Seminar 10

Murray C Meikle
DDSc, MSD, PhD, FDSRCS, FRCS
Emeritus Professor of Orthodontics

Craniofacial growth

Following the introduction of the cephalostat by Broadbent in 1931, orthodontic research became dominated for the next forty years by studies of craniofacial growth using cephalometric radiography. Many of these were by-products of the major US growth studies discussed in Seminar 8; others originated from university orthodontic departments around the world, particularly in the United States and Scandinavia. Much of what we know about the growth and form of the face and jaws at the morphological level, and how it can be modified by mechanical means, we owe to the numerous investigators who undertook this research. The aim of this Seminar is to review the key cephalometric investigations from this period and how they have influenced our thinking and clinical practice. The mechanisms regulating craniofacial growth and development at the cellular and molecular level will not be included. They have already been discussed at some length by the present author in *Craniofacial Development, Growth and Evolution* (Meikle, 2002) and earlier Seminars in this series.

Conceptual foundations

Prior to the introduction of cephalometric radiography any discussion of the growth of the jaws in textbooks by the leading orthodontists of the day (Angle, 1907; Lischer, 1912; Dewey, 1914; Case, 1921; McCoy, 1922, 1931; Strang, 1933), was for all practical purposes non-existent. It is not as if nothing was known about the subject. Both John Hunter (1778) and Sir George Humphry (1866) had carried out famous experiments on the mandible in pigs using vital staining and implanted wire rings. Furthermore, von Kölliker had drawn attention to the important role played by the condyle and its cartilage in human mandibular growth, comparing it to the epiphyseal growth plate of a long bone (von Kölliker, 1853, p. 373). Many excellent studies of facial growth had appeared during the early part of the twentieth century (Keith and Campion, 1922; Brash, 1924; Hellman, 1927a,b; Todd, 1930, 1932; Goldstein, 1936), but with research predominantly involving craniometric measurements of skulls from museum collections, the subject was perceived as belonging to comparative anatomy and physical anthropology by most orthodontists. It seemed to have little relevance to everyday clinical practice.

The first ten years

Cephalometric radiography proved to be an ideal method for distinguishing between treatment changes and normal dentofacial growth. Several important cephalometric studies were published in the 1930s that were to have a significant impact on orthodontic concepts of facial growth and whether it could be altered by orthodontic treatment. Broadbent continued to publish data on the normal developmental growth of the face based on subjects from the Bolton Study (Broadbent, 1937a,b); others came mainly from the graduate division of the orthodontic department at the University of Illinois in Chicago (Brodie *et al*., 1938; Brodie, 1940, 1941). This had been established in 1930 under the chairmanship of Dr Allan Brodie and had developed a reputation as a leading, if not *the* leading orthodontic training programme in the United States.

The face of the normal child

In 1937 Broadbent published his landmark paper entitled *The Face of the Normal Child*. Slide 3 shows the tracings of a participant considered to be representative of the 200 or more children in the study between nine and 14.5 years, the age range characterized by transition from the mixed to the permanent dentition. Serial headfilms were superimposed on the Bolton–nasion plane and its registration point R, the distance midway on a perpendicular from the Bo–N plane to sella. It shows a uniform increase in size of the components of the face, the growth of which follows a downward and forward direction.

Slide 3. Tracings of an individual at the age of 9 and 14½ years orientated on the Bolton–nasion plane (Bo–Na) registered at point R; the Frankfort horizontal and orbital planes are also shown. Facial growth follows an orderly downward and forward path. (From Broadbent (1937a), *The Angle Orthodontist*)

The paper also contains one of the most famous series of headfilm tracings in cephalometry, showing the normal developmental growth of the face from one month to adulthood (Slide 4). This illustration served to reinforce the idea that facial growth followed an orderly downward and forward direction, and was not the complex erratic process that it seemed to be from craniostatic drawings of the skulls of dead children.

