedly, each child's measurements will be correlated to other measurements close in time, and the growth patterns will seem more homogeneous than they actually are due to lower estimated standard errors (Bock and du Toit 2004). Growth and development are far more variable among children than within a sample of the same children. For these reasons, cross-sectional data are better suited for age estimation; they can also be used for establishing age-specific standards of development (Roche 1992).

There is also another statistical issue to be reckoned with when using longitudinal data to estimate age. The estimated mean ages for events such as epiphyseal appearance are point estimates, and the statistical error, or uncertainty, was not accounted for. All summary statistics – including means and percentiles – and methods of fitting curves to data – must be estimated from samples, which may be small (Hughes and Hase 2010; Littell 2006). Larger samples are better because they produce less uncertainty in statistical estimates. The uncertainties can be rather large based on our experience with estimating them, even with much larger sample sizes (see Results). Due to the complexities of estimation, software will be programmed to aid forensic professionals in predicting age from metric or non-metric observations, and to aid clinical professionals in determining whether a child's growth is within the range of acceptable limits, with appropriate prediction intervals based on radiographic data.

It is clear that data are needed from a large, modern, ethnically diverse sample of subadults to better estimate age in subadult remains and test methods currently in use in forensic anthropology. As mentioned, subadult skeletal collections are quite rare. Radiographs obtained from medical examiner offices provide anthropologists with a means of assembling large amounts of data from modern subadults with known age, sex, ancestry, date of birth, and other demographic information.

Purpose, Goals, and Objectives

The general objective of this project is to provide up-to-date information for the optimal estimation of biological parameters to aid in identifying the remains of modern fetuses, infants, children, and adolescents. Specifically, the goal of this project is to establish a database of digital radiographs and demographic data from modern and diverse American subadults and, to a limited degree, investigate methods of statistical analysis. In all research involving growth, it is essential to obtain large samples by age, ancestry/ethnicity and sex, and not merely a large sample in total. A radiographic sample derived from a morgue population of subadults is essentially the only modern source that can provide enough radiographic and demographic information, especially from the very young. Full-body radiographs are not taken in a clinical context, but extensive and often full-body radiographs are routinely collected by medical examiners and coroners during postmortem examination of fetuses, infants, children, and many subadults. Clinical radiographs, however, provide samples from ages that are poorly represented in MECOs. Clinical offices have many patients between five and 14 years of age, in contrast to MECOs, which have relatively few individuals in this interval.

Research Design and Methods

Visits to 20 to 25 MECOs were planned for the project. Involvement of offices from several regions was necessary to remove possible regional biases and produce a diversity of ancestry groups more representative of the American population as a whole. To ensure that only modern growth trends are evaluated, sampling was limited to individuals who were examined after January 1, 2000. The confidentiality of decedent and patient information and other research requirements were tailored to the demands of each office. No personally identifying information was recorded from the decedents. All efforts were geared toward minimal infringement upon daily morgue or clinic operations.

The primary application of this radiographic database is to provide a basis for age estimation based on appearance and union of epiphyseal centers and on measurements of long bone lengths. Both binary (epiphyseal appearance, union) and metric data (bone lengths) require special statistical methods for age estimation and they have been partially investigated, and will be further researched and developed. Because the process of radiography magnifies and distorts the actual bone shape, any study incorporating measurements from radiographs must compensate for those effects. Most offices use reference objects such as radiographic scales and markers, which were documented so actual bone measurements can be estimated more accurately.

Though magnification and distortion effects are unavoidable in radiographs, it does not mean that they are insurmountable. To estimate the sources of measurement error in radiographs, the height and center of the x-ray beam source can be calculated in offices using a high-quality scale. Radiographic standards are well known by radiographers, and Stull (2008) found evidence for consistently exposed radiographs in the high correlations between bone lengths and age in her study from Erie County, NY. When objects of known size (coins, straight pins, safety pins, etc.) are found in any radiographs, they will serve as a check on calculations and assumptions. Calculation of the magnification and distortion pattern will be crucial to obtaining the best possible estimates of bone size. Measurements taken from radiographs using calipers have proven to be highly accurate compared to actual bones through adjustments based on radiographic scales. When measurement points are taken from the digitized radiographs, the raw and adjusted measurements can be calculated through a computer program that has incorporated the information from the RRD to calculate the beam position for that site. In this way, corrected point-to-point distances taken anywhere in the radiograph theoretically can be calculated.

An unexpected additional application of the radiographic data is for growth and development reference standards. During the course of the grant we discovered that not only are the forensic standards out of date, but the current clinical standards are out of date too. For example, the seventh edition of *Atlas of Radiographic Measurement* (Keats and Sistrom 2001), like other recently published reference works, reproduces the figures from Girdany and Golden (1952). Other large-scale longitudinal studies were undertaken since the Fels study but none have been started in order to update the classic basis of our knowledge of growth and development. Based on the preliminary results from Ertl (2012), software is needed for clinical applications that will calculate probabilities of epiphyseal appearance based on known age, and compared to the radiographs, so that children with especially retarded or advanced development can be identified.

Results

As the research team discovered, radiographic procedures vary a great deal by office, and in general, the clinical offices produced the highest quality radiographs. In the MECOs, the quality of radiographs was quite variable due to large disparities in the quality of x-ray equipment, in the training of personnel, and in office protocols. As a result, radiographs were scored as very good, good, or poor quality based on exposure level, sharpness, and contrast. We were quite surprised to discover that, despite clear standards and an obligation of medical examiner's offices and coroner's offices to record images for forensic documentation purposes, in some offices the most basic procedures were not followed: the standard 40 inch source- to-image distance; an indication of side of the x-rayed individual in the radiograph; and permanent recording of case number on the film. Relatively few offices used a radiological scale (Frazee et al. 2009). Due to the great variability in radiographic procedures and infrequent use of scales in some offices, the opportunities for converting measurements from radiographic images to bone lengths are more limited than we had hoped. A preliminary metric study of radius length (Waldock 2011) was performed using the office-specific markers, but more work is needed. In order to be valid, research using bone measurements may have to proceed carefully on an office-by-office basis, or even on a case-by-case basis. With the greater use of digital radiographic systems, however, the opportunities for metric research should improve as long as the digital images are calibrated for size and radiographic scales are used to validate the electronic scales.

Twenty offices were visited during the course of the grant, two of which were clinical offices. Clinical radiographs include typical kinds of non-fatal trauma and also allow the possibility of measuring fracture healing progress because follow-up radiographs were taken at different times from many of the patients. Information regarding age, sex, stature, ancestry, birth date, anthropometric data such as stature or crown-heel length, weight, and manner of death were recorded when available. Preterm babies were noted as such and the intrauterine weeks were often recorded by the offices.

The number of radiographs collected greatly exceeded expectations. A total of 44,220 radiographic images were assembled from 9,709 different individuals, almost 4,000 of which were x-rayed on multiple occasions at the clinical offices. Some images in the database are MRI series, however, and have information that can be better analyzed using appropriate software. Also, due to varying radiograph quality, not all radiographs will be useable for every radiographic study, even when enhanced through Photoshop or other computer programs. Of the 9,709 individuals, 4,061 are females, 5,610 are males, and 38 are of unrecorded sex. Many individuals in the database are infants that were premature, stillborn, or died quite soon after birth. All major ethnic groups and ancestries in the US are reasonably well represented. In terms of ancestry, there is a great deal of diversity in the database, including radiographs from Hispanic Americans, who are little known radiographically. Non-US nationalities include individuals predominantly from East Asia and India.

The radiographic database has two main data tables, one for individual demographic information and one for the skeletal inventory of each scan. The database was created using Advantage DB from Sybase and converted to MySQL from Oracle Corporation for web integration. Demographic information from the individuals in the database includes age on several scales (days, weeks, and years), sex, race, ancestry, and external measurements of the individuals. In order to preserve decedent and patient confidentiality, the original case numbers have been modified and the dates of birth, exam, and death will not be available to the public. Birth and death dates are known but information available to the public include only year of birth and death or examination to protect private information. When researchers wish to study bone healing in the longitudinal clinical records, pseudo-dates with the correct time intervals will be used. The numerous physical measurements recorded at most MECOs are also part of the demographics table. For example, over 1,400 crown-rump lengths were recorded from neonates, and from all individuals, over 9,500 weights and over 8,500 body lengths/statures were recorded. The skeletal inventory table includes information specific to each radiographic image including which areas of the body are seen, scan orientation, presence of trauma or other pathology, and overall quality of the image.

The database, including images, will complement the Forensic Data Bank at the University of Tennessee, which has proven indispensable in numerous forensic applications involving modern adults (Jantz and Moore-Jansen 1987; Ousley and Jantz 1997). Like the Forensic Data Bank, the radiographic database will be supplemented by additional cases in the future, continually adding up-to-date information from subadults of various ethnic backgrounds.

It is a certainty that new methods of analyzing subadult remains will come from the radiographic database, as has happened with the Forensic Data Bank.

