Human growth in the past

studies from bones and teeth

EDITED BY

ROBERT D. HOPPA
Department of Anthropology
University of Manitoba
Winnipeg, Manitoba, Canada

CHARLES M. FITZGERALD
Department of Anthropology
McMaster University
Hamilton, Ontario, Canada

CAMBRIDGE
UNIVERSITY PRESS

PUBLISHED BY THE PRESS SYNDICATE OF THE UNIVERSITY OF CAMBRIDGE
The Pitt Building, Trumpington Street, Cambridge, United Kingdom

CAMBRIDGE UNIVERSITY PRESS
The Edinburgh Building, Cambridge CB2 2RU, UK www.cup.cam.ac.uk
40 West 20th Street, New York, NY 10011–4211, USA www.cup.org
10 Stamford Road, Oakleigh, Melbourne 3166, Australia
Ruiz de Alarcón 13, 28014 Madrid, Spain

First published 1999

Printed in the United Kingdom at the University Press, Cambridge

Typeset in Times 10/12.5pt [VN]

A catalogue record for this book is available from the British Library

Library of Congress Cataloguing in Publication data

Human growth in the past: studies from bones and teeth / edited by
Robert D. Hoppa, Charles M. FitzGerald.
p. cm. – (Cambridge studies in biological and evolutionary anthropology)
ISBN 0 521 63153 X
1. Human growth. 2. Teeth — Growth. 3. Human skeleton – Growth. 4. Dental anthropology. 5. Physical anthropology. I. Hoppa, Robert D., 1967– . II. FitzGerald, Charles M., 1947– . III. Series.
GN62.9.H85 1999
599.9 – dc21 99–11536 CIP

ISBN 0 521 63153 X hardback

Contents

1 *From head to toe*: *integrating studies from bones and teeth in biological anthropology*

ROBERT D. HOPPA AND CHARLES M. FITZGERALD

Introduction

From its inception physical anthropology has been preoccupied with human variation (Hrdlička 1927). Since growth is the process that produces variation, it is therefore not surprising to find that biological anthropologists have a long history of studying human variation and growth in numerous populations and within many temporal frameworks (cf. Goldstein 1940; Garn 1980; Beall 1982). Understanding variation in growth patterns among populations permits a better understanding of observed morphological differences (Johnston 1969; Eveleth and Tanner 1976; Johnston and Zimmer 1989). Moreover, this curiosity has not only been about population-wide growth, but also about growth as an ontogenetic process.

With the expansion of physical anthropology and the inevitable concomitant specialisation of interest, two broad streams of growth studies developed (this division, in fact, occurred early in the evolution of the discipline). In one stream, the application of auxological studies to populations from the distant past represented a natural extension for physical anthropologists interested in unravelling the mystery of human evolution. In the other, researchers interested in prehistoric skeletal populations were quick to apply techniques borrowed from anthropometric studies to their samples. Both clearly recognised that juvenile specimens contained a potential wealth of information on the evolution of human ontogeny. However, for the most part these two areas of enquiry, palaeoanthropological studies and bioarchaeological studies, have remained separated, the former tending toward increased scrutiny in dental development and the latter focusing more on linear growth in the appendicular skeleton. While the topical separation was clear – palaeoanthropological studies focused on very detailed analyses of a few fragments (many consisting of dental elements) and bioarchaeological studies aimed to assess population level indices of many individuals – it is unfortunate that the practitioners of each have remained so isolated from one another.

Our specific objective (and the leitmotif of this whole volume) is to reduce the barriers between those two subdisciplines and to bring closer together all of those interested in human growth and development of past populations, whatever their specialty. We believe that there are obvious significant benefits in such an integration and that it might be more easily achieved with the use of more inclusive vocabulary. We propose the term 'palaeoauxology' to classify or group together growth and development studies of past populations. First used by Tillier (1995), this word aptly describes the generality of such studies, and it carries with it no divisive historical connections.

Of course, an interest in human growth is not confined to biological anthropologists, there are other disciplines also enmeshed in the subject. In its broadest sense it impinges on oral biology, dental morphology, forensic odontology, developmental biology, and a variety of clinical medicine specialties, to name just a few. However, in order to stay within reasonable bounds of space, the focus here is narrow. It is restricted to a discussion of growth and development derived from bones and teeth within the two streams of biological anthropology just identified, and even more particularly to studies that can be related directly to *Homo sapiens* or its evolution. This topic is too expansive to cover comprehensively and we have therefore been very selective in presenting an overview of the relevant research.