Although the subjects in the Bolton Study were measured longitudinally, the study was originally set-up as a mixed–longitudinal investigation (Seminar 8). Groups of children were radiographed simultaneously at 3 months, 6 months and 3, 6, 9, 12, 15 and 18 years of age. The headfilm tracings used to compose the figure therefore, did not come from one individual, but were representative examples of several stages, *i.*e. the data was cross-sectional. The figure is also androgynous; the only difference between boys and girls was one of comparative size.

Broadbent did recognize that there was considerable variation in facial form and dentofacial relationships (Broadbent, 1937b), but given that the aim of cephalometric radiography was to make longitudinal studies of facial growth possible, this cross-sectional figure unfortunately created the wrong impression. We now know from the growth pattern of individual patients, that the concept of facial growth occurring in an orderly, consistent manner was incorrect.

Slide 4. Normal developmental growth of the face from one month to adulthood from the Bolton Study records. A, angle of Frankfort plane of the first record to the Bolton-nasion plane of orientation; GN, gnathion; GO, gonion; KR, key ridge; NA, nasion; OR, orbitale; OS, spheno-occipital synchondrosis; MN, mandibular notch. The landmarks in the mid-sagittal plane move forward and downward, with the exception of nasion which moves forward and slightly upward. (From Broadbent (1937a), *The Angle Orthodontist*)

Cephalometric appraisal of orthodontic results

A Broadbent–Bolton cephalometer had been installed in the University of Illinois orthodontic department in 1932, and the first cephalometric study of orthodontic results was published in 1938 by Brodie, Downs, Goldstein and Myer who were staff members in the department. The material consisted of 23 patients who had been treated by graduate students using the Edgewise technique; the cases included Class I (6), Class II (11) and Class III (6) malocclusions and in keeping with the Angle philosophy (Angle, 1928, 1929; Brodie *et al*, 1937), all had been treated nonextraction irrespective of either the degree of crowding or the skeletal relationship. This consisted of tipping the maxillary teeth distally into a Class I relationship by means of second order (tip-back) bends and Class II elastics; the mandibular arch was maintained as a stationary anchorage unit.

Nevertheless, several important observations regarding orthodontic treatment were made, most of which are still valid today. Some can be seen in Slide 5. Brodie *et al.* found that (1) tooth movement was not as great as clinical observation had suggested and that the best results were obtained in those cases where growth was most active; in Class II patients this applied particularly to mandibular growth. (2) The use of intermaxillary elastics changed the occlusal plane by elevation of teeth at both ends of the elastic traction. However, the occlusal plane tended to return to its original position subsequent to treatment. (3) Disturbed axial inclinations (*i.e.* tipping) showed a tendency to return to their pre-treatment position. (4) The effects of orthodontic treatment were restricted to the dentoalveolar process and tooth movement (Slide 6).

Slide 5. Case DF, male, Class II division 1 malocclusion. The cephalometric tracings show the case before treatment and after all retention had been removed. All the class II malocclusions in the series were treated according to the Angle method. Note tipping of the occlusal plane and the growth of the mandible, but surprisingly an absence of lower incisor proclination. No cephalometric analyses or satisfactory maxillary and mandibular superimpositions were included in the paper as they had yet to be invented. (From Brodie *et al.* (1938), *The Angle Orthodontist*)

The growth pattern of the human head

As a result of the 1938 paper and the apparent inability of orthodontic treatment to alter anything beyond the alveolar process, Brodie selected the cephalometric radiographs of twenty-one normal males from 3 months to 8 years of age for a study of the normal growth pattern of the head; the subjects were derived mainly from the Bolton Study. The results of the investigation were reported in the *American Journal of Orthodontics and Oral Surgery* (Brodie, 1940) and the *American Journal of Anatomy* (Brodie, 1941) and provided the research for his PhD dissertation. The head was divided into four areas for analysis (Slide 7), and in this illustration can be seen the emergence of a framework for future cephalometric analyses.

