10 Dental Age revisited

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10.1 Introduction

Tooth formation spans childhood, with hard tissue formation beginning during the first trimester in utero, continuing during infancy up to adulthood, and ends with maturation of the root apices of the third permanent molars. This long duration makes developing teeth a very useful indicator of maturation in the clinical setting and estimator of age of minors who lack official identification and/or seek asylum, forensic identification and for immature skeletal remains obtained from archaeology contexts. Measuring tooth formation is complex and differs to other maturing body systems, and some knowledge of the difficulties and challenges of different methods is needed to appropriately estimate age. This chapter builds on work by Scheuer and Black (2000), and is divided into two sections, quantifying dental formation and estimating age. Each section includes definitions, descriptions of difficulties, how to measure growth and maturation of teeth and the dentition, how to estimate age from growth and maturation references, some comparison between methods and finally recommendations.

10.2 Quantifying dental formation

10.2.1 Definitions of dental growth and maturation

Although growth and maturation are intimately related, some definitions are needed to clarify the differences between these two processes and techniques used to measure them. Two recent books review the principles and methodology of human growth and maturation (Cameron, 2002; Hauspie et al., 2004) and are highly recommended. Growth represents an increase in the size/volume and once dentine and enamel begin to form, growth of a tooth can be quantified by measuring crown height, root length/ volume, root cone angle, apex width or other dimensions. Growth of the dentition can be measured by counting the number of developing teeth within the jaws or erupted teeth present in the oral cavity.

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Maturation is the process of change from an immature to a mature state. A developing tooth will grow in size, volume and length but it also matures from cusps tips to a fully formed crown, full length root and a mature root apex that appears closed radiographically. In multi-rooted teeth, the distal root usually matures later than the other roots. When assessing maturation of a multi-rooted tooth the observer should base their estimate on the later-maturing distal root. During root formation, the tooth erupts into the oral cavity (a maturity event). Eruption occurs at the same time as alveolar bone resorption and formation as well as development of the periodontium and gingivae. These latter processes continue until the tooth is fully erupted into a functionally occluding position with the tooth in the opposite jaw. Once the third molar root is complete, the dentition has reached full maturity. Maturation of individual teeth has been well documented, although there is considerable discrepancy between reference studies despite large samples, wide age ranges and sound statistical methods. Dental maturity of the developing dentition has also been quantified using tooth formation and/or eruption where scores convert to an age scale, expressing age up to full maturity.

10.2.2 Differences between the dentition and other body systems

Growth and maturation of individual teeth and the dentition as a whole differ from other maturing body systems in three important ways. The first difference is that dental maturation appears to be independent of both skeletal and secondary sexual maturation and less influenced by nutritional and other environmental insults. A child’s height and weight reflects health and nutrition. This is true on both individual and population levels. Differences between populations in these parameters (including age of puberty) are due to interaction between genetic and environmental factors, hence the reason for population specific references. Substantial environmental influences have not been demonstrated for dental maturity. Rather, dental maturity appears to be largely genetically controlled on both individual and population levels (Pelsmaekers et al., 1997), but clear genetic differences in maturation of the dentition have not, as yet, been documented.

The second difference between the dentition and other systems that mature is that tooth formation proceeds at a chronologically regular rate. An inherent problem of skeletal and secondary sexual maturation is that individuals exhibit considerable uneven maturation (see Cameron, 2002). There is marked variation in the rate or tempo of maturation with different bones or organs, each maturing at different speeds within an individual. This is very different to the developing dentition because once the process of dentinogenesis begins, the crown, root and pulp will continue development until the root apex and periodontal attachment are mature and the tooth is fully erupted.

10.2.3 How tooth formation differs between individuals/groups

Three factors can influence tooth formation that result in differences. Firstly the time of initiation can be different, secondly the rate of formation can vary and thirdly the morphology (including root length) can differ. If the initial timing of cusp tip mineralisation differs, then individuals and groups differ in the timing of all subsequent crown and root stages. Radiographic verification of this is difficult because, with few exceptions, the minimum age of subjects is between two and three years of age; in some cases, considerably later.

Tooth formation can also differ in the rate of crown or root formation. Some knowledge of dental histology is necessary to appreciate that the most likely way in which the rate of amelogenesis and odontogenesis can differ, is a change in the number of differentiating cells that secrete hard tissue. Histological analysis of the entire dentition and the few studies that document the timing and duration of individual teeth, reveal that the interval of molar crown development differs little between European, African and North American groups (Reid and Dean, 2006). Some differences in the rate of anterior crown formation have been documented from this study, although it remains to be seen if these are apparent at the resolution seen on radiographs. The third difference relates to morphology of the crown and root including root length. If a tooth, say a third molar, has a short root, the duration of root formation will be shorter and age at full maturity of this individual will be considerably earlier than an individual with a long rooted tooth.

10.3 Measuring dental growth and maturation

10.3.1 How do we measure dental growth?

Dental growth can be quantified in several ways including tooth length or volume from either isolated teeth or radiographs as well as combinations and ratios of crown, root, apex, pulp dimensions or root cone angle for age (Stack, 1960, Harris and Nortjé, 1984; Cameriere, et al.. 2004; Cameriere, et al., 2006; Dean, 1985; Deutsch et al., 1985; Liversidge et al., 1993; Kullman et al., 1995; Liversidge and Molleson, 1999; Mörnstad et al., 1994). Growth of the dentition can be measured by counting the number of teeth present in the mouth or number of developing teeth in the jaws. This can be expressed as number of teeth erupted at specific ages or average age when a specific number of teeth are present, but only a handful report standard deviation. More recent studies that do, include a meta-analysis of the number of deciduous teeth in the mouth (Townsend and Hammell, 1990), one from Finland (Nyström et al., 2000; Nyström et al., 2001), Sweden (Hägg and Taranger, 1985), two groups from Kenya (Hassanali and Odhiambo, 1982), Zambia (Gillett, 1997) and Punjabi children from India (Kaul and Pathak, 1988).