The first topic to be addressed then, is an important one faced by all investigators confronted with unknown human skeletal or dental material: estimating age at death and determining sex. Since our perspective is growth and development, interest will of course be focused on methods of estimating sex and age at death in non-adult remains.

The basics: estimation of age and sex in non-adults

Determination of sex from the skeleton has, to the regret of many researchers, been restricted to those who have survived past adolescence and who then manifest changes in the skeleton reflective of sex. While a variety of studies have investigated traits that might be sexually dimorphic in infants and juveniles (Thompson 1899; Reynolds 1945; Boucher 1955, 1957; Sundick 1977; Weaver 1980; Schutkowski 1986, 1987, 1989, 1993; DeVito and Saunders 1990; Hunt 1990; Mittler and Sheridan 1992; Introna *et al.* 1993; Majo *et al.* 1993) only a few have had sufficient levels of accuracy to warrant their application in osteological analyses. More promising, but still restricted by cost and time, is the possibility of determining sex by extracting ancient DNA from bones or teeth of individuals (e.g. Fattorini *et al.* 1989; Faerman *et al.* 1995; Stone *et al.* 1996; Lassen 1997). As a result of the limited reliability of morphometric techniques for sexing pre-pubescent individuals, non-adults have remained, for most investigations, lumped within a single group representing both males and females.

Age estimation of children is based, in order of precision, on dental development, epiphyseal closure, and diaphyseal length. Estimation of age in the non-adult is much easier and more accurate by far than in the adult. While there may be fewer techniques than are available for adult age estimation, each has a smaller range of error, as the processes being measured are finite in the sense that there is a beginning and an end to each phase.

In general, most investigators agree that dental development shows a slight degree of sexual dimorphism, but far less than other osseous traits (Gleiser and Hunt 1955; Hunt and Gleiser 1955; Lewis and Garn 1960; Lauterstein 1961, for a recent review of sex determination using teeth see also Teschler-Nicolar and Prossinger 1998). Further, while variation occurs in almost all forms of maturation within the body, tooth formation has proved no more variable than other factors (Lewis and Garn 1960). Of all of the methods of assessing the age of subadults that rely on exogenous references, dental development standards, particularly those assessing tooth formation (e.g. Schour and Massler 1940a,b; Moorrees *et al.* 1963a,b; Demirjian *et al.* 1973; Gustafson and Koch 1974; Anderson *et al.* 1976; Demirjian and Goldstein 1976; Staaf *et al.* 1991) have traditionally been seen as the most accurate, under the strongest genetic control, and least subject to external pressures and population differences. Most studies of dental development have been carried out on the permanent dentition, despite the fact that most skeletal samples contain large proportions of infants and young children; there is still a distinct shortage of detailed standards for the early formation of deciduous crowns that can be applied to foetal and neonatal skeletons (Skinner and Goodman 1992). In addition to tooth formation, dental eruption standards that assess emergence of teeth through the alveolar bone or gums have also been widely utilised, but are a poor surrogate for tooth formation. Recent investigations of dental metrics (Liversidge *et al.* 1993) and more rigorous statistical approaches to estimating age (Jungers *et al.* 1988; cf. Konigsberg and Holman, Chapter 11, this volume) hold promise for improving the reliability of estimates of developmental age. Perhaps most promising of all are techniques based on analysis of dental microstructures, since these obviate the need to apply exogenous standards. These are discussed in a later section of this chapter.

While tests of age prediction using children of known age have been reported from studies of living children (for a review of this literature, see Smith 1991) only a few researchers (Bowman *et al.* 1992; Saunders *et al.* 1993a; Liversidge 1994) have examined the accuracy of dental age estimates in archaeological samples. Crossner and Mansfield (1983) observed that 70% of tooth formation estimates from permanent mandibular and anterior maxillary teeth in 23 childrens' teeth fell within $\pm$ 3 months of true age and discrepancies of no more than 6 months were found for age estimates when tested against the standards of Liliequist and Lundberg (1971) and Gustafson and Koch (1974). Haag and Matsson (1985) compared several dental formation standards using permanent teeth and found standard deviations of the difference between dental and chronological age to be approximately 10% of age. Demirjian and colleagues (1973) estimated a subject's chronological age within 15–25 months with 95% confidence. Tests of these standards on other population samples produced mixed results. Proy and colleagues (1981) observed a mean advancement of 9 months in the dental development of French children, while Kataja and co-workers (1989) found that the models predicted dental age reliability (Kataja *et al.* 1989). More studies exploring interpopulation efficacy of standards need to be conducted.

