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Age estimation of children from prehistoric Southeast Asia: are the dental formation methods used appropriate?

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Abstract

Inter-population differences in skeletal and dental growth and maturation are acknowledged frequently in the biological anthropological literature. These growth differences have implications for the reliability of standards for the estimation of age at death of archaeological subadults. The number of archaeological projects that are recovering human burials from non-European contexts, including Southeast Asia, and the increasing interest in subadult bioarchaeological studies provides the impetus for investigating this issue of ageing subadult individuals from these populations. This paper aims to address some of the problems of the representativeness of ageing standards for non-European children in bioarchaeology. This is achieved through a literature review of the issue of growth variability and age estimation, and a basic comparison of the commonly applied age estimation method based on North American children with a dental formation study of modern Thai children. Although these studies do not employ similar methods the Thai study is the only comparable data available and therefore serves as a starting point to address these issues. The results raise an important question for bioarchaeologists of the appropriateness of available ageing methods. In addition this paper emphasises the need for the use of appropriate methodologies in the collection and presentation of dental formation data.

Keywords: Bioarchaeology; Age estimation; Ageing methods; Subadults; Dental formation; Thailand; Non-European

1. Inter-population variability in skeletal and dental growth

For bioarchaeological, human evolutionary and palaeodemographic studies accurate age at death estimation is crucial as it has repercussions for the interpretation of biological and cultural data. Bioarchaeologists are faced with the problem of using estimates of physiological age from available dental and skeletal data, which may be different from the chronological or actual age of the individuals studied. Accurate age estimation is important in bioarchaeological studies because mortality is a crucial parameter of health. As stated by Brothwell and Higgs (1969, p. 27) ‘‘[a]n important and revealing aspect of the study of early peoples is that of mortality. As is evident from modern populations, age at death is highly correlated with living standards in a community, economic status, and pressure of disease.’’ To illustrate the inappropriateness of the standards available for bioarchaeologists working with material that is non-European in origin an overview of literature pertaining to skeletal and dental growth in modern and non-modern contexts and methods for ageing subadults is presented. This is followed with a case study comparing the commonly applied Moorrees et al. (1963b) method of dental formation based on North American children with data from Thai children (Raungpaka, 1988).

When one seeks to understand the biology of past populations, the study of subadults must ultimately be based on the knowledge gathered from the examination of living children (Lampl and Johnston, 1996, p. 345). Hoppa (2000, p. 185) notes a ‘‘fundamental assumption made by skeletal biologists is that both the pattern and rate of age-related morphological changes observed in modern reference populations are not

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significantly different in past populations." Ubelaker (1999, p. 63) succinctly encapsulates the problems inherent in the age estimation of skeletal remains:

> "Estimation of age at death involves observing morphological features in the skeletal remains, comparing the information with changes recorded for recent populations of known age, and then estimating any sources of variability likely to exist between the prehistoric and the recent populations furnishing the documented data. The third step is seldom recognized or discussed in osteological studies, but represents a significant element."

Research that has shown different growth rates and patterns in living children attributed to nutritional, social, genetic and economic variables are justification for questioning the validity of the representativeness of European standards for age estimation (for example, Crowell et al., 1992; Eveleth and Tanner, 1990; Lampl and Johnston, 1996; Malcolm, 1969; Tompkins, 1996). Crowell et al. (1992) have shown in a study of 'race' specific mean live birth weights that in the pre- to post-term period there was specific heterogeneity. The ranking of cohorts from heaviest to lightest in average birth weight was Caucasian, Hawaiian, Japanese and Filipino respectively which emphasises that even from an early stage of development there were inter-population growth differences (Crowell et al., 1992, p. 242). This has important implications for age estimation in bioarchaeology as there is a strong relationship between foetal weight and skeletal growth. Van Loon et al. (1986) have found a similar pattern of heterogeneity in growth in cross-sectional research of nearly seven thousand children between birth and six years of age in areas of Africa and Asia. Ulijaszek (1994) investigating the extent to which environmental and genetic factors contribute to growth in height among populations argued that Asiatic populations may have different genetic potentials for growth from European, African and Indo-Mediterranean populations.

As with skeletal growth there are also differences in the timing of dental eruption and formation among populations, which also question the appropriateness of available dental ageing methods for ageing non-European populations (El-Nofely and Iscan, 1989; Lampl and Johnston, 1996; Tompkins, 1996; Ulijaszek, 1996). Dental eruption is affected by extrinsic and intrinsic factors including dental infection, the early loss of a deciduous precursor and environmental factors including nutritional status (Fanning, 1962; Ulijaszek, 1996). However, there are conflicting reports on the severity of under-nutrition that is needed to affect dental eruption (el Lozy et al., 1975; Holman and Yamaguchi, 2005; Jelliffe and Jelliffe, 1973; McGregor et al., 1968), while other research argues that under-nutrition has no effect on this process (Pindborg et al., 1967). An early study by Barrett and Brown (1966) investigating the clinical emergence of teeth in children from a Central Australian aboriginal settlement found a delayed emergence in their first year of life and a difference in the timing and sequence of eruption in older children compared with other groups of children. This difference in tooth emergence has been used to explain some of the differences in dental wear of deciduous teeth between Aboriginal and Caucasian children (Springbett et al., 1999). Ulijaszek (1996) has investigated the age of gingival emergence of deciduous dentition in Anga children in Papua New Guinea. This report shows that their dental emergence was delayed when compared with European (Canadian) reference values.

