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REVIEW

Application of Osteology to Forensic Medicine

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The four main features of biological identity are sex, age, stature, and ethnic background. The forensic osteologist aims to establish these attributes for an individual from their skeletal remains. Many techniques are available for the osteological determination of sex in the adult but it is one of the most difficult biological factors to ascribe to juvenile remains. Conversely, there are a multitude of markers to estimate age in the young skeleton but ageing becomes less accurate with increasing years. Stature is usually a relatively straightforward parameter to establish in the adult. In the juvenile, it is naturally correlated with age but is complicated by differences in rates of growth both between the sexes and between individuals. Determination of ethnic identity is the least reliable and is hampered by lack of data on many populations. This paper reviews the principal methods used to establish identity and comments on their reliability and accuracy in the forensic context. Clin. Anat. 15:297–312, 2002.

Key words: forensic osteology; skeletal remains; sexing; ageing; stature estimation

INTRODUCTION

Forensic osteology is a branch of the larger subject of forensic anthropology that includes the study of topics such as facial superimposition, facial reconstruction, forensic odontology, bone pathology, and archaeology. The forensic osteologist is usually asked to provide information that may confirm, or assist in determining, the identity of an individual from their skeletal remains. This may be at the scene of an unexplained or natural death, a homicide, suicide, or mass disaster. More recently, forensic osteologists have become members of teams investigating war graves and providing evidence of atrocities during ethnic cleansing. Many anatomists and skeletal biologists will be familiar with the classical methods used to sex and age skeletons. In a forensic situation, however, osteology requires a more specific focus. Levels of accuracy need to be higher than those considered acceptable in a general archaeological context and the legal consequences of identification of individuals are more significant.

When skeletal remains are discovered, the first question that the police, coroner, procurator fiscal or forensic pathologist usually ask is whether the bones are human or animal. The recognition of human bone will depend primarily on the experience of the forensic osteologist and also on the elements of the skeleton that are present. A small, relatively featureless section from the shaft of a long bone or a fragment of rib is difficult to distinguish from animal remains, especially those of pig or sheep. Sometimes, the smell resulting from heating the bones in a microwave oven or on a radiator in a plastic bag will give a clear indication that the remains are those of a pork or lamb dinner. Occasionally the so-called 'bone' is not composed of bone at all and several recent inquiries have been instigated because of the increasing use and careless disposal of polymer-resin based students' anatomical teaching sets (Black, 2000).

The second question is to determine whether, although human, the remains are of forensic or archaeological provenance. Usually an interval of about 70 years is accepted as the dividing line between these two categories because, beyond this time, it is unlikely that a guilty person could be brought to justice or any reliable witness would come forward. The time

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elapsed since death is one of the most difficult questions to answer as many different factors may alter the composition of bone. After burial, the decomposition of the body and the subsequent skeletonization and preservation of the bones are affected by both the physical conditions and by the activities of humans and animals. These can include temperature, pH of soil, level of the water table, the growth and metabolism of bacteria and vegetation and disturbance by animals. Skeletonization can take place in hot, dry conditions in as little as 2 weeks or may take centuries as witnessed by the bog-men and the ice-man. Taphonomy, the study of the way in which elements of a dead body are scattered and degraded, has been investigated mainly by animal bone specialists rather than in humans. Some of the factors involved in the decay of human bone are discussed by Boddington (1987), Henderson (1987), Grupe and Dreses-Werringloer (1993), Waldron (1994), and Bell et al. (1996).

There are numerous potential chemical indicators of time since death including ^{14}C (Taylor et al., 1989) and ^{90}Sr levels (MacLaughlin-Black et al., 1992; Neis et al., 1999), equilibrium between ^{210}Po and ^{210}Pb levels (Swift, 1998), ultraviolet fluorescence and analysis of nitrogen content by various means (Knight and Lauder, 1967, 1969). Some of these methods are complex, time consuming procedures that require a specialist laboratory and none give a very satisfactory answer within the forensic time frame. Thus the postmortem interval remains one of the most difficult questions to answer with any degree of reliability although there is increasing literature on the use of botanical (Vanezis et al., 1978; Willey and Heilman, 1986) and entomological evidence (Erzinçlioğlu, 1983; Rodriguez and Bass, 1983). In the absence of circumstantial evidence to the contrary, it is therefore advisable to assume that the remains are of forensic importance and proceed accordingly.

Unfortunately the bone specialist is often presented in the mortuary or laboratory with a bag of bones that have been retrieved by persons not specialized in the excavation or examination of a skeleton. This is usually because advice is sought after other lines of investigation have been exhausted. Ideally the forensic osteologist should be present at the scene of recovery that is best supervised by an archaeologist specialized in forensic techniques. First, the circumstances of a burial sometimes provide a means of distinguishing the forensic from the archaeological case. A deep burial associated with the remains of a burial container, coffin nails or grave goods, is not usually of forensic importance, whereas a shallow concealment, especially if accompanied by the remnants of a blanket, carpet or plastic sheet is unlikely to be an archaeological interment. Caution is necessary, however, as there are occasions when a carefully concealed, deep grave is associated with a crime or, conversely, skeletons of archaeological provenance are discovered eroding from the surface of the ground. Second, the presence of an experienced osteologist will aid retrieval of the maximum amount of bone and calcified tissue.

An osteologist was asked by the police to come to the local mortuary and examine some bones. They had been discovered by a farmer whilst ploughing a field and brought to the police station in a plastic carrier bag. On examination they proved to include about a dozen adult human bones and a single neonatal humerus. If the police and the osteologist had been called to the scene immediately, there would have been a possibility of retrieving at least two intact individuals and a possible identification could have been made. Unfortunately the scene had been destroyed and in this case there was no identification.

In a juvenile, the unfused constituents of the skull, vertebrae, and pelvis and the epiphyses of long bones may lie unrecognized by the non-specialist. These elements could add important information leading to the identity of the deceased.