Bowman and colleagues (1992) recently examined the skeletal remains of 26 juveniles from the crypts of St Bride's Church, Fleet Street, 16 of which were fully documented as having died between the years of 1794 and 1841. These investigators examined the relationship between the skeletal and dental age, and documented chronological age at death, observing that, while long bone growth progressively underestimated age, dental calcification and eruption were similar to modern populations. Saunders and co-workers (1993a) also examined the accuracy of dental formation standards, on a 19th century archaeological sample (St Thomas' Church, Belleville, Ontario) with a small subsample of children of documented age. Dental age estimates in the St Thomas' sample based on a single tooth have a standard deviation of ± 0.94, while the average standard deviation when all possible teeth are used is ± 0.38 years (Saunders *et al.* 1993a).

Smith (1991) has stated that none of the tested systems are particularly suited to age prediction, and has provided a series of recommended formation values for age prediction based on her determination of the appropriate method for constructing chronologies of growth stages. She argued that, for age prediction, it is more appropriate to assign an age that is the midpoint between the mean age of attainment of a subject's current stage of formation and the subsequent one since, at the time of observation, the subject is in between the attainment of one stage and the next. Smith's own test of age prediction accuracy utilised four Canadian children of British origin who were used to test dental age standards in the study by Anderson and co-workers (1976). The chronological ages of these children were compared to her calculated values for predicting age from the stages of permanent mandibular tooth formation derived from the data of Moorrees and colleagues (1963a). The results were 'remarkably accurate' (Smith, 1991: 162) differing by a maximum of 0.2. Within-individual inaccuracy based on a single tooth yielded a standard deviation of ± 0.56 years, while mean values for five or more teeth decreased the standard deviation to ± 0.09 years, suggesting that dental age can be estimated to within 2 months for young children. Saunders *et al.* (1993a) calculated within-individual coefficients of variation for mean dental age for all individuals aged by more than one tooth. In contrast to the lower mean coefficient of variation (CV) (10) reported by Smith (1991), within-individual CVs in the St Thomas's sample had an average value of 20. However, most of the individuals from their sample had ages estimated from five teeth or fewer. Saunders and colleagues (1993a) found little difference in the average level of accuracy of age estimation when using age prediction versus age-of-attainment tables.

The accuracy of several methods of age estimation based on developing teeth was tested on an archaeological population of children by Liversidge (1994). The sample consisted of the dental remains of 63 individuals of known age at death, between 0 and 5.4 years, from Christ Church, Spitalfields, London, interred between 1729 and 1856. Liversidge tested the atlas method of Schour and Massler (1941), Gustafson and Koch's (1974) diagram method, Moorrees *et al.* (1963a,b) mineralisation standards and Smith's (1991) modification of them, and her own quantification standards for length, incorporating regression equations for weight from Deutsch *et al.* (1985). Her results show that the atlas and diagram methods were considerably more accurate for this population and age group than the other methods tested, although the quantification method performed well for the youngest age children. Liversidge agreed with Smith (1991) that prediction methods gave better results than age-of-attainment methods of estimating age using dental development.

However, analysing any results obtained from testing exogenous standards against individuals of known age is not easy. Interpretations are confounded by the difficulties of comparison because of methodological inconsistencies and differing approaches in data collection and assessment of tooth maturity from study to study. For instance, it is well known that tooth formation as traditionally measured by the appearance of growing teeth on radiographs is fraught with methodological problems (Risnes

1986; Aiello and Dean 1990; Beynon *et al.* 1991; Beynon *et al.* 1998a). Also, some studies have used as few as three fractional stages to gauge tooth development, others as many as 20. Not only do these and other difficulties make cross-study comparisons difficult, but they raise a more fundamental question: is the high ontogenetic intra- and interpopulation variability commonly seen in dental standards really a feature of modern human dental development, or is some or all of it an artefact of the methodology used to determine it (FitzGerald *et al.* 1999)?

