# Estimating subadult age-at-death from skeletal remains: Dentition analysis

## Traditional biological profile reconstruction in forensic archaeology and anthropology

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### Abstract

Estimating age-at-death of skeletal remains is a vital method of biological profiling. Dentition analysis is presented in this essay as a highly accurate and valuable means of estimating the age-at-death of juvenile skeletons. Throughout this essay prominent dental-aging methods will be critiqued and analysed for their accuracy and relevance to age-at-death estimation. It is argued that Gustafson and Koch (1974) and Ubelaker's (1987) published standards present the most accurate estimation methods of age-at-death compared with competing standards. The application and reliability of these methods is illustrated through osteological individuation in forensic case studies and further demonstrated in medico-legal contexts.



### Keywords

skeletal, dentition, subadult, osteology, forensic


# Introduction

Osteology refers to the scientific subdiscipline of anatomy, anthropology, and archaeology whereby human skeletal remains are recovered and analysed. Often, the objective of studying skeletal ('hard tissue') remains is to reconstruct an osteobiography through which information regarding the deceased's identity can be ascertained. Skeletal identification is paramount, particularly in forensic contexts where anthropologists supply their findings to medicolegal investigations: homicides, mass death events, and natural disasters (Franklin 2010). Osteological examination studies numerous biological entities pertaining to the life and death of individuals, including pathology, histology, biophysics, ontogeny, molecular genetics, and biochemistry.

There are four principle parameters for assessing biological identity in the investigation of human remains: age-at-death, sex, stature, and ethnicity. Multimethodological approaches are required for reliability in identification. These approaches differ depending on whether the remains are adult or subadult (juvenile or immature). For the purpose of this paper, the term *subadult* will refer to Buikstra and Ubelaker's (1994) first four categories of aging in osteological human remains: foetus (prenatal), infant (0–3 years), child (3–12 years), and adolescent (12–20 years).

Literature on the topic of osteology and individual identification is extensive where the morphology of cranial and postcranial traits contributes greatly in the sexing and determination of stature in adults. Sexing in subadults, however, is eminently difficult to establish as a result of extreme similarities in the female and male endoskeleton, with virtually no methods of differentiating between male and female bone morphology. Stature in prepubescent and pubescent subadults can also be difficult to estimate, due to varying levels of development. Physiological age is estimated by the development of tissue systems where maturation can be defined by irreversibly scaled events (Moorrees 1963). Predicting age-at-death in adults is greatly based on degenerative, morphological features of the skeleton whereas estimating age-at-death of subadults focuses primarily on developmental indicators (White and Folkens 2005). Age-at-death estimation in subadults is attributed commonly to dental attrition, formation and eruption, incremental growth markers in enamel, and fontanelle closure (White and Folkens 2005). Epiphyseal fusion and long-bone length are also used as postcranial methods (Pfau and Sciulli 1994).

Age-at-death estimation is regarded as the most reliable parameter of subadult identification from skeletal analysis, due to the precise morphological measurements and categories in which ontogenic skeletons can be classified.

The purpose of this paper is to critically analyse various methodological approaches for the age-at-death estimation of subadult skeletal remains and evaluate the methods, accuracy, and research concerning these techniques. Standards of dental attrition, eruption, and growth will be identified and analysed. The subsequent portion of this paper will exemplify forensic case studies which have demonstrated the application of dentition analyses as a vehicle in estimating the age-at-death, assigning identity, and presenting relevant evidence relating to juvenile skeletal remains in a medicolegal context.

# Dentition

Dentition represents a pre-eminent developmental characteristic useful for biological aging, particularly in juveniles. Tooth-crown morphology can only be altered by attrition, trauma, or demineralisation succeeding crown eruption. Dentition can determine information such as age, sex, ethnicity, occupation, and habits as well as dental pathology, restorations, and dental anomalies (Krishan et al. 2015). Chronological age can be determined using forensic odontology techniques pertaining to root development radiography, mineralisation, tooth emergence, formation patterns, attritional wear, and enamel histology (Moorrees et al. 1963). Enamel maturation occurs via crystallite growth upon mineralisation. The major marker of the enamel is the striae of Retzius, an incremental brown striae (linear ridged marking) within the tooth enamel which reflects physiological stress associated with ontogeny and growth, similar to that of the neonatal line; it is produced by the shock caused by the birthing process (Moorrees et al. 1963). It is important to note that the striae of Retzius is not due to a matrix malformation, but rather a mineral unavailability displaying gaps in the enamel (Skinner and Anderson 1991).