Forensic case where the bones of a boy were found in the garden of an empty house in a London suburb. His family had moved house and he had gone back to the old home and in trying to climb over a wall into the garden, had fallen and subsequently perished. On examination, the skeleton was obviously juvenile with many unfused epiphyses. The ilium, ischium, and pubis were beginning to fuse in the region of the acetabulum. This usually occurs between the ages of 12 and 15 years. The unfortunate boy was identified quickly from the missing persons list and proved to be 13 years of age.

BIOLOGICAL IDENTITY

The four main attributes of biological identity that most forensic osteologists hope to determine are the sex, age, stature, and ethnic background of the individual. The accuracy with which they are determined will depend on which particular elements of the body are present and also on their state of preservation. Reliability also varies according to whether the individuals are adult or immature. Where there is a multiple burial of commingled remains, the first task is to allocate the skeletal elements to specific individuals, at first assuming the least number of persons present. At this point the ability to assign a bone to the correct side of the body becomes important, a skill now considered to be of little consequence by the majority of anatomy teachers. For instance, if two right radii are found, there must be at least two individuals. Other factors that may help in separating bones of specific individuals in commingled remains are the relative size and robusticity of the bones, and their pathological condition and color, although this last can vary among different bones of the same skeleton if they are separated and come to lie in different physical conditions. Adult and juvenile elements may usually be distinguished both by their size and by the state of skeletal development. The ability to separate commingled juveniles depends on a detailed knowledge of the osteology of immature bones. For example, the presence of a separate pars lateralis of the occipital bone together with a proximal ulnar epiphysis will signify at least two children as these elements do not co-exist as separate elements in a single individual.

In Kosovo, at a mass burial, relatives knew that there were the remains of three adult females, and eight children belonging to their family. They wished to be sure that the remains of all the individuals were present and could be buried in separate coffins. The adults were two sisters in their 40s and their elderly mother. The children included two babies of 6 months and 18 months, a 4-year-old, a 5-year-old, an 8-year-old, a 12-year-old and twin boys of 14 years. The bodies had been fragmented during a mortar attack and were in an advanced state of decomposition. The children's remains could only be separated into individuals by a forensic anthropologist with extensive experience of juvenile skeletons.

DETERMINATION OF SEX

Adults

In the adult skeleton, sex determination is usually the first step of the identification process as subsequent methods for age and stature estimation are sex-dependent. Also preliminary determination of sex will approximately halve the search for an unknown individual from a missing persons list. Sexual dimorphism manifests in the skeleton in two forms. First, male bones are generally bigger and more robust than female bones. Second, the male pelvis is primarily adapted to bipedal striding whereas the female pelvis displays size and shape differences that reflect the compromise between efficient locomotion and the modifications necessary for the safe passage of a large fetal head through the birth canal. The reliability of sex determination depends on the completeness of the remains and the degree of sexual dimorphism inherent in the population but it is generally accepted that the two most sexually dimorphic elements of the skeleton are the pelvis and the skull. Many workers claim a sexing accuracy of 80% from the cranium alone, 90% from the skull and mandible and 98% from the pelvis (Mays and Cox, 2000), but these figures may be lower if levels of sexual dimorphism in the population under consideration differ from those in the standard comparison.

Generally the shape of the male pelvis is high and narrow whereas that of the female is wider and shallower and has a larger outlet. These differences are reflected in the shapes of both of the greater sciatic notch and the subpubic angle and in the relative proportions of the body and alae of the sacrum. A wide, shallow greater sciatic notch is considered to be a female characteristic (Hager, 1996) as is the greater width of the ala of the sacrum compared to the width of the body (Kimura, 1982). The pubic bone is probably the element of the skeleton that can offer the most reliable indication of sex (Fig. 1). It is unfortunate that, owing to its thin cover of compact bone and its ventral position in most burials, it is also one of the parts of the skeleton that survive inhumation least well.

Phenice (1969) identified three features characteristic of the female pubic bone: a subpubic concavity; a ventral arc that is an elevated bony ridge extending from the pubic crest to the pubic ramus on the ventral surface of the bone; and a ridged medial border to the inferior pubic ramus, which he claimed could correctly sex with an accuracy of 95%. The Phenice method, although widely used (Krogman and İşcan, 1986; Sutherland and Suchey, 1991) has been criticized both in the US where it was developed (Lovell, 1989) and in Europe (MacLaughlin and Bruce, 1990) where levels of accuracy have been well below those claimed by Phenice. Other indicators of sex that have been used are the greater sciatic notch/acetabular index (Kelley, 1979a; MacLaughlin and Bruce, 1986) and the morphology of the sacro-iliac joint (İşcan and Derrick, 1984; St. Hoyme, 1984; Ali and MacLaughlin, 1991). The accuracy of many of these methods falls well below that necessary for forensic identification when tested on a population sample other than that from which the method originated. Most of the techniques for sexing pelvic bones currently in use in forensic osteology were developed on large sample sizes of archaeological provenance where accuracy in sexing of about 85% was considered reasonable. This means that about one in every seven individuals would be incorrectly assigned which, in a forensic situation, is not acceptable.

