# Developmental Juvenile Osteology

## Second Edition

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# First Edition Foreword: The Development of Juvenile Osteology

The importance of this volume will be immediately obvious to anyone who has been confronted with fetal or juvenile human osteological material in an archaeological, palaeontological, forensic or physical anthropological context. There is simply no currently available reference work that deals with the fetal and juvenile human skeleton in sufficient detail to be practically useful. Louise Scheuer and Sue Black have recognized a major gap in the field and have responded with a volume that is sure to become a classic wherever there is an interest in the identification and interpretation of the human fetal and juvenile skeleton.

It is perhaps easy, or relatively so, to recognize a need for a major reference work. It is much more difficult to fill that need. Both Scheuer and Black are highly experienced anatomists with many years of classroom and research experience. There is no doubt about their qualifications to carry out this task. But even so, I doubt if at the beginning they realized the enormity of the project, they had set themselves or the length of time that would be needed to bring it to fruition. One major obstacle was their conviction that the book must be based on skeletal material of known age to avoid the circularity of discussing age-specific skeletal development on the basis of material that itself was aged using skeletal size or morphology. This proved to be difficult because such skeletal material is so rare and required considerable detective work to bring together. A second obstacle was the wealth of previously published material scattered in many disparate references relevant to many different disciplines and published in many different languages. The bibliography is large, spans 300 years and the information presented therein has been meticulously sorted and summarized. This in itself is a highly valuable contribution to the field. The absolute insistence on documentation and accuracy of both the skeletal and the contextual information in the book will ensure that it becomes a classic in the field.

In recent times, descriptive anatomy has taken a definite back seat to the various biochemical approaches to skeletal analysis. Among others, these new approaches include DNA analyses that have the potential to uncover the genetic basis of skeletal growth, the sex and possible familial and/or ethnic affiliation of skeletal material and the infectious diseases that the individual suffered in life. There is also the possibility, through stable isotope analysis, of determining the diet of the individual. In many academic departments, topographic anatomists live in the shadow of the perceived cutting-edge importance of these newer biochemical approaches to the understanding and interpretation of skeletal material. There is no doubt that these approaches are important, have enriched the disciplines that deal with the interpretation of skeletal material and have great potential to continue to do so. But there is still much to learn and understand through the study of whole organisms. Macro-anatomy gives much more than context and background for these newer biochemical techniques. It is here that this contribution will provide an invaluable and unparalleled resource.

Archaeologists, forensic pathologists and anthropologists will simply not be able to do without it in the context of recognizing and identifying fetal and juvenile material. It will also be invaluable to anyone interested in human growth and development. For example, in my own field of human palaeontology, there is a growing realization that there have been major changes in the tempo and mode of ontogeny in human evolution and that a good understanding of these ontogenetic patterns will provide significant insight into our own evolution. To date, this work has focused primarily on the dentition, but this volume will provide the necessary comparative context to facilitate the interpretation of skeletal growth and development in pre-human fetal and juvenile material.

Scheuer and Black have put considerable thought into the organization of this work, making it not only informative, but also accessible and practically usable. The meticulous descriptions of each individual bone are clearly written and logically presented. The 'practical notes' for identification of all bones are invaluable to the field worker, as are the clear and beautifully executed illustrations by Angela Christie. There is no doubt that this reference will outlive the current generation of researchers. The authors and artist should be congratulated on providing a resource that will facilitate the research of so many current and future scientists whose work touches on the analysis of human fetal and juvenile skeletal material. On behalf of all of us, I offer them a sincere and well-deserved thank you.

***Professor Leslie C. Aiello***
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# Second Edition Foreword

It is difficult to believe it is 16 years since the publication of the first edition of what is known in the trade as 'Scheuer and Black'.

First, 'hats off' to the editor who managed to persuade the powers that be to commission a second edition of this important reference book. Academic publishers prepared to look further than the next budget cycle are as rare as hen's teeth, so Elsevier's investment in the future of *Developmental Juvenile Osteology* is a welcome reversion to the traditional values of academic publishing.

In the Foreword to the first edition, Leslie Aiello set out the case for a book about the developing modern human skeleton. There is clearly a forensic need to identify immature skeletal remains. But there is also a need for a book that reminds anatomists, and especially paleoanthropologists, that skeletal ontogeny has a lot to tell us about human evolution. Few juveniles seem to make it into the fossil record, but I suspect that some juvenile fossils go unrecognized because most researchers are programmed to look for, and to recognize, the remains of adults. In this respect 'Scheuer and Black' has helped educate our community.

One of the many ways modern humans differ from our closest relatives, chimpanzees and bonobos is the rate at which we progress through the important developmental way stations we call life history. The hard tissue fossil record is a potential window into the evolutionary history of these life history differences, and one of the most important advances in paleoanthropology in the past several decades has been the exploitation of dental microstructure to calibrate pre- and postnatal growth and development. There is also tantalizing evidence that the histology of fossil bone may also provide a window into growth and development. These advances, plus the reality that hard tissue research is even more specialized now than it was in 2000, have been recognized in the second edition of *Developmental Juvenile Osteology* by inclusion of a separate chapter contributed by Helen Liversidge on the dentition.

The original authors, now joined by a new senior author, Craig Cunningham, have obviously thought long and hard about how to improve an instant 'classic', and their decisions about what to leave well alone and what to change are well-judged. Plus two of the great strengths of the first edition, the illustrations and the copious bibliography, have been, respectively, augmented and updated.

The first edition of Henry Gray's human anatomy book was published in 1858. A second edition rapidly followed in 1860, but this was to be the last by Gray for he died a year later of smallpox. Thankfully, Louise Scheuer and Sue Black are in rude health. By my calculation they are 142 years behind Henry Gray, but as his initial vision lives on, now so does theirs. May it long continue to do so.

***Professor Bernard Wood***
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# Preface

In the 16 years since the publication of the first edition of *Developmental Juvenile Osteology*, much has advanced in the field of skeletal development, with a resurgence of interest in the growing skeleton. This, combined with new published literature, has greatly enhanced our understanding of the human skeleton. This revised edition has attempted to bring together this new and diverse array of research literature to provide an updated account of skeletal development and to furnish the reader with an expanded bibliography. Indeed, a strength of the first edition was its extensive bibliography and this edition adds more than 1000 new references, documenting many of the significant contributions to the field in the intervening period.