# Age variation at formation stages

Prominent tooth-formation standards often applied are those of Moorrees et al. (1963); permanent and deciduous teeth and the composite visual system are largely of Buikstra and Ubelaker (1994). Incremental growth markers in enamel have also been reviewed as a relevant method for aging juvenile dentition, posed by Skinner and Anderson (1991).

Moorrees et al.'s (1963) *Age Variation of Formation Stages* is a study based on the dental development and calcification of North American white children of middle-socioeconomic grouping (136 M, 110 F), which gave rise to a series of subadult aging chronologies (tooth-formation stages) frequently used in determining age of teeth. Materials of the study also included data from Harvard University's Forysth Dental infirmary and permanent maxillary and mandibular central and lateral incisor intraoral-radiographs (Moorrees et al. 1963). Results indicated permanent mandibular teeth (C-M3) were formed postnatal, where initial crown formation occurred of the permanent canine at the age of six months, the first premolar at 1.8 years, the second premolar at three years, 3.5 years for the second molar and 9.4 years for the third molar (Moorrees et al. 1963). At twelve years of age, the mature root length was identified for all permanent teeth, excluding the third molar in which the tooth crown completion was attained (Moorrees et al. 1963). The 'normal' tooth-formation stages of permanent mandibular canines, premolars, and molars have been charted along a chronological age axis as a method for aging individuals from 0–25 years (Moorrees et al. 1963). Whilst this method presents helpful guidelines for the aging of subadult dentition, in practice the assessment of dental maturation would be affected by: variation of developmental rates, experience of recognising sequential stages of development, availability of earlier records of the individual to reference previous dental development, and a variance sex rate of 0.5 years. Hence, these factors would influence accuracy in a forensic age-at-death context of indeterminate sex (Moorrees et al. 1963).

## Human skeletal remains: Excavation, analysis and interpretation

Ubelaker's (1987) *Estimating Age At Death From Immature Skeletons* system provides schematic representations of tooth formation and eruption relevant to remains aged five months in utero through to 35 years. Ubelaker's categoric charts have been extensively reviewed and modified for different ancestral groups and separate female and male charts have been developed. The data of this standard is derived greatly from previous studies of Native North American populations. The juvenile component is based on literature of Caucasian North American and Canadian groups. Fully developed dentition often occurring at approximately 14 years makes aging sexually-matured subadults difficult and poses a limitation to this age-at-death estimation standard (Ubelaker 1987).

# Incremental enamel development in modern human deciduous molars

An additional dentition method based on incremental enamel development of deciduous anterior teeth has contributed another substantiated method for aging subadults based on dentition. Incisors and canines are examined in this study, in cohesion with previous research for deciduous molars (Mahoney 2012) to identify developmental evolvement along the tooth row. Mahoney (2012) tested whether links exist between deciduous incremental enamel development and the eruption sequence. This paper is focused around Retzius and intradian line periodicity, pre- and postnatal cusp growth and crown formation time of enamel secretion being reconstructed from incremental growth markings (of deciduous maxillary and mandibular anterior teeth), which remain postmortem (Mahoney 2012). It was outlined by Mahoney that enamel of mandibular and maxillary teeth have differing growth trajectories. It was also found that Retzius line periodicity remained constant along the deciduous tooth row where chronological age correlated to the prevalence of enamel on deciduous teeth. Because of this, Mahoney's (2012) study of reconstructed incremental enamel development can be applied to estimating the age-at-death of subadult dental remains.