10.3.2 Dental maturity indicators

Maturity of individual teeth is a continuous process and in order to measure this process, this continuum is arbitrarily divided into discrete maturity indicators or in this case, crown and root stages. The number of stages should be a balance between a sufficient number to quantify variability yet maintain adequate reliability. Too many stages decrease reliability, while too few compromise sensitivity. For this reason, the fourteen stages developed by Moorrees and coworkers (1963) and adaptions of this scheme remain popular. Estimating fractions of crown height or root length are subjective. Measurement of root length relative to the crown height partly overcomes this difficulty. The eight stages of Demirjian and co-workers (1973) are clearly described and accompanied by a radiograph and line drawing for each stage and tooth type.

Choice of maturity indicators is determined by a number of factors (see Cameron, 2002). Among other things, these indicators should be reliable (good intra- and inter-observer agreement) and show a quality of completeness (increase in prevalence from 0 to 100% in a short period of time). This last feature presents a challenge with regard to dental formation and highlights the need for a large number of children within each age year cohort. This is illustrated in Figure 1a showing preliminary results of a radiographic investigation of the timing of initial mineralisation (1a) and apex maturation (1b) of mandibular third molars. The proportion of two groups of children in London (Bangladeshi and white) at each stage is plotted by age group; N 807 and 946. These cumulative curves show the youngest age of each stage up to the age when all children have reached the stage. At age five, no child shows initial cusp tip formation, by age 14 all children do. Similarly, no 15 year olds have reached apex closure, while 100% of 24 year-olds have.

10.3.3 How is dental maturity measured?

Maturity can be measured in several ways. The three methods applicable for assessment of the developing dentition are the atlas, timing of crown and root stages of individual teeth, and a maturity scale using tooth-specific scores.

The atlas is by far the easiest method. With an atlas, maturity is compared to reference drawings of developing teeth at specific ages. This method suffers from several difficulties. The first is the problem of age, for not all children match the drawings. In fact, not all teeth will match the maturity levels. Another limitation is assessing eruption on a dry specimen. Alveolar eruption is not equivalent to clinical emergence into the mouth. To date the variability and timing of eruption stages not been incorporated into an updated atlas. A further difficulty is maturity overlap. This occurs when a tooth or group of teeth is not in synchrony with the rest of the developing dentition. In such cases, the researcher is forced to choose whatever drawing for age that fits most closely to the individual being assessed.

The second method measuring maturity involves calculation of the timing of maturity indicators for individual teeth. This can be done in two ways. The first involves calculation of the average age of entering the stage. This can be illustrated by plotting a cumulative frequency distribution or cumulative percentage curve of children who have reached a maturity indicator by age. This will demonstrate if the age range is appropriate (see Figure 1). The average age at entry or mean age of attainment is best calculated using logistic or probit regression equivalent to the age when half the children (50th percentile) reach or have surpassed that maturity indicator/ stage. Many maturity indicators show high variance and children who mature early will enter a defined stage considerably earlier than a child who matures. The appropriate way to compare groups is to compare the average age for each maturity stage. Look again at Figure 1. The proportion of children with 'Ci' increases with age until 100% of the age group have attained the stage. The average age of entering stage ‘Ci’ (cusp initiation) and ‘Ac’ (apex closure) is the age when 50% of the whole sample attains these stages. If the third molar takes about ten years to form, the extremes of formation time in the groups shown in Figure 1 will be 6 to 16 in an early maturing child and 13 to 23 years of age in a later maturing individual. The 50th percentile as well as extremes (3rd and 97th percentile) are useful to describe maturity of this stage. One group (dotted line, Bangladeshi) appears to be earlier at the 50% level and for most of the age groups except for 7 and 13 for ‘Ci’ and 17 and 22 year olds for ‘Ac’.

Although a number of studies claim that population differences exist in tooth formation, scrutiny of their methodology and age distribution suggest that neither cumulative methods nor sufficient age range are used. One large study of children of European origin showed neither consistent nor systematic difference in the timing of mandibular permanent teeth, (Liversidge *et al.*, 2006). To date, few comparisons of tooth formation from different regions have been documented except for third molars (Liversidge *et al*., 2005; Harris 2006). Results from a large worldwide study show that initiation of the third molar is significantly delayed in