From head to toe: assessing growth in skeletal samples

Both palaeoanthropological and bioarchaeological studies have, for the most part, focused on specific areas of the skeleton with regard to growth and development. In the case of palaeoanthropology this has largely been the result of many studies having to rely on the limited number of skeletal elements associated with a particular site. In the case of bioarchaeology it is often because of the need to examine growth variables, such as long bone length, that can be easily placed within a comparative framework with other archaeological samples. Relatively few studies have examined growth and development within skeletal samples from a broader perspective, although research by Steyn and Henneberg (1996a,b) on Iron Age remains or Smith (1993) on the Turkana Boy provide good examples against which future research strategies should be modelled.

While there is a wealth of information on skeletal growth and development, physical anthropologists have been relatively selective in the kinds of data that have been explored for past populations. Many studies, particularly bioarchaeological studies, have been primarily descriptive in nature, with theoretical and methodological issues forming a secondary role in the literature. Yet, there has been in the human biology and medico-legal disciplines a significant amount of literature dealing with specific methodologies for examining subadults that can be exploited by current researchers in the field of palaeoauxology.

Assessments of growth in length (or width) of the long bones are the most commonly employed assessment of statural growth in skeletal remains. Studies of allometric growth, often utilised in palaeoanthropology studies, are seen less frequently in bioarchaeological research. More often, simple measures of diaphyseal length, clavicle length or iliac breadth are made, and the distributions analysed in the context of some independent assessment of age – usually dental development. In doing so, a cross-sectional 'growth curve' or skeletal growth profile (SGP) can be constructed to

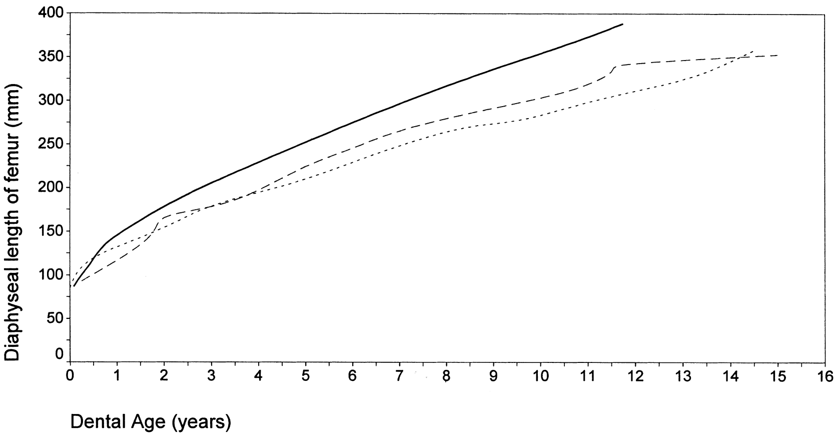

Fig. 1.1. Typical skeletal growth profile (SGP) plotting diaphyseal length of femur against chronological age estimated from dental development standards. Here comparisons of two archaeological samples, 9th century Slavic (dotted line; Stloukal and Hanáková 1978) and Altenerding, a 6th–7th century collection from Munich (dashed line; Sundick 1978), are made with a modern reference sample (continuous line, Maresh 1970).

exhibit the age-progressive trend in long bone length up to the time of epiphyseal fusion (Fig. 1.1). In contrast, studies of appositional bone growth in earlier populations have been less frequent (Armelagos *et al.* 1972; Huss-Ashmore *et al.* 1982; Hummert 1983; Mays 1985, 1995; Van Gerven *et al.* 1985; Saunders and Melbye 1990; cf. Mays, Chapter 12, this volume).

The major limitation of cross-sectional data is that it does not allow one to observe individual variability in the rate or velocity of growth or in the timing of the adolescent growth spurt, although attempts to examine the rate of growth have been undertaken (e.g. Lovejoy *et al.* 1990). In comparative analyses between populations, however, the means and variations of the 'population' rather than the patterns unique to the individual are often more important (Eveleth and Tanner 1976). As others have noted though, the nature of the data used to construct the SGPs often prevents adequate statistical comparison between population samples, and more powerful techniques are likely to reveal little more than is observable from simple examination of the graphs (Merchant 1973). Further, differences between SGPs may be, in part, a result of differences in adult stature related to longer-term adaptations (Eveleth 1975). In order to control for this, some researchers have constructed skeletal growth profiles as a percentage of mean adult long bone length or mean adult stature for individual populations (Lovejoy *et al.* 1990; Wall 1991; Hoppa 1992; Goode *et al.* 1993;

Saunders *et al.* 1993b). Utilising mean adult long bone lengths is recommended as this will take into account variation in limb proportions and differences in the regression equations utilised to reconstruct mean stature (Hoppa and Saunders 1994; Sciulli 1994).