Slide 7. The beginnings of a cephalometric analysis can be seen in this illustration showing the various craniometric points and planes used to divide the head. The variations in stippling indicate the four areas studied: calvarial, nasal, occlusal, mandibular. B, Bolton point; SO, spheno-occipital synchondrosis; S, sella; SE, sphenoethmoidal suture; O, orbitale; N, nasion; PTM, pterygomaxillary fissure; J, zygomatic buttress; PNS, posterior nasal spine; NS, anterior nasal spine; OCC, occlusal plane of the teeth; GO, gonion; GN, gnathion. (From Brodie (1940), *American Journal of Orthodontics and Oral Surgery*)

The most surprising outcome as far as Brodie was concerned was the apparent regularity in the growth pattern of the face and cranium. On examining the nasal area for example, he found that while there was a slight decrease in the angle S–N–NS during the first six or nine months of life indicating a relative retreat of the nose, the angle then stabilized and thereafter did not change (Slide 8A). The angle N–NS–PNS showed a similar stability, so that the nasal floor maintained a constant relationship to the anterior cranial base (S–N). Uniformity was also a feature of mandibular growth, the angle between the occlusal plane and the lower border maintaining a consistent relationship. The most pronounced change was seen at gnathion where the chin appeared to gain on the lower incisal edge until 4 years of age (Slide 8B). After that time the relationship seemed to stabilize.

Slide 8. **(**A) Mean composite of the growth of the nasal area of twenty-one males from 3 months to 8 years of age. S, sella; N, nasion; NS, anterior nasal spine; PNS, posterior nasal spine; PTM, pterygomaxillary fissure. (B) Mean composite of growth of the body of the mandible of twenty-one males from 2 years to 8 years of age. GO, gonion; GN, gnathion. (From Brodie (1940), *American Journal of Orthodontics and Oral Surgery*)

Brodie recognized that these observations were derived from mean values and could only be accepted as indicating general trends or tendencies. He therefore looked at individual cases to see how closely they conformed to average behaviour. Slide 9A shows the facial pattern of two individuals with the greatest deviation from the mean, and in Slide 9B two cases having identical S–N distances, but two distinct facial types. However, despite the differences in type, all these cases taken individually showed a constancy of pattern throughout the period studied.

Slide 9. A. Facial polygons comparing extremes in the angle S–N–GN on the pattern of the mean (8 years), registered at S. It also shows how variance in the length of S–N will influence angular measurements of the face in relation to the anterior cranial base. B. Superimposed patterns of two cases having identical S–N dimensions. (From Brodie (1940), *American Journal of Orthodontics and Oral Surgery*)

At the same time that Brodie had been carrying out this investigation, Johnson (1940), who had been working with Stockard at the Cornell Experimental Farm on the crossbreeding of various dog types, showed by means of hybridization experiments that the genetic constitution was a vital factor in the development of skull form and dental occlusion. Johnson's results combined with Brodie's conclusion that the morphogenetic pattern of the individual was established at an early age, and that once attained did not change (Brodie, 1940, 1941), plus the earlier finding that orthodontic treatment was limited to dentoalveolar remodelling (Brodie *et al*., 1938), were interpreted as implying (1) the immutability of the skeletal pattern of the individual, and (2) the inability of the clinician to influence it, or the growth pattern in any way (Slide 10). These conclusions were to have an profound effect on orthodontic practice in the United States for the next 30 years.

The face in profile

For his doctoral research project, Björk studied facial growth in Swedish children and army conscripts, the results of which were published in *The Face in Profile* (1947), another classic of the cephalometric literature. The investigation, which was cross-sectional, was carried out to determine (1) the normal range of variation in the facial skeleton of the Swedish population, and (2) growth changes in the face. The material consisted of 322 twelve-year-old boys from the town of Västerås 60 miles from Stockholm where Björk practiced dentistry, and 281 Swedish army conscripts aged twenty-one to twenty-three years. The conscripts were from the Dalkarlia Regiment and were considered to be reasonably representative of the male population as a whole. The reference points employed in the analysis and the mean values of the two groups are shown in Slide 11.