The main core of the text persists by describing each individual component of the human skeleton from its embryological origin through to its final adult form. This systematic approach has been shown to assist the processes of both identification and age estimation and acts as a core resource for the basic understanding of normal human skeletal development. In addition, new sections have been introduced where there have been significant advances in the field, including dental development and age estimation from living individuals.

Throughout the text, data tables have been updated with the most relevant and up-to-date information. Easy-to-read compilation summaries of key skeletal events and associated literature have also been expanded. Additionally, material that was presented in *Developmental Juvenile Osteology*'s sibling texts: *The Juvenile Skeleton* and *Juvenile Osteology*: *A Laboratory and Field Manual* have been incorporated into this edition. New illustrations and schematics have been introduced and as with the first edition, most have been sourced directly from actual bone specimens housed in what has become widely known as the Scheuer collection.

As stated in the first edition, it has always been the intention that *Developmental Juvenile Osteology* would be primarily aimed at skeletal biologists, forensic anthropologists, forensic pathologists, archaeologists and palaeontologists but it is hoped that this revised edition may perhaps prove both interesting and useful to a wider clinical and scientific audience.

Finally, thanks must be conveyed to those who have assisted throughout the production of this edition and our gratitude remains with those previously listed in the first edition. However, thanks are extended to Helen Liversidge, an acknowledged authority on tooth development and ageing, who has compiled a new chapter on the dentition. Lucina Hackman, Paul Felts and Catherine Carr are acknowledged for their contributions to sections on age estimation in the living, bone histology and embryology, respectively. Gratitude is extended to Joslyn Paguio, Elizabeth Brown and Lisa Jones from Elsevier who have looked after the production of this revised edition and have provided their support and encouragement throughout the revisions. Thanks are also given to Christopher Rynn who assisted in the design of the front cover and to Katie Tyldesley who completed initial literature searches in the early stages of this revised edition.

***Craig Cunningham***
***Louise Scheuer***
***Sue Black***

Chapter

# 1 Introduction: A Guide to the Text

*It must surely be clear that if we wish to safeguard the interests of our science (physical anthropology), and of those innocents who identify themselves with it, and who by so doing voluntarily condemn themselves to a precarious, albeit interesting life brachiating as it were from one lower income bracket to another, then it is our duty to see to it that they are properly equipped for the work which they wish to do and which so urgently requires to be done.*

**(Montagu (1941))**

The correct identification of the skeletal components of the juvenile skeleton is critical to the analysis of skeletal remains, regardless of whether they are of archaeological or forensic origin. Without such information it is virtually impossible to establish the number of individuals represented, let alone ascertain their identity and make meaningful inference on demographic or health-related issues. Indeed, a lack of familiarity with immature remains has led, on more than one occasion, to their classification as 'non-human' or 'of uncertain origin'. Once the remains have been confirmed as human, the next step is usually an attempt to establish the four principal parameters of biological identity (sex, age at death, stature and ancestry). However, with juvenile skeletal remains it is often only the estimation of the age at death that can be established with any degree of reliability. Sex estimation from juvenile remains is tentative at best, and stature is so closely linked to the age of the individual that it is often used to predict it. Ancestry is difficult to establish in the adult, so in the child it is highly speculative at best, especially when only skeletal remains are presented.

The value of understanding juvenile skeletal remains should not be overlooked in both the medical and the anatomical fields of study. A glance through the reference section will demonstrate the critical nature of understanding normal juvenile development to facilitate diagnosis and treatment of aberrant conditions.

The first edition of this text was published in 2000 and in the intervening period there has been a resurgence of interest in this fascinating field, but the main purpose of this book remains the same. Its aim is to describe each individual bone of the skeleton, or indeed different components of a bone, and follow development from embryological origin through to the final adult form. This systematic approach has been shown to assist the processes of both identification and age estimation of the juvenile skeleton and to aid as a core source for basic understanding of normal human skeletal development. The passage of time has ensured that the already full reference section is enhanced further and although the main core of the text persists, new sections have been added where it was felt that the expertise of others would enhance the original concept.

Chapter 2–4 form a general introduction to the juvenile skeleton. Chapter 2 considers many of the fundamental issues concerning juvenile skeletal remains including the origin of such material, the various techniques by which it has been studied, the variability of child growth, the dilemma of biological versus chronological age and skeletal versus dental age. Age estimation in the living has become a major issue for border control, migration and human trafficking, and our thanks are extended to Dr. Lucina Hackman who has introduced this subject here to demonstrate that age determination from the skeleton is not restricted to the domain of the deceased. Chapter 3 examines the more specific cellular and vascular nature of bone growth and development. It discusses the ontogenetic development of bone from its mesenchymal origins, through a cartilaginous or membranous template, to its eventual transformation into bone. Bone growth is considered, as is the influence of its vascularity. Dr. Paul Felts enhances the value of this section not only in relation to the basic cellular composition but also the

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relevance to bone modelling and remodelling as it pertains to not only normal growth but also to repair and pathology. Chapter 4 has been reviewed and updated by Dr. Catherine Carr and provides a very brief outline of the early embryological development of the human body as a whole, and sets the scene for the more specific developmental aspects of the skeleton that are discussed in subsequent chapters.

Chapters 5–12 respectively form the core of the text and describe the morphological development of the immature skeleton in a way that permits the ready identification of each skeletal element and thus allows an evaluation of the age at death of the individual. The chapters are arranged in a topographical order, commencing with the axial skeleton and continuing with the upper and then the lower limb girdles and their associated appendages. Each chapter is essentially separated into four sections–the adult bone, early development, ossification and practical notes. Chapter 6 takes a different format as it considers the dentition, and Dr. Helen Liversidge, has greatly enhanced this section from the original text and included the latest data on ageing from the dentition.