Dissemination has been achieved through presentations at professional conferences, including Frazee et al. (2009); Stull et al. (2009); Ousley et al. (2010a); Ousley et al. (2010b); and Hunt and Ousley (2013). At least two initial publications are planned, one an overview of the database, and another providing updated standards for estimating age in subadults, to be submitted to peer-reviewed journals.

There have been four theses at Mercyhurst College and University that utilized scans collected during the NIJ grant. The scans have been limited to internal use thus far because of privacy concerns and because in many cases, the demographic data were not fully ready for external analysis. Fojas (2010a, 2010b) examined the appearance of the distal radial epiphysis and its use in estimating age. Fojas used logistic regression to derive 95% confidence intervals for age and found that if the distal radial epiphysis is present, the estimated age is at least 29 weeks (7 months), and if absent, the child is less than 79 weeks (one year, eight months) old. Waldock (2011) analyzed the maximum length of the radius calculated from images in the radiographic database. Her most significant results were that the ages estimated using Merchant and Ubelaker (1977), Ubelaker (1978), and Maresh (1970) tended to show more positive bias (producing greater and greater overestimates of age) the older the child, beginning at age 2, similar to the results of Schillaci (2012). Diefenbach (2012) examined the appearance of ossification centers of the elbow and may be the first researcher to incorporate uncertainty into estimating age rather than merely providing point estimates (Figure A).

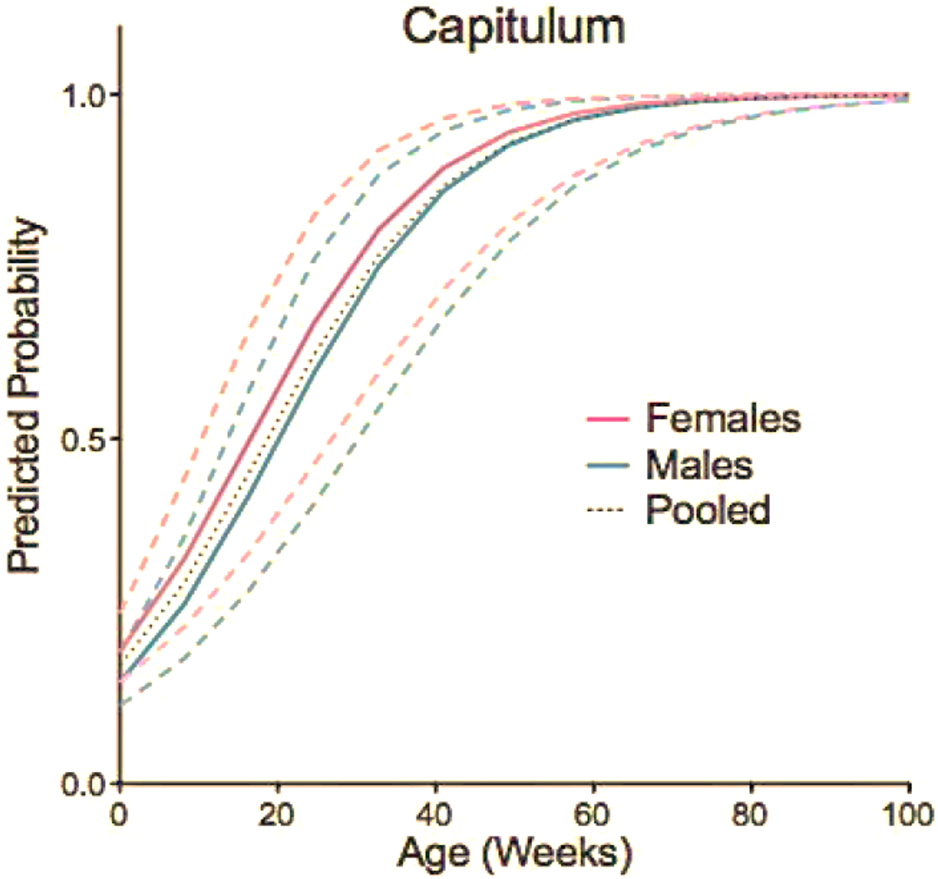

Figure A. Probability of capitulum appearance, by sex, using logistic regression (solid lines) and incorporating lower and upper 95% bounds in the probabilities (dashed lines). From Diefenbach (2011).

Clinical applications for the radiographic database are illustrated by Ertl (2012), who assessed numerous ossification centers from birth through nine months of age from over 900 infants to derive updated guidelines for normal growth and newly calculated probabilities incorporating prediction intervals (Figure B).

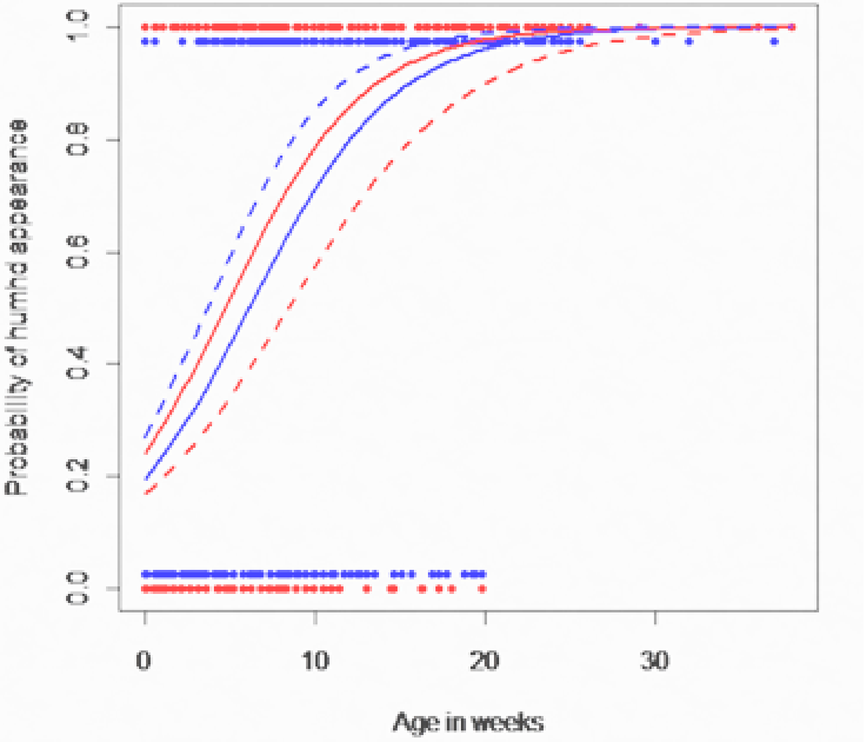

Figure B. Probability of appearance of the humeral head for males (blue) and females (red) with lower confidence bounds for males and upper confidence bounds for females (dashed lines). From Ertl (2012).

A web site has been constructed, and is still under construction, for the database. The web site will allow visitors to query the demographic information in the database and download the related radiographic images. It will be more or less finished by March 15, 2013, though it will be functional before then and updated often afterwards. The interactive query system for the database is accessible through: http://math.mercyhurst.edu/~sousley/databases/radiographic_database/. Dr. James Adovasio, Provost, and Dr. Thomas Gamble, President, of Mercyhurst University, provided funds to purchase a web server for the radiographic database. Dr. Roger Griffiths of the Mathematics and

Computer Science Department set up and maintains the server, and provides much-needed internet programming help.

Conclusions

The radiographic collection has tremendous potential for research in age, sex, and ancestry estimation methods, trauma analysis, and bone healing rates, and the database is expected to grow further. Four Master's students at Mercyhurst have utilized the radiographic scans in their thesis work so far and their results confirm and better illustrate that children today are taller for a given age and are maturing faster skeletally than the currently used forensic and clinical standards suggest.

The radiographic database created complements data from adults compiled in the Forensic Data Bank at the University of Tennessee, Knoxville, established through a grant from the NIJ in 1986 (Jantz and Moore-Jansen 1987; Ousley and Jantz 1997). The radiographic database will continue to grow through ongoing contributions from medical examiners and clinics from around the country. This growth will be facilitated by the increased use of digital radiography. The creation of such a database will not only provide the basis for assessing growth and development in modern American children in the clinical setting and offer the most reliable sex and age standards with statistically determined age prediction intervals in the forensic setting, but will also open up further methods of analysis for other goals.

Ongoing dissemination will be primarily through a web site managed by Mercyhurst University. After the grant is finished, a copy of the database, software, and images will be sent to the NIJ, and approximately ten additional copies will be sent to other institutions, primarily large medical examiner offices and universities with well-established forensic programs. The database will be made available on DVD to other interested institutions at cost. Based on Ertl's (2012) data, a computer program will be written so doctors can analyze pediatric radiographs in order to detect developmental anomalies requiring intervention. The database, software, and analytical methods will continue to be updated and improved, so the web site will be the best medium for sharing resources. Software will be available for free on the web site and a certain number of radiographic scales will be provided to offices for free upon request. Additional software applications will be practical once new methods for estimating age, sex, and ancestry are established, and can be incorporated into Fordisc (Jantz and Ousley 2005) and/or created as an independent computer program.