Other commonly used pelvic indicators of sex are the so-called 'scars of parturition', thought to be indi-

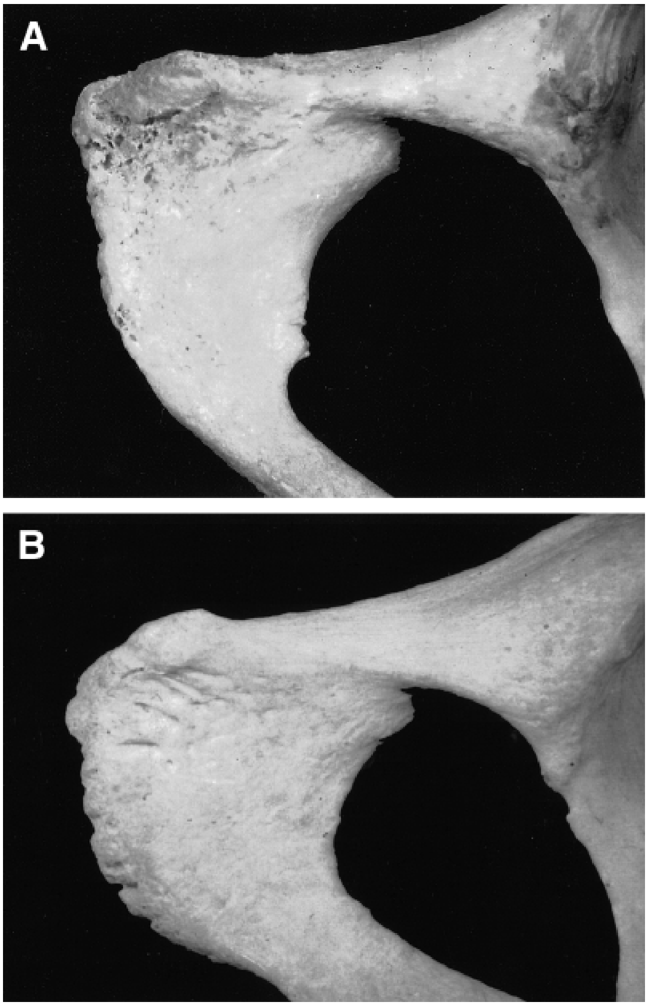

Fig. 1. Anterior view of left pubic bones. **A:** male. **B:** female. The body of the male bone is shorter mediolaterally than the female and consequently appears triangular compared to the quadrangular appearance of the female bone. The female bone slopes away inferiorly into the curved subpubic concavity whereas the male bone has a straighter inferior ramus.

cations that an individual was female and had borne children. Some authors even went as far as declaring that the number of pubic pits could reflect the parity of the individual. They include the presence of a deep pre-auricular sulcus, pitting on the dorsal aspect of the pubic body and extension of the pubic tubercle (Houghton, 1974; Kelley, 1979b; Tague, 1988). All these factors have been extensively investigated and whilst their presence is more common in females, they are not as sex definitive as first claimed or indeed indicative of parity status. In fact, it was reported that pubic pitting was more likely to be associated with age at death than obstetric events. Pubic pits are thought to reflect sites of ligamentous attachment, more obvious in the female because of extensive remodeling (Suchey et al., 1979; Tague, 1988; Cox and Scott, 1992).

Sexual dimorphism exhibited by the skull is mainly dependent on changes that occur in the male at puberty that reflect increased muscle attachment whereas the female skull tends to retain pedomorphic features. In the male, supra-orbital ridges, glabella, mastoid process, and the nuchal and malar areas become more prominent in contrast to the female where all these elements are smaller and the forehead remains vertical with more pronounced frontal bosses. In the female, the orbits are more rounded, have sharper margins and are relatively larger compared to the upper facial skeleton than in the male (Ferembach et al., 1980; Krogman and İşcan, 1986). The male mandible generally has a greater body height, a more prominent chin and robust lower border and more prominent muscle markings than in the female. The gonial angle formed between the body and ramus is less obtuse than in the female. Calcagno (1981) and Maat et al. (1997) found that accuracy of sexing was seriously affected by the size of the mandible. More recently Loth and Henneberg (1996, 1998) described a flexure in the posterior border of the ramus that was present in male, but absent in female mandibles, which they claimed sexed with an accuracy of 94%. Although this level has been supported by Indrayana et al. (1998), it has been criticized by Koski (1996) and Donnelly et al. (1998). The larynx begins to display sexual dimorphism toward the end of the pubertal growth spurt. In the male the differential growth of the thyroid laminae results in a larger size and a more acute angle (Ajmani et al., 1980; Ajmani, 1990; Harjeet and Jit, 1992; Eckel et al., 1994).

In the remainder of the postcranial skeleton, sex differences generally reflect the larger size and bigger muscular development of the male especially as reflected in overall joint size. Recent studies on various elements, some of which are on populations with no previous data, have included the humerus (France, 1983, 1988; Holman and Bennett, 1991; İşcan et al., 1998), the radius (Allen et al., 1987; Berrizbeitia, 1989), hand bones (Scheuer and Elkington, 1993; Smith, 1996), the femur (İşcan and Miller-Shaivitz, 1984a; Trancho et al., 1997; Seidemann et al., 1998), the patella (Introna et al., 1998), the tibia (İşcan and Miller-Shaivitz, 1984b; Holland, 1991; İşcan et al., 1994), foot bones (Riepert et al., 1996; Smith, 1997), ribs (Cöloğlu et al., 1998) and the vertebral column (MacLaughlin and Oldale, 1992).

Forensic case in which a murderer had attempted to destroy a body by repeatedly burning it until it consisted of about 1,500 small pieces most of which were