Studies of infrancranial growth, however, need not be restricted to long bones. For example, Miles and Bulman (1994, 1995) have examined growth in shoulder, hip, hand and foot bones from a 16th to 19th century Scottish island sample. Several studies have investigated vertebral growth in archaeological samples (Clark *et al.* 1986; Porter and Pavitt 1987; Clark 1988; Grimm 1990; Kneissel *et al.* 1997). Clark (1988) examined vertebral neuronal canal size and vertebral body height in the Dickson Mounds skeletal population in an attempt to determine why previous research has observed a decrease in diaphyseal growth over time, but no difference in adult stature. Clark proposes that since vertebral canals usually stop growing by early childhood, but vertebral body height continues to grow through young adulthood, if canal size is reduced but body height is not, this implies an early disruption in growth followed by catch-up growth. In contrast, if both areas are reduced in size, growth disruption was probably chronic. From his analysis of the Dickson Mounds sample, Clark (1988) concluded that early interruptions in growth were followed by catch-up growth.

The appearance and eventual union of primary and secondary centres of ossification in bone are also of interest. As Stewart (1954) has pointed out, the age of *appearance* of various primary centres has limited application in the analysis of archaeological skeletal remains, as these are rarely recovered during excavation. However, the development and union of such remains are more easily assessed in older individuals at which time the various epiphyses are beginning to unite. Nevertheless, some studies of epiphyseal fusion in past populations have been explored (e.g. Hoppa 1992; Albert 1995).

Palaeoanthropological studies

The pattern of anatomically modern human growth is characterised by an extended period of infant dependency, prolonged childhood and a rapid increase in adolescent growth at the time of sexual maturation. Most agree with Bogin (1988: 61) that 'the prolonged delay in human growth due to the evolution of a childhood period of growth is one feature of the human growth curve that distinguishes it from all others' (although see Leigh 1996). Therefore, understanding the evolutionary development of delayed maturation and prolonged infant dependency among modern humans will reveal important information about the way our ancestors lived and how they were related to each other. Clearly, increased brain size associated with the complex behaviours connected with human culture necessitated the extension of the childhood stage. More time was required for learning. However, such an adaptation could not be made without other sociobiological consequences. As a result, the processes and mechanisms that have allowed early hominids to survive and evolve are of considerable interests to physical anthropologists (cf. Bogin 1997; Leigh and Park 1998).

The question remains whether these uniquely human life history variables evolved in concert or in a mosaic fashion, and, if the latter, which appeared when in our evolutionary history. Of course, life cycles cannot be studied directly from skeletal or dental material, particularly material as fragmentary as that with which palaeoanthropologists have to contend most of the time. To a large extent inferences have been made by reconstructing patterns based on assessments of chronological or biological growth derived from the skeletal material, although other approaches have also been used to investigate ontogeny. For instance, enamel thickness, traditionally studied as a phylogenetic indicator, has also been recruited to help reconstruct life history (Macho 1995). The focus here will be on growth assessment. However, that raises a fundamental issue: just how does one go about assessing the development of long extinct life forms?

Since until recently no reliable ways existed by which to endogenously determine development (see discussion below), in practical terms the preoccupation has been with deciding what reference standards to use to assess patterns of development in early hominids. The problematic nature and the applicability of exogenous standards to non-referent populations has already been intimated in an earlier section in the context of anatomically modern humans. In the case of extinct hominids, these difficulties are compounded. The choice of whether to apply modern human or modern ape growth standards has significant consequences for the estimate of a specimen's chronological age (Smith 1986, 1994; Mann *et al.* 1987, 1990; Lampl *et al.* 1993; cf. Nelson and Thompson, Chapter 4, this volume). To address this issue, comparative studies of human and ape growth have become the focus of many researchers (e.g. Dean and Wood 1981; Smith 1989, 1994; Smith *et al.* 1994; Simpson *et al.* 1996; Braga 1998; Reid *et al.* 1998; Dainton and Macho 1999; cf. Dainton and Macho, Chapter 2, and Humphrey, Chapter 3, this volume).