Slide 11. A. Reference points used by Björk in his investigation of Swedish children and army conscripts. Most correspond to standard craniometric points: *a*, articulare; *kk,* point of intersection between the mandibular base and ramus tangents to the mandible (*i.e.* gonion); *mi*, mesial contact point of the lower first molar projected to the plane of occlusion; *ms*, mesial contact point of the upper first molar projected to the plane of occlusion; *snp*, spina nasalis posterior. B. Comparison of the facial diagrams (polygons) of conscripts and twelve-year-old boys, based on the mean values for the two groups and illustrating the growth changes. The corresponding angles in the two are the same, with the exception of increased angles of maxillary and mandibular prognathism (see text) and a reduced chin angle (by 4.3 ± 0.48 degrees) in the polygon representing the adults; this is an important cause of lower incisor crowding during adolescence. (From Björk (1947), *The Face in Profile*)

Facial prognathism

Björk was particularly interested in facial prognathism – the relative protrusion of the jaws to the anterior cranial base represented by the line nasion–sella. Between the ages of 12 and 22, maxillary prognathism (S–N–Pr) increased by 1.2 ± 0.31 degrees, and mandibular prognathism (S–N–Po) increased by 2.8 ± 0.32 degrees, resulting in a straightening of the facial profile. Björk found that the degree of prognathism tended to be influenced less by jaw length, but rather more by changes in the angular relationships of the facial skeleton, and the shape of the cranial base (Slide 12).

For example, as the saddle angle (N–S–Ar) at the sella turcica decreases (Slide 12A), the temporomandibular joint will be displaced forward with the secondary effect of a forward displacement of the jaws. Similarly, a change in the joint angle (S–Ar–Go) has a pronounced effect on the degree of prognathism (12B). However, a change in the gonial or jaw angle formed by the horizontal and vertical rami of the mandible was found to have relatively little effect. A change in the chin angle significantly altered dentoalveolar prognathism (12C).

The two linear dimensions found to significantly influence prognathism were anterior cranial base length and mandibular length; a decrease in the former and an increase in the latter will increase it. It is important to remember, however, that the data shown in Slide 12B represents average changes. Examination of the actual changes in individual cases indicated that the causes of prognathism vary considerably from patient to patient. Another important finding was that the increase in mandibular prognathism and consequent uprighting of the lower incisor teeth was likely to be a major contributory factor to lower incisor crowding during adolescence. A significant factor in post-retention lower incisor crowding.

Slide 12. Effect of angular changes on facial prognathism. A. Reduction in the saddle angle (N–S–Ar) at the sella turcica is accompanied by an increase in prognathism. B. A reduction in the joint angle (S–Ar–Go) is accompanied by an equal increase in prognathism; changes in the gonial angle have relatively modest effects on facial prognathism. C. Changes in the chin angle significantly alter dentoalveolar prognathism. For some reason Björk chose incision superioris–pogonion to mandibular plane in this figure to construct the chin angle. (From Björk (1947), *The Face in Profile*)

Lande (1952) a graduate orthodontic student in Brodie's department at the University of Illinois, studied the growth of the human bony profile in 34 male subjects, using serial cephalometric radiography for his Master's research project; 33 were from the Bolton Study and one from the department of orthodontics. The data were initially analyzed in three age groups; 3 to 7 years, 7 to 12 years, and 12 to 18 years. Although one can debate the validity of the plane S–N being registered at nasion rather than sella, the mean profile changes (Slide 13) illustrate that over the time scale of the investigation, there was a decrease in the convexity of the face represented by the angle N–A–Gn. Most of the series also showed a decrease in the angular relationship between the lower border of the mandible and the S–N plane.