Each of the main chapters begins with a description of the **adult bone(s)** but this is far from an exhaustive consideration of the subject as there are many excellent texts written specifically to fulfil this purpose. However, it was deemed necessary to include this section primarily to ensure consistency of terminology used in the subsequent sections on the development and ossification of the bone. Where possible, the accepted standard anatomical planes and terminology have been used throughout, although more commonly used names and others that reflect a historical origin have sometimes been included. Several anomalies of the adult skeleton have been addressed as the understanding of variation is an important concept that is diminishing as teaching of anatomy in particular moves away from more traditional methods towards computer models and plastic skeletal teaching aids. While it is appreciated that these minor skeletal variants may be of limited clinical value, they can occasionally prove extremely important in the identification of the deceased. In anthropological terms of course, many of these anomalies are referred to as non-metric traits that may be considered indicative of potential genetic influences (Berry, 1975; Finnegan, 1978). A variety of relevant clinical conditions has also been introduced in this section where they have some bearing on the future development of the bone. Comment has often been made with regards to the value of that particular element in the assessment of some parameters of biological identity (sex, ancestry and stature). While this is not the primary aim of this text, it serves only to direct the reader to other sources of reference.

The illustrations of the adult bones are represented by stippled line drawings with muscle attachments indicated. The illustrations throughout the book always depict the right-hand side of the body.

The **early development** of each bone is described directly after the discussion of the adult morphology. Each description follows on from the stage outlined previously in Chapter 4 and deals with the specific embryological and early fetal development of that particular bone. This section charts its development from the blastemal condition up to the stage prior to the commencement of ossification. It also includes reference to various congenital conditions and anomalies that may arise during this period and which could subsequently alter the final adult morphology of the bone.

The section on **ossification** describes the development of the bone from the time of appearance of the first centre(s) of ossification up to the stage of final fusion of the epiphyses. In most chapters, this section is in three parts: primary centres, secondary centres and pattern of epiphyseal fusion. It is in this section of the book that the illustrations are most important as they not only highlight the earliest stage at which a particular element can be identified with certainty, but also describe the morphological changes that occur in that bone throughout its development. However, it has not always been possible to illustrate a specific stage of development due to the limited availability of material. The illustrations in this section are half-tone drawings of bones, many of which are of known age and sex and again only the right side of the body is depicted. It should be mentioned that all of the drawings from Mrs. Angela Christie are derived from actual bone specimens which are now housed in the Scheuer collection at the University of Dundee. As an active repository for juvenile skeletal remains, it is an invaluable source but it cannot in any way be considered as a 'population' as the origins of the material are diverse–anatomical specimens, archaeological material and forensic casework.

The final section within each chapter is headed **Practical Notes**. This represents a summary or morphological timetable of critical osteological events from the commencement of ossification to final epiphyseal fusion (or the attainment of final adult form). The practical notes include guidelines on the sideing of remains and how to orientate them to achieve correct identification of the skeletal element. In addition, there is a small section that offers suggestions on which other bones that have a similar morphology may cause some confusion and thus result in misidentification.

Finally, some tables of metric information are included that may prove useful in the estimation of age at death. This tends to include primarily observations on individuals of *documented* age to remove the inherent errors of the circular argument that ensues when age is subsequently predicted on the basis of the accuracy of another method (see Chapter 2). Naturally, this reduces the number of studies that could be included but it may serve to highlight where further research could be pursued. The additional sources of information collated for *The Juvenile Skeleton* (Scheuer and Black, 2004) and for *Juvenile Osteology* (Schaefer *et al.*, 2009) have been included in this second edition.

By far the most comprehensive account of fetal bone remains is that published by Fazekas and Kósa (English translation of 1978) referring to a group of 136 fetuses ranging from 12 to 40 weeks gestation. However, the sample was essentially of undocumented age at death and age was assigned on the basis of its well-documented relationship with body length (Streeter, 1920; Scammon and Calkins, 1929; Schultz, 1929a). There is, however, no other detailed text on fetal osteology and given the fact that all fetal material must, by necessity, be of uncertain age (see Chapter 2) its inclusion remains justified.

As each bone of the skeleton is considered from its earliest formation to its adult morphology, it is obvious that each would display its own idiosyncrasies and resist being forced into a standard chapter format. As a result, while an attempt has been made to adhere to an organized structure, each chapter is, by necessity, slightly different in terms of its layout. For example, in Chapter 5 (Skull) there is a general introduction to the early development of the skull as a whole to prevent needless repetition of material that is common to a structure composed of so many conjoined elements. Also, there is no section on secondary centres, as these do not occur in the skull. Similarly in Chapter 7, as the vertebral column is an axial structure, there is obviously no section on side identification and instead this is replaced by identification of position within a series.

In addition to the principal elements of the skeleton, other structures such as the costal cartilages have been included. Being composed of hyaline cartilage, these structures maintain the potential to ossify and may do so at an age when the remainder of the skeleton is still in its late developmental phase. For this reason it is important that the structures can be identified, as they may be encountered in the excavation or retrieval of immature remains. While such ossifications have always tended to be considered entirely within the domain of the elderly, the inaccuracy of this assumption is highlighted and awareness of their existence can lead to an increase in successful retrieval rates.

One of the overwhelming comments to arise from the first edition of this text was the value of the extensive reference section which has been expanded in this edition to ensure currency. The quantity of literature differs for each bone and so by necessity some areas are more heavily referenced than others. Many of the most basic descriptions of bones are historical and are where we tend to find the greatest attention to detail, so we make no apology that the references span over 300 years. Wise (1995) accused many authors of ignoring the contributors of the past, stating that 'we may have stood on the shoulders of giants but we did not cite them'. He attributes this to authors becoming victims of technology, relying on the use of information retrieval systems that tend not to extend to more than 25 years ago–but that does not mean that they should be consigned to obscurity because of modern laziness that keeps us in front of our screens and does not see us resort to the original source. Many of the older texts may also express views and descriptions that would not now be considered ethically acceptable. Titles of these papers have obviously been given as they stand and, where appropriate, the text has been quoted *verbatim* in the hope that accusations of political incorrectness may not be directed at this text. O'Rahilly (1996) raised the criticism that rather than seek out the original reference, many authors substitute reviews of the subject or even cite student textbooks where, in all fairness, original research is rarely published. In addition, he further accused authors of repeating information from one text to another without due recourse to the original work, which can of course lead to the perpetuation of errors. Where possible this text has remained true to its original ethos and attempted to avoid these pitfalls by extensive literature searches with recourse to the original texts but it is inevitable that vital references, perhaps in another language, may have been omitted and errors may indeed have been unwittingly perpetuated. It is hoped that readers may identify these and make them known to the authors of this text so that due rectification can be made.