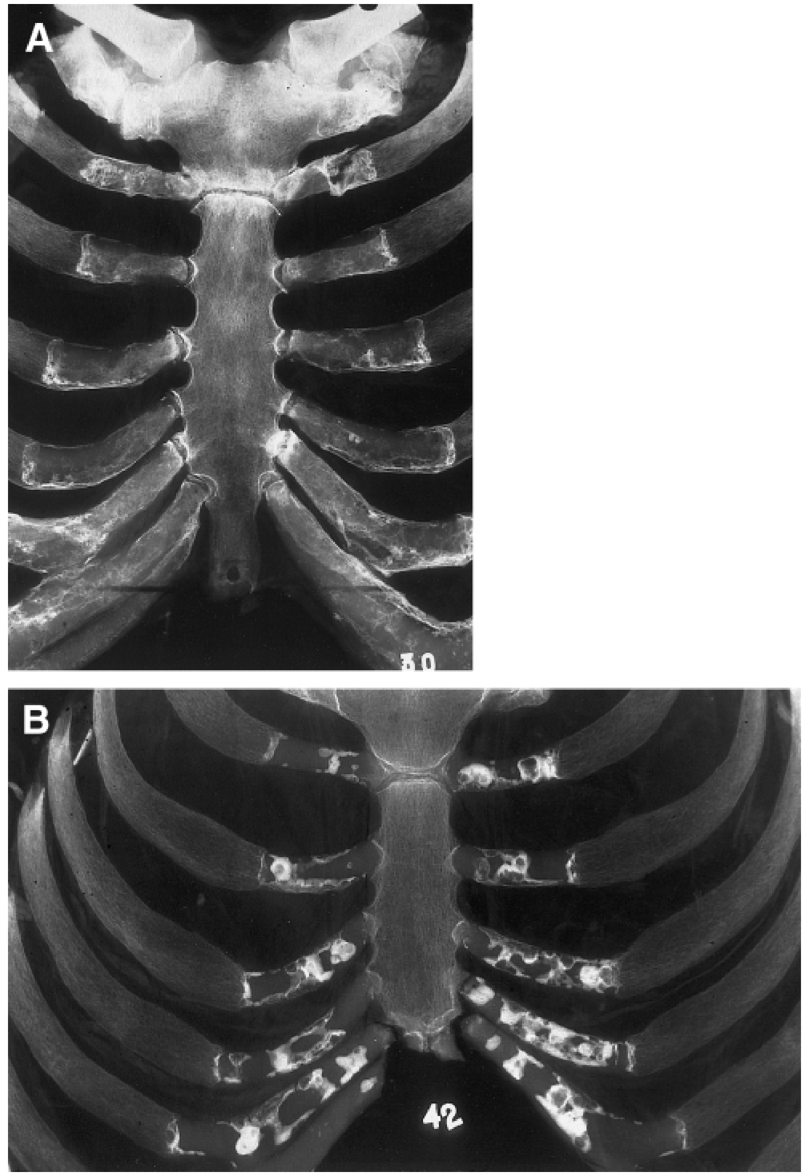

Fig. 2. AP radiographs of chest plates. **A:** male. **B:** female. Male calcification is characterized by 'claw'-like areas of trabecular bone at the ventral end of each rib that appear to outline the costal cartilage. Female calcification is characterized by islands of dense, sclerotic deposits throughout the costal cartilage.

no bigger than a thumb nail. Amongst these were two fragments of orbits with no brow ridging, a piece of flat frontal bone, a sciatic notch with pitting and an extremely small terminal hand phalanx. This eventually led to the identification of a missing female of 4 ft. 10 in. in height.

It has long been established that there is a distinct difference in sex pattern of costal cartilage calcification (Sanders, 1966; Navani et al., 1970). For human remains where some soft tissue is retained, a radiograph of the chest plate (Fig. 2) can provide a useful method of sexing (McCormick and Stewart, 1983; McCormick et al., 1985; Rao and Pai, 1988).

Juveniles

The literature on sexual dimorphism in the immature skeleton has tended to concentrate on the same morphological regions that show differences in the adult such as the pelvis and skull. Fazekas and Kósa (1978) reported up to 80% accuracy in sexing from the greater sciatic notch and lengths of the ilium and femur but Schutkowski (1987), using the same material, achieved barely 70%. More recently, Schutkowski (1993) has described differences in the greater sciatic notch and mandible that have yet to be tested on a comparable series. In an investigation of the sacro-iliac joint, Weaver (1980) described an elevated surface that characterized females and a non-elevated surface that was associated with males. Tests of this method by Hunt (1990) and Mittler and Sheridan (1992) have shown it may have limited use in sexing and it was suggested that the differences might be morphological variations during the growth phase. Some traits of the orbit and mandible used by Molleson et al. (1998) show promise if used under carefully controlled conditions but remain to be tested further on an assemblage of known sex. At the present time, however, it has to be concluded that although sexual dimorphism may exist from an early age, it does not reach a sufficiently high level for accurate sexing until pubertal modifications have taken place. This means that the juvenile skeleton cannot be sexed with any degree of reliability from morphological observations alone. Consequently, because males and females mature at different rates especially during the adolescent period, subsequent age categories are necessarily wider than they would have been had sex been known.

The whole problem of sexing of skeletal remains has changed somewhat since the isolation and amplification of DNA from bone (Hagelberg et al., 1989; Hagelberg and Clegg, 1991). It is now possible in certain circumstances to sex both adult and juvenile material (Naito et al., 1994). The amelogenin gene, responsible for the production of one of the organic components of the enamel of teeth, has sequence differences on the X and Y chromosomes. A method utilizing molecular genetic techniques was developed by Stone et al. (1996) and sex was identified correctly in 19 out of 20 skeletons of known sex. Smith et al. (1993) have published technical guidelines for the management and sampling of dental DNA. At the present time there are problems of contamination and degradation of DNA obtained from both bone and teeth. With the improvement of current techniques and the development of new methods, however, sex-typing from genetic material could become routine in forensic cases. Some of the problems in working with DNA extracted from bone are discussed by Brown (2000).

AGE AT DEATH

Age-related changes in the skeleton may reflect three different phases of the lifespan: growth and development, equilibrium and senescence. The first phase is represented by children and young adults, who undergo changes that proceed at a reasonably predictable rate in a well-documented pattern. Once growth has ceased, the changes in the adult, even within a single skeleton, vary greatly and are more individual and population specific. They are also affected by factors such as health status, occupation, nutrition and endocrine function. In addition most of the methods in use for adult ageing rely on methods developed from large archaeological samples of unknown sex and age. Bocquet-Appel and Masset (1982, 1985) argued that ageing methods developed on such samples have reflected misconceptions about longevity in past populations and in turn have resulted in the replication of the original sample's mortality profile. When tested against samples of known age this has resulted in systematic errors, the most important of which has been the tendency to under-age individuals of over 40 years.