Slide 13. Mean changes in profile of 34 male subjects from 3 to 18 years of age. From 3 to 7 years no significant change in the anteroposterior position of points A, B or Gn was recorded. From 7 to 12 years Gn moved forward 1.3 mm while points A and B remained unchanged. From 12 to 18 years point A moved forward 1 mm, point B 2.2 mm, and Gn 3.7 mm. (From Lande (1952), *The Angle Orthodontist*)

The increase in mandibular prognathism was similar to that reported by Björk (1947), but what makes this study particularly important is that special attention was focused on individual variation within the sample. Expressing data numerically as mean ± standard deviation may be statistically *de rigeur*, but does not have the same visual impact as (Slide 14) in which the subjects are ranked in order of increasing forward movement of gnathion. The amount of change in the position of gnathion in an anteroposterior direction ranged from –3.7 mm (B2049) to +12.75 mm (B1168). Anteroposterior change in the position of point A similarly ranged from –4.25 mm (B2005) to +3.25 mm (B2252). Ten of the 34 subjects had a Class II dental base relationship, but in none of these did the retrognathic face tend to become more retrognathic. Lande also found that while the majority of cases did not vary in the overall direction of change, there was variation in the individual series. This is illustrated in subject B2102 where the changes are in the same direction, whereas subject B2070 demonstrates irregularity in the direction of growth (Slide 15).

Slide 14. Profile changes (N–A–Gn) in each of the 34 male subjects ranked in order of increasing forward movement of gnathion. What this figure illustrates is the wide range of individual variation within the group compared to the mean profile changes shown in Fig. 3.9. I rate this as one of the most important figures in the cephalometric literature (From Lande (1952), *The Angle Orthodontist*)

Slide 15. A. Profile change in subject B2012 at 3, 8, 13 and 18 years of age; Gn moves downwards and forwards in the same direction in an orderly, consistent manner. B. Profile change in subject B2070 showing a more irregular growth pattern; between 6 and 11 years Gn moved downwards and backwards. (From Lande (1952), *The Angle Orthodontist.*)

Facial growth at puberty

A high degree of association between the pubertal growth spurt in body height (Seminar 8), and a corresponding increase in growth velocity for facial dimensions has been well documented, although the timing may be asynchronous (Nanda, 1955; Bambha, 1961; Hunter, 1966; Brown *et al*., 1971; Bergersen, 1972; Thompson *et al*., 1976; Lewis *et al*., 1982, 1985). In contrast, the early studies of Broadbent (1937a) and Brodie (1940, 1941) suggested that the face grew in a gradual consistent manner. The cephalometric standards from the University of Michigan Growth Study (Riolo *et al*., 1974) and the Bolton Study (Broadbent *et al*., 1975) similarly show a gradual increase in facial dimensions with no identifiable circumpubertal change (Slide 16). Bishara *et al*. (1981) reported that pubertal spurts in the mandible were uncommon, and Moore *et al.* (1990) from the University of Nebraska, also concluded that there were no growth spurts in any of the facial dimensions they measured, although their data suggests otherwise. How these differences might be reconciled would seem to depend upon (1) the facial dimension and how it is measured; (2) the manner in which the data was processed, *i.e.* pooled versus individual

Evidence in support of pubertal spurts in facial growth

Several major contributions to the literature have been based on the participants in the longitudinal growth studies that had been established at the Child Research Council, Denver and the Fels Research Institute, Ohio. All the subjects in these studies were born either in Denver or Southwestern Ohio of the upper middle socioeconomic class, and North European (Caucasian) descent.

Child Research Council, Denver

The investigations of Nanda (1955), Bambha (1961), Hunter (1966) and Bergersen (1972) were carried out on participants in the growth study at the Child Research Council, University of Colorado that was active between 1927 and 1967. In the first of these, Nanda (1955) measured the individual patterns of growth of seven linear facial dimensions in 10 males and 5 females. Spurts in facial growth were small, but demonstrable and generally occurred a little after the pubertal maximum or peak height velocity (PHV) in body height. However, not all the spurts in the growth of the various facial measurements occurred contemporaneously or in the same order in individual subjects (Slide 17).

Slide 17. Curves of the relative growth rate for three facial dimensions. A, nasion–gnathion; B, gonion–gnathion; C, sella–gnathion for each of the 10 boys ranked according to the age at which their circumpubertal maximum occurred (indicated by the arrow). The age at PHV is represented by the small vertical line. The curve at the bottom of each of the figures is the median incremental curve for the 10 boys. (From Nanda (1955), *American Journal of Orthodontics*.)