A second edition gives the opportunity to address errors and omissions in the first text, and we are grateful to those who pointed out where they occurred and we hope this new edition will have corrected those that were most obvious and not introduced too many new ones.

Chapter

# 2 Skeletal Development and Ageing

## Chapter Outline



*The childhood shows the man*
*As morning shows the day*

**(John Milton, Paradise Regained)**

Biological identity is used for different purposes depending on the aims of the investigator. Skeletal biologists, physical anthropologists and palaeodemographers use the information to construct demographic profiles of populations from both historic and prehistoric times and then draw conclusions about lifestyle, death rates and life expectancies. In a skeletal assemblage that includes subadult specimens, the identification and age at death of the juvenile component will be particularly relevant as it is deemed a reflection of the overall health and well-being of that population.

It is equally important that forensic scientists can also recognize juvenile components of the skeleton and establish a reliable age at death to assist in determining, or to confirm, the identity of an individual. Forensic anthropology uses the biological identity to assist in determining 'personal' identity and this demands accuracy and reliability, as it is only when the deceased has been given a name that an investigation can proceed.

This chapter considers the basic concepts of growth and its relationship to age and then attempts to distinguish the many different categories of database from which information on the developing skeleton is drawn. It then summarizes the estimation of age from skeletal and dental material and ageing from the living. Finally, aspects of documentation, sampling, representativeness

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and sexing that are particularly associated with the juvenile component of a skeletal assemblage are discussed.

## GROWTH

Growth is a term that is used to describe progressive changes in size and morphology during the development of an individual. In general, it is correlated positively with age and so estimation of age at death utilizes the many incremental changes that occur during development. Growth consists of two components, increase in size and increase in maturity, and while these two elements are closely related, their relationship is not linear. As a result, individuals reach developmental milestones, or biological ages, along the maturity continuum at different chronological ages. For example, two boys, both aged 8 years, may differ considerably in height or similarly, two girls, aged 13, may both be at sexually and skeletally different stages of maturity. Generally speaking, growth in size is a regular process, although there are distinct increases in rate, between 6 and 8 years in mid-childhood and at the adolescent growth spurt. However, the only consistent characteristic of growth is its variability.

There are variations in growth rate between different tissues and organs of the body in all individuals. The brain and head attain their adult size early in childhood, while the lymphoid system reaches its peak in late childhood. The reproductive system displays yet another rate and develops later in the adolescent period (Tanner, 1978). Growth also varies between the sexes, between individuals of the same population and between populations themselves. The underlying basis of this variation is primarily genetically determined but the influence of environmental factors is critical in controlling the expression of the growth process. This interplay between genetic and environmental influences is the basis of the 'nature versus nurture' argument. In spite of much research, the causal picture still remains unclear. On the one hand, it is almost impossible to study the effects of a single factor alone and on the other, the effects of a factor on an individual may vary, depending at which stage of development it acts. Thus the causes responsible for differences in any particular person are complex and difficult to isolate.

Genetic inheritance is the background for differences of size and maturity between the sexes, which, although small, can be discerned, even before birth (Choi and Trotter, 1970; Pedersen, 1982). These manifest in the timing of ossification of bones and mineralization of teeth (Garn *et al.,* 1966a; Mayhall, 1992). Postnatally, skeletal maturation is more advanced in girls than boys (Pyle and Hoerr, 1955; Brodeur *et al.,* 1981) but bone mineral density is significantly less in girls than boys, the latter having a higher mineral density and larger long bones (Maresh, 1970; Specker *et al.,* 1987; Miller *et al.,* 1991). As puberty approaches, sexual dimorphism increases by differential hormone secretion and this is reflected in the adolescent growth spurt. Although the timing varies between individuals of the same sex (early and late maturers), girls are, in general, about 2 years in advance of boys in maturity at the same age. The later growth spurt in boys allows more growth beforehand and therefore has its greatest influence at a different critical phase of growth. It results in a greater adult size, predominantly because muscle mass increases rapidly during this period, which affects overall skeletal robusticity (Tanner, 1978). Some studies show that, as in childhood, bone mineral density and the rate of accumulation of peak bone mass vary between the sexes during puberty (Gordon *et al.,* 1991). However, Baxter-Jones *et al.* (2003) have questioned the significance of this.

Genetic differences are the basis for differences between population groups and it is self-evident that the adults of different genetic ancestry have overall size differences; witness a group of Japanese and a group of Dutch tourists. A comprehensive survey of variation in the growth of children worldwide can be found in Eveleth and Tanner (1990). The difference that the environment may make on this intrinsic genetic factor is complex, and one interesting approach to its elucidation has been longitudinal growth studies on monozygotic and dizygotic twins and their siblings (Tanner, 1962). By far the most important environmental factors are those that can be grouped together under the umbrella of socio-economic influences and they may be subdivided into the effects of nutrition, disease and social status itself. Although all of these factors dominate most strongly in infancy and childhood, their extremes can affect growth and development even before birth. The starvation conditions in both Russia and the Netherlands during World War II caused a significant decline in both birth weight and vitality of infants (Antonov, 1947; Smith, 1947). Similarly, research following women who were pregnant during the 1998 Quebec ice storms has shown that prenatal maternal stress has long-term consequences on the child (Cao-Lei *et al.,* 2014). The effects on optimum size and weight at birth and poor growth in the early years have been shown to affect not only final adult size, but also susceptibility to disease (Frisancho *et al.,* 1970; Clark *et al.,* 1986; Barker *et al.,* 1993). Maternal undernutrition appears to be one of the links in the causal chain between socio-economic factors and fetal growth (Lechtig *et al.,* 1975). Nutrition and disease have long been accepted as factors in raised childhood morbidity and mortality rates in countries with low socio-economic levels. Even in countries with a general high standard of living, minority groups with a lower than average income, raise children who show delayed postnatal ossification rates and tooth emergence times (Garn *et al.,* 1973a,b).