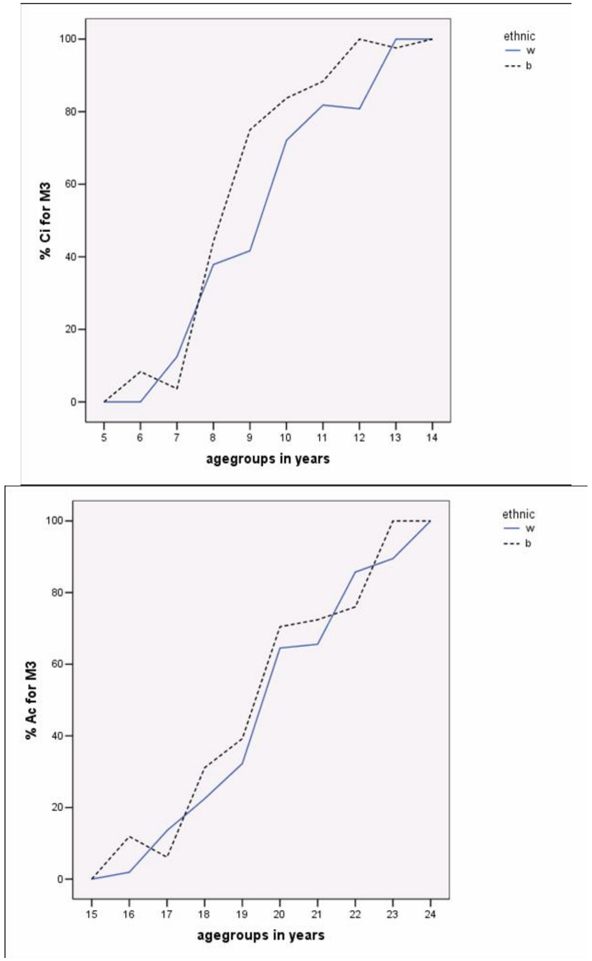

Figure 10.1. Cumulative percentage of children in London with ‘Ci’ initial mineralisation of cusp tips(a) and ‘Ac’apex closed (b) of M_3 plotted against the beginning of the age group. w= white (n=946), b= Bangladeshi (n=807).

two London groups and one Cape group compared to Black children from Southern Africa (Liversidge, 2007).

Timing of individual maturity indicators can also be determined, secondly, by calculating the average age of children who show the stage in question. The average is influenced by sample size and age distribution and ideally 3rd to 97th percentile should be included. This method is not suitable for the most mature stage of formation. Studies that report 'population differences' (particularly of the third molar) using average age midstage rather than mean age at entry should be interpreted with in mind.

The third method to quantify dental maturity employs tooth-specific scores that add up to dental age, based on the principle first used to quantify bone age. The maturity of individual wrist bones does not coincide and maturity can be expressed using a weighted score from a combination of bones (see Cameron, 2002, p117). This minimised disagreement thereby overcoming the problem of uneven maturity. The frequency of individuals in the sample increases for each bone[tooth] maturing from 0 to 100% and maturity of a child is compared to the reference study. Each left mandibular developing tooth is given a score, depending on the stage of crown or root formation. The sum of these scores converts to percentage mature and dental age. The most widely used application is by Demirjian and co-workers on a large French-Canadian sample (Demirjian *et al.*, 1973; 1986; 1994) where maturity of seven permanent mandibular teeth is assessed. Demirjian's method is appropriate from 2.5 to 16 years of age. The dental maturity minimum score is around 12% corresponds to age 2.5 at the 50th percentile; the maximum score is 100 % mature at age 16 (defined as the second molar distal root apex closed with a uniform width of the periodontal ligament).

10.3.4 Difficulties with Demirjian's dental maturity score and it's interpretation

Demirjian's method is a useful method to assess dental maturity, however, it is compromised by several problems. The first is the difficulty determining variation from the graphs. Variation is provided not in age but in scores for 3rd, 10th, 50th, 90th and 97th percentiles. If a boy has a score of 54, the 50th percentile is 7 years. If we look at the 3rd and 97th percentile scores for a seven year old boy they are 35 and the 74. These scores can be traced back on the graph to the 50th percentile of 5.4 to about 8.4 years. If we take the extremes, then a boy with a score of 35 at the 97th percentile could be aged 3.5 and similarly, the 97th percentile of score 74 is dental age almost ten. If this was an average maturing child, his dental age would correspond to known age and when calculating dental age using this method it is reasonable to assume that the child is an average maturing child at the 50th percentile. Another difficulty with this method is the weighted score, adjusted by a number of researchers using much smaller samples and one larger sample (Chaillet *et al*., 2005). The easiest and most accurate (see later) gives scores that add up directly to give dental age (Willems *et al.*, 2001). The standard deviation peaks around 8 years of age for both sexes (Chaillet *et al.*, 2005) while the difference in scores between boys and girls is greatest at 12 to 13 years. Such results reflect the weighted scoring and do not mirror the biological variation of tooth formation. We know that the variation in the timing of dental formation stages increases with age (Moorrees *et al.*, 1963) and that the largest sex difference in timing are the canine late root stages (Thompson *et al*., 1975). It is not surprising those differences between individuals and between groups peak at the age when standard deviation is highest. The majority of maturity indicators occur in girls during the fourth year. Figure 2a shows the timing of the 39 maturity indicators for girls and how these decrease with age. This means that a one stage difference in older children can result in a large jump in dental age. For example, if all mandibular teeth are in stage H (mature apices) except for the second molar which is stage G (walls of distal root are parallel/ open apex), dental age is 14.6 years. A one stage difference from stage G to H of M_2 results in a jump in dental age to 16 years.