Through the use of the database and software, and presentations and publications, it is hoped that more clinicians, medical examiners, and coroners will voluntarily contribute radiographs to the database. Participants compiling and mailing digital radiographs on a DVD will be an especially simple way to contribute new information. Scanned radiographs of subadult teeth from dentists are another obvious addition to the database. Having a central repository for radiographic data will greatly enhance its applicability and scope. The Department of Applied Forensic Sciences at Mercyhurst will provide the necessary administrative oversight and staff support to incorporate new information into the database.

1. INTRODUCTION

Current techniques in forensic anthropology for estimating age at death in subadults (fetuses, infants, and children) are of questionable validity due to data from outdated cohorts, limited ethnic diversity in samples, and a lack of optimal statistical methods. Classic growth and development studies started in the early part of the 20th century and provide the data for forensic estimation, but applying those data to modern age estimation is inherently problematic: Bone growth data were collected to derive growth and development standards for children of known age, but forensic anthropologists utilize known bone lengths or the appearance of epiphyses to estimate age from unidentified remains. Forensic anthropologists navigate through published data often limited to means, minimums, and maximums of bone lengths for known ages and guesstimate an age estimate through extrapolation and “eyeballing”. As a result, statistical approaches have been very limited if not impossible. Furthermore, today's children from many groups are maturing earlier and growing faster, showing what are known as secular trends. Age estimation in subadults usually involves dental development, appearance and fusion of epiphyses, or long bone lengths, and each shows a secular trend. Modern children are taller for a given age and mature faster skeletally, dentally, and sexually than before (Cardoso et al. 2010; Cole 2003; Nichols 2006; Meadows-Jantz and Jantz 1999; Shirley and Jantz 2010). Also, most American growth and development studies involved children exclusively of European descent in the US, such as the Fels Longitudinal Study, and there is abundant evidence that other groups grow and develop differently.

Whether explicitly acknowledged or not, nearly all available information concerning skeletal growth and development in the US has come from growth studies started in the later 1920's or early 1930's, such as the Fels study, which started in 1929 (Roche 1992). Stanley Garn worked extensively with the Fels data over several decades and published the most useful information relating to age estimation while also acknowledging the shortcomings of virtually all reference standards available, first and foremost being antiquated reference data, from anatomical collections and published sources, which

> "proved unfortunate, yielding, for the most part, values implausibly late by contemporary standards, for example, from 18 to 25 years as the age for union of the epiphyses of the metacarpals. Yet some of these values, based on dissecting-room studies of paupers who died well over a century ago, still find their way into reference manuals, compendia of radiographic values, and even textbooks of recent date." (Garn et al. 1967:45)

In other words, many standards were simply obsolete: "Because of the well-known secular change -- the tendency toward earlier skeletal maturation -- radiographic standards applied to contemporary populations must themselves be contemporary", yet "…compilers of standards who employ secondary, tertiary, and quaternary reference sources are not always aware of the antiquity of some of the values they currently cite." (Garn et al. 1967:45). Garn et al. also acknowledged ethnic limitations of the data:

> "Because few radiographic studies have been conducted on well-to-do children of different races – children having caloric adequacy, 40 to 50 grams of animal

> protein per day, and protection against childhood diseases – we cannot say that present norms for American children of northwestern European ancestry are or are not applicable to the mass… The norm or standards that seemed so simple and so accessible to radiologists in 1901 are not yet completely within our grasp as we view the world in wider perspective." (Garn et al. 1967:45).

Garn et al. (1967) then noted that the growth and development of subadults from the same ethnic background, but of different socioeconomic status, or from different American and British cities, showed differences.

Graham (1972) echoed several problems in clinical growth publications that are still pertinent. Contemporary popular growth charts lacked differences between males and females, minimum and maximum ages provided were often undefined, data sources are not provided, and according to Graham, "The ages given, especially for osseous fusion, contradict current experience" (1972:186). Graham derided the "woeful ignorance of the expected range of developmental events" and that "otherwise authoritative textbooks promote 'normal ranges' which are only one-half or even one-fourth as wide as the actual ranges" (1972:188). He also remarked that standards for epiphyseal fusion contradict recent findings that they fuse many years earlier, and that published charts use obsolete data and oversimplified representations rather than more valuable tabular data. Finally, he also acknowledged a good deal of unappreciated ethnic variation, specifically, that Chinese-American and African-American children are advanced over European-Americans in osteological development.

Over 40 years later, none of the problems outlined by Garn et al. (1967) and Graham (1972) has been solved. Nearly all current methods of estimating age from bone observations have at least one shortcoming related to the age of the sample, sample composition, or summary statistics. To the best of their abilities, Garn et al. (1967) made up for the deficiencies they acknowledged. Though their data came from the Fels study, they provided essential information that has been rarely given, such as 5th, 50th, and 95th percentiles for the estimated age of epiphyseal appearance. One of the most recent publications dealing with forensic age estimation is *Juvenile Osteology: A Laboratory and Field Manual* (Schaefer, Black, and Scheuer 2009), in which Maresh (1970) and tables from many other studies are cited. Maresh's 1970 study, perhaps the most often cited reference in the forensic literature for subadult age estimation, was based on data collected on children from the Denver area as part of the Child Research Council longitudinal study, which was started in 1935. A total of 121 females and 123 males were repeatedly x-rayed, but a good number of individuals were not x-rayed every year (Maresh 1970). More specifically, in a comparison between Maresh's (1970) stature medians and WHO standards, Maresh's girls after 4 and boys after six years of age start showing progressively larger stature deficits (Schillaci 2012).

In 2010, despite clear indications of secular changes, *Brogden's Forensic Radiology* presented a revised developmental chart that was reproduced from Girdany and Golden (1952). Girdany and Golden had compiled information from available sources and presented 10th and 90th percentiles for appearance and "approximate" age at fusion, and for the most part merely repeated the fusion ages from Camp and Cilley (1931). Camp and Cilley wrote "Many of the drawings have been copied, with certain modifications, from standard anatomy texts and other references pertaining to the subject. The appended information has been compiled from the same sources", but also warned at the bottom of their chart, "There is considerable normal variation at any given age" (1931:905). Brogdon's very useful Table 8.1, which shows 5th and 95th percentiles for bone element appearance, is a reproduction of a table in Graham (1972), which repeated the percentiles from Garn et al (1967). Unfortunately, the ages in Brogdon's table contradict the ages in his figure.

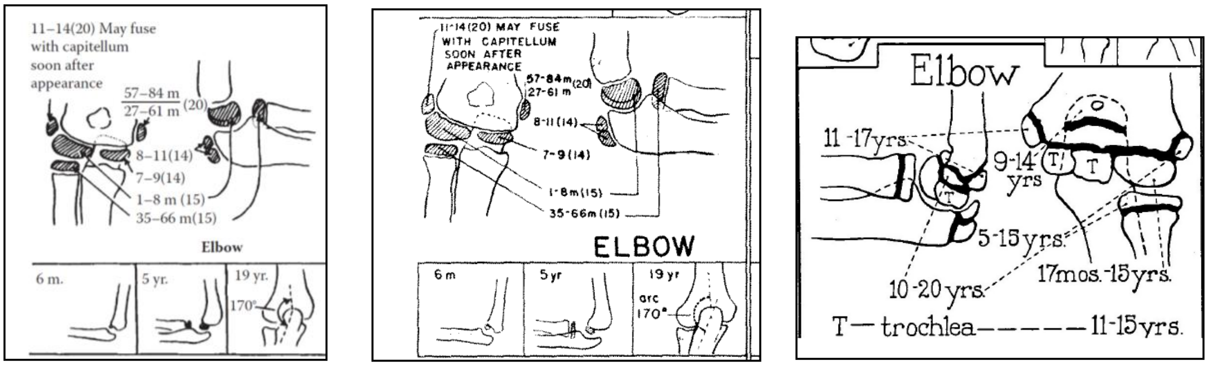

Figure 1. Charts for skeletal development in the elbow from a. Brogdon (2010); b. Girdany and Golden (1952); c. Camp and Cilley (1931).

The lack of appropriate methods has rarely been acknowledged in the forensic literature, though Ubelaker (1987:1255) is an exception: "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." Modern data, however, are lacking, with few relatively recent growth and development estimation and validation studies. For example, Warren (1999) published a recent and rare study with estimation equations for CRL that tested age estimation methods from Fazekas and Kosa (1978). More recently, Crowder and Austin (2005) evaluated a large sample of radiographic data to update epiphyseal union in the ankle area in modern groups and found significant differences by ethnicity, though their statistical methods were minimal. Differences in hand-wrist maturity by age were also noted in a large sample of African-Americans, Euro-Americans, Asian-Americans, and Hispanic Americans, though the approach was strictly clinical (Zhang et al. 2009). Most recently, Ubelaker (2010) listed "numerous" references regarding studies of the appearance of ossification centers but the most recent publication he listed was published in 1982, for fetal bone development (Ubelaker 2010:179).