In comparison with dental eruption the formation of teeth is thought to be less influenced by environmental factors (Garn, 1965; Lewis and Garn, 1960). Even so, inter-population differences have been reported in the timing of dental formation stages (for example, Fanning and Moorrees, 1969; Harris and McKee, 1990; Loevy, 1983; Mappes et al., 1992). Tompkins (1996, p. 97) found significant population differences in relative permanent tooth development among South Africans, French-Canadians and White Americans. Liversidge (2003a,b) has produced a thorough comparative review of published reports of tooth formation and eruption in regions including the Americas, Africa, Asia, Australia, Europe and the Pacific Islands. This review found no clear pattern of differences in tooth emergence, but small differences were found in crown and root formation of late-forming teeth among groups (Liversidge, 2003a,b). A study of dental development in Rarotongan boys undertaken by Fry (1976) showed advanced permanent dental emergence compared with a standard based on White children. On average the maxillary gingival dental emergence was advanced by 0.76 years and the mandible by 0.28 years (Fry, 1976).

2. Recognition of growth variability and its implications for age at death estimation in bioarchaeology

The investigation of this growth variability in reference to ageing individuals from past populations has been prompted by the questioning of the reliability of adult age estimation and thus feasibility of palaeodemographic research. This has been largely precipitated by Bocquet-Appel and Masset's (1982) publication on the biases of methods for adult age estimation and resulted in a number of studies investigating the reliability of these methods (Hoppa, 2000; Kemkes-Grottenthaler, 1996; Lucy et al., 1995; Murray and Murray, 1991; Pfeiffer, 1998; Stout and Lueck, 1995). Conversely, there has been little attention given to issues of the appropriateness of standards for ageing subadults from non-European populations in bioarchaeology (Lampl and Johnston, 1996; Saunders, 2000; Sundick, 1978; Tompkins, 1996). There is a general perception that subadult age estimation is very accurate. This may be in part because age-related changes occurring during the post-developmental phase that are highly irregular and variable at the intra-individual, inter-individual and inter-population level receive much attention in the literature, leaving issues of the accuracy of subadult age estimation comparatively overlooked. However, small differences in age are crucial when investigating aspects of mortality and growth near the start of life. These difficulties inherent in subadult ageing are of considerable concern for any research that aims to use mortality data within an interpretive context including growth and developmental studies, palaeopathology and palaeodemography (Lampl and Johnston, 1996).

Although the issue of the representativeness of subadult age estimation standards is not unfamiliar to bioarchaeologists, its exploration has been greatest in the context of forensic anthropology with the testing of population specific studies of various ageing criteria (Hoppa, 2000; Iscan et al., 1987; Katz and Suchey, 1989; Lovejoy et al., 1985; Simmons, 1999). In the medico-legal context age at death estimation is considered to be the most accurate biological identifier (Lewis and Rutty, 2003, p. 203). The greater exploration and testing of dental ageing methods has arisen in part because the accuracy of the results have more immediate implications for identification. The age estimation of an unidentified deceased child has more urgency because it has potential serious legal ramifications compared with assessing the age of an archaeological individual. This question has also been explored less with respect to past populations because of the relative scarcity of samples of known age distribution. To complicate this issue further, the differences between chronological and physiological age may be greater in the past (Angel et al., 1986; Iscan and Loth, 1989).

One of the few studies that have specifically addressed the issue of the representativeness of subadult age estimation standards in bioarchaeology is Owsley and Jantz's (1983) investigation of the representativeness of Moorrees et al.'s (1963b) method for the dental development of children from the Arikara site at Indian Knoll, North America. This study's objective was to show how age assessments using different teeth could vary within an individual, the hypothesis being that the age estimation from a particular tooth should be similar to estimates from other teeth if tooth development is similar to the population or sample on which the standard is based. The results of pairwise contrasts of teeth revealed consistent differences in dental ages that could affect age assessment. To help alleviate this error they advocated more weight be put on selected teeth that do not show significant differences in age estimation between one another using a standard (Owsley and Jantz, 1983). A shortcoming of Owsley and Jantz's (1983, p. 23) suggestion is that the tooth types that give the most similar age estimations can only be determined after comparing samples of reasonable sizes. In addition, although some teeth may show similarities in age estimation to one another using a standard, there may still be differences in the timing of attainment of these stages for these teeth between the population studied and the reference group.