In Bambha's series of 25 males and 25 females eight cranial and facial dimensions were measured from the centre of the sella turcica to the following bony landmarks; Bolton point, lambda, bregma, nasion, subspinale, infradentale, gnathion and gonion (Bambha, 1961). He found that the three cranial dimensions completed most of their growth by four years showing very small increments thereafter. In contrast the facial growth curves showed a gradual rise followed by a steep ascent for a small period during puberty (Slide 18). Bambha confirmed Nanda's findings of a definite circumpubertal growth spurt in facial growth occurring just after the growth spurt in body height (Nanda's sample of 10 males were included in Bambha's sample), and that the face continues to grow after growth in body height is completed. Although the numbers involved in each of the above studies were relatively modest, it did enable both Nanda and Bambha to illustrate longitudinal data in individual subjects showing clear, albeit small growth spurts (Slide 19). These become less obvious or disappear when the data is pooled; average growth curves are not representative of the individual.

Slide 18. Growth curves of facial dimensions (solid lines) and cranial dimensions (stippled lines) of girl number 110 and boy number 85. The cranial dimensions complete most of their growth by the end of 4 years (a neural pattern of growth), whereas the facial dimensions show a skeletal pattern of growth. (From Bambha (1961), *Journal of the American Dental Association*.)

Slide 19. Growth velocity curves for cranial and facial dimensions and body height of boy 85 and girl 110 expressed as percentage increase. (From Bambha (1961), *Journal of the American Dental Association*.)

Seven linear measurements were used to evaluate facial growth by Hunter (1966) in 59 subjects (28 males; 34 females). He found that in the majority (39) maximal facial growth was coincident with PHV. And of the remainder it occurred in 6 before PHV and after in 10. Of all the facial measurements the anteroposterior length of the mandible (articulare–pogonion) showed the most consistent relationship with growth in height in both males and females; the correlation coefficient between gain in length of the mandible and body height during the pubertal growth period was $r = 0.76$. As one would expect there was a wide variation in the timing of maximal facial growth within both the male and female samples. Bergersen (1972) in a study of 23 male subjects also found no difference in the timing of the pubertal spurt for body height and articulare–gnathion, nasion–menton and sella–gnathion.

Fels Research Institute, Ohio

Lewis and his co-workers published several studies based on 34 male and 33 female subjects enrolled in the longitudinal growth study at the Fels Research Institute. These have shown that pubertal spurts occur in the growth of the cranial base and mandible of most children (Lewis and Roche, 1972, 1974; Roche and Lewis, 1974; Lewis *et al.*, 1982, 1985). Differences between the timing of PHV and craniofacial spurts varied widely and in some children mandibular spurts did not occur until the third year following PHV. Spurts were defined as increases between successive cranial base increments exceeding 0.75 mm/year in boys or 0.5 mm/year in girls. For the mandible the criteria was 1.0 mm/year in either sex. In the mandible growth spurts were more common in boys than girls and tended to be larger (Slide 20). Pubertal spurts generally occurred after the onset of ossification of the ulna sesamoid bone but before menarche. However, they reported that although common, mandibular spurts were not universal and did not occur in some children.

Slide 20. Median annual increments (mm/year) in cranial base and mandibular length in relation to peak height velocity (PHV). Mandibular spurts (Ar–Gn; Go–Gn; Ar–Go) were more common in boys than girls, were larger and tended to occur in the years after PHV. (From Lewis *et al.,* (1985), *The Angle Orthodontist*)

The agnostic view

Bishara *et al*. (1981) measured longitudinal changes in standing height and mandibular parameters in 20 male and 15 female subjects from the Facial Growth Study at the University of Iowa, begun in 1946 by Howard Meredith and L B Higley. The mean increase in mandibular length (articulare–pogonion) during the 2 years of maximum growth velocity was found to be 6.3 ± 1.3 mm in 10 males and 4.8 ± 1.0 mm in 10 females. The growth profile of Ar–Pog had a correlation coefficient with standing height of r = 0.83 for girls and r = 0.47 for boys. They concluded that significant circumpubertal acceleration in mandibular growth parameters could not consistently be validated in their population sample and that mandibular growth was due to a gradual increase in dimensions. They did go on to say, however, that this does not mean that accelerations do not occur in any one person, but that changes which could be described as spurts do not occur in a consistent pattern in many persons.