Juveniles

In the juvenile age range, before cessation of growth in height, age may be estimated from numerous markers from the teeth and skeleton so that estimated age bands can usually be narrower than those for adults. Dental age estimates are derived from the eruption or degree of mineralization of the teeth. Skeletal age may be estimated from the developmental state of centers of ossification and the size and length of the long bones. It is commonly observed, although not fully understood, that dental age estimates are closer to actual chronological age than those of skeletal age. A possible reason is that the development of all the deciduous dentition and part of the permanent dentition takes place before birth in a protected environment whereas skeletal growth and development, although having a strong genetic basis, is exposed for a longer time to external factors such as nutrition, socio-economic status and possibly climate.

Strictly speaking, eruption is the continuous process by which teeth move from the alveolar bone to full occlusion in the mouth but most studies are confined to emergence, often wrongly referred to as eruption (Demirjian, 1986). The presence of emerged teeth may be observed easily by the osteologist to give a rapid estimate of age. Increased accuracy, however, can be obtained from the stage of calcification of the teeth. This necessitates radiographic analysis and comparison with defined stages of crown and root mineralization that is both time consuming and requires a considerable degree of experience. Dental microstructure is able to provide an even more accurate method of age determination by counting the perikymata, the incremental lines on the surface of enamel. This is an absolute method of age determination independent of the growth standards of a specific population so could prove to be relevant in individual forensic cases. It requires the facilities of a hard tissue laboratory, experience in the technique and, in addition, is very time consuming and expensive. One particular incremental line, the neonatal line, can be of special medicolegal significance in determining if an infant was liveborn or stillborn. It is formed in all teeth that start to mineralize before birth i.e. the whole deciduous dentition and the first permanent molars. In practice it may be visualized by light microscopy if a child has survived for about 3 weeks after birth, or by electron microscopy, within a day or two of birth (Whittaker and MacDonald, 1989). It has been suggested that further observations of the relationship of the neonatal line to other enamel striae could provide information about certain birth defects and sudden infant death syndrome (Skinner and Dupras, 1993).

In theory, it is possible to age a juvenile skeleton from three features of primary or secondary centers of ossification: first, the time at which the center appears; second, by the size and morphology of the center; and finally, the fusion time of primary and secondary centers. Most centers of the skull, vertebrae, and primary centers of the long bones and their girdles commence ossification in the embryonic and fetal periods whilst the majority of secondary centers develop within cartilaginous templates throughout postnatal life. With a few exceptions, ossification centers commence as nondescript spherical or ovoid nodules of bone and are only identifiable by their anatomical position. In the forensic context their use in ageing is therefore strictly limited to the examination of a body where there is sufficient soft tissue to hold them in place. Preservation of ossification centers varies widely depending on physical conditions but can extend to hundreds of years in the case of mummified remains.

Recognition that a fetus has reached full-term may be of legal importance in some forensic situations. The presence of the secondary ossification centers of the distal femur and proximal tibia and possible presence of ossification in the calcaneus and talus is usually taken to signify this stage (Knight, 1996).

When a primary or secondary center has reached its second phase of development so that it may be recognized by its distinctive morphology, it may be used to advantage in ageing. The critical period for each bone varies and so accuracy will depend on what skeletal elements are available. Most of the bones of the skull, vertebrae, ribs and major long bones of the limbs and girdles are recognizable from mid-fetal life onwards. Some of the tarsal bones and certain early forming long bone epiphyses may be identified in the early years but carpal bones and the later forming secondary centers do not reach a useful stage until later childhood. Age estimation will naturally be determined with greater accuracy using those bone elements that undergo distinct changes within a relatively short period of time. For instance, the fusion of the ischium and pubis at their rami takes place between 3 and 10 years so is not very useful, whereas the changes in shape and fusion between the main epiphysis and the tuberosity of the upper tibia are more constrained in time and are therefore more helpful (Fig. 3).

Until recently, information on these changes has been mainly restricted to isolated accounts in the literature and to standard 2D views of major joints found in radiological atlases (Pyle and Hoerr, 1955; Greulich and Pyle, 1959; Hoerr et al., 1962; Brodeur et al., 1981). Fazekas and Kósa (1978) commented briefly on the appearance of bones in the perinatal period. Redfield (1970) and Scheuer and MacLaughlin-Black (1994) provided more detail of component parts of the occipital bone. The developmental morphology of all the epiphyses of the skeleton are described and illustrated in Scheuer and Black (2000).

The third phase of bone development is when fusion occurs between one or more primary centers or between a primary center and its secondary epiphyses. This stage also covers a wide age range, partly in response to the function of the soft tissues with which the bones are associated. The primary centers of the skull and vertebral column, reflecting the precocious development of the human nervous system, are normally fused by the age of 6 years whereas the fusion of secondary epiphyses of the long bones, associated with locomotion, cover the adolescent and early adult periods. The difficulties of sexing juveniles (see above) complicates the use of fusion times in the adolescent period so that estimated age ranges are necessarily wider than they would be if sex were known. Details of fusion times for all bones of the skeleton may be found in Scheuer and Black (2000).

The lengths of long bone shafts may also be utilized to estimate age but the accuracy will vary depending on the period of life. Lengths of fetal long bones are closely related to gestational age and data are available from dry bones (Fazekas and Kósa, 1978; Keleman et al., 1984; Bareggi et al., 1994, 1996), radiographs (Scheuer et al., 1980; Bagnall et al., 1982) and ultrasound images (Jeanty et al., 1981; O'Brien et al., 1981; Filly and Golbus, 1982; Jeanty et al., 1982; Seeds and Cefalo, 1982; Bertino et al., 1996). Postnatally, estimation of age from long bone lengths is more unreliable than in the fetal period. This is due both to increasing variability with age and a lack of data for comparison. Data on lengths of long bones are drawn from several systematic, non-repeatable cross-sectional and longitudinal radiological surveys of children from at least two generations ago, the majority being drawn from white, middle-class origins (Tanner and Whitehouse, 1959; Maresh, 1970; Tanner et al., 1983).