In an analysis of the linear growth of long bones and the breadth of the ilium of Arikara children, Merchant and Ubelaker (1977) showed that apparent differences in growth between this sample and other prehistoric Indian samples were the result of methodological discrepancies between ageing methods used in these studies. They found when comparing ages obtained using both Schour and Massler's (1940) and Moorrees et al.'s (1963a,b) dental ageing methods, that the former were consistently older than the latter. When these methodological biases were taken into account there were few differences in growth between the Arikara and other Indian samples, a finding that challenges previous comparative growth studies on these populations (Johnston, 1962). They urged future growth research to consider this inherent problem of ageing methods.

Lovejoy et al. (1990) in a study of long bone growth in the prehistoric Libben population from Ohio attempted to reduce the ageing error between the sample and the dental formation ageing standard by measuring the difference in gingival emergence of Euro-Americans and Amerindians. They noted a progressive age difference in gingival emergence between the populations with the discrepancy reaching 0.69 years at the age of 12 years and applied a sliding scale based on this assessment to correct their age estimations. For example, an Amerindian at age 10 would be the equivalent of an Euroamerican of 10.575 years ($10 + 10 \times 0.69/12$). Although this is a novel approach there are limitations with using this method based on dental gingival emergence to correct dental formation age estimation.

3. Dental ageing methods

Teeth are extremely useful in the estimation of age in subadults and preferable over other skeletal methods for a number of reasons. They are particularly durable in archaeological contexts, have minimal remodelling, and the growth of permanent and deciduous teeth continues over the entire juvenile period (Costa, 1986; Scheuer and Black, 2000b). Formation of deciduous teeth begins *in utero* at about 4 months and permanent teeth complete formation at approximately 25 years of age (Costa, 1986, p. 248; Scheuer and Black, 2000b). Also, dental development, in particular dental formation, is less affected by environmental factors than skeletal growth and development used in the estimation of age including epiphyseal fusion and long bone growth (El-Nofely and Iscan, 1989; Garn et al., 1958, 1965; Lewis and Garn, 1960; Liversidge et al., 1998; Merwin and Harris, 1998; Pelsmaekers et al., 1997; Smith, 1991).

There are two main methods used in dental ageing in bioarchaeology, dental eruption and dental formation. Dental eruption is the process where teeth move from within their crypts, erupt through the alveolar bone and occlude with opposing teeth in the mouth (Hillson, 1996, p. 138). Ageing methods based on dental eruption make use of the ordered sequence that teeth erupt and are exfoliated. The two main methods available to anthropologists for analysing dental eruption are those developed by Schour and Massler (1941) and Ubelaker (1999). The Schour and Massler (1941) eruption charts are based largely on the work of Logan and Kronfield (1933, cited in Costa, 1986, p. 252 and Hillson, 1996, p. 142) on 30 individuals who suffered from chronic diseases. This chart illustrates the progression of dental eruption from five months *in utero* to 35 years of age. Ubelaker's (1999) chart is based on an update of Schour and Massler's (1941) chart with the addition of dental data from modern Native

American Indians and other "non-White" populations. This chart, although originally created for anthropological work with American Indians, has been approved by the Workshop of European Anthropologists (WEA, 1980).

Most clinical research of deciduous teeth is limited in archaeological contexts because "eruption" is defined as the emergence of teeth through the gingiva or gum, whereas archaeological evidence is of alveolar emergence. Although the timing difference between gingival and alveolar emergence has been acknowledged (Konigsberg and Holman, 1997, p. 269; Scheuer and Black, 2000b, p. 13), there has been little research carried out to investigate these differences (Hillson, 1992; Konigsberg and Holman, 1997; Liversidge and Molleson, 2004, p. 176). Konigsberg and Holman (1997, p. 269) speculate that alveolar emergence in deciduous teeth "…probably occurs some short time before gingival emergence." A clinical study by Hulland et al. (2000) on dental emergence of deciduous teeth reported a mean difference of only two months between the cusps being palpable in the mouth (alveolar emergence) and occlusion of teeth. In a cross-sectional study of children from Helsinki, Finland, Haavikko (1970) identified differences in timing between alveolar and gingival emergence of permanent teeth. Teeth with deciduous predecessors had a mean difference between alveolar and gingival emergence of 0.6 years and first and second molars had a difference of 1.4 years. This difference was even greater for the third molar. Because of these differences between alveolar and gingival emergence, if eruption standards are used researchers should be aware that definitions of eruption vary and may be describing either alveolar emergence, gingival emergence or teeth reaching the occlusal plane. Also, unfortunately, many studies of deciduous tooth eruption rely on the simple counts of teeth present, regardless of eruption stages (Konigsberg and Holman, 1997, p. 268).