The few studies that have utilized better statistical methods for age estimation in subadults have not been conducted using modern samples, or if so, are very limited in their application so far, though they have great promise. Black et al. (1980) applied linear and logistic regression to fetal long bone data for age estimation, but the data were not from a modern cohort. Transition analysis is a sophisticated approach that models times that specific transitions from one phase to another occur, such as from a separate epiphysis to a partially fused one (Boldsen 2002). Passalacqua (2011) used transition analysis to derive the 95% prediction interval for age based on the fusion of the calcaneal epiphysis, but his sample came from Americans born predominantly in the 19th century. Shirley and Jantz (2010) applied transition analysis and Bayesian methods for estimating age based on fusion of the medial epiphysis of the clavicle. Age estimation in the living seems to have progressed more in Europe than in the US because the European Union evaluates refugees based on chronological age. Younger refugees have more rights than older refugees, and because records in their home countries are often poor, independent methods of age estimation are necessary (Smith and Brownlees 2011). Studies and guidelines for age estimation in the living have been published by individuals and forensic working groups such as the *Arbeitsgemeinschaft für Forensische Altersdiagnostik* (Study Group on Forensic Age Diagnostics of the German Association of Forensic Medicine) and the 22 country European Migration Network (European Migration Network 2010; Schmeling et al. 2004; Schmeling et al. 2006a; Schmeling et al. n.d.). Methods for automatic computerized analysis of radiographic images, including "BoneXpert" (*http://www.bonexpert.com/home*), have also been developed, predominantly for the hand, to calculate bone developmental "age" and the results can be used to estimate chronological age (Giordano 2009; van Rijn et al. 2009; Thodberg 2009; Zhang 2007). Any new methods of age estimation will need to compensate for recently investigated genetic and environmental factors, such as ancestry, ethnicity, and per capita income levels, which influence growth and development, and therefore age estimation (Schmeling et al. 2006b; Zhang et al. 2009).

It is clear that data are needed from a large, modern, ethnically diverse sample of subadults to test methods currently in use in forensic anthropology and to better estimate age in subadult remains. Because skeletal collections of subadults are quite rare (Shapiro and Richtsmeier 1997), other sources of subadult data are needed. Radiographs obtained from Medical Examiner Offices provide anthropologists with a means of assembling large amounts of data from modern subadults with known age, sex, ancestry, date of birth, and other demographic information. This grant award established a database of digital radiographs and demographic data from modern and diverse American subadults and has investigated methods of statistical analysis and investigated, to a limited degree, how well the ageing standards perform on modern children.

The primary application of this radiographic database is to provide a basis for age estimation based on appearance and union of epiphyseal centers and on measurements of long bone lengths. Both binary (epiphyseal appearance, union) and metric (bone measurement) data require special statistical methods for age estimation and they have been partially investigated for this study, and will be further researched and developed. Radiographs magnify and distort the actual size and shape of the dry bone, but most offices use reference objects such as radiographic scales and markers, which were documented at each location so actual bone measurements can be estimated more accurately.

Collecting cross-sectional data is a fast way to compile large amounts of data on growth and development, is better for age estimation, and solves some problems inherent with longitudinal data. The classic growth studies used longitudinal data sampling, and, though expensive, provided very good sources for establishing age standards and is ideal for estimating growth rates in individuals. Longitudinal data are not as useful as cross-sectional data for age estimation. As in most longitudinal studies, children in the classic longitudinal growth studies were measured near their birthdays, which causes data "heaping", with nearly all observations very near birthdays. Interpolation was used to estimate ages at specific events, such as the appearance of an epiphysis, from the heaped data, rather than from more evenly distributed ages.

Longitudinal data have another problem, that of autocorrelation: because each child was measured repeatedly, each child's measurements will be correlated to the others a year apart, and the growth patterns will seem more homogeneous than they actually are due to lower estimated standard errors (Bock and du Toit 2004). Growth and development are far more variable in a cross-section of children than within a longitudinal sample of the same children. For these reasons, cross-sectional data are better suited for age estimation; they can also be used for establishing age-specific standards of development (Roche 1992).

There is another statistical problem with using longitudinal data to estimate age. The estimated ages for events such as epiphyseal appearance in Garn et al. (1967) are point estimates, and the statistical error, or uncertainty, has not been accounted for. All summary statistics – including mean age and percentiles – and methods of fitting curves to data – must be estimated from samples, whether large or small (Hughes and Hase 2010; Littell 2006). Larger samples are better because they have less uncertainty in their estimates. The uncertainties can be rather large based on our experience with estimating them, even with relatively large sample sizes. Due to the complexities of estimation, software will be programmed to aid forensic professionals in predicting age from metric or non-metric observations, and to aid clinical professionals in determining whether a child's growth is within the range of acceptable limits, with appropriate prediction intervals based on radiographic data.

One unexpected additional application of the radiographic data is for growth and development reference standards. During the course of the grant we discovered that not only are the forensic standards out of date, but the current clinical standards are out of date. The seventh edition of *Atlas of Radiographic Measurement* (Keats and Sistrom 2001), as many other recently published reference works, merely reproduces the figures and ages from Girdany and Golden (1952). Other large-scale longitudinal studies have been undertaken since the Fels study but none have updated the classic basis of our knowledge of growth and development.

2. MATERIALS AND METHODS

A total of 20 offices were visited during the award period, and the visit dates and counts of radiographs are shown in Table 1. To ensure that only modern growth trends are evaluated, sampling was limited to individuals who were examined after January 1, 2000. Data collection in each office began with the most current cases and progressed backwards through time. Visiting the offices involved 1) locating relevant radiographic material, 2) recording the associated biological demographic information, and 3) high resolution scanning of radiographic images. The confidentiality of patient information and other research requirements were tailored to the demands of each office. During the course of the grant, additional sources of data were required because the age distribution of medical examiner cases shows very few cases between 5 and 14 years of age. Therefore, clinical radiographs were obtained from two locations. Clinical radiographs include typical kinds of non-fatal trauma and also allow the possibility of measuring fracture healing progress because follow-up radiographs were taken at various times from many of the patients. Demographic information such as age, sex, stature, ancestry, and birth date were collected during the visits, as were any recorded anthropometric data such as stature or crown-heel length, and weight. Many infants in MECOs had additional anthropometrics recorded such as head circumference, abdominal circumference, and foot length, in addition to weight. Preterm babies were noted as such and the intrauterine weeks were often noted by the offices.

Table 1. Offices visited during the grant period and counts of individuals and total scans in the radiographic database. N_i: Number of individuals; N_r : Number of radiographs.

Office	**City / Office**	**Date Visited**	**N_i**	**N_r**
ME	Buffalo, NY /Erie Co	October 2008; June, August 9/2009	232	819
ME	Pittsburgh, PA / Allegheny Co	November 10-12, 2009	109	472
Coroner	Toledo, OH / Lucas Co	November 17-20, 2009	93	256
ME	Phoenix, AZ / Maricopa Co	January 5-16,2009	439	1,864
ME	San Diego, CA / San Diego Co	January 19-30,2009	480	1,420
ME	Castle Rock, CO / Douglas Co	February 2-4, 2009	60	203
ME	Denver, CO / Denver Co	February 9-21, 2009	211	1,403
Coroner	Golden, CO / Jefferson Co	February 23-27,2009	65	211
Coroner	Centennial, CO / Arapahoe Co	March 2-6, 2009	143	496
ME	Tucson, AZ / Pima Co	March 23- April 4, 2009	313	839
ME	Baltimore, MD / Baltimore Co	July 7-31,2009	537	2,233
ME	Providence, RI / State	August 3-7, 2009	103	774
ME	Hartford, CT / State	August 10-14,2009	211	926
ME	Burlington, VT / Chittenden Co	January 19-22, 2010	120	580
Clinical	York, PA / OSS Health	January, February, June, July 2010	8,669	20,347
ME	Wichita, KS / Sedgwick Co	February 16-19, 2010	200	759
ME	Portland, OR / Clackamas Co	March 23 - April 6, 2010	260	937
ME	St. Louis, MO / Several Cos	March 8-19, 2010	499	7,283
ME	Salt Lake City, UT / Salt Lake Co	April 19-29,2010	131	320
Clinical	Gainesville, FL / Shands	November 29, 2010	198	2,078

One goal of the grant was to assemble enough information from the offices to be able to measure bone lengths on the radiographs and then estimate actual long bone lengths. As mentioned, in comparing actual long bone lengths to those in radiographs, the magnification and distortion effects of radiography cannot be avoided. The amount of radiographic magnification primarily depends on two distances, the Source-Image Distance (SID) and Object-Image Distance (OID), as seen in Figure 1, which illustrates the effects of x-raying remains. The standard for SID has been 40 inches for quite some time. There are no standards for OID, but offices typically use a Bucky cartridge system or a similar setup that keeps the SID constant and the OID within reasonable limits, depending on soft tissue thickness. Magnification and distortion effects also depend on how far the object is from the center of the beam. The further from the center of the beam an object is, the greater the distortion because the x-rays are projected at a wider angle. Thus, an object x-rayed close to the center of the beam will appear to be smaller than if it is x-rayed further from the center of the beam (Carlton and Adler 2001).