Some earlier studies, predicated on what must be said to be circular reasoning (arising from the use of modern human dental standards), inferred from dental development that australopithecines had a delayed maturation similar to that of modern humans (Mann 1975). However, Bromage and Dean (1985) demonstrated from their analysis of dental enamel microstructures that australopithecines and early *Homo* may have developed at rates that were more similar to living apes, than to modern humans. These investigators applied a histological approach that relies on the interpretation of certain microscopic features of enamel and dentine as incremental growth markers (see Fig. 1.2). These microstructures are formed during the regular appositional pattern of growth of both of these dental hard tissues. Although initially challenged, the time dependency of dental microstructures is no longer seriously disputed (cf. Dean 1987a; FitzGerald 1998; Shellis 1998) and most concede that they record normal growth in a way that permits the developmental and chronological history of a tooth to be accurately reconstructed. Estimates of age and development from dental microstructures overcome one of the principal handicaps associated with most other age estimation techniques – the precise and accurate correlation between biological age and chronological age. More importantly in the context of palaeoanthropology, using standards derived from the fossils themselves overcomes the problems associated with relying on those based on maturation studies of modern humans or apes (some of which were identified earlier).

The premise of different development patterns between early and late hominid groups first identified by Bromage and Dean has been supported by a number of subsequent studies of enamel microstructure (e.g. Dean 1985a,b, 1987a,b, 1989; Beynon and Wood 1987; Beynon and Dean 1988; Ramirez-Rozzi 1991, 1993, 1995) and dentine microstructure (Dean 1995, 1998; Dean and Scandrett 1995, 1996; see also Dean, Chapter 5, this volume). Independent corroboration has also come from investigators using non-histological approaches. For instance, Smith's studies (e.g. 1986, 1987, 1989, 1992, 1994) and Smith and Tompkins' (1995) study of dental development concluded that early hominids had a developmental pattern that was unlike that of any living primate, many specimens more closely resembling pongid patterns. Also, Tompkins' (1996) analysis of dental development among recent human populations, Upper Palaeolithic specimens, and Neandertals, identified dental development differences between the two early groups and the modern one. Upper Palaeolithic and Neandertal specimens seem to share a more similar pattern of dental development, which differed somewhat from that of modern populations. What has clearly emerged from these and other studies is that attempts to characterise any hominid taxon's growth as being either 'ape-like' or 'human-like' is a gross oversimplification. Not surprisingly perhaps, it appears that each hominid group probably has a unique suite of dental and