The use of dental formation is recommended over tooth eruption in the estimation of age because standards cover a continuum of maturation and also a longer period of time through subadulthood (Demirjian, 1986; Smith, 1991). During the formation of teeth there are distinct morphological stages beginning with the formation of the tooth cusp and finishing with the closure of the root apex (Saunders, 2000, p. 142). These morphological changes can be observed both macroscopically and with radiographs. Often in archaeological material the walls of the tooth crypts have been damaged, exposing the tooth root and/or crown for observation, which eliminates the need for the production of radiographs. There are a number of published methods for age estimation based on dental formation (for example, Demirjian et al., 1973; Fanning, 1961; Gustafson and Koch, 1974; Moorrees et al., 1963a,b). Commonly applied methods used by bioarchaeologists have been developed by Moorrees et al. (1963a,b) based on longitudinal radiographic studies of American children. These charts include data on crown and root development of individual permanent and deciduous teeth. Separate age ranges for males and females are presented.

4. Are the dental development standards available appropriate for non-European populations?: a Thai case study

To illustrate the potential effects of using non-population specific methods to age Thai subadults, this paper compares data from Moorrees et al. (1963b) with Thai dental formation data (Raungpaka, 1988). At present there are no ageing standards based on data from Southeast Asian subadults and most of the methods used are established from European and American skeletal series (for example, Demirjian et al., 1973; Gustafson and Koch, 1974; Moorrees et al., 1963b; Schour and Massler, 1941). This issue is relevant to bioarchaeological research in Southeast Asia as numerous studies on living children in this area attest to differences in growth rates and patterns compared with European and North American populations (Bailey et al., 1984; Baldwin and Sutherland, 1988; Chandrapanond et al., 1973; Chavalittamrong and Vathakanon, 1978; Eveleth and Tanner, 1990; Khanjanasthiti and Wray, 1974; Khanjanasthiti et al., 1973; Smith and Hauck, 1961).

Until 30 years ago archaeological investigations were sporadic in Southeast Asia, creating a patchy knowledge of human biology in the prehistory of this region. Since its delayed beginnings there has been a proliferation of archaeological investigation in Southeast Asia, particularly in Thailand. These include large multidisciplinary projects that are contributing to increasing the sample size available for bioarchaeological inquiry (Domett, 2001; Higham and Bannanurag, 1990; Kijngam, 1984; Pautreau et al., 2003; Pietrusewsky and Douglas, 2002; Tayles, 1999; White, 1986). At present over 600 prehistoric subadult (defined as under 15 years of age) burials have been excavated in Thailand from a number of sites. As a result of the increasing number of bioarchaeological studies of humans from prehistoric Southeast Asia (see Oxenham and Tayles, 2006) questions are being raised of the appropriateness of available subadult ageing methods for these populations (Domett, 2001, pp. 27, 29–30; Douglas, 1996; Pietrusewsky and Douglas, 2002, p. 11).

Few studies have investigated Thai or Southeast Asian dental formation and eruption (Holman and Jones, 1998, 2003; Kamalanathan et al., 1960; Raungpaka, 1988) and even fewer have attempted to produce new or amend existing methods to make them more representative (cf. Domett, 2001, pp. 29–30). The few clinical studies that do look at dental development in Southeast Asian children present their data in such a way that it cannot be used to test and develop new standards or adjust existing ones (for example, Krailassiri et al., 2002). Krailassiri et al. (2002) in a clinical study of 139 male and 222 female Thai children ranging from seven to 19 years of age investigated the relationship between dental formation and skeletal maturity stages. Their objective was to determine whether dental formation stages could be used as an indicator for assessing maturational status in the context of medical and orthodontic treatment and diagnosis (Krailassiri et al., 2002, p. 155). They found that stages of formation in specific teeth had a statistically significant correlation with stages of skeletal maturation (Krailassiri et al., 2002). However, although this paper may have been useful to assess the question of whether there were any differences between available age estimation methods and Thai dental formation, no data was given on the ages that these dental formation stages occurred.

Also, Kamalanathan et al. (1960) investigated gingival emergence times in a group of children from a Thai village. Domett (2001, p. 30) noted that there were consistent differences in tooth emergence times between the results of this study and Ubelaker's (1999, p. 64) tooth eruption standard. The chart showing these differences presented by Domett (2001, p. 30) is reproduced here with modifications from the original text (Table 1).

It should be noted, however, that Kamalanathan et al. (1960) measured gingival emergence as opposed to Ubelaker (1999) who used data based on radiographic methods and therefore assessed alveolar emergence. As discussed previously, this produces problems with the comparison of these data. Liversidge (2003b) included data from Kamalanathan et al.'s (1960) study in her review of published reports on dental eruption and formation. It was found when comparing the timing of the eruption of the first molar in the Thai study with other populations that it was a late outlier. However, as children under the age of seven were not included in Kamalanathan et al.'s (1960) research, the average age of eruption may have been earlier than seven years and therefore closer to the ages of eruption of the comparative studies.