Fig. 3. Lateral radiographs of juvenile knees. **A:** A child between 5 and 9 years of age. **B:** An adolescent. In the younger child, the distal femoral epiphysis and diaphysis are not the same width whereas the epiphyses of the proximal tibia and fibula are the same width as their diaphyses. The patella has just reached a biconcave form but remains very small. In the older juvenile, the distal femoral epiphysis and the patella are fully adult in form. The proximal tibial epiphysis, which develops in two parts, already has the ossified tuberosity fused to the main part. All growth plates are narrow and ready to begin fusion.

There are many populations for whom there is no adequate sample for comparison. As age increases, the accuracy of age estimation decreases due to the increasing effects of external factors on growth and also to individual and sex variation in height especially during the adolescent growth spurt.

Young Adults

Several areas of the skeleton do not complete their growth until the second and third decades of life and are consequently valuable for estimating age at death in young adulthood. This period extends from the cessation of growth in height, signaled by the fusion of all the long bone epiphyses, until final fusion of all other epiphyses. Skeletal elements include the jugular growth plate of the skull and postcranially, the sacral vertebral bodies, the iliac and ischial epiphyses, vertebral column, scapula, costal notches of the sternum, and medial clavicle.

Traditionally, the closure of the spheno-occipital synchondrosis has been used in this age range and most anatomical and forensic texts quote the age of closure at 18–25 years (Krogman and İşcan, 1986; Williams et al., 1995). This is almost certainly an overestimate as original studies report that closure occurs in the majority of individuals during adolescence and coincides with the

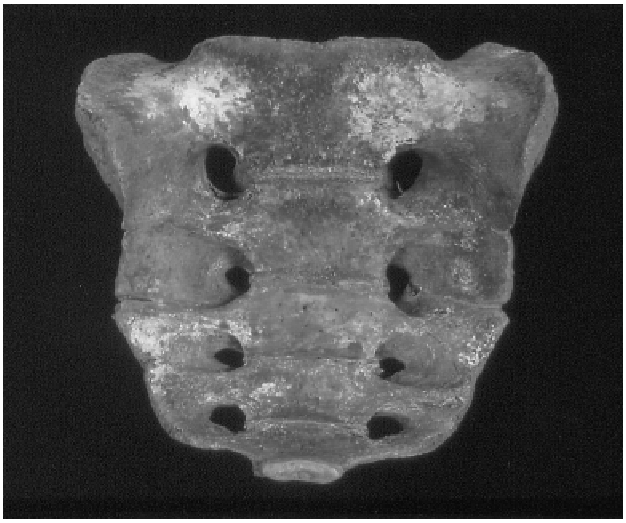

Fig. 4. Late adolescent sacrum. The lateral costal elements are fusing with most closed except at their lateral extremities. Those between S2 and S3 are the least advanced. The vertebral bodies are almost fused but show a larger space between S1 and S2.

eruption of the second molar teeth (Powell and Brodie, 1963; Konie, 1964; Melsen, 1969, 1972; Ingervall and Thilander, 1972; Sahni et al., 1998).

The cartilaginous jugular growth plate (jugular synchondrosis/petro-exoccipital articulation), a small part of the occipitomastoid suture, has been studied by Maat and Mastwijk (1995) and Hershkovitz et al. (1997a) in two different samples. Although the results do not entirely concur, it is obvious that this area could be useful in assigning age in the young adult. The suture is rarely closed under the age of 20 years and is unlikely to be open after the age of 40 years.

There is very little information on fusion times of the sacral vertebral bodies due to the scarcity of young adult skeletons of documented age. Observations suggest that fusion takes place between the late teenage years and continues during most of the third decade with fusion between S1 and S2 being the last to close (Fig. 4).

The fusion time of the epiphysis of the iliac crest has been used clinically for some years to assess remaining growth potential on which to base surgery for scoliosis (Risser, 1958; Scoles et al., 1988; Wagner et al., 1995). It has also been studied in a large forensic series by Webb and Suchey (1985) who reported details of age ranges for fusion of the iliac crest and medial clavicle. The epiphysis on the ischiopubic ramus commences growth on the ischial tuberosity and extends anteriorly on to the ramus. It remains unfused at 19–21 years (McKern and Stewart, 1957; Jit and Singh, 1971) and details of ages of fusion may be found in Scheuer and Black (2000).

There is scant information on the fusion times of the annular ring epiphyses of the vertebral column but McKern and Stewart (1957) and Albert and Maples (1995) suggest that they usually remain unfused until the middle of the second decade of life. In the sacral area of the column, spaces between the vertebral bodies usually signify an individual younger than 20 years of age. If there is lack of complete fusion only between S1 and S2, then the individual is likely to be younger than 27 years (Scheuer and Black, 2000).

> A forensic case of a partial skeleton consisting of the thorax and pelvis and a few long bones was found under a hedge but the skull was missing. From the configuration of the pelvis and the relative gracility of the bones the individual was thought to be female. All the epiphyses of the long bones were fused but there were no signs of age-related pathological change. The estimated age range was thus rather wide and placed between 16+ and 45 years. When the periosteum was scraped from the anterior surface of the sacrum, the bodies of the sacral vertebrae were all fused except those of S1 and S2. This narrowed the age range down to 25–30 years. Later, the skull was recovered and the individual positively identified from dental records. She was 26 years old.

The scapula has at least seven secondary centers of ossification that appear between 8 and 17 years. They include those for the subcoracoid and glenoid, the coracoid and acromial processes, the inferior angle and several for the medial border. Fusion occurs between the ages of 15 and 23 years (Scheuer and Black, 2000).