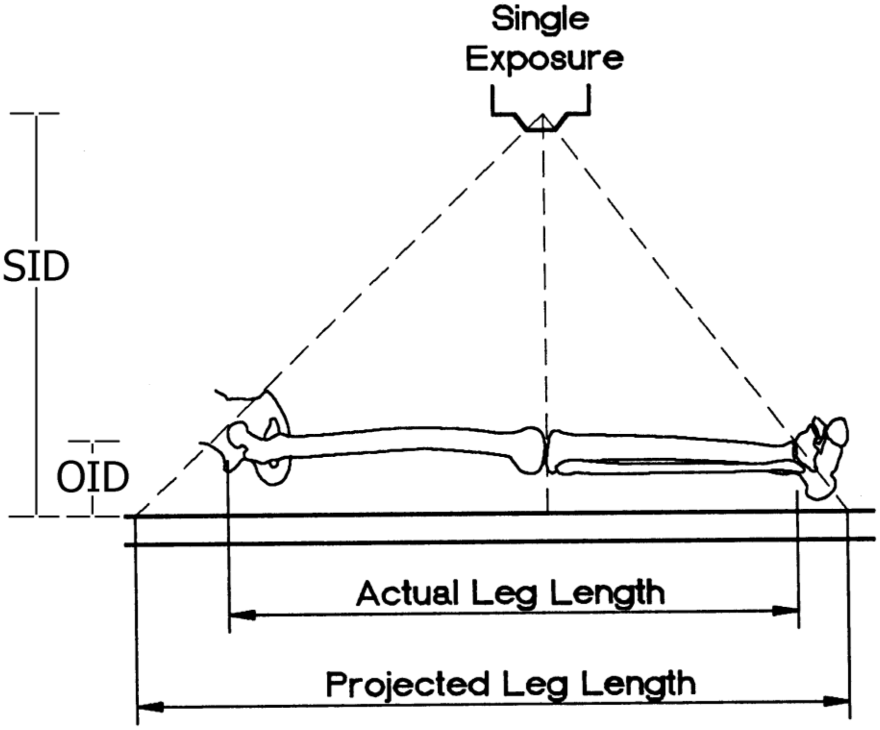

Figure 1. The magnification of bone dimensions on radiographs and the Source-Image Distance (SID) and Object-Image Distance (OID). Adapted from Carlton and Adler (2001).

Though magnification and distortion effects are unavoidable in radiographs, it does not mean that they are insurmountable. To estimate the sources of measurement error in radiographs, the height and center of the x-ray beam source can be calculated using a high-quality scale, or even better, a radiographic registration device (RRD) illustrated in Figure 2. Because each RRD is a 10 mm thick piece of Plexiglas with nine 1 mm ball bearings 30 mm apart, any magnification and distortion effects will be represented in two dimensions when the RRD is projected on a radiograph, and the position of the x-ray source can be estimated using geometric formulae. Once the position of the x-ray source is calculated, measurements taken from any points on the radiograph can be adjusted for distortion and magnification effects. Ideally, each radiograph would have already been exposed with a RRD, but at each morgue the anthropologists initially placed two RRDs on the radiographic surface and exposed a radiograph. If the morgue staff reported in interviews and through the questionnaire that the radiographic setup (x-ray apparatus, x-ray table, SID) has not changed recently, and if there are no obvious indications from past radiographs that the setup has changed, then the baseline radiographs should represent past radiographic conditions. Radiographic standards are well known by radiographers, and Stull (2008) found evidence for consistently exposed radiographs in the high correlations between bone lengths and age in her study from Erie County, NY. When objects of known size (coins, straight pins, safety pins, etc.) are found in any radiographs, they will serve as a check on calculations and assumptions. Calculation of the magnification and distortion pattern will be crucial to obtaining the best possible estimates of bone size. Measurements taken from radiographs using calipers have proven to be highly accurate compared to actual bones through adjustments based on radiographic scales (Beattie et al. 2005; Conn et al. 2002; Segev et al. 2010; The et al. 2005). After measurement points are collected from the digitized radiographs, the raw and adjusted measurements can be calculated through a computer program that has incorporated the information from the RRD to calculate the beam position for that site. In this way, corrected point-to-point distances taken anywhere in the radiograph theoretically can be calculated.

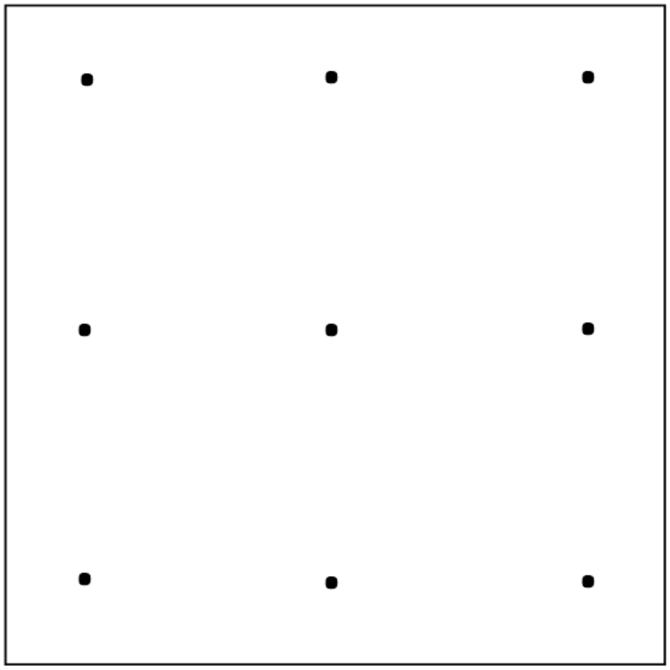

Figure 2. A radiographic registration device (RRD). An RRD is a 10 mm thick piece of Plexiglas with evenly spaced ball bearings 30 mm apart and at the same depth (5 mm). When placed on the radiographic surface, its projection onto the radiograph enables calculations of the position of the x-ray source.

The other distortion factor in fleshed remains is due to the distance from the bone to the surface where the child is placed and the RRD rests, above the radiographic film. Fortunately, in most radiographs, the outline of the soft tissue can be seen and the distance from the exterior skin surface to the bone can be measured in two dimensions (parallel to the radiographic surface) and the soft tissue thickness underneath the bone can be estimated. An example of a radiograph with the RRD in place is shown in Figure 3. Because relatively few radiographs were collected using the RRDs, if radiographic markers were being used in offices, their dimensions were recorded through photography against a scale and by direct measurement. Additionally, clinical ultrasound data from infants are widely published for comparison. The measurements will be valuable both to medical examiners who estimate age using radiographs of fleshed remains and to forensic anthropologists who estimate age from dry bones.

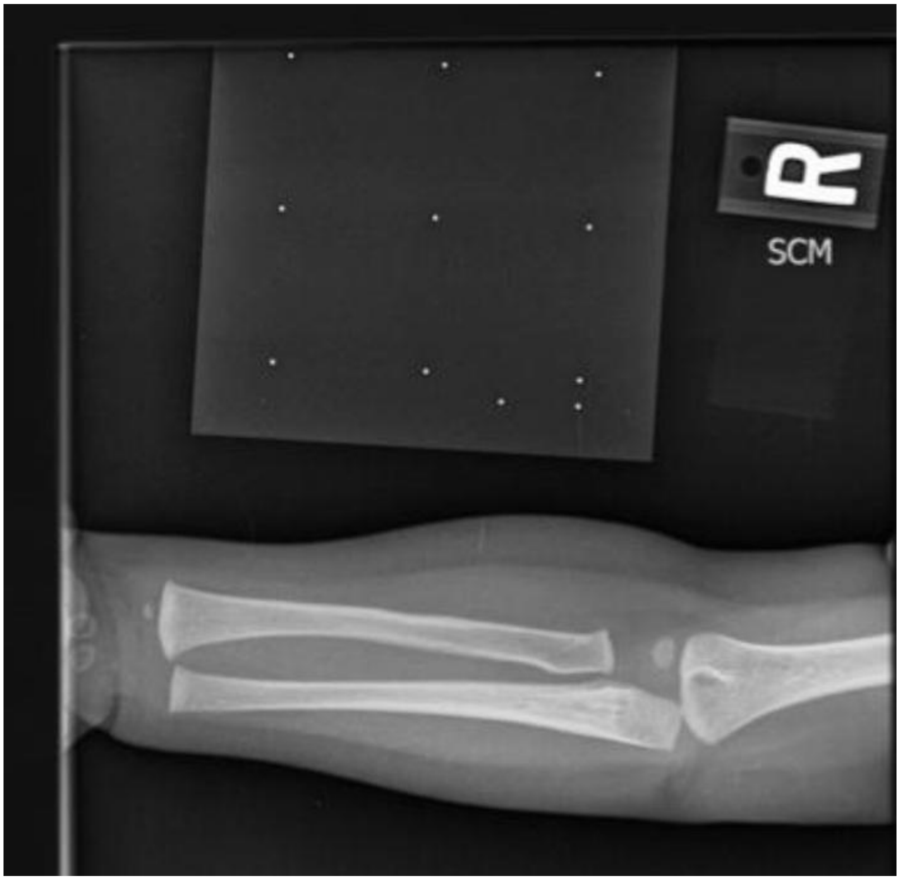

Figure 3. Radiograph image from a site that used the RRD.