Numerous studies of dental maturity of groups in different parts of the world have demonstrated an advancement compared to the Canadian reference and these have been interpreted as population differences or a secular trend. It is probable that neither of these is correct. A secular trend would need a comparative reference sample that antedates World War II, but all large dental radiographic studies are later than this (see Cole, 2003). Differences in maturity score between groups are difficult to interpret, are complicated by the scoring matrix and may have no biological meaning (Prahl-Andersen *et al*., 1979). This is supported by the lack of any consistent tooth differences in the timing of these stages between children from a large data base from Australia, Belgium, Finland, France, Quebec, Korea and Sweden (Liversidge *et al*., 2006). In fact, a curious finding in this large data base was the late apical maturation of the first permanent molar in children from Quebec – might this account for the difference in dental maturity between the reference and other groups? Figure 2b shows differences in dental maturity for girls expressed in standard deviation or z-scores. These are from studies that document difference in years or score by age group (Nyström *et al.*, 1986; Farah *et al*., 1999; Hedge and Sood, 2002; Zhao *et al*., 1990; Eid *et al*., 2002, Nyarady *et al*., 2005; personal comm. Fatemi). Differences more than 1 z-score are mostly between ages 4 and 8 years of age and tail off for later ages when few maturity indicators occur.

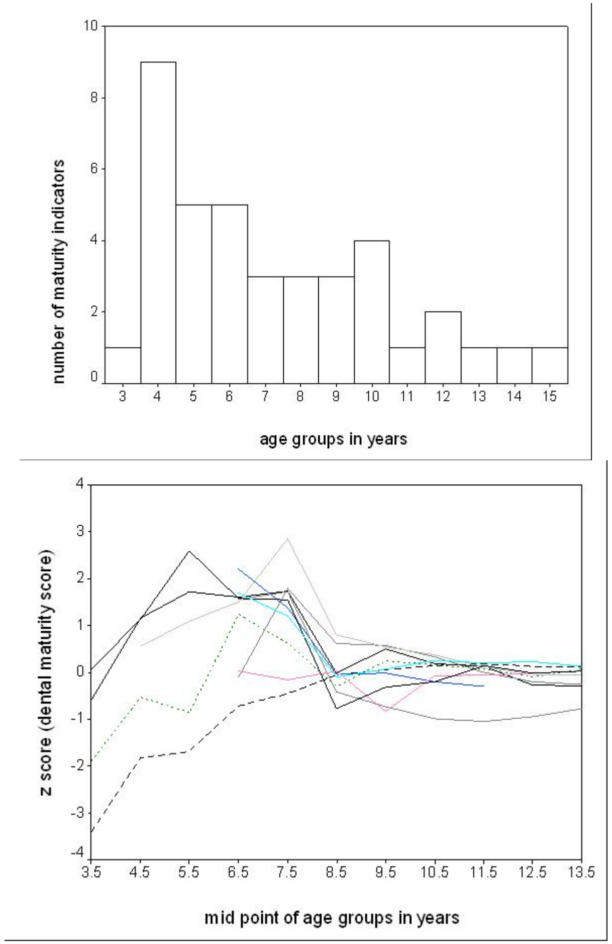

Figure10. 2 (a. Dotplot of the timing of maturity events in girls with Demirjian's dental maturity score. (b) Z scores of difference in Demirjian's dental maturity plotted against age group

10.3.5 Other difficulties with tooth formation/dental maturity data

A common and major misconception of any maturity grade/score is the fundamental principle that it is not *per se* is not a parameter; it is not a measurement, for it has no units and therefore parametric statistics using numerical maturity scores are flawed. The interval between different crown or root stages differs and consecutive maturity indicators are not of equal duration hence the choice of nominal or tooth formation stages (A to H from Demirjian, 1 to 10 from Nolla, 1960). Changing nominal maturity indicators to numerical values (stage A=1, B=2…) and calculating the 'average stage' goes against the basic principle of measuring maturation and is incorrect. Despite this, numerous studies of third molar formation show a lack of understanding of principles of dental growth and maturation. Further difficulty that complicate interpretation of findings from comparisons of dental formation and maturity between groups include small sample sizes, uneven age/sex distribution, and non-random selection. If the sample size is large enough, outliers will not greatly alter the 50^{th} percentile and, if only a few individuals for a year of age are included, this is unlikely to include sufficient individual who are 'average'.

The exact age at which a maturational event occurs in a child will only be observed if that child is followed longitudinally at frequent intervals. Assessing maturation of teeth is retrospective as one can only see if the event has or has not occurred; i.e. if the tooth has erupted into the oral cavity or if the crown is complete. The duration of crown or root stages of individuals is best determined from longitudinal radiographic studies and because of this the precious historical collections from the middle of last century represent a rich and precious source.

10.4 Estimating age

10.4.1 Definitions and how accuracy is measured

Accuracy is a measure of how close dental age can estimate known age. Hence, a method with high accuracy will provide an estimate of age that is close to known age, while an inaccurate method will over- or underestimate known age. The difference between dental age and known age is one way to express accuracy. Lovejoy *et al.* (1985) describes the difference between estimated and known age as bias as it measures the amount of over- and underestimation. Another measure is the proportion of the test sample where estimated age is within ±0.5 years, ±1 year etc. of known age or age class. This has an advantage that skewness, kurtosis and rank distribution for each age class can be quantified. Some studies correlate estimated and known age or tooth stage and age, however, although this measures association, it is influenced by age range and gives little information of how close estimated age is to known age. Sensitivity (true positive), specificity (true negative), likelihood or odds ratio and area under the Reciever Operating Characteristic (ROC) curve are designed for diagnostic discrimination. Discriminating between age categories such as younger or older than 14 or 18 years is likely to prove useful in the legal context.