Raungpaka (1988) investigated permanent tooth development in modern Thai children from Bangkok using panoramic radiographs of 585 children (295 girls and 290 boys) and present a sex specific summary of the mean stage of development of each tooth between six and 13 years of age. For each age category the age refers to the midpoint of the age range. For example, the seven-year age group includes individuals between 6.5 and less than 7.5 years of age. In the Raungpaka (1988) paper, dental scores were given numerical values and their mean values calculated at each specific age. In terms of statistical methodology this treats nominal data as parametric and is inappropriate (Liversidge, 2003b, p. 104). Nevertheless this paper provides the only modern comparative dental formation data on a Southeast Asian population and is therefore used in the case study for comparison with Moorrees et al. (1963b).

5. Aims and materials

In light of the problems surrounding age estimation of non-European subadults discussed, it is important to assess the appropriateness of available standards for ageing these individuals. To address this issue for Thai prehistoric subadults a comparison of dental formation data is presented. To illustrate the differences possible this paper presents a comparison of data for the age of attainment of dental formation stages of permanent dentition by Moorrees et al. (1963b) as presented in Harris and Buck (2002) and that by Raungpaka (1988) of Thai dental formation. Harris and Buck (2002) have presented sex-specific means and standard deviations of Moorrees et al.'s (1963b) data with the aim of making it more accessible and useful for statistical purposes. Moorrees et al.'s (1963b) method for ageing from permanent dentition was developed using radiographic images of North American children. The data for the development of the permanent maxillary and mandibular incisors came from Boston children (48 males and 51 females) and data collected in a longitudinal study carried out by the Fels research institute for determining the timing of the development of canines, premolars and molars. The Fels programme collected data at half-year intervals from White middle socio-economic status children from Ohio who all had excellent dental health (136 males and 110 females). Dental formation for permanent mandibular teeth was categorised into 13 and 14 stages for single and multi-rooted teeth respectively (Table 2).

Raungpaka (1988) investigated the stages of dental formation of 14 permanent teeth of the mandible and maxilla (excluding the third molar) using the scoring system of Gat (1972, pp. 25–26) (see Fig. 1) which categorises dental formation into stages including:

Stage 0 No signs of dental calcification
Stage 1 From signs of calcification up to 1/2 crown development
Stage 2 From 1/2 up to fully formed crowns. No signs of root formation
Stage 3 Root development up to 1/2 of its length
Stage 4 Root development from 1/2 up to 1/1 of its length, with no apical closure
Stage 5 Tooth completely formed, with apices closed.

Table 1
Comparison of the eruption stages of permanent teeth between Ubelaker's (1999, p. 64) and Kamalanathan et al.'s (1960) studies (modified from Domett (2001, p. 30, Table 3.1)

Tooth	Jaw	Ubelaker (1999) (age range in months)	Kamalanathan et al. (1960) age (years)	
			Male	Female
First molar	Mand and max	6 years (±24)	Less than 7	Less than 7
Central incisor	Max	7 years (±24)	8.1	7.8
Lateral incisor	Mand	7 years (±24)	8.1	7.6
Lateral incisor	Max	8 years (±24)	9.1	8.8
First premolar	Mand	10 years (±30)	11.1	10.4
Second premolar	Mand and max	11 years (±30)	11.8–11.9	11.5–11.6
Second molar	Mand	11 years (±30)	11.7	11.6

Mand = mandibular; max = maxillary.

Table 2
Moorrees et al.'s (1963b, p. 1493, Table 1) dental formation stages and corresponding coded symbols

Stage	Coded symbol
Initial cusp formation	C_i
Coalescence of cusps	C_{co}
Cusp outline complete	C_{oc}
Crown 1/2 complete	$Cr._{1/2}$
Crown 3/4 complete	$Cr._{3/4}$
Crown complete	$Cr._c$
Initial root formation	R_i
Initial cleft formation	$Cl._i$
Root length 1/4	$R_{1/4}$
Root length 1/2	$R_{1/2}$
Root length 3/4	$R_{3/4}$
Root length complete	R_c
Apex 1/2 closed	$A_{1/2}$
Apical closure complete	A_c

Moorrees et al. (1963b) do not present the stage $Cl._i$ for ageing from single rooted teeth as this only occurs in multi-rooted teeth.

A comparison of these different stages of tooth formation of Moorrees et al. (1963b) and Raungpaka (1988) is presented in Table 3. For comparative purposes intermediate stages of 1.5, 2.5, 3.5 and 4.5 have been extrapolated between each of the age categories presented by Raungpaka (1988). Applying these tooth stages assumes that dental formation occurs at a constant rate. It is acknowledged that this is not the case (Hillson and Bond, 1997). However, this assumption is often made in bioarchaeological methods mostly for assessing the timing of the formation of dental defects (Sciulli, 1992, p. 31) and is made in this case due to the lack of alternative options.