# Dental eruption and tooth formation

A dental eruption and tooth-formation age-at-death method published by Gustafson and Koch (1974) consists of numerous sources summarising anatomical, radiographic and gingival eruption to orchestrate a schematic representation standard. Gustafson and Koch also were the first to demonstrate the similarity in incremental lines between contralateral teeth, further investigated by Boyde (1963). Revised by Johanson (1971) and Reppien et al. (2006), it was concluded by Gustafson and Koch (1974:297) '*In cases with developing dentition the estimated age range can be narrowed to 2–4 years. Depending on the degree of development the dentition of a small child can be estimated within a range of 2 years.ˆ* This is in substantial contrast to the age range of adults, where 10–20 years is deemed an appropriate error range by Reppien et al. (2006), evidencing the great accuracy of estimating age-at-death of subadult dentition.

# Sequencing eruption and development

A paper published by AlQahtani et al. (2014) titled 'Accuracy of dental age estimation charts: Schour and Massler, Ubelaker, and the London Atlas' provides a comparative analysis of three of the most prominent subadult dentition techniques at the time of its publication. The initial method used is that of Massler and Schour (1941), which consists of 21 images sequencing eruption and development corresponding to age, from in-utero to adulthood (AlQahtani et al. 2014). The various stages illustrate one side of the jaw with the outline of erupting teeth relative to the (assumed) gingival line. Criticism of this technique often regards the minimal information of the materials and methods involved in the analysis of the study, additionally the undefined tooth stages and limited age ranges are used to question this method's validity (AlQahtani et al. 2014). Secondarily, Ubelaker's dentition chart published in 1987advanced the atlas of Massler and Schour (1941) by including a vast range of sources to narrow age ranges whilst accounting for variation (White and Folkens 2005). Greatly similar to the Massler and Schour (1941) paper, Buikstra and Ubelaker's (1994) standard illustrates 21 stages of the eruption and development of maxillary and mandibular dentition from 28 weeks in-utero to 23 years (White and Folkens 2005). The tertiary standard analysed is the London Atlas, a 31 stage schematic based on 704 radiographs of known-age individuals, illustrating tooth eruption and development for each individual tooth. Median, minimum, and maximum tooth stages and alveolar eruption levels for each age category are included and the standard illustrates the enamel, dentine, cementum, and pulp relevant for each category (AlQahtani et al. 2014). The objective of this review was to assess the accuracy of Massler and Schour's (1941) atlas, Buikstra and Ubelaker's (1994) standard, and the London Atlas in estimating age from developing teeth (AlQahtani et al. 2014). A sample size of 1506 individuals was used, in the form of skeletal remains and panoramic dental radiographs, of known age (Goltz 2016). It was found in applying these three methods to the sample size, that all methods underestimated the age of the individuals; however the London Atlas was identified as the most accurate, whereby 39 per cent of individuals were assigned to the correct age using Massler and Schour's (1941) atlas, 40 per cent using Buikstra and Ubelaker's (1994) standard, and 53 per cent using the London Atlas (AlQahtani et al. 2014).

# Biological profiling in a forensic context

This section of the paper will focus on forensic case studies, which have exhibited the crucial role of dental analysis in the aging of subadult remains, prescribing identity and further evidencing events and identities in the context of legality and prosecution. The examination and study of dentition comes under forensic odontology, a category within dentistry often defined as the handling and studying of dental evidence to evaluate and present ante-, peri-, and postmortem dental findings in the context of justice (Krishan et al. 2015). This discipline plays a significant role in the identification of individuals, specifically, in providing age-at-death estimations of subadult remains. As previously stated, morphologically sex and ancestry can be difficult to determine in juvenile skeletons; however, dentition is an extremely reliable method for estimating biological age. Dental expertise often becomes necessary when little or no other tissue is viable for analysis such as skeletonised remains, archaeological, mummified, or chemically influenced remains. Events such as fire, chemical accelerants, and other environmental factors influence human remains significantly. Bone being constituted of collagen, calcium phosphate, and calcium carbonate makes it strong and much more substantial than soft tissues (Krishan et al. 2015). Dental matter, being greatly made up of inorganic constituents (pulp, dentin, enamel, and cementum), is significantly more durable, preservable, and is not as subject to decomposition, in comparison to other tissues.