The continuous maturation process of the tooth, from crypt formation to apical maturation is arbitrarily divided into stages. When one examines a developing tooth we recognise and classify it into a defined crown or root stage; however, it entered this stage some time previously, it might be midstage, or it might be very close to entering the next stage. Smith (1991) suggested that a midpoint between entering tooth stages would be more accurate than age at entry and adapted data from Moorrees *et al.* (1963) for estimation. A sensible approach is to assume that the individual for whom age is to be estimated, was an average child whose biological age reflects their chronological age.

10.4.2 Difficulties comparing published results

Several problems come to light when the published results of accuracy tests of methods that estimate age using dental maturation are compared. These problems results from how accuracy is measured and the nature of the test sample. It is useful to report both accuracy (closeness to true age) as well as absolute accuracy. Comparing accuracy between different crown or root stages, different teeth, age groups or methods is difficult when accuracy is measured in so many different ways. This is further complicated if a separate test sample is not used, or if the test sample is small with a narrow or uneven age range or is grouped. Test samples usually use autopsy collections, recent archaeological collections of known age and larger groups of living children. Ideally a test sample should be of sufficiently large size, an even age distribution (similar numbers in each year of age), encompasses an appropriate age range and a separate test to study sample. If a new method of age prediction is described, the accuracy should be tested on a different sample.

Similar difficulties that hamper dental maturity studies also affect test samples. For example, if the test sample age range small and consists of fewer than ten children for a year of age, it will probably not include enough average maturers and several advanced or delayed children may skew results. This also occurs if the age range of the test sample is inappropriate. With increasing age and maturation, the number of developing teeth decreases so that by about age 14

usually only the third molar is incomplete. This presents another problem for tests of accuracy if individual teeth are used to estimate age. From the age of thirteen, a few children will have completed apical maturation of the second premolar and second molar and so drop out of the test sample. This means that the later age groups are smaller and these children are those that are slow to reach maturity (above the 90th percentiles). This is a reflection of maturity data being slightly skewed to the right. Even with a large test sample, it is not unusual to find a small number of children with delayed tooth formation and age for these children will be considerably under-estimated.

10.4.3 The level of accuracy

An acceptable level of accuracy has not been clarified. Accuracy is likely to be more accurate for younger children where maturity indicators are more frequent and the rate of growth and maturation is most rapid. Calculating age of an individual who died prior to completion of tooth formation is possible by making histological sections of all teeth and counting enamel cross striations from the neonatal line (see Boyde, 1963). The neonatal line allows the exact timing and duration of tooth formation in an individual to be calculated (Dean and Beynon, 1991; Dean *et al*., 1993; Reid *et al*., 1998) but this method is highly skilled and time consuming. The best deciduous tooth to view the neonatal line in dentine and enamel is the second deciduous molar (personal comm. W. Birch). It is thought that the presence of this accentuated growth line in deciduous teeth (and the mesiobuccal cusp of the first permanent molar) indicates that the individual survived birth by probably one or two weeks. Absence of this line does not rule out a live birth, as the neonatal line is visible in most but not all histological sections of deciduous teeth; Schour could identify it in 90 of 100 sections (Schour, 1936). Factors that influence this include position of the section and quality of the preparation.

10.4.4 Which tooth formation method is most accurate?

Maber *et al*., (2006) compared the difference between estimated and known age using several dental maturity methods Demirjian (1994), Willems *et al.* (2001), Nolla (1960) and individual teeth from Haavikko (1970) on a test sample of 946 children aged 3 to 16.99 years. These data have been further analysed for this chapter, with the addition of several methods and calculation of absolute median difference shown in Table 1. All methods tested underestimated age, with the exception of Demirjian (1994). The two methods with least difference between estimated and known age were Liversidge midstage (see Table 3) and Willems *et *al.* (2001) adapted scoring. Absolute difference takes no account of the direction of over or under-estimation and reports the time distance from known age. The median absolute difference was least for Willems *et al.* (2001) at 0.52 year followed by 0.55 and 0.56 year using updated scores (Chaillet *et al*., 2005) and adapted data (cumulative mean age of attainment plus half the interval to the next stage, see Table 3) using Liversidge *et al.* (2006) respectively. These two last mentioned studies are different approaches to the same dataset, firstly using all teeth to calculate a dental age, and secondly calculating the timing of individual tooth stages.

Table 10.1. *Average difference and median of absolute difference between estimated and known age in years for different methods. Sample is 946 radiographs used in Maber et al. 2006.*

Method	N	Difference mean	Absolute difference median
Demirjian 1994	946	0.23	0.59
Willems *et al.* 2001 scores	946	-0.12	0.52
Chaillet *et al.* 2005	946	-0.26	0.55
Nolla 1960	946	-1.02	0.93
Haavikko 1970	832	-0.67	0.64
Moorrees *et al.* 1963	833	-1.19	1.00
Smith 1991 (Moorrees adapted)	833	-0.67	0.64
Liversidge *et al.* 2006 (mean entering…)	812	-1.13	0.98
Liversidge *et al.* 2006 (adapted)	812	-0.20	0.56
Liversidge *et al.* 2006 (mean age midstage)	827	-0.12	0.78

These results suggest that estimated age using developing teeth will have an absolute difference of between six months and a year, depending on which method is used to assess developing teeth. The percentage of individuals from this sample aged to within half a year was greatest (48%) using Willems *et al.* (2001), 46% for both Chaillet *et al*., (2005) and Liversidge adapted, while other methods fared considerably worse. If all teeth are available to estimate age, the scoring of Willems *et al.* (2001) is the method of choice for both ease and accuracy, followed by Chaillet *et al*., (2005) that has the advantage of giving percentiles. If only some teeth are available to estimate age, data adapted from Liversidge (Liversidge *et al.* 2006) are recommended (see Table 3). Nolla (1960) and mean age of entering a stage data (Moorrees *et al.* 1963; Liversidge *et al.* 2006) are not recommended for age estimation.