Minor factors such as season and climate are also thought to affect rates of growth and maturity. It is known that growth in height and weight differs according to the time of year but it is debatable as to what extent climate affects these processes. Studies comparing ethnic minorities in their adopted countries to populations still living in their original homeland have often given contradictory results. Again, it is difficult to isolate climate from the many changes that have acted on the immigrant community.

Evidence has accumulated that over the past 150 years there has been an increase in height and weight of adults and a decrease in the age at which adult size is achieved in many west European and North American populations (Tanner, 1962; Floud *et al.*, 1990; Hoppa and Garlie, 1998). There has also been a marked tendency for menarche and the adolescent growth spurt to occur earlier (Tanner, 1978; Roede and Van Wieringen, 1985; Hoppa and Garlie, 1998). The reasons for this so-called 'secular trend' are difficult to disentangle from the overall one of improvement in socio-economic circumstances with its concomitant better nutrition and living conditions. In fact, Maresh (1972) failed to find such changes in a stable economic and educationally privileged group that was studied over a 45-year period in the United States.

The variability of growth and some of the factors responsible are discussed in detail in Tanner (1962, 1978), Sinclair (1978) and Eveleth and Tanner (1990). It is clear that the relationship between growth and age is far from simple and because of this variability, growth can never be considered a reliable indicator of the chronological age of a child. However, growth is the marker by which society invariably measures development and maturity.

## AGE

There are many practical situations that require the establishment of the age of a child. For example, clinicians in specialities such as orthopaedic surgery, orthodontics or growth hormone treatment often need to establish the stage of skeletal or dental maturity of a child almost regardless of their chronological age. A critical window of time can then be identified for corrective treatment so that intervention does not impede future development and an optimum time may be left for catch-up growth. The judicial system demands that a child of unknown age be assigned an age to ensure that appropriate procedures are observed in the processing of a legal case. In some countries, permits for refugees lacking proper documents are dependent on the establishment of adult status. In some developing countries, the ages of children may not be accurately known or may, for personal reasons, be falsified. For example, parents are known to falsify the ages, particularly of their sons, to obtain preferential educational opportunities (Chagula, 1960; Eveleth and Tanner, 1990). Skeletal biologists use child death rates and life expectancies to construct a demographic profile of a population and this is based on the estimated ages of juveniles in the sample. This is often interpreted as a reflection of health in an attempt to reconstruct the lifestyle of past peoples, both in prehistoric and historic periods. Forensic scientists who are called to investigate immature skeletal remains may need to establish age at death as part of the procedure to discover the identity of a particular individual.

Many terms are used to designate different phases of the life span of an individual and while a few are established clinical definitions, others are not universally accepted and their usage varies in different contexts and in different countries. Some commonly used terms, including those adopted in the present text, can be found in Appendix 1.

Postnatally, chronological or true calendar age is calculated from the day of birth. While this may appear to be rather obvious, as with all third party recording statistics, it is not always accurate. Dates of birth are sometimes simply incorrectly recalled, may be falsified for personal reasons or may not be recorded. UNICEF reports that almost half of the world's children do not have a birth certificate. Todd (1920) reported that, in the Terry Collection, the listed ages at death for adults displayed peaks around 5-year intervals, indicating that perhaps in later life people giving information tended to round to the nearest quinquennium. Lovejoy *et al.* (1985a), investigating the cadaver records for the Hamann-Todd collection (Cleveland, Ohio), discovered gross discrepancies between 'stated' and 'observed' ages at death.

### Prenatal Age

In the prenatal period, chronological age *per se* does not technically exist as it is not possible to establish a starting point (i.e. fertilization) with any certainty and in fact, obstetricians and embryologists record age slightly differently (O'Rahilly, 1997). In the clinical context, the only known date is usually that of the first day of the last menstrual period (LMP) of the mother but even the accuracy of this date may be affected by factors such as postfertilization bleeding, inconsistencies of maternal recollection or intentional falsification. The actual known date of insemination is rarely known and tends to be restricted to cases of rape or *in vitro* fertilization. In addition, the period between insemination and fertilization is itself variable. Clinically, normal term is calculated as 280 days (40 weeks/10 lunar months). The ranges of weights and lengths of a baby at term are population dependent but for forensic purposes in the United Kingdom are taken as 2550–3360 g, 28–32 cm crown-rump length (CRL) and 48–52 cm crown-heel length (CHL) (Knight, 1996). Gestational age is also frequently estimated in the live newborn infant by evaluation of its neurological maturity (Dubowitz *et al.*, 1970; Dubowitz and Dubowitz, 1977).

Developmental embryologists calculate age from the time of fertilization (postovulation) which takes place approximately 2 weeks after the first day of the LMP and anatomical prenatal age averages 266 days (9.5 lunar months). This can vary with the interval between ovulation and fertilization and it is extremely rare to know the actual age of an embryo (Tucker and O'Rahilly, 1972). Studies of early human development were carried out on embryos obtained from spontaneous or elective abortions. Historically, age was expressed in terms of the CRL, CHL or foot length of the embryo (Streeter, 1920; Noback, 1922; Scammon and Calkins, 1923).

Because of the variation that inevitably occurs when a single criterion such as age is used, it was difficult to make valid comparisons between embryos of the same size but of obviously different developmental stages. This problem was overcome in the human embryonic period and also in a number of commonly used laboratory animals, by a practice called stageing. This entails the division of the first 8 postovulatory weeks (the embryonic period proper) into 23 stages, originally called Streeter developmental horizons but now known as Carnegie stages. Each stage was characterized by a number of external and internal morphological criteria, which were independent of size but indicative of maturity. Stageing was initiated by Streeter (1942, 1945, 1948, 1951) and continued by O'Rahilly *et al.* (O'Rahilly and Gardner, 1972, 1975; O'Rahilly and Müller, 1986; Müller and O'Rahilly, 1994, 1997). Details of the morphological criteria can be found in O'Rahilly and Müller (2001) (see also Appendix 2, Table 1).