Identification of dentition relies heavily on the comparison of data. Many of the anthropological methods used in forensics involve charts, image sequencing, and growth indicators that can guide individuation parameters—specifically age-at-death—to an accurate estimation. Age-at-death is often the initial way to specify a smaller group of potential individuals; it is often then morphology, pathology, and ante- and postmortem records that prescribe the identity and individuation of the remains. The role of hard tissue analysis of human remains is paramount not only in assigning the identity of the deceased but also presenting circumstances of death: suspicious or otherwise, provenance, and likely actions of the perpetrator. A critical role of the forensic anthropologist is to study human remains, their context and condition, and, at the request of a governing party, to present biological findings relevant to legal representatives and broader society. It is through forensic files and case studies that the importance of human skeletal analysis—namely dentition—can be demonstrated in bringing about justice, societal peace of mind and identification of persons in a significant array of forensic cases.

# Case study 1: Canada 1968

The evaluation of the first case study aims to convey and demonstrate how the use of dentition has given rise to accurate age-at-death estimation and identity determination in the context of juvenile remains. The cranium of a subadult was found on the bank of a river in Northern Canada in March of 1968 (Speller et al. 2012). The remains had initially been identified as being those of a seven-year-old boy, presumed to have drowned in the river three years prior. The dentition of the cranium included the eruption of the upper right second deciduous molar (which in initial forensic reporting had been mistakenly identified as a permanent first molar), assigning an incorrect age-at-death estimation of seven to nine years (Speller et al. 2012). It was stated in April 1969 that the cranium did not resemble the dental or ontogenic stage of the missing child (Speller et al. 2012). After a conclusion refuting the identity of the cranium as belonging to the missing child, the case remained in trust for 36 years until scientific techniques became available to repatriate and identify the cranial remains. Based on taphonomic indication of cartilage and bone preservation and exfoliation of hard tissue, the death of the individual was estimated to have occurred between 1958 and 1963, and the time elapsed since discovery to be between five and 10 years (Speller et al. 2012). This case, in particular, exemplifies the ability that anthropology has on solving 'cold' or untouched cases, as a result of technological advancement and expertise of individuals in bioarchaeological examination. In 2005, the remains were distributed to the Simon Fraser University's department of Archaeology in a tertiary attempt to establish the identity of the child (Speller et al. 2012). The initial aim of the reinvestigation was to analyse hard tissues and seek surviving kin for further testing. In addition to hard tissue analysis and geographic origin, seasonality was also tested using botanic materials and bomb-pulse dating to assist in providing evidence of identity.

Of the remains, several unerupted permanent teeth of the upper right maxilla were identified. The 5.5 (FDI (Federation Dentaire Internationale) nomenclature: deciduous maxillary right second molar) was also present (Speller et al. 2012). The primary means of analysis was age-at-death estimation methods of dentition, with the support of skeletal ossification methods, craniometrics, radiographs, and microscopy (Speller et al. 2012). Using the H.G Fischer model for radiographing the developing dentition, both native and non-native standards were used in comparative analysis. The bomb-pulse dating method was applied in order to measure the amount of carbon-14 ($^{14}C$) deposited in the enamel of the tooth (Speller et al. 2012). The use of radiocarbon dating, such as bomb-pulse, detects the amount of incorporated atmospheric carbon atoms within the tissues of organisms, accumulated through the food chain, where increased deposition occurs predictably with increased age and the year of dental formation (in neonates) can be determined (Speller et al. 2012). The bomb-pulse method has been regarded as an exceptional indicator for age-at-death, based particularly on carbon deposits in dentition. It has accurately determining the year-of-birth in numerous forensic cases for the last 50 years. From the radiocarbon analysis of tooth 5.5, a recording of 1.206 (fraction modern) concentration was obtained, indicating that the formation of the crown's enamel occurred between 1959 and 1961 (Speller et al. 2012). Tooth 5.5's crown formation period is generally from 11 weeks prenatal to 11 months postnatal, and so it was assumed the crown enamel formation midpoint was at 1.5–6.5 months postnatal (Speller et al. 2012). This testing is indicative of a birth year between 1958 and 1962. The enamel of tooth 1.5 yielded a $^{14}C$ concentration of 1.553 (fraction modern); the tooth was incomplete at the time of death, indicating that death occurred during or after 1963 (Speller et al. 2012). Both teeth analysed for $^{14}C$ intersected on the bomb-pulse curve. Based on the carbon-14 dating in support of age-at-death techniques, the individual was born between 1958 and 1962 and died between 1963 and 1968 (Speller et al. 2012).