3. RESULTS

As the research team discovered, radiographic procedures varied a great deal by office, and in general, the clinical settings produced highest quality radiographs. In the MECOs, the quality of radiographs was quite variable due to large disparities in the quality of x-ray equipment, in the training of personnel, and in office protocols. As a result, radiographs were scored as very good, good, or poor quality based on exposure level, sharpness, and contrast. We were quite surprised to discover, despite clear standards and an obligation of medical examiner's offices and coroner's offices to record images for forensic documentation purposes, that the most basic procedures were not consistently followed in all offices: the standard 40 inch source to image distance; an indication of side of the x-rayed individual in the radiograph; and permanent recording of case number on the film. Relatively few offices used a radiological scale (Frazee et al. 2009). Due to the great variability in radiographic procedures and resultant quality, and infrequent use of scales, the opportunities for converting measurements from radiographic images to bone lengths are more limited than we had hoped. A preliminary metric study of radius length has been done based on available scales on radiographs and the office-specific markers (Waldock 2011) but more work is needed. In order to be valid, research using measurements may have to proceed carefully on an office-by-office basis, or even on a case-by-case basis. With the greater use of digital radiographic systems, however, the opportunities for metric research should improve as long as the digital images are calibrated for size and offices use radiographic scales to validate the electronic scales.

The number of radiographs collected greatly exceeded expectations. A total of 44,220 radiographic images have been assembled from 9,709 different individuals, almost 4,000 of which were x-rayed on multiple occasions at the clinical offices. Some images in the database are MRI series, however, and have information that can be better analyzed using appropriate software. Also, due to varying radiograph quality, not all scans will be useable for every radiographic study, even when enhanced through Photoshop or other computer programs. Image Converter Plus version 8, from fCoder Group, Inc., was used to convert the original TIFF files from 600 dpi scans of the film radiographs to smaller files. After conversion, the TIFF files, some of which were originally over 135 MB in size, were shrunken down to TIFF files for the most part less than 5 MB in size with no apparent loss of information. Any personally identifying information (name, patient number, or case number) present in any radiographic scan was blocked out electronically.

Of the 9,709 individuals, 4,061 are females, 5,610 are males, and 38 are of unrecorded sex. In terms of ancestry, there is a great deal of diversity in the database, including radiographs from Hispanic Americans, who are little known radiographically. The breakdown of the total sample by official US Census and Office of the Budget Directive 15 racial designation is shown in Table 2. White Americans predominate; two Hispanic individuals are included in the black count and 244 Hispanic individuals are included in the white count. Table 3 shows counts for whites and blacks with no ethnic designation, and for Hispanics. Individuals with non-US nationality include individuals predominantly from East Asia and India.

Table 2. Counts by racial designation
in the radiographic database.

Race	**N**
Biracial	31
Black	1,290
East Asian	48
Multiracial	4
Native American	70
Other	84
Pacific Islander	22
Unknown	3,274
White	4,325

Table 3. Counts by racial/ethnic group and sex in the radiographic database.

Race/Ethnicity	Sex	N
Black	F	458
Black	M	826
Hispanic	F	153
Hispanic	M	352
White	F	2,000
White	M	2,671

The age distribution of individuals in the radiographic database is shown in Table 4, which shows counts for individuals scanned once as well as individuals scanned multiple times at the clinical offices. The counts reflect the large number of teenagers who were injured more than once and/or had follow-up radiographic examinations at the same age. The large numbers during the teen years are especially useful because different individuals had different injuries to different body parts, allowing optimized cross-sectional sampling as well as longitudinal sampling to examine bone growth and bone healing rates. A plot of the age distribution for individuals younger than 5 years old is shown in Figure 4. Many in the sample are infants that were premature, stillborn, or died quite soon after birth.

Table 4. Age distribution by year of individuals in the radiographic database.

Age interval	Number of Individuals	Number of Scans
0-1	2,235	2,292
1-2	491	542
2-3	300	357
3-4	220	278
4-5	198	286
5-6	241	366

6-7	221	349
7-8	274	411
8-9	289	419
9-10	409	600
10-11	530	780
11-12	584	973
12-13	600	1,143
13-14	787	1,321
14-15	771	1,546
15-16	485	1,655
16-17	367	1,580
17-18	317	1,457
18-19	326	1,079
19-20	314	615
20-21	209	489

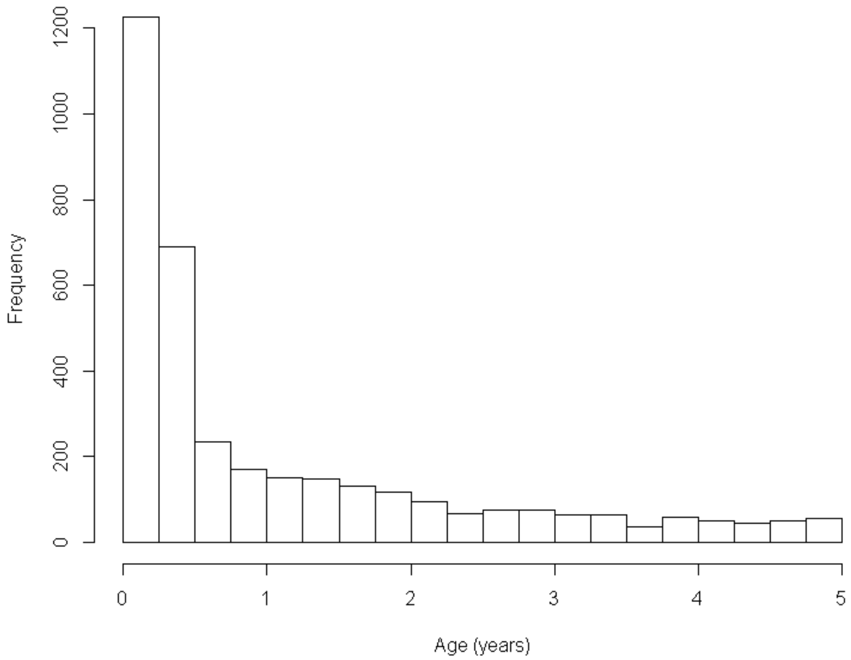

Figure 4. Age distribution of individuals in the database less than 5 years of age.

Cause and manner of death are known for most cases from the MECOs. Table 5 lists the manner of death and counts in the database if it was recorded. A further 65 cases were pending at the time of data collection. Counts for cause of death from all manners of death are shown in Table 6. Cause of death includes Sudden Unexpected Death of an Infant (SUID), deaths which may be further investigated, as well as the more specific Sudden Infant Death Syndrome (SIDS), when noted, which is assigned after other causes of death (diseases, disorders, infections, neglect, poisoning, suffocation, etc.) have been ruled out. The cause and manner of death are important because outliers in growth and development observations are often children who fell behind due to diseases or neglect.

Table 5. Manner of death in the radiographic database.

Manner of Death	**N**
Accident	842
Homicide	1,077
Natural	1,300
Suicide	189
Undetermined	797

Table 6. Cause of death in the radiographic database. SIDS: Sudden Infant Death Syndrome; SUID: Sudden Unexplained Infant Death.

Cause of Death	**N**
Asphyxiation	356
Blunt Force Trauma	435
Disease	328
Drowning	123
Fire and Smoke	63
Gunshot wound	830
Infection	237
Motor Vehicle Trauma	46
Sharp Force Trauma	99
SIDS	761
Stillborn	89
SUID	314
Toxicity	99

The Structure of the Database

The radiographic database has two main data tables, one for individual demographic information and one for the skeletal inventory of each scan. The database was created using Advantage DB from Sybase and converted to MySQL from Oracle Corporation for web integration. Demographic information from the individuals in the database includes age on several scales (days, weeks, and years), sex, race, ancestry, and external measurements of the individuals. The demographic table structure is shown in Table 7. Birth and death dates are known but information available to the public include only year of birth and death or examination to protect private information. There were numerous physical measurements recorded. For example, over 1,400 crown-rump lengths were recorded from neonates, and from all individuals, over 9,500 weights and over 8,500 body lengths/statures were recorded.