In the fetal period (from 9 weeks to term), a satisfactory stageing system is not yet available and the stage of development is still usually expressed in terms of CRL or related data. CRL itself is a rather inexact measurement and actual sizes do vary considerably, although the morphological differences between fetuses become less obvious as term approaches. O'Rahilly and Müller (2000, 2001) advise the use of greatest length (GL), the length of the fetus minus leg length. This is because the crown and rump are not always evident and do not exist in very young embryos, and GL is the length measurement of ultrasound so that comparison may easily be made with living individuals. However, GL is very similar to CRL which was the measurement used in older studies. Texts that provide equivalent ages vary slightly, but there is, nevertheless, an accepted correlation of ranges of CRL or GL with age (Appendix 2, Table 2).

The relationship between various measurements and gestational age was discussed by Birkbeck (1976). Croft *et al.* (1999) used obstetrical ultrasound to determine the most suitable parameters for ageing formalin-fixed human fetuses. They found that both foot length and head circumference were superior to CRL, which, after the first trimester, was inaccurate due to distortion of the spine caused by compression in storage. This would also apply to GL. Sherwood *et al.* (2000) examined a series of spontaneously aborted fetuses to provide a means of obtaining accurate ages for fetuses between 15 and 42 weeks. They found that skeletal measurements taken from radiographs provide better estimates than either anthropometric or ultrasound measurements.

The inherent levels of variability in growth and the uncertainty of establishing actual age in a number of situations mean that the concept of biological age is used as an indicator of how far along the developmental continuum an individual has progressed. Biological age encompasses both skeletal and dental age. The estimation of skeletal age uses both the times of appearance and fusion of ossification centres and the size and morphology of bones. Dental age is expressed either as time of tooth emergence, or in terms of the state of maturation of the teeth assessed from various stages of mineralization. Both skeletal and dental age require the individual to be compared to a known standard and this in turn will introduce areas of incompatibility. For these reasons, the establishment of age at death from juvenile remains, while more reliable than that for adults, is always an estimation.

### Postnatal Age

The terminology used to designate stages of the postnatal life varies both in different countries and as used by clinicians, auxologists and evolutionary and skeletal biologists. Some of these are accepted definitions but usage varies as to other commonly used terms (see Appendix 2).

Cox (2000) has stressed that the present 'obsession' with age has driven us to try to estimate accurate age at death for past populations regardless of what meaning this may have had at that time. For much of the past historical period, the majority of people would have been illiterate and innumerate and consequently age was probably not exactly known, nor indeed relevant. The important phases of life would have been biological and physical such as weaning, dependence on parents, puberty and the attainment of adulthood with the important additions of female fertility and menopause. Behavioural biologists have used these more meaningful phases of the life span that refer to physical attributes or physiological states independent of actual chronological age.

In the UK and North America, the terms immature, subadult and non-adult are used for any stage of life that is not truly adult i.e. when all growth plates are closed. Gradually, however, in more recent publications the term juvenile is replacing these terms and it is used as such in the present text.

## SOURCE MATERIAL

The methodologies that have been developed for the evaluation of age at death have been derived from a variety of skeletal sources. The data recorded before birth are from an entirely different source from those obtained postnatally and observations commonly use different techniques. In general, early development has been studied on aborted embryos and fetuses, and there is a limited amount of information from ultrasound. In contrast, much postnatal information comes from radiographs of living children, although there are a few radiological and histological studies on postmortem and amputated limbs. There is also a wealth of archaeological data from skeletons of individuals whose age at death has been estimated from morphological criteria. Because of this variety of skeletal sources and methods of observation, it is vital in any study of individuals of unknown age that, if at all possible, the provenance of the material used in comparison be known and where appropriate, comparable.

### Prenatal Material

Studies of early human development were carried out on embryos obtained from spontaneous or elective abortions and, while the latter may technically be considered to constitute a normal sample, the former may have exhibited abnormalities that would negate the usefulness of the data. A number of factors, including single or multiple occupation of the uterus, nutrition of the mother, and the introduction of teratogenic components such as alcohol, nicotine and other drugs could affect development and in most cases such information would have been unknown (Roberts, 1976).

Both skeletal and dental structures have been studied by a variety of methods. Until the end of the 19th century, remarkably detailed observations were made from gross dissections. A review can be found in Noback (1943, 1944). Drawings of the fetal skeleton by Kerckring (1717), Albinus (1737) and Rambaud and Renault (1864) are still some of the best recordings taken from gross specimens and are a salutary lesson in observation.

Subsequently, three principal methods were used:

1. Histology – Bone is a tissue that is defined in histological terms and therefore its critical detection must, by definition, be via histological techniques (O'Rahilly and Gardner, 1972). It is the most sensitive method and observations using histology nearly always result in earlier reported times of appearance of bone than for any other method. The examination of serial sections is time-consuming and labourious work but most of the classical papers describing the human embryonic skeleton have been made by this method (Fawcett, 1910a; Macklin, 1914, 1921; Lewis, 1920; Grube and Reinbach, 1976; Müller and O'Rahilly, 1980, 1986, 1994; O'Rahilly and Müller, 1984).
2. Alizarin stain – Examination of alizarin-stained embryos involves 'clearing' of whole specimens with potassium hydroxide followed by staining with alizarin red S. This was only used in the very early stages of development but it provided a good overall picture of the embryo especially the establishment of periosteal bone collars and mineralization of tooth germs (Zawisch, 1956; Meyer and O'Rahilly, 1958; Kraus and Jordan, 1965). However, the method is not specific for actual formation of bone and some accounts have used the first sign of osteoid as the beginning of ossification. Use of this method has therefore brought forward the range of reported times of appearance of ossification centres. Its disadvantages are that it destroyed the soft tissues and so ruined the use of the specimen for further examination and it could only be used in the very early period when the embryo was small enough to be transparent (O'Rahilly and Gardner, 1972).
3. Radiological – Radiological examination can be used at any period of life and leaves the specimen intact but it is the least sensitive method for detection of calcified tissue. Even after enhancement by soaking in silver solutions, calcification is not detected until a sufficient quantity of material has accumulated to render the tissue radiopaque. Also, as both bone and cartilage are radiopaque, the presence of trabeculae must be seen for the presence of bone to be confirmed (Roche, 1986). Observations using radiology provide dates that are at least 1 week later than those made from alizarin or histology (Noback, 1944).

During the later fetal period, data were derived from aborted fetuses and stillbirths, and size measurements were made on either dry bone or from standard radiographs. More recently, clinical ultrasound observations have provided data on living individuals *in utero*.