The comparison of these studies that use differing methodologies is not ideal. However, this was undertaken as Raungpaka's (1988) research is the only Thai data available and Moorrees et al.'s (1963b) paper has been adopted as a standard in bioarchaeology for the estimation of dental age (Buikstra and Ubelaker, 1994), even though this was not the intent of the original study.

6. Results

Raungpaka (1988, p. 77) presents the mean stage of development of each tooth type from 11 to 17 and 41 to 47 using the Fédération Dentaire Internationale (FDI) system (Alt and Türp, 1998). For example, 41 refers to the permanent right mandibular central incisor and 47 is the permanent right mandibular second molar. Raungpaka (1988, p. 77) presents the mean stages of formation separately by sex in yearly age groups. The mean stage of formation rounded to the nearest formation stage for the combined sexes of each tooth (from 41 to 47) at different ages extrapolated from Raungpaka (1988, p. 77) are presented in Table 4. There are problems with combining the sexes. However, as subadults are unable to be reliably sexed in archaeological contexts using existing morphological techniques (Brown, 2000, p. 463; Saunders, 2000; Scheuer and Black, 2000a) bioarchaeologists often resort to this (Domett, 1999, p. 30; Lewis, 2002). Hillson (1996, p. 131) states in regard to Smith's (1991) version of Moorrees et al. (1963b) that "in archaeological and forensic material, it is often not possible to establish the sex of juvenile material and Smith found that little extra error resulted from averaging the estimates provided by both male and female tables."

To improve the comparability of the data a further refinement of the Moorrees et al. (1963b) data has been made by taking the value at the midpoint of the stages. For example, for stage 4 ($R_{1/2}$–R_c) the age of attainment was taken to be when $R_{3/4}$ was attained. Some data were omitted from the comparison because of differences in data collection methods. It is acknowledged that the age groups (six to 13 years) in the Raungpaka (1988) study do not include the full range of development for the permanent dentition. Therefore when the

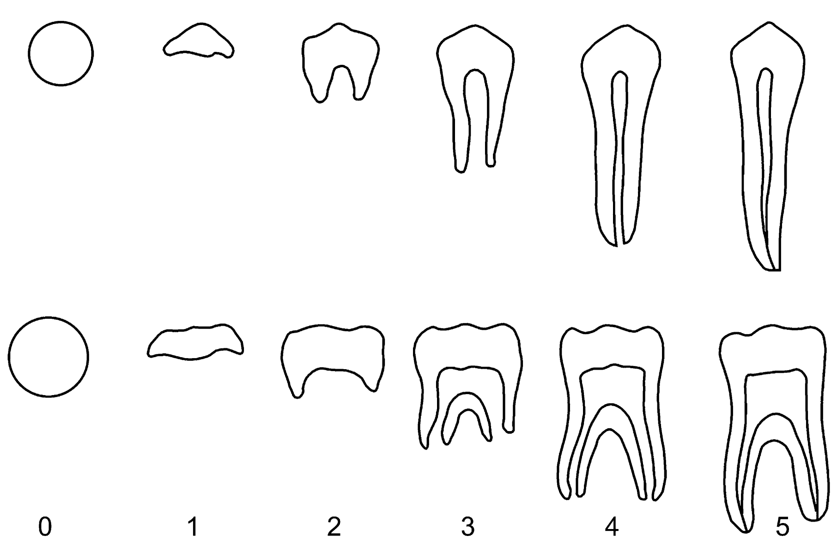

Fig. 1. Stages of tooth formation of single and multi-rooted teeth from Gat (1972, p. 25). Each representation depicts the end of the stage.

Table 3
Equivalent permanent dental formation stages of Moorrees et al. (1963b) and Raungpaka (1988)

Raungpaka (1988) stages	Moorrees et al. (1963b) corresponding stage symbols
0	No equivalent stage
1	C_i–$Cr_{1/2}$
1.5	$Cr._{1/2}$
2	$Cr._{1/2}$–$Cr._c$
2.5	$Cr._c$ –R_i
3	R_i–$R_{1/2}$
3.5	$R_{1/2}$
4	$R_{1/2}$–R_c
4.5	R_c
5	A_c

average age was given as the lowest age of the children included in the study these were omitted from the comparison. For example, as Raungpaka (1988) did not include children under the six year age group, a mean value of six years of age in his data does not necessarily indicate that younger children did not also attain these formation stages. Similarly, if the final stage of attainment (A_c) was at 13 years of age this was omitted from the comparison, as it does not represent individuals that attained this stage at a later age. Table 5 is a comparison of age of attainment of dental formation from Raungpaka (1988) and Moorrees et al. (1963b) for one quadrant (right side in the mandible). There are differences of over one year in the ages of attainment of tooth formation stages in 17 of the 24 comparative results. Five of the seven results of ages of attainment that do not have differences of at least 1 year occur in the fourth formation stage.