Inspection of the surrounding alveolar bone can help estimate age if the tooth is not in position. The shape of the tooth crypt at the depth of the developing root apex intimately mirrors the root shape and will be broad and rounded if the root is still growing. Similarly if the furcation shape of a molar crypt is visible, the roots will have matured past the cleft stage. A bony groove on the normally sharply defined alveolar bone crest may be seen around an erupting tooth and this may be seen even if the tooth is not present. If a fractured root tip is in situ, it may be possible to see if the apical root canal is wide open suggesting that the apex is not yet mature.

We have to make several assumptions about the individual for whom we are estimating age. The most important is that the child was an average child and at the mean value or 50^{th} percentile of growth and maturity. We assume that he/she entered this tooth stage at the average age and is half way between this and the subsequent stage. We know that the standard deviation in timing of any tooth formation stage can be up to a year; for instance the mean age and SD of M_1 stage E (includes initial root, cleft and quarter root) is 4.98 $\pm$1.02 year (pooled sex, Liversidge *et al*., 2006). It is possible that the child was advanced and in the 3^{rd} percentile having reached this stage at a considerably younger age than average. On the other hand, the child may have been dentally delayed (in the 97^{th} percentile) and reached this stage at a much older age. Hence the need for documented measures of variation (3^{rd} and 97^{th} centiles or standard deviation). The 3^{rd} and 97^{th} centiles can be calculated as mean ± kxSD where SD is standard deviation and k is the multiplier, in this case 1.88, provided the distribution is Gaussian (see Cole, 2002). These extreme values and also the first and last stages of maturation can provide one sided age limits 'at least' and 'older than' categories. If a tooth has reached apex closure, the individual might have reached this a considerable time earlier and only a minimum estimated age is appropriate, although the 50^{th} or 97^{th} percentile of entering that stage increases precision of an estimated minimum age.

The recommendations for age estimation are as follows.

1. In early childhood, tooth length of developing deciduous teeth is an easy and accurate method
2. The timing of eruption stages of teeth, such as alveolar eruption is also useful. Age of alveolar eruption adapted for age estimation for mandibular deciduous and some permanent molars are shown in Table 2 (boys and girls combined).

3. Tooth formation stages with high reproducibility are more likely to have better accuracy than subjective crown or root fractions. Crown completion, especially of skeletal material, root length equal to crown height and root apex open are useful stages. They are also useful cut off points and provide guidance that an individual is younger/older than the average age of the stage.
4. The average age of crown completion of the permanent first molar occurs at 3 to 3.3 years. The ages for anterior permanent crown completion are detailed in Reid and Dean (2006).
5. Estimating age from individual developing teeth is best using adapted age at entry methods. These are detailed in Table 3 for mandibular permanent molars for tooth formation stages described by Moorrees et al (1963) and Demirjian (1994) for boys and girls combined.
6. Dental maturity calculated from seven mandibular teeth is marginally more accurate using scores from Willems *et al.* (2001) compared to Demirjian scores or updated scores (Chaillet *et al*. 2005).

Table 10.2. *Average age in years of eruption stages for mandibular deciduous teeth and first two permanent molars (sexes pooled) adapted for estimating age. Alveolar eruption, cusp tip(s) at alveolar bone level, partial eruption, cusp tip(s) or occlusal level of tooth between alveolar bone level and occlusal level of fully erupted teeth.*

	Alveolar eruption	Partially eruption
i1	0.46	0.78
i2	0.84	1.15
c	1.18	1.62
m1	1.05	1.43
m2	1.72	2.28
M_1	5.25	6.24
M_2	10.78	12.01

10.5 Summary

Understanding the principles of growth and maturation is essential in order to compare maturation between groups of children and appropriately use reference studies to estimate age. The average age at entry (the age when half the sample has reached or passed the stage in question) is appropriate for comparison. Using such data to estimate age will under-estimate age by more than a year. There is a need for population specific references of tooth formation from major regions and groups of the world and several studies are underway. To date, the only clear difference between groups appears to be the age of initiation of the third molar. Assessing dental maturity of small regional groups of narrow age range is now of little interest, especially for children of European origin. The biological meaning of differences in Demirjian's dental maturity between groups is unclear.

Far more interesting questions concern differences in the timing of initiation and completion of teeth, the overlap between tooth types and how root growth and length can differ between groups. Other questions include how morphologic differences occur between groups and how these relate to tooth formation as well as jaw growth, space within the mandible and interaction between crown /root morphology and formation.