The study of fetal osteology by Fazekas and Kósa (1978) contains much valuable information, including measurements of most bones of the skeleton from three lunar months to term. However, the age/bone-size correlations involve an inherent circular argument as their material, being of forensic origin, was essentially of unknown age. For their study, fetuses were grouped according to crown-heel length, each group being assigned an age at half-lunar month intervals in accordance with the widely accepted correlation between body length and age using Haase's rule (Fazekas and Kósa, 1978). Their 'regression diagrams' (graphs) are of body length as the independent variable against bone length as the dependent variable. While there is undoubtedly a close correlation between fetal age and size, as grouping was based on crown-heel length, all the bones, especially those of the lower limb that actually contribute to body length, inevitably show a high correlation and lie virtually on a straight line. 'Modified regression diagrams' show age in lunar months superimposed onto these graphs.

Other length data can be found in Balthazard and Dervieux (1921), Hesdorffer and Scammon (1928), Moss *et al.* (1955), Olivier and Pineau (1960), Olivier (1974), Keleman *et al.* (1984), Bareggi *et al.* (1994a, 1996) and Huxley and Jimenez (1996). Length measurements from radiographs can be found in Scheuer *et al.* (1980) and Bagnall *et al.* (1982). Measurements from this source are, of necessity, cross-sectional (see below) and in addition may have introduced some abnormal data.

Starting from the early 1980s there has been increasingly detailed data provided on long bone lengths, and skull and thorax size from ultrasound studies (Jeanty *et al.,* 1981, 1982; O'Brien *et al.,* 1981; Filly and Golbus, 1982; Seeds and Cefalo, 1982; Bertino *et al.,* 1996). These 'ages' commence from conception and have to be adjusted if dates are established from LMP (McIntosh, 1998). Ultrasound norms are derived either from cross-sectional surveys or from longitudinal surveys that involve a limited number of observations per pregnancy (Bertino *et al.,* 1996).

## Postnatal Material

Nearly all information on postnatal known-age material has come from systematic, longitudinal radiological growth studies of living children. These were carried out between about 1930 and 1960 before the full risk of repeated exposure to X-rays was appreciated and are therefore non-repeatable. They involved large groups of children, mostly of middle-class, white Europeans or North Americans of European origin, who were radiographed, often three times during the first year of life, at 6 monthly, and then yearly intervals until cessation of growth in height. This continued exposure to radiography may of itself have had a damaging effect on development.

The 'normal' growth data were originally compiled for clinical purposes. First, screening programmes could identify individuals at risk who might then benefit from treatment and response could be evaluated by paediatricians. Second, larger groups were used to reflect the general health of the population in particular communities or between social classes (Tanner, 1978). Other studies, some limited to fewer bones and shorter time periods, are by Ghantus (1951), Anderson *et al.* (1964) and Gindhart (1973). The data are now of course three generations old and therefore changes in the so-called secular trend, or tendency for increase in height, weight, and decrease in age of maturity, need to be taken into account in their use as comparison populations.

In addition to these large longitudinal surveys, there have been other studies either of a cross-sectional nature or, as often happens, a mixture of the two. Both offer a different type of information and have their merits and disadvantages (Tanner, 1962, 1978). The statistical methods and sampling problems encountered in large studies of this kind are discussed by Goldstein (1986), Healy (1986) and Marubini and Milani (1986). Briefly, a longitudinal study consists of following the same group of individuals over a period of time, whereas a cross-sectional study measures a number of people once only at a particular time in their development. Longitudinal studies, especially those that extend over a number of years, are expensive and time-consuming and require great commitment on the part of both the investigators and subjects. They are the only way to reveal true individual differences in growth velocity such as those that occur in the adolescent growth spurt. As there is always a drop-out rate in recording, so-called longitudinal studies are rarely exclusively longitudinal and often include, by necessity, some cross-sectional data. Because cross-sectional data collection only requires a single measurement (or set of measurements) for each individual, it is potentially easier to include greater numbers. Essentially, it will give information about whether an individual has reached a certain stage of development compared with the mean for that age group.

Many of the large growth studies were used to compile reference atlases specific to a particular joint or topographical region. They consist of a series of standards, separate for males and females, usually at 6-monthly intervals, each of which was compiled from approximately 100 films judged to be the most representative of the anatomical mode. The atlas of the hand and wrist (Greulich and Pyle, 1959) illustrates development of the primary centres of the carpals, secondary centres for the metacarpals, phalanges and distal ends of the radius and ulna. The atlas of the foot and ankle (Hoerr *et al.,* 1962) shows development of the primary centres of the tarsals and secondary centres of the calcaneus, metatarsals, phalanges and distal ends of the tibia and fibula. Similarly the atlas of the elbow (Brodeur *et al.,* 1981) illustrates the development of secondary centres in the distal humerus and proximal radius and ulna, and that of the knee (Pyle and Hoerr, 1955) shows the appearance of the patella and secondary centres of the distal femur and proximal tibia and fibula.

The skeletal age of an individual can be estimated by comparing the pattern and sequence of appearance of the ossification centres on a radiograph with the maturity stages in the atlas. However, this inspectional technique suffers from a number of disadvantages. First, systematic and variable errors occur in evaluation (Mainland, 1953, 1954, 1957; Cockshott and Park, 1983; Cundy *et al.,* 1988). Second, there are methodological objections to this way of assessing maturation (Acheson, 1954, 1957). It presupposes a fixed pattern and order of development in the appearance of centres, which is by no means universal. There is also necessarily a certain time interval between standard films so that a distinction can be made between successive standards. However, this is often too long for good matching to take place. Finally, Garn and Rohmann (1963) and Garn *et al.* (1965a) warn that as a general rule, ossification centres appearing in early postnatal life tend not to be normally distributed but are particularly skewed. As the mean and median no longer coincide, data presented with percentiles are more accurate than those with means, and the atlas method cannot take this into account.