7. Discussion

The analysis indicates a consistent difference in the ages of formation between the two studies compared. In all cases Thai dental formation was delayed compared with that reported in Moorrees et al. (1963b), in that the stages were attained at a later age. Although differences in methodologies preclude any definitive statement on precise differences in ages of attainment of dental formation stages between the studies, the patterns seem to represent a genuine delay in tooth formation of the Thai sample. By root length completion (R_c) all teeth compared had a difference of at least one year in the age of attainment. Differences in attainment of dental formation stages were greater in later stages of root development and reach up to over two years by root length completion in some teeth. These differences may have been greater in the stages of root development because of the longer and later time of development compared with the crown. It has been shown in dental developmental studies that the age variation in attainment of tooth formation stages is less in the early formation stages compared with the later stages (Liversidge, 2003b, pp. 102–104). On this basis is can be assumed, as is consistent with the results of this study, that population differences are going to be the greatest in the later stages of dental formation (Liversidge, 2003b, p. 104).

At Gat's (1972) fourth stage of dental development ($R_{1/2}$–R_c) there seemed to be a less clear difference between the age of attainment in Moorrees et al.'s (1963b) and the Thai data (Raungpaka, 1988). However, this could have been a product of the ambiguous nature of stage four in Gat's (1972, p. 25) standard where the illustration depicting the end of the stage shows a three quarter formed root but is described as being fully formed (Fig. 1).

These results can be compared with data on dental gingival eruption of Thai children reported by Kamalanathan et al. (1960). As discussed, Domett (2001, pp. 27, 29–30) found, using Thai data from Kamalanathan et al. (1960), that a number of teeth showed later eruption times compared with those presented in Ubelaker's (1999) chart. This difference in dental eruption could be interpreted as a product of Thai children experiencing more environmental stress. However, the fact that there is also a similar and constant difference in the age of attainment of dental formation stages between the two data sets, with the acceptance that this is under stricter genetic control than dental eruption (Garn et al., 1965), a genetic contribution to this difference is plausible. Also, given that Ubelaker's (1999) chart is, in part, based on data from chronically ill subadults, this argument of differences being attributed to stress from nutritional deficiencies and disease in the Thai children is less convincing. It is interesting that Liversidge (2003b, p. 96) notes in her recent thorough overview of literature on dental eruption and formation in different human populations that the timing of dental formation stages in Moorrees et al. (1963b) is "considerably earlier than other studies". As Moorrees et al.'s (1963b) method is widely used in bioarchaeological studies, this provides the impetus for further investigation of the important issue of the appropriateness of ageing methods (Liversidge, 2003b, p. 104).

There are numerous problems with comparing Raungpaka's (1988) data and the Moorrees et al.'s (1963b) study. As mentioned, the Thai data is limited to children in specific age groups (six to 13 years). This is in contrast with Moorrees et al. (1963b) who present data on the ages of dental formation stages in permanent teeth from just after birth to 25 years of age. Direct comparison between ages of attainment of dental formation stages is also complicated because of the different scoring systems used in the studies. The data in Raungpaka (1988) is presented as average formation stages

Table 4
Summary chart of dental formation stages of teeth (41–47) in a modern sample of six to 13-year-old children from Bangkok. Data extrapolated from Raungpaka (1988)

Tooth	Age (years)							
	6	7	8	9	10	11	12	13
41	3.5	4	4.5	4.5	5	5	5	5
42	3	4	4	4.5	5	5	5	5
43	2.5	3	3	4	4	4	4.5	5
44	2	2.5	2.5	3.5	4	4	4.5	5
45	2	2	2.5	3	3.5	4	4	4.5
46	3.5	4	4	4.5	5	5	5	5
47	2	2	2	2.5	3	4	4	5

Tooth stages rounded to nearest stage as presented in Table 3.

Table 5
Comparison of age of attainment of dental formation stages of Thai children by Raungpaka (1988) and the midpoints of those presented in Moorrees et al. (1963b)