Table 10.3. *Average age in years of some tooth formation stages for some mandibular permanent molars adapted for estimating age. Demirjian (1994) stage D corresponds approximately to Moorrees et al. (1963) stages Cc, stage E includes Ri, Rcl and R1/4, stage F corresponds to R1/2 and R3/4, while G is similar to Rc. Timing of midstage and Liversidge adapted are from Liversidge et al. (2006). Data for Liversidge midstage are for sex pooled.*

	Moorrees stage	Smith (1985) Boys	Smith (1985) Girls	Demirjian stage	Liversidge adapted Boys	Liversidge adapted Girls	Liversidge midstage
M1	Cc	2.5	2.4	D	-	-	3.90 ±1.18
	Ri	3.2	3.1				
	Rcl	4.1	4.0	E	4.80	4.58	4.98 ±1.02
	R1/4	4.9	4.8				
	R1/2	5.5	5.4	F	6.20	5.81	6.25 ±1.09
	R3/4	6.1	5.8				
	Rc	7.0	6.5	G	8.38	7.84	8.45 ±1.36
	A12	8.5	7.9				
M2	Cc	6.8	6.6	D	7.78	7.45	7.81 ±1.10
	Ri	7.6	7.3				
	Rcl	8.7	8.4	E	9.74	9.35	9.54 ±1.14
	R1/4	9.8	9.5				
	R1/2	10.6	10.3	F	11.46	10.84	11.08 ±1.15
	R3/4	11.4	11.0				
	Rc	12.3	11.8	G	13.74	12.92	13.16 ±1.44
	A12	13.9	13.5				

References

Boyde, A. 1963. Estimation of age at death of young human skeletal remains from incremental lines in dental enamel. Proceedings of Third International

meeting of Forensic Immunology, Medicine, Pathology and Toxicology, London.
Cameriere, R., Ferrante, L., and Cingolani, M. 2004. Precision and reliability of pulp/tooth area ratio (RA) of second molar as indicator of adult age. *Journal of Forensic Sciences* 49, 1319-1323.
Cameriere, R., Ferrante, L., & Cingolani, M. 2006. Age estimation in children by measurement of open apices in teeth. *International Journal of Legal Medicine* 120, 49-52.
Cameron, N. 2002. *Human growth and development*, Academic Press, San Diego, California, USA.
Cameron, N. 2004. Measuring maturity. Methods in Human Growth Research. (ed. By Hauspie, R., Cameron, N., and Molinari, L), pp. 108-140. Cambridge University Press, Cambridge.
Chaillet, N., Nyström, M., and Demirjian, A. 2005 Comparison of dental maturity in children of different ethnic origins: International maturity curves for clinicians. *Journal of Forensic Science* 50, 1164-1174.
Cole, T. J. 2003. The secular trend in human physical growth: a biological view. *Economics and Human Biology* 1, 161-168.
Cole, T. J. 2002. Growth references and standards. Human Growth and Development. (ed. by Cameron, N), pp. 383-413. Academic Press, San Diego, California, USA.
Dean, M. C. 1985. Variation in the developing root cone angle of the permanent mandibular teeth of modern human man and certain fossil hominids. *American Journal of Physical Anthropology* 68, 233-238.
Dean, M. C., and Beynon, A.D. 1991. Histological reconstruction of crown formation time and initial root formation times in a modern human child. *American Journal of Physical Anthropology* 86, 215-228.
Dean, M. C., Beynon, A.D., Reid, D. J., and Whittaker, D. K. 1993. A longitudinal study of tooth growth in a single individual based on long and short period incremental markings in dentine and enamel. *International Journal of Osteoarchaeology* 3, 249-264.
Demirjian, A. Dental Development on CD-Rom. 1994. Silver Platter Education Inc., Norwood.
Demirjian, A. 1986. Dentition. Human Growth: A Comprehensive Treatise, Postnatal Growth and Neurobiology (ed. by. Falkner F, Tanner. J), pp. 269-298. Plenum Press, New York.
Demirjian, A, Goldstein, H., and Tanner, J. M. 1973. A new system of dental age assessment. *Human Biology* 45, 211-227.
Deutsch, D, Tam.O. and Stack, M. V. 1985. Postnatal changes in size, morphology and weight of developing postnatal deciduous anterior teeth. *Growth* 49, 202-217.
Eid, R. M., Simi, R., Friggi, M. N., and Fisberg, M. 2002. Assessment of dental maturity of Brazilian children aged 6 to 14 years using Demirjian's method. *International Journal of Paediatric Dentistry* 12, 423-428.
Farah, C. S., Booth, D. R., and Knott, S.C. 1999. Dental Maturity of children in Perth, Western Australia, and its application in forensic age estimation. *Journal of Clinical Forensic Medicine* 6, 14-18.
Gillett, R. M. 1997. Dental emergence among urban Zambian school children: An assessment of the accuracy of three methods in assigning ages. *American Journal of Physical Anthropology* 102, 447-454.
Haavikko, K. 1970. The formation and the alveolar and clinical eruption of the permanent teeth. *Proceedings of the Finnish Dental Society* 66: 103-170.
Hägg, U., and Taranger J. 1985. Dental development Dental Age and Tooth counts. *The Angle Orthodontist* 55, 93-107.
Harris, E. F. 2006. Mineralization of the mandibular third molar: A study of American blacks and whites. *American Journal of Physical Anthropology* 132,98-109.
Harris, M. J., and Nortjé, C. J. 1984. The mesial root of the third mandibular molar. A possible indicator of age. *The Journal of Odonto-Stomatology* 2, 39-43.
Hassanali, J., and Odhiambo, J.W. 1982. Estimation of calendar age from eruption times of permanent teeth in Kenyan Africans and Asians. *Annals of Human Biology* 9, 175-177.
Hauspie, R., Cameron, N., and Molinari, L. 2004. *Methods in Human Growth Research*, Cambridge University Press, Cambridge.
Hedge, R. J., and Sood, P. B. 2002. Dental maturity as an indicator of chronological age: Radiographic evaluation of Dental age in 6 to 13 years children in Belgaum using Demirjian Methods. *Journal of Indian Society of Preventative Dentistry* 20, 132-138.
Kaul, S. S., and Pathak, R. K. 1988. Estimation of calendar age from the emergence times of permanent teeth in Punjabi children in Chadigarh, India. *Annals of Human Biology* 15, 307-309.
Kullman, L, Martinsson, T., Zimmerman, M., and Welander, U. 1995. Computerized measurements of the lower third molar related to chronological age in young adults. *Acta Odontologica Scandinavica* 53, 211-216.
Liversidge, H. M. 2007. The timing of third molar formation in four groups. *American Journal of Physical Anthropology* S42.