Improvements on the inspectional atlas technique were developed by Acheson (1954, 1957) and Tanner *et al.* (1983). The appearance of metaphyseal ends of the long bones and the epiphyses of each region was awarded a score in units as change in shape occurred during development. In this way, each individual bone element made its own contribution to a total maturity score, regardless of the order of development of individual units. It thus avoided the assessor being compelled to match an individual's X-ray to a standard picture in an atlas and so circumvented the problem of a fixed order of development. As the ossification sequence is also sexually dimorphic, the 'score' method had the added advantage that it allowed direct comparison between the sexes, because the units were those of maturity and not time (Garn *et al.,* 1966). It proved to be a more accurate procedure than the direct inspectional method but was obviously more labourious and time-consuming. The principle is similar to that used for assessing mineralization stages of tooth development in the estimation of dental age (see Chapter 6).

In general, size appears to be more affected by adverse circumstances than is maturity and the majority of studies have recorded diaphyseal measurements of the major long bones. Until recently, apart from the changes in shape used in the scoring methods and isolated case reports in the clinical literature, the use of detailed developmental morphology of ossification centres is a neglected area of osteology (Scheuer and Black, 2000). Fazekas and Kósa (1978) comment briefly on fusion of major elements of the skull. Age changes in early childhood in the occipital bone have been studied by Redfield (1970) and Scheuer and MacLaughlin-Black (1994) and in the temporal bone by Humphrey and Scheuer (2006) (see Chapter 5). Paucity of information on the anatomy of all these bony elements is undoubtedly due to the difficulty in obtaining juvenile skeletal material for study. Postmortem specimens are fortunately rare, and rightly difficult to obtain, because of the sensitivity and obvious emotional consequences of a child's death.

There is, however, a large body of data from dry bone measurements from archaeological material from

Africa, Europe and North America. Most of the data consists of measurements of the long bones of undocumented archaeological populations where age has been estimated, often from dental development, thus entailing a double set of estimations. The documented length data commonly used for comparison with archaeological collections are that from the University of Colorado (Maresh, 1943, 1955, 1970).

Searches of archaeological skeletal collections lacking age-at-death data have shown that epiphyses, especially those of the later developing group, are particularly rare, which is partly due to the age profile of most of the samples. Children succumb to adverse environmental circumstances in the early years of life, but if they survive the first 5 years, few die in later childhood. Material from the ages of 6–12 years is particularly rare. It is fairly common to find early forming epiphyses, such as those of the proximal humerus, distal radius, proximal and distal femur and tibia, but those that make a later appearance and then fuse early, for example, elbow epiphyses, are extremely rare in archaeological excavations. Improved knowledge of timing of skeletal development and the ability to recognize these small elements would undoubtedly result in a better retrieval rate during skeletal excavations. Obviously, age estimation will be determined with greater accuracy using those bone elements that undergo distinct changes within a relatively short time range. Together with diaphyseal length, this aspect of evaluating maturity could then improve accuracy of age estimation.

The reported times of fusion are very variable and, as with the times of appearance, this is due to different methods of observation and also to the fact that variability increases with increasing age. Stevenson (1924), Todd (1930) and Stewart (1934) carried out early studies of fusion using dry bone and radiographs. In their investigation of the Korean War dead, McKern and Stewart (1957) used Stevenson's (1924) categories of fusion and although their data were more extensive in number, their sample was necessarily restricted to males of active military age. As a result, their 'late union' group of epiphyses probably displayed the full range, but their 'early union' group was inevitably truncated at its lower end. Their conclusions pointed to a constant order irrespective of age and to the innominate bone as being the best indicator throughout the particular age range studied (17–23 years). Webb and Suchey (1985), in a forensic series, reported on large numbers of both sexes in a study of ageing from the anterior iliac crest and medial clavicle. These epiphyses are different from those of the long bones in that they fuse relatively soon after formation and so different stageing categories were employed. Results showed that both bones were useful, at least in the forensic situation, where a complete cadaver was present, which meant that their first stage of 'no epiphysis present' was capable of confirmation. Again it was emphasized that the best indicators of age are those whose ranges of fusion are the most restricted in time.

There are several methodological problems involved with reporting epiphyseal union. The degree of union is generally divided into at least four morphological phases – no fusion, commencement of fusion, advanced fusion and complete fusion (Stevenson, 1924; McKern and Stewart, 1957). However, some authors have condensed this to only three stages (Hasselwander, 1910), while others have expanded it to five (MacLaughlin, 1990) or even nine stages (Todd, 1930a). The distinction between different stages can be difficult to identify and as expected, intra- and inter-observer errors increase as the process of union is divided into an ever increasing number of stages. Radiographic studies are either confined to atlases of limited regions of the body, as discussed previously, or appear as scattered reports in the clinical literature. Again, as with appearance times, there is the similar problem of matching an individual to a particular atlas pattern.

It is also difficult to correlate observations from dry bone with those from radiographs. It is obvious in bone specimens whether fusion has begun and indeed whether external fusion is completed as bridges of bone are seen at the periphery of the epiphyseal/metaphyseal junction. However, much of the research in this area has used radiographic images, which have the distinct disadvantage of providing only two-dimensional information (Haines *et al.*, 1967). Epiphyseal union commences with the formation of a mineralized bridge and ends with the complete replacement of the cartilaginous growth plate (Haines, 1975). Although this entire process can extend over quite a considerable period of time, it can also occur quite rapidly within the space of a matter of months and so in this situation it is often difficult to capture a critical moment in dry bone specimens, let alone in radiographic images. Much of the detailed histological information is therefore extrapolated from animal models and so must be viewed with caution when applying it to human conditions (Dawson, 1929; Smith and Allcock, 1960; Haines and Mohuiddin, 1962; Haines, 1975).

Timing of fusion is much affected by variation in the onset of the adolescent growth spurt and not all accounts give total age ranges or sex differences. The inability to determine sex in juvenile skeletal remains until adolescent sexual dimorphism is well-established, complicates the use of fusion times to estimate age in this group until secondary sexual characters are reflected in the skeleton.

More recently, following the tragic events in the Balkans, Rwanda and Sierra Leone, information on war crimes has provided further skeletal data. Forensic anthropologists have had the opportunity to examine more recent remains of previously undocumented populations, assess techniques and modify methods accordingly if necessary.

## ESTIMATION OF SKELETAL AGE

To establish the skeletal age of an individual from a bone, or bone element, it is necessary to identify it in one of its three phases of development. First, the time at which the ossification centre appears; second, the