Midpoint of formation stage	Tooth													
	41		42		43		44		45		46		47	
	T	M	T	M	T	M	T	M	T	M	T	M	T	M
Cr_c (stage 2.5)	–	–	–	–	–	–	**7, 8**	**5.1**	**8**	**6.2**	–	–	**9**	**6.4**
$R_i–R_{1/2}$ (stage 3)	–	–	–	–	**7, 8**	**5.5**	–	–	**9**	**7.7**	–	–	**10**	**8.6**
$R_{1/2}$ (stage 3.5)	–	–	–	–	–	–	9	8.3	10	9.1	–	–	–	–
$R_{1/2}–R_c$ (stage 4)	**7**	**6.0**	7, 8	6.8	9, 10, 11	9.0	10, 11	9.4	11, 12	10.4	**7, 8**	**5.5**	11, 12	10.7
R_c (stage 4.5)	**8, 9**	**6.8**	**9**	**7.8**	**12**	**9.5**	**12**	**10.1**	**13**	**11.1**	**9**	**5.9**	–	–
A_c (stage 5)	**10**	**7.9**	**10**	**8.9**	–	–	–	–	–	–	**10**	**8.3**	–	–

Ages presented in the "M" columns are the midpoint values of the male and female means of the Moorrees et al. (1963b) data as calculated by Harris and Buck (2002) (figures are rounded to one decimal place). "T" refers to the Thai data extrapolated from Raungpaka (1988) as presented in Table 3. Bold font indicates that there is a difference of at least 1 year in the age of attainment of dental formation stages between the two studies compared. – indicates that data was not available or has been omitted from comparison for reasons discussed in the text.

for specific one-year age groups. Alternatively, Moorrees et al. (1963b) present the mean ages of attainment of particular dental formation stages. As a consequence no statistical analysis of differences of dental formation was possible. In addition, inter-observer error in scoring these dental formation stages could also be a contributing factor to the differences in formation rates observed between the two data sets (Liversidge, personal communication). However, even allowing an error of up to one year due to different methodologies for collection and presentation of data between the studies, the differences in age of attainment exceed this in most cases.

This comparison corroborates the previously recognised need to further investigate population differences in dental formation and, if need be, make ageing methods more representative by incorporating data based on populations that are most comparable to the archaeological samples in question in terms of both environment and heredity (Saunders, 2000, p. 153). Saunders (2000, p. 153) has advocated the examination of dental development in these comparable populations, in which she noted there is a possibility of amassing large samples of cross-sectional data from clinical radiograph databases. Also, longitudinal studies of tooth development or data collection from existing radiographs of dentitions from subadults of known ages from comparable populations are essential for further development of representative standards.

It is well known that there are preferable methodologies for the collection and analysis of dental development data (Hillson, 1996, p. 130; Smith, 1991). Raungpaka (1988) used an unfavourable data collection method, where the mean formation stage was collected for each age group, and as mentioned inappropriate statistical analysis of the data. The problems in the present study in terms of the lack of comparable statistical analysis that could be undertaken between Raungpaka's (1988) and Moorrees et al.'s (1963b) studies highlights the need for the application of appropriate methodologies for developing dental standards for age estimation in the future (Hillson, 1996, p. 130). Given the problems discussed we caution that the results of the present paper are not used to adjust age at death estimates of Southeast Asian subadult archaeological remains.

Furthermore, there are problems when using modern population data to infer information on past populations due to secular trends in growth, especially in the last 50–60 years (Nadler, 1998). The evidence of this secular trend in the referenced paper, however, is based on small samples and relies on late root stages that have low reproducibility. Of relevance to this issue for Southeast Asians, Buckley found in a research project investigating the appropriateness of traditional ageing methods that modern and prehistoric Thai growth patterns are similar. It may be assumed that prehistoric Thai children probably experienced more stress than modern populations, increasing the inter-population disparities of tooth formation rates. Buckley advocates the use of ageing standards developed from Thai populations and then an assessment of how these differ from original age estimations using non population-specific standards as a tool to investigate health and disease in past subadults. The results of this could result in a better understanding of the timing of physiological disturbances of dental and skeletal development caused by environmental stressors.

Advancements in dental methods to age subadults including microstructural analysis of enamel and dentine which have been reported to give a very close estimation of chronological age could be a future avenue to test the reliability of available ageing standards for archaeological samples (Antoine et al., 2000; Wittwer-Backofen et al., 2004). These methods could be used to test whether the archaeological samples have the same relationship between skeletal or dental age and chronological age as determined from dental microstructure to modern reference samples meaning that their time-consuming and destructive processes could have a wider and more practical application (Scheuer and Black, 2000b, p. 17).

8. Conclusion

There are differences in growth and development among populations that affect the reliability of the ageing standards used by bioarchaeologists. The results of this case study raise the question of the applicability of the adopted dental formation standard for ageing prehistoric Southeast Asian children and by implication all non-European children. In a perfect world we would acquire dental formation data from known-age subadults from Southeast Asia using the same methodology of adopted bioarchaeological standards to test these results. In the absence of such data we have used what is available and suggested in the circumstances that there is validity in this approach. Because of the difficulties of accurately ageing prehistoric subadults ''…whose age at death determinations form the basis for controversial aspects of human evolution and biology'' (Lampl and Johnston, 1996, p. 354), there is no easy solution in reconstructing past health patterns, but rather a multitude of promising research topics for the future.

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