Due to the immature nature of the remains, neither sex nor ancestry could be ascertained using conventional anthropological standards. There was no exhibition of discrete traits such as enamel extensions or lacking wormian bones to indicate the individual was of Canadian Indigenous descent. Due to the ability of age-at-death dental techniques having extreme precision, personal identification of subadult remains relies heavily on this parameter. Determining age-at-death of these remains, dental formation, attrition, and eruption heavily constituted the basis of chronological age determination, with the assistance of skeletal-ossification and head-circumference methods. The stage of permanent tooth formation (assigned 3.19–5.45 years of age-at-death) was estimated based on the radiographic evaluation of four developing maxillary permanent teeth based on Canadian dentition standards adapted from Ubelaker's (1987) standards (Speller et al. 2012). The stage of deciduous root formation aged the remains at 2.79–4.52 years based on tooth 5.5 exhibiting incomplete apices at stage $A_{1/2}$, a characteristic completed by age 3.48 in European children (Speller et al. 2012). The root apex formation of tooth 5.5

indicated, more accurately, an age-at-death between 3.5 and 3.9 years of age. Basi-occipital fusion and cranial dimensions placed the age at 4.6–6 years (Speller et al. 2012). Cranial circumference, however, aged the individual more broadly, at 'older than 3 years' for an averaged result of 3.53–5.32 years old at the time of death. An average was deduced based on the above four age-at-death-indicators to be that of 4.4 (±1) years (Speller et al. 2012). Chemical testing of botanical remains—leaf buds of *Populus balsamifera* (black cottonwood)—found within the interior of the cranium indicated that deposition occurred in the spring season (Speller et al. 2012).

Two teeth from the cranium, including the previously-mentioned deciduous upper-second molar (5.5) and a permanent-successional second-upper premolar (1.5 FDI), underwent enamel preparation and accelerator mass spectrometry (Speller et al. 2012). Two unerupted teeth—permanent upper first premolar (1.4 FDI) and permanent first upper molar (1.6 FDI)—in addition to a 2.41g section of the right occipital squama were subject to extensive chemical decontamination in preparation for DNA analysis (Speller et al. 2012). Methods used also included: UV radiation, crushing into powder by means of cryogenic mill, incubation, and centrifugation to produce approximately 100 µL of DNA solution from each of the three samples (Speller et al. 2012). The DNA analysis targeting mitochondrial DNA is an easily detectable component in degraded remains in comparison to that of nuclear DNA. PCR amplifications, including negative controls and extraction blanks for accuracy, were then visualised by electrophoresis where the determined mtDNA sequence was compared to forensic databases and potential kin (Speller et al. 2012). Further chemical testing targeting short fragments of amelogenin was conclusive of both X and Y chromosomes being present, indicating the juvenile remains were indeed male (Speller et al. 2012).

As age-at-death (4.4±1 years) and sex (male) had been confirmed by dentition and DNA, haplogroup K also indicated a likely European ancestry. Further investigation continued in an attempt to identify the individual. The initial indication that a male aged 4.63 years had gone missing and drowned was further investigated by mtDNA reference of a maternal relative. A complete mtDNA profile was attained for the cranium, to compare to a maternal DNA reference of a potential sibling, obtained by a buccal swab (Speller et al. 2012). The investigation was undertaken in an attempt to attain a paternal DNA reference from a putative father. Through mini-STR analysis, both the DNA from the putative father and the remains exhibited a heterozygote peak pattern, of which both loci evidenced a paternal allele, hence a parent-child relationship was determined (Speller et al. 2012).