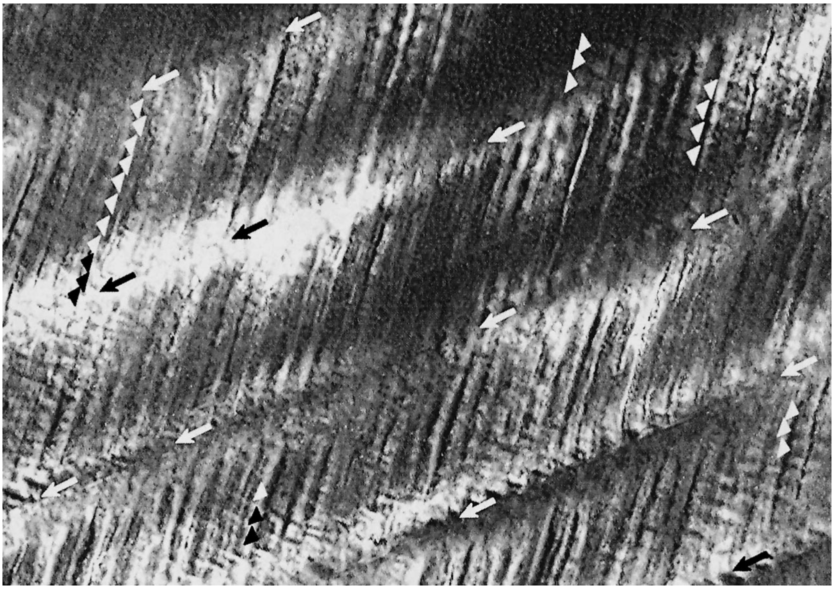

Fig. 1.2. This is a photomicrograph at 400 × magnification of a longitudinal section of enamel near the tooth surface taken in polarised light. It illustrates the two types of incremental growth marker used in enamel histological ageing techniques. Enamel prisms can be seen, inclined at a slight angle, running from the top of the photo, which is toward the enamel–dentine junction, to the bottom of the photo and the tooth surface, just out of frame. The triangles point to some examples of cross-striations, the circadian markers that appear as successive dark and light bands occurring along the full length of enamel prisms. Cross-striations therefore represent the amount of appositional enamel produced in one day, and carefully measuring them yields the daily rate of enamel production. The arrows point to brown striae of Retzius, long period markers that cross-cut prisms at regular circaseptan intervals (usually 7–10 days, although in this photo a sequent run of 11 cross-striations is indicated toward the top left). Imbricational (non-cuspal) striae emerge at the tooth surface as perikymata, visible as 'wrinkles' on the exterior of tooth crowns. The number of cross-striations between adjacent striae, called the circaseptan interval, differs from individual to individual, but is uniform within and among all of the teeth in one dentition. These markers can be utilised in several different ways to arrive at crown formation times; for instance, in one approach the number of striae of Retzius are counted and then multiplied by the circaseptan interval, which need be established only once within a tooth, to yield formation time in days. For a full and recent discussion of these and other techniques and examples of their application, see the special issue, of the *Journal of Human Evolution* (1998) **35**(4/5).

developmental characteristics that reflect their distinctive evolutionary trajectories.

Despite this debate, which throws into question the appropriateness of any modern development standards to assess non-modern populations, studies of hominid ontogeny using traditional comparative approaches have proceeded. Antón (1997) recently re-evaluated the Mojokerto child remains from Java, whose developmental and taxonomic status have been controversial. On the basis of her comparisons of the partial calvaria with a series of *H. sapiens*, Neandertal and *H. erectus* juveniles, she concluded that the Mojokerto child represents a *H. erectus* child of between 4 and 6 years of age. Smith's (1993) study of the well-preserved juvenile *H. erectus* skeleton, KNM-WT 15 000, observed a pattern of growth and development that was more modern when compared to other earlier hominids. However, comparisons of dental and somatic indicators of growth implied an advanced skeletal maturation relative to the dentition, making it less similar to the modern rate and pattern of growth. A variety of studies of archaic *H. sapiens* and Neandertal juvenile specimens have also been undertaken over the past decades (e.g. Heim 1982; Tillier 1983, 1988; Dean *et al.* 1986; Hublin and Tillier 1988; Zollikofer *et al.* 1995; Tompkins 1996), although it is still not clear how the Neandertal pattern of growth fits between the more primitive *H. erectus* and modern human patterns (cf. Nelson and Thompson, Chapter 4, this volume).

Bioarchaeological studies

Given the abundance of remains from archaeological populations relative to those of earlier hominids, it is hardly surprising that a larger corpus of growth studies has accumulated in bioarchaeology. The basic assumption of growth-related studies of past populations is that the growth of a child reflects his or her health and nutritional status better than any other single index (Johnston 1969; Eveleth and Tanner 1990). Anthropometric studies support this statement, with many researchers observing higher rates of morbidity and subsequent mortality associated with varying degrees of stunting and wasting in children. Like anthropometric studies of living populations, studies of skeletal growth from archaeological collections often use linear growth as a proxy for health and thus make interpretations regarding the overall health and well-being of a population from the apparent growth of children. Since many studies imply that long bone growth is differentially affected by the nutritional and health status of the individual, osteologists have attempted to utilise cross-sectional analyses of long bone growth as a non-specific indicator of nutritional status within subadult skeletal samples (cf. Johnston and Zimmer 1989; Saunders 1992). The premise of such studies stems from experimental and contemporary studies that demonstrate the permanent effects of a variety of stressors on skeletal growth and bone dimensions (Buikstra and Cook 1980; cf. King and Ulijaszek, Chapter 7, this volume). The demonstration of differential growth between samples is then employed as evidence for differential health status between entire populations, either geographically or temporally. It must be noted though, that growth-related measurements remain non-specific indicators of health, and are sensitive to many factors. As such, they can reveal that there is a problem, but say very little about its cause (Martorell and Ho 1984: 51).