Fusion between the individual sternebrae of the mesosternum commences inferiorly in childhood but sternebrae one and two may still be delimited in males between the ages of 17 and 18 (McKern and Stewart, 1957). Remnants of fusion may be seen on the anterior surface and in the region of the costal notches up to the age of 30 years.

The slowly maturing, flake epiphysis at the medial end of the clavicle is a useful marker in the young adult age group. A clavicle with no evidence of a fused or fusing epiphysis is likely to have come from an individual less than 18 years of age. A well-defined fusing flake occurs in individuals between the ages of 16 and 21 years and one that covers most of the articular surface is typical between 24 and 29 years. Final fusion is unlikely before 22 years and is nearly always complete by 30 years (Szilvassy, 1980: Webb and Suchey, 1985; MacLaughlin, 1990; Black and Scheuer, 1996).

Adults

In the mature adult, ageing has traditionally used changes in the fusion of the cranial sutures and morphological changes that occur with age in the pubic symphysis and the sacro-iliac joint. More recently, ageing from ventral rib ends has been in common use. Closure of the ecto- and endocranial aspects of the vault sutures have proved very unreliable as age markers despite much work on attempts to test and refine original systems (Ferembach et al., 1980; Meindel and Lovejoy, 1985; Saunders et al., 1992; Key et al., 1994; Hershkovitz et al., 1997b). This is unfortunate as the cranial vault survives inhumation probably better than any other skeletal element. Barber et al. (1995) recently observed that the granular foveolae, pits on the endocranial surface of the frontal and parietal bones that accommodate arachnoid granulations, increase in number with age. Early results showed a high correlation with age but this method needs to be tested for reliability on a large sample of age-documented individuals.

The epiphyseal morphology of the ventral demiface of the pubic symphysis undergoes a prolonged period of age-related change up to the age of 35–40 years and is used for age estimation using component phase analysis (McKern and Stewart, 1957; Gilbert and McKern, 1973). Age ranges are given for different phases each with its own distinct morphology. The original methods, based on archaeological samples, have been subjected to extensive study, testing and modification but still produced large age ranges with enormous overlaps that are not really accurate enough for forensic identification. (Acsádi and Nemeskéri, 1970; Suchey, 1979; Katz and Suchey, 1986; Brooks and Suchey, 1990).

Chronological changes in the appearance of the sacro-iliac joint have also been used to estimate age at death as part of a multifactorial method (Lovejoy et al., 1985). Tested as a single indicator of age, it was again found that age ranges were too large for forensic application (Murray and Murray, 1991). Also the joint may not be visible after the age of 50 years as it frequently undergoes ankylosis.

More recently, a phase analysis system has been developed for ageing from the sternal end of the fourth rib (İşcan, 1985; İşcan et al., 1984, 1985; Loth, 1995) that the authors claim has a similar accuracy to that obtained from the pubic symphysis and better than ageing from cranial sutures. Further analysis, however, showed that it aged males better than females and under-aged individuals over the age of 60. Disadvantages are that it uses one of the least well-preserved parts of the skeleton and also requires the identification of the fourth rib that is difficult in disarticulated material. Saunders et al. (1992) also found that the method had a high degree of inter-observer error that makes it more than usually reliant on the experience of the observer. Dudar et al. (1993), using the method together with a histological technique on a documented sample, reported a poor correlation with chronological age.

Determination of age at death has employed the ability of hyaline cartilage to mineralize even into old age by examination of costal and laryngeal cartilages. The partially calcified tissue that may occur at these sites is often not recovered or even recognized and is, of course, easily damaged. Costal cartilage calcification has been reported in the teenage years but does not usually appear until the middle of the fourth decade (McCormick and Stewart, 1983) and in the upper four ribs until after the age of 50 years (Rao and Pai, 1988). Ossification of the laryngeal cartilages has been much studied (Keen and Wainwright, 1958; Hately et al., 1965; Harrison and Denny, 1983; Turk and Hogg, 1993) and it appears to be accepted, contrary to the evidence, that increasing ossification is positively correlated with age (Krogman and İşcan, 1986; Loth and İşcan, 1989). Most studies have demonstrated that ossification increases with age and there appears to be a recognizable progressive pattern. Timing is highly variable, however, and the correlation between actual age and the degree of ossification involves a wide margin of error. It is not a realistic parameter on which to base age estimation so it is unfortunate that two main texts (Krogman and İşcan, 1986; Loth and İşcan, 1989) quote an age-related pattern (Cérny, 1983) that has been tested on only five individuals.

The appearance of degenerative joint disease as signaled by lipping of vertebral bodies and osteophytes surrounding other joints and muscle attachments does not normally appear until after the age of 40 years. The onset of these features, however, is again very variable and dependent on such factors as genetics, nutrition and life style so that the later decades of life are difficult to estimate with any degree of accuracy. With advancing years sclerotic fusion of the manubriosternal joint is seen, predominantly in females. The primary cartilaginous joints between the manubrium and first costal cartilages may also synostose with advancing years but does not occur in the same individual as manubriosternal fusion (Scheuer and Black, 2000). Synostosis of the sacro-iliac joint is also seen after the age of about 50 years. Sashin (1930), Weisl (1954) and Waldron and Rogers (1990) reported that this is about four times more common in males so it could be used as a corroboration of sex.