Moore *et al*. (1990) from the University of Nebraska College of Dentistry, analyzed four linear craniofacial measurements on 39 males and 47 females from the Bolton Study and related them to standing height measurements and hand–wrist radiographs scored by the Tanner–Whitehouse TW2 method. Their results indicated that statural height and hand–wrist skeletal maturation were significantly related in both sexes. However, the children demonstrated a large variety of growth patterns and growth spurts could not consistently be observed on an individual basis. Mandibular growth was assessed according to changes in the linear dimension gonion–gnathion. (This is a measure of the body of the mandible, not overall mandibular length and is not a valid measurement of mandibular growth since it excludes changes at the condyle – the same can be said of measurements involving articulare.)

What do facial growth standards tell us about pubertal growth?

During the 1970s two volumes of facial growth standards were published. One from the University of Michigan Growth Study (Riolo *et al.,* 1974), the other from the Bolton Study (Broadbent *et al.,*1975) and both have become standard reference manuals for clinical and research purposes. In a discussion of whether mandibular growth spurts exist, Bishara (2001) refers to these studies to support the view that pubertal spurts in facial growth do not occur (Slide 21). One is bound to ask in the light of clinical experience, is this statement true?

University of Michigan Growth Standards

Annual cephalometric radiographs of participants in the longitudinal growth study at the University of Michigan began in 1953, and of the original sample, 83 individuals (47 male, 36 female) from the age of six to sixteen years were used to compose *An Atlas of Craniofacial Growth* (Riolo *et al.,* 1974). In the Michigan atlas, the mean changes in the mandibular linear dimension (condylion–gnathion) show a gradual increase with age (Slide 22). Although the growth curves in the atlas are based on longitudinal measurements of individual participants in the study, they are presented in a cumulative cross-sectional manner. These may be useful for producing growth standards, but do not reveal the distinctive features of pubertal growth represented by velocity curves (Seminar 8). Other problems with the Michigan manual is that the standards stop at the age of 16 (orthodontic patients do not stop growing at that age), and are subject to a 12.9% enlargement. It would have been helpful if the authors had gone to the trouble of normalizing the data prior to publication.

Slide 22. Growth curves showing cumulative mandibular changes in the linear dimension condylion–gnathion (Co–Gn) of participants in the University of Michigan Growth Study. There is no evidence for a pubertal spurt in mandibular growth. (From Riolo *et al.* (1974), *An Atlas of Craniofacial Growth*)

Facial growth curves are useful if one wishes to know the average growth for a given population sample, but like growth curves for height they reveal little about the dynamics of pubertal facial growth or the growth of an individual patient. The problem of course is the wide personal variation in the timing (referred to in the growth literature as the *tempo of growth*), and magnitude of growth at puberty, as well as the accuracy and validity of what is being measured. This is of particular relevance when it comes to measuring mandibular growth. As pointed out forcefully by Tanner (1987), if the investigator fails to understand the problem, ignoring differences in tempo produces standards of growth at puberty that are biased, grossly inefficient, and make the anatomical and physiological changes at puberty disappear. This is clearly illustrated in Slide 23 showing the relationship between individual and mean velocities of five boys during their pubertal growth spurt. If individual growth curves are averaged without regard to these different timings, the mean curve will have a quite different shape from the curve of any one individual (Tanner, 1987). That averaging individual growth velocity curves results in a mean curve with an artificially flattened peak has been recognized for many years (Shuttleworth, 1937), but unfortunately has been largely ignored by orthodontic researchers.

Slide 23. Relation between individual and mean velocities of 5 boys during their pubertal growth spurt. (A) The height curves are plotted against chronological age and illustrate that boys of the same age can vary widely in the timing of puberty. The mean curve ignores individual differences in tempo. (B) The height curves are plotted according to