The analysis of human skeletal growth in archaeological samples first became popular with the works of Stewart (1954) and Johnston (1962). The 20 years that followed saw a variety of publications dealing specifically with growth (Johnston 1968; Mahler 1968; Walker 1969; Armelagos *et al.* 1972; Sundick 1972, 1978; Merchant 1973; y'Edynak 1976; Merchant and Ubelaker 1977; Stloukal and Hanáková 1978). In the 1980s the issue of growth stunting for assessing health within past populations became a popular interpretative tool associated with palaeopathological studies (Hummert 1983; Hummert and Van Gerven 1983; Cohen and Armelagos 1984; Jantz and Owsley 1984a,b; Mensforth 1985; Owsley and Jantz 1985; Storey 1986). Beginning in the late 1980s and early 1990s there was a resurgence of interest in studies dealing specifically with subadult growth (Jungers *et al.* 1988; Hühne-Osterloh 1989, Hühne-Osterloh and Grupe 1989; Johnston and Zimmer 1989; Molleson 1989, 1990; Lovejoy *et al.* 1990; Wall 1991; Hoppa 1992; Saunders 1992; Saunders *et al.* 1993b; Jantz and Owsley 1994; Miles and Bulman 1994, 1995; Ribot and Roberts 1996; Steyn and Henneberg 1996a; Hutchins 1998).

Most of these osteological studies of growth and development have compared linear size measurements of long bones and skeletal maturity, although studies of appositional bone growth and cross-sectional geometry have also been undertaken. Interpretations of health from such studies are derived primarily from comparisons of skeletal and dental development with previously published studies or with modern standards (e.g. Maresh 1943, 1955, 1970; Anderson and Greene 1948; Gindhart 1973). However, interpretations of the resultant differences and their significance concerning conditions of health in past populations are often difficult given (1) the lack of a single consistent methodology when constructing skeletal growth profiles from archaeological samples and (2) whether the reference samples utilised are in fact appropriate.

An issue that has had considerable attention for such studies is the fact that growth as reflected in the subadult cohort associated with a burial sample are essentially non-survivors. That is, they represent individuals who, for whatever reason, have not survived to complete maturation and therefore whose level or pattern of growth and development might not be representative of the true pattern of growth in the population. Long recognised as a theoretical obstacle by researchers, this issue re-emerged with the publication of the *Osteological Paradox* in which Wood and colleagues (1992) argued that skeletal samples are intrinsically biased because they are the products of selective mortality or non-random entry. Selective mortality refers to the fact that skeletal samples do not represent all susceptibles for a given age cohort, but only those individuals who have died at that age. For example, 5 year old individuals in the skeletal sample represent only those 5 year olds who died and not all of the 5 year olds who were alive in the population at risk; other susceptibles who survived, went on to contribute to older mortality cohorts. In a review of the child survival literature, Saunders and Hoppa (1993) examined this issue of mortality bias specifically with respect to growth in children. They concluded that while there did appear to be statistically significant differences between the growth of survivors and non-survivors in the clinical literature, the actual magnitude of this difference for cross-sectional studies of long bone growth would be minimal, and probably less important than the error introduced by methodological issues like ageing standards.

A serious problem that confronts both osteological and dental development studies of human growth is the general lack of a consistent methodological approach for the collection and analysis of data. Since comparative data for growth studies are sparse, the lack of comparable methodologies between various investigators has resulted in many studies becoming isolated analyses whose interpretation cannot be adequately evaluated against other data (Saunders *et al.* 1993b). Teeth in intermediate stages of growth must be characterised in arbitrary fractional stages of completion and there is a variety of idiosyncratic approaches that have been adopted to accomplish this, making cross-study comparisons difficult or impossible. Dental data may also be collected cross-sectionally, semi-longitudinally, and rarely, longitudinally, adding to comparison problems.

Skeletal data are often placed into age cohorts representative of a group of individuals who are developmentally similar. While such categorisation does accommodate the presentation of variation in length, it does not allow for the presentation or analysis of the equally important variance of the age distribution within individual cohorts (Hoppa 1992). Many studies provide standard deviations to illustrate the distribution of lengths around a cohort mean, but few, if any, calculate the confidence limits of individual cohort means. Naturally, the precision of such confidence limits will be dependent on both sample size and variance, with variance expected to increase with age as well as from the pooling of data for both sexes. In