The ability to reconstruct a biological profile of human skeletal remains, through anthropological methods, has provided sufficient evidence to secure legal identification of this deceased child. A portion of the skull and incomplete dentition was enough to determine age-at-death, and with the addition of DNA, a positive identification was made. In 2009, the identity of the remains was confirmed as the missing child presumed drowned in the spring of 1965; a death certificate was issued, the case closed, and loved ones gained peace of mind (Speller et al. 2012). Age-at-death dentition techniques were critical in the process of assigning an identity to the child's remains, 40 years later. This forensic case exemplifies the potential biological anthropology has in the identification of remains through biological profile construction. In collaboration with modern mtDNA analysis, radiocarbon assessment of enamel, and the role of bomb-pulse methodology in determining birth year via tooth formation, this case was solved.

# Subsequent case studies

Two additional cases illustrating the use of age-at-death estimation to construct a biological profile are briefly summarised. Both of these cases involve a focus on the analysis of dentition for subadult age-at-death remains within a forensic context, whereby identity has been prescribed, criminal evidence communicated, and justice served. In 2005, human remains were recovered in a Scottish woodland with severe facial and head injuries; identification could not be determined (BDJ 2011). Authorities were searching for a missing five-year-old girl at the time, who lived in close proximity to where the remains were found (BDJ 2011). Postmortem dental age estimation by means of Buikstra and Ubelaker's (1994) eruption and formation stages confidently estimated the age-at-death of the subadult to be approximately 5 years ± 3 months (BDJ 2011). Postmortem radiography confirmed the presence of a carious, lower-left, deciduous molar with apical pathology, confirming the identity of the child from a previous dental record of an untreated abcess (BDJ 2011). This conclusion was further supported by clinical examination and DNA testing. The mother and stepfather of the five-year-old were suspects in the trial. The child's stepfather was convicted of manslaughter. This closing of the case and bringing of justice came about as a result of a heavy dependence on forensic dental identification.

Thirdly, a case of juvenile skeletal remains, found by a fast-flowing river, was investigated from 1991–1993 (BDJ 2011). There was no skull, although a mandible, sections of a pelvis, and numerous pieces of rib and vertebrae were among the remains (BDJ 2011). Clinical and radiographic dental examination gave a precise age-at-death estimation—based on standards of Buikstra and Ubelaker (1994) and Gustafson and Koch (1974)—of 8.3 years ± 3 months (BDJ 2011). Posterior deciduous teeth were missing from the mandible, posing some aspect of identity determination. After DNA testing and ante-mortem dental records evidencing the deciduous teeth extraction, the identity of the remains was identified as being those of a young boy, Jaime Lavis, reported missing a year earlier (BDJ 2011). Jaime was last seen on a public bus, alone, groomed by the bus driver (Vickers) to remain on the bus for the rest of the day, according to security footage of the bus station depot. A sexually motivated crime, the bus driver was then found to have dispersed sections of the remains in various locations; no more of them have been recovered (BDJ 2011). He was sentenced to life in prison. If forensic odontology was unable to identify the age-at-death and identity of Lavis by means of radiographs and dental records, Vickers would not have been prosecuted. Jaime Lavis was 8 years and 6 months old—within two months of the age-at-death estimation deduced from dental-eruption stage methods of the teeth of the lower mandible (BDJ 2011).

It is through the extensive scientific research that anthropological methods have been developed to accurately construct biological profiles of deceased individuals. In subadult contexts, age-at-death estimation poses the greatest potential in determining identity, by fontanelle closure, epiphyseal fusion, and, in particular, through analysis of dentition. The individuality and preservable nature of teeth make them invaluable in forensic investigation, and in cohesion with other skeletal parameters, age-at-death and identity can be estimated to a great degree of accuracy.

It is in these forensic cases that the importance of biological profile reconstruction is foregrounded. Particularly identifiable in the first case study, the application of eruption and development sequences proves successful in the aging and subsequent identification of subadult remains. Similarly, the secondary and tertiary cases where dental approaches were applied allowed for the accurate age-at-death of the subadult's dental remains attributed to Ubelaker's (1987) and Gustafson and Koch's (1974) standards. Of all of the above cases, remains were accurately aged based on dental approaches and successfully identified by individual dental records. Age-at-death estimation by forensic odontology applies numerous standards and methods to analyse dental parameters, estimate age-at-death, and accurately conclude identity.

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