Table 7. Fields in the demography table. Char: character field; Double: double-precision number; Integer: integer number; Memo: Memo field; ModTime: Date and time of last record change (automatic).

Field name	**Field type**	**Explanation**	**Public**
SITENo	Integer	Site number	N
CASENo	Char	Case number	N
SNCN	Char	SiteNo + Caseno (Key)	N
WebPtID	Integer	Patient identification number	Y
WebPtseq	Integer	Patient ID and Visit Sequence	Y
TotalScans	Integer	Total number of scans	Y
RACE	Char	Racial designation (OMB 15)	Y
RACE_HE	Char	OMB 15, Hispanics separate	Y
ANCESTRY	Char	Ancestry	Y
ETHNICITY	Char	Ethnicity	Y
NATIONALITY	Char	Nationality	Y
SEX	Char	Sex	Y
DOB	Date	Date of birth	N

DOX	Date	Date of exam	N
DOD	Date	Date of death	N
YOB	Integer	Year of birth	Y
YOX	Double	Year of exam	Y
YOD	Integer	Year of death	Y
AGEYEARS	Double	Age in years	Y
AgeWeeks	Double	Age in weeks	Y
AGEDAYS	Integer	Age in days	Y
AgeYearsTrunc	Integer	Truncated age in years	Y
HT_in	Double	Height in inches	Y
HT_cm	Double	Height in cm	Y
WT_LB	Double	Weight in pounds	Y
WT_KG	Double	Weight in kilograms	Y
WT_G	Integer	Weight in grams	Y
MOD	Char	Manner of death (Homicide, etc.)	Y
COD	Memo	Cause of death	Y
CHL_IN	Double	Crown-heel length in inches	Y
CHL_CM	Double	Crown-heel length in cm	Y
CRL_IN	Double	Crown-rump length in inches	Y
CRL_CM	Double	Crown-rump length in cm	Y
HeadC_IN	Double	Head circumference in inches	Y
HeadC_CM	Double	Head circumference in cm	Y
ChestC_IN	Double	Chest circumference in inches	Y
ChestC_CM	Double	Chest circumference in cm	Y
AbdC_IN	Double	Abdominal circumference in inches	Y
AbdC_CM	Double	Abdominal circumference in cm	Y
FootL_IN	Double	Foot length in inches	Y
FootL_CM	Double	Foot length in cm	Y
AntFont	Char	Anterior fontanelle open/closed	Y
PostFont	Char	Posterior fontanelle open/closed	Y
BrainWtGms	Integer	Brain weight in grams	Y
PATHOLOGY	Memo	Pathology description	Y
TRAUMA	Memo	Trauma description	Y
NOTES	Memo	Case Notes	Y
BIRTH_INFO	Memo	Birth Information	Y
NOTES2	Memo	Case notes 2	Y
Preterm	Char	Preterm?	Y
IUWeeks	Integer	Intrauterine weeks	Y
LastEditDate	ModTime	Date-time of last edit	N
RecordNo	Integer	Unique Record Number	Y

The radiographic inventory table includes information specific to each radiographic image including which areas of the body are seen, scan orientation, if trauma or other pathology is present, and overall quality of the image. The field names are shown in Table 8.

Table 8. Fields in the skeletal inventory table. Char: character field; Double: double-precision number; Integer: integer number; Logical: True/False; Memo: Memo field.

Field Name	**Field Type**	**Data in Field**
SiteNo	Integer	Site number
CaseNo	Char	Case number
SNCN	Char	SiteNo+CaseNo (key in demographic table)
Ptid	Integer	Patient identification
Webfilename	Char	Image filename (key)
WebPtID	Integer	Patient identification number
WebPtseq	Integer	Patient ID and Visit Sequence
ScanNo	Integer	Scan number
TotalScans	Integer	Total number of scans
ScanSuff	Integer	Scan suffix
RECR	Char	Recorder
EntryDate	Date	Date entered
Vault	Char	Vault present
Midface	Char	Midface present
Dentition	Char	Dentititon present
Mandible	Char	Mandible present
LClav	Char	Left clavicle present
RClav	Char	Right clavicle present
CervVerts	Char	Cervical vertebrae present
ThorVerts	Char	Thoracic vertebrae present
LumbVerts	Char	Lumbar vertebrae present
RShJoint	Char	Right shoulder joint present
RHumP3rd	Char	Right humerus proximal third present
RHumM3rd	Char	Right humerus middle third present
RHumD3rd	Char	Right humerus distal third present
RElbJoint	Char	Right elbow joint present
RRadP3rd	Char	Right radius proximal third present
RRadM3rd	Char	Right radius middle third present
RRadD3rd	Char	Right radius distal third present
RUlnP3rd	Char	Right ulna proximal third present

RUlnM3rd	Char	Right ulna middle third present
RUlnD3rd	Char	Right ulna distal third present
RWrist	Char	Right wrist area present
RHand	Char	Right hand present
LShJoint	Char	Left shoulder joint present
LHumP3rd	Char	Left humerus proximal third present
LHumM3rd	Char	Left humerus middle third present
LHumD3rd	Char	Left humerus distal third present
LElbJoint	Char	Left elbow joint present
LRadP3rd	Char	Left radius proximal third present
LRadM3rd	Char	Left radius middle third present
LRadD3rd	Char	Left radius distal third present
LUlnP3rd	Char	Left ulna proximal third present
LUlnM3rd	Char	Left ulna middle third present
LUlnD3rd	Char	Left ulna distal third present
LWrist	Char	Left wrist area present
LHand	Char	Left hand present
Sacrum	Char	Sacrum present
Lilium	Char	Left ilium present
Lisch	Char	Left ischium
Lpubis	Char	Left pubis
Rilium	Char	R ilium
Risch	Char	R ischium
Rpubis	Char	Right pubis
LHipJoint	Char	Left hip joint
LFemP3rd	Char	Left femur proximal third
LFemM3rd	Char	Left femur middle third
LFemD3rd	Char	Left femur distal third
LKnee	Char	Left knee area
LTibP3rd	Char	Left tibia proximal third
LTibM3rd	Char	Left tibia middle third
LTibD3rd	Char	Left tibia distal third
LFibP3rd	Char	Left fibula proximal third
LFibM3rd	Char	Left fibula middle third
LFibD3rd	Char	Left fibula distal third
LAnkle	Char	Left ankle area
LFoot	Char	Left foot
RHipJoint	Char	Right hip joint
RFemP3rd	Char	Right femur proximal third
RFemM3rd	Char	Right femur middle third
RFemD3rd	Char	Right femur distal third

RKnee	Char	Right knee area
RTibP3rd	Char	Right tibia proximal third
RTibM3rd	Char	Right tibia middle third
RTibD3rd	Char	Right tibia distal third
RFibP3rd	Char	Right fibula proximal third
RFibM3rd	Char	Right fibula middle third
RFibD3rd	Char	Right fibula distal third
RAnkle	Char	Right ankle area
RFoot	Char	Right foot
Orientation	Char	AP, ML, or Oblique view?
RefScaleText	Logical	Reference scale present?
Trauma	Logical	Trauma present?
Pathology	Logical	Pathology present?
VisCaseNo	Logical	Visible case number present?
Quality	Char	Scan Quality: Poor, Good, Very Good
Enhanceable	Logical	Can image be enhanced?
UnknownSide	Logical	Is side unknown?
Notes	Memo	Image notes

The radiographic database will complement the Forensic Data Bank at the University of Tennessee, which has proven indispensable in numerous forensic applications involving modern adults (Jantz and Moore-Jansen 1987; Ousley and Jantz 1997). Like the Forensic Data Bank, the radiographic database will be supplemented by additional cases in the future, continually adding up-to-date information from subadults of various ethnic backgrounds. It is a certainty that new methods of analyzing subadult remains will come from the radiographic database, as has happened with the Forensic Data Bank.

In order to preserve decedent and patient confidentiality, the original case numbers have been modified and the dates of birth, exam, and date of death or exam will not be available to the public. When researchers wish to study bone healing in the longitudinal clinical records, pseudo-dates with the correct time intervals will be used.

Research Findings

There have been four theses at Mercyhurst College and University that utilized the scans collected during the NIJ grant. The scans have been limited to internal use thus far because of privacy concerns and because in many cases, the demographic data were not ready for analysis.