Liversidge, H. M., Chaillet, N., Mörnstad, H., Nyström, M., Rowlings, K, Taylor, J. and Willems, G. 2006. Timing of Demirjian tooth formation stages. *Annals of Human Biology* 33, 454-470.
Liversidge, H. M., Dean, M.C., and Molleson, T. I. 1993. Increasing human tooth length between birth and 5.4 years. *American Journal of Physical Anthropology* 90, 307-313.
Liversidge, H. M., and Molleson, T. 1999. Developing permanent tooth length as an estimate of age. *Journal of Forensic Science* 44, 917-920.
Liversidge, H. M., Townsend, G., Nortje, C. J., and Peariasamy K. 2005. The timing of third molar formation. *International Journal of Paediatric Dentistry (*Supp. 2) 15, 3 abstact.
Lovejoy, C.O., Meindl, R. S., Mensforth, R. P. and Barton, T.J. 1985. Multifactorial determination of skeletal age at death: a method and blind tests of its accuracy. *American Journal of Physical Anthropology* 68, 1-14.
Maber, M, Liversidge, H.M., and Hector, . P. 2006. Accuracy of age estimation of radiographic methods using developing teeth. *Forensic Science International* 159, 68-73.
Moorrees, C. F. A., Fanning E. A., and Hunt, E. E. 1963. Age variation of formation stages for ten permanent teeth. *Journal of Dental Research*, 42, 1490-1502.
Mörnstad, H., Staaf,.V.and Welander,U. 1994. Age estimation with the aid of tooth development: a new method based on objective measurements. *Scandinavian Journal of Dental Research* 102, 137-143.
Nolla, C. M. 1960. The development of the permanent teeth. *Journal of Dentistry for Children* 27, 254-266.
Nyarady, Z., Mörnstad, H., Olasz, L., and Szabo, G. 2005. Age estimation of children in south-western Hungary using the modified Demirjian method. *Fogorvosi Szemli* 98, 193-198. (in Hungarian.)
Nyström, M., Kleemola-Kujala, E., Evalahti, M., Peck, L. and Kataja, M. 2001. Emergence of permanent teeth and dental age in a series of Finns. *Acta Odontologica Scandinavica* 59, 49-56.
Nyström, M., Peck, L., Kleemola-Kujala, E., Evalahti, M., and Kataja. 2000. Age estimation in small children: Reference values based on counts of deciduous teeth in Finns. *Forensic Science International*, 110, 179-188.
Nyström, M., Haataja, J., Kataja, M., Evalahti, M., Peck, L., Kleemola-Kujala E. 1986. Dental maturity in Finnish children, estimated from the development of seven permanent mandibular teeth. *Acta Odontologica Scandinavica* 44, 193-198.
Pelsmaekers, B,, Loos, R., Carels, C., Derom, C., and Vlietinck, R. 1997. The genetic contribution to dental maturation. *Journal of Dental Research*, 76, 1337-1340.
Prahl-Andersen, B., Kowalski, C.J., and Heydendael, P. 1979. *A Mixed-Longitudinal, Interdisciplinary Study of Growth and Development.* San Francisco: Academic Press.
Reid, D. J., Beynon, A.D., and Ramirez Rozzi, F. 1998. Histological reconstruction of dental development in four individuals from a medieval site in Picardy, France. *Journal of Human Evolution*, 35, 463-477.
Reid, D. J., and Dean, M. C. 2006. Variation in modern human enamel formation times. *Journal of Human Evolution* 50, 239-246.
Scheuer, L. and Black, S. 2000. *Developmental Juvenile Osteology.* San Diego, Academic Press.
Schour, I. 1936. The neonatal line in the enamel and dentin of the human deciduous teeth and first permanent molar. *Journal of the American Dental Association* 23, 1946-1955.
Smith, B. H. 1991. Standards of human tooth formation and dental age assessment. In Advances in Dental Anthropology, eds. M. Kelley & C. S. Larsen, pp. 143-168. New York, Alan R. Liss.
Stack, M. V. 1960. Forensic estimation of age in infancy by gravimetric observations on the developing dentition. *Journal of Forensic Science* 1, 49-59.
Thompson, G. W., Anderson, D.L., and Popovich, F. 1975. Sexual dimorphism in dentition mineralization. *Growth* 39, 289-301.
Townsend, N., and Hammel, E.A. 1990. Age estimation from the number of teeth erupted in young children: an aid to demographic studies. *Demography* 27, 165-174.
Willems, G., Van Olmen, A., Spiessens, B. and Carels, C. 2001. Dental age estimation in Belgian children: Demirjian's technique revisited. *Journal of Forensic Science* 46, 893-895.
Zhao, J, Ding, L., and Li, R. 1990. Study of dental maturity in children aged 3-16 years in Chengdu. *Journal of West China University of Medical Sciences* 21, 242-246.