The remodeling that bone undergoes throughout adult life has been used in various ways to provide estimates of age at death. Histomorphometric methods are based on quantifiable patterns of intact and fragmentary osteons viewed in bone sections taken from specified sites in the body. Different methods and their variations have been reviewed by Stout (1989, 1992) and Stout and Paine (1992). Some authors claim histological methods to be accurate to within 5.5 years but this has not been confirmed by others. More recently, Wallin et al. (1994) have used a semi-automatic image analysis system to reconsider the degree to which osteon remodeling is affected by age and concluded that determination of age at death by this method is considerably less precise than generally stated in the literature. Other disadvantages are that these methods require specialized laboratory facilities that can prepare undecalcified bone sections and staff with experience and training in bone histology to interpret results adequately. Other methods are based on trabecular bone loss reflected in radiographs of either whole bones or cross-sections of the midshaft. Macchiarelli and Bondioli (1994) employed a radiographic densitometric analysis of the femoral neck. They found that patterns of trabecular bone loss showed marked variation among individuals of the same age in both sexs, and suggested that bone loss with age was episodic rather than continuous. Accordingly, previous reports of useful age information were thought to be overestimated. Feik et al. (1997) subjected complete cross-sections of femoral mid-shaft to automatic video image analysis to quantify varying amounts of cortical and medullary bone at different ages. Again, the variation with sex and age between individuals precludes this method from being used as a predictor of age in forensic cases.

There is a large literature on ageing from individual teeth using changes that occur in root dentine translucency and in the number of annulations of the cementum. Most of the methods need specialized laboratory facilities and an experienced operator for both the microscopic examination and interpretation of results. The present position on ageing from the dentition is discussed by Whittaker (2000).

STATURE

The establishment of the height of an individual from skeletal remains can be, with certain exceptions, one of the most straightforward parameters to be established. The greatest accuracy will be obtained when undamaged long bones of known sex and ethnic identity are available. Standard forensic texts contain tables from which adult male and female stature may be calculated from regression equations (Krogman and İşcan, 1986). Equations with the lowest standard error of the estimate are those using the femur and tibia as these bones form part of an individual's height. There may be occasions, however, when the preferred skeletal elements are not available and an attempt at stature estimation must be made from a metacarpal, metatarsal, clavicle or even fragmentary long bones (Jit and Singh, 1956; Steele and McKern, 1969; Steele, 1970; Musgrave and Harneja, 1978; Byers et al., 1989; Rao et al., 1989; Simmons et al., 1990; Holland, 1992, 1995; Prasad et al., 1996). Accuracy will decline rapidly with the use of incomplete bones and there are many populations for which no data are available.

ETHNIC IDENTITY

The determination of race or ethnic origin is the most difficult and unreliable attribute that the forensic osteologist has to try to establish. Much of the original work on the topic came from the US and is based on so-called Black and White differences in the skull and pelvis (Krogman and İşcan, 1986). Attempts to evaluate racial affinity from the femur rely on differences in anterior shaft curvature and intercondylar shelf angle (Walensky, 1965; Gilbert, 1976; Craig, 1995). There is some evidence that intermembral indices can give an indication of racial affinity. For the upper limb, the brachial index is radial length × 100/humeral length and for the lower limb, the crural index is the tibial length × 100/femoral length. Tables in standard texts show that the ranges for Black, White, and Asian categories are wide with considerable overlap so that identification of race by this method should only ever be used as corroborative rather than diagnostic evidence (Krogman and İşcan, 1986).

In the following two forensic cases of unknown individuals, the use of intermembral indices greatly reduced police time spent on searching the missing persons lists:

A. An unknown male body in a fairly advanced state of decomposition was found floating in the sea off the south coast of England. Length measurements of the humerus, radius, femur and tibia were taken from radiographs of the upper and lower limbs and the brachial and crural indices calculated. Both indices were nearer the mean of those for Blacks than Whites or Asians. The appropriate missing persons list was searched and a positive identification was made.

B. An unknown, clothed male body was found in a shallow burial in a field in the south of England. The same length measurements were taken and indices calculated as for the above case. Indices were nearer the mean for Asians and the individual was quickly identified.

DETERMINATION OF PERSONAL IDENTITY

Occasionally some pre-mortem procedure or record will be available to confirm a personal identity. This is most commonly the dental record of the individual but it may be an existing medical record such as a radiograph of a fracture or some other medical procedure. Several studies have used the distinctive frontal sinus pattern for identification of unknown persons (Ubelaker, 1984; Yoshino et al., 1987; Kullman et al., 1990) and Rhine and Sperry (1991) employed the mastoid sinus pattern in a similar case. There has been extensive use of facial superimposition techniques. Given a good photograph, preferably with the anterior teeth showing, an image of the skull may be superimposed and a match either confirmed or rejected (Clement and Ranson, 1998).

The biggest single factor in the confirmation of identity from skeletal remains has come with the technique of DNA analysis extracted from bone. This is only possible, however, when a missing person has been tentatively identified when samples can be obtained from living relatives or from a match in a DNA database. Possible identification by matching of DNA sequences is a technique involving the statistics of probability that are not easily understood by non-scientific personnel or the general public.

The forensic osteologist may feel pressurized by investigating authorities anxious to solve a case, to make a positive identification of an individual. This is a serious responsibility, however, and it is essential to be absolutely sure that the remains are those of the missing person and that the identification process rests on secure evidence. The consequences could mean the end of distressing uncertainty and eventual closure for the family of a deceased individual with the acceptance of death and the beginning of the process of grieving. In the case of a possible crime, it could also mean the arraignment and trial of a suspect.

Throughout the forensic examination of skeletal remains, there are various legal, and sometimes political, issues and procedures such as confidentiality and continuity of evidence that must be carefully followed. These usually involve cooperation with other personnel such as forensic pathologists, archaeologists, odontologists and forensic dentists. Most of a forensic osteologist's written skeletal reports will be accepted as evidence by a pathologist, coroner, procurator fiscal or police force but sometimes a personal appearance at an inquest or other court is required. Legal proceedings may occur many months, or even several years, after the initial investigation when recall of a case can be difficult especially under the harassing conditions of a courtroom. Care must be taken not to be drawn outside the area of expertise if harangued by a lawyer determined to prove incompetence. The osteologist is the expert witness on bones and it is essential that this can be endorsed by a report that is as detailed, accurate and free from jargon as possible.

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