Fojas (2010a, 2010b) examined age estimation using the appearance of the distal radial epiphysis . Scheuer and Black (2000) cite an age of appearance at 1 to 2 years of age, but Schaefer et al. (2009) add that if the epiphysis is if present, the individual is greater or equal to 4 months old, and if absent, the individual is less than 2.5 years old, based on results from previous studies. Fojas used logistic regression to derive 95% confidence intervals for age and found: if the epiphysis is present, the individual is at least 29 weeks (7 months) old; if absent, the child is less than 79 weeks (one year, eight months) old. These ages can be compared to Graham's republished ages from Garn of six months to two years, four months for boys and five months to 1 year, eight months for girls. Boys have apparently experienced a greater secular increase in the development of the distal radius. There were some indications of different rates depending on race and sex (blacks were advanced compared to whites and girls were advanced compared to boys), but they were not statistically significant and more study is needed.

Waldock (2011) analyzed the maximum length of the radius calculated from scans in the radiographic database. Her most significant results were that the ages estimated using Merchant and Ubelaker (1977), Ubelaker (1978), and Maresh (1970) tended to show more positive bias (produced greater and greater overestimates) the older the child was, beginning at age 2, similar to the results of Schillaci (2012). By age six, the bias was estimated to be three years.

Diefenbach (2012) examined the appearance of ossification centers of the elbow and may be the first researcher to incorporate uncertainty into estimating age rather than merely providing point estimates. She confirmed secular changes in development through earlier point estimates for centers appearing than they should according to the oft-cited literature. Differences between males and females were not statistically significant and were small compared to the uncertainty in estimation (Figure 5).

Clinical applications for the radiographic database are illustrated by Ertl (2012), who assessed numerous ossification centers from birth through nine months of age from over 900 infants. She derived updated guidelines for normal growth and newly calculated probabilities incorporating confidence intervals (Figure 6), which should reduce the false negative findings in lagging children due to secular changes, and reduce the false positive findings in accelerated children due to secular changes and quantified uncertainty. Based on her data and results, a computer program will be written for doctors to analyze pediatric radiographs in order to detect developmental anomalies requiring intervention.

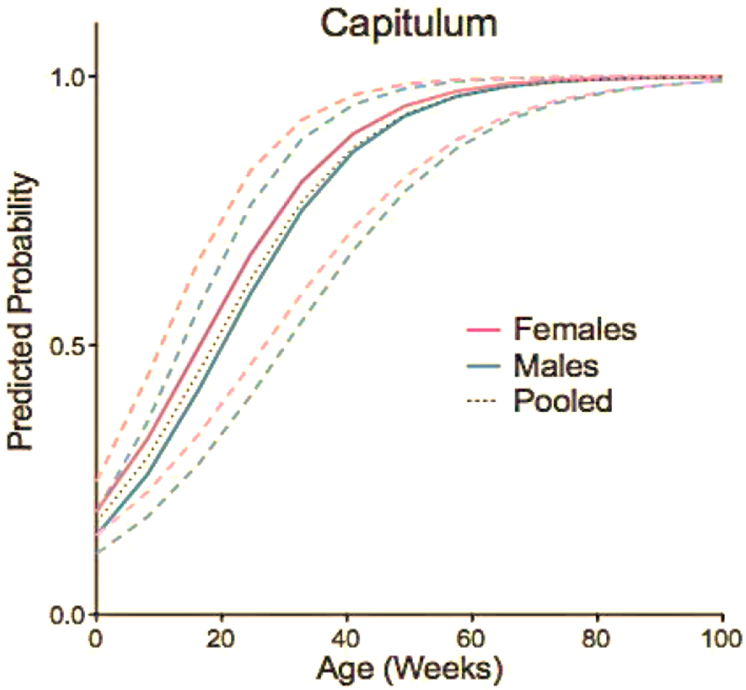

Figure 5. Probability of capitulum appearance, by sex, using logistic regression (solid lines) and incorporating lower and upper 95% bounds in the probabilities (dashed lines). From Diefenbach (2011).

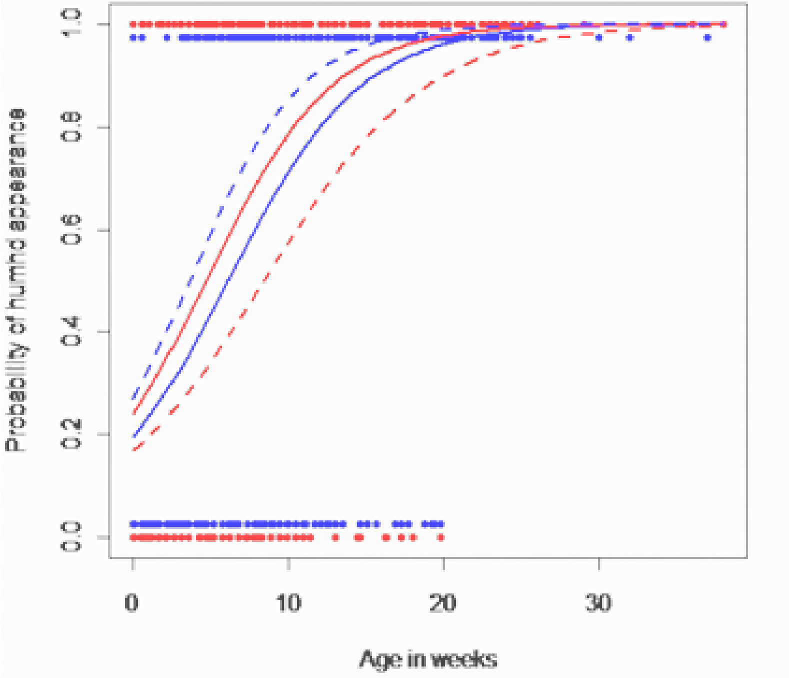

Figure 6. Probability of appearance of the humeral head for males (blue) and females (red) with lower confidence bounds for males and upper confidence bounds for females (dashed lines). From Ertl (2012).

Web Site

A web site has been constructed, and is still under construction, for the database. The web site will allow visitors to query the demographic information in the database and download the related radiographic images. It will be functioning by March 15, and more or less finished by April 1, 2013, though it will be updated often. The interactive query system for the database is accessible at: http://math.mercyhurst.edu/~sousley/databases/radiographic_database/

4. CONCLUSIONS

The radiographic database established through a grant from the NIJ complements data from adults compiled in the Forensic Data Bank at the University of Tennessee, Knoxville, which was established through a grant from the NIJ in 1986 (Jantz and Moore-Jansen 1987; Ousley and Jantz 1997). The radiographic database will continue to grow through ongoing contributions from medical examiners and clinics from around the country. This growth will be facilitated by the increased use of digital radiography. The creation of such a database will not only provide the basis for assessing growth and development in modern American children in the clinical setting and offer the most reliable sex and age standards with statistically determined age prediction intervals in the forensic setting, but will also open up further methods of analysis for other forensic and clinical needs.

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6. DISSEMINATION OF RESULTS

Dissemination has been achieved through presentations at professional conferences. Presentations include Frazee et al. (2009), which covered our preliminary findings of the state of radiographic documentation, and a poster by Stull et al. (2009) on challenges to estimating age from bone lengths at the annual meeting of the National Association of Medical Examiners; posters by Ousley et al. (2010a; 2010b) highlighting the creation of the radiographic database and collection efforts at the annual meetings of the American Academy of Forensic Sciences and American Association of Physical Anthropologists; and a poster by Hunt and Ousley (2013) highlighting the connection of the radiographic database to the Forensic Data Bank, at the annual meeting of the American Association of Physical Anthropologists. At least two publications are planned initially, one an overview of the database, and another providing updated standards for estimating age in subadults, to be submitted to *Journal of Forensic Sciences, Radiology, Paediatrics*, and/or *American Journal of Physical Anthropology*.

Ongoing dissemination will be primarily through a web site managed by Mercyhurst University. After the grant is finished, a copy of the database, software, and images will be sent to the NIJ, and approximately ten additional copies will be sent to other institutions, primarily large medical examiner offices and universities with well-established forensic programs. The database will be made available on DVD to other interested institutions at cost. But the database, software, and analytical methods will continue to be updated and improved, so the web site will be the best medium for sharing resources. Through the web site, researchers will be able to download data and images to derive new forensic methods and evaluate published findings on their own, greatly improving the validity and reliability of new methods and conclusions. Software will be available for free on the web site and a certain number of radiographic scales will be provided to offices for free upon request. Additional software applications will be practical once new methods for estimating age, sex, and ancestry are established, and can be incorporated into Fordisc (Jantz and Ousley 2005) and/or created as an independent computer program.

Through the use of the database and software, and presentations and publications, it is expected that more clinicians, medical examiners, and coroners will voluntarily contribute radiographic scans to the database. Hopefully, if free software for age estimation is available, the medical examiners and coroners will realize that they can benefit from contributing radiographic data to the data bank. Participants compiling and mailing digital radiographs on a DVD will be an especially simple way to contribute new information. Scanned radiographs of subadult teeth from dentists are another obvious addition to the database. Having a central repository for radiographic data will greatly enhance its applicability and scope. The Department of Anthropology/Archaeology or Applied Forensic Sciences at Mercyhurst will provide the necessary administrative oversight and staff support to incorporate new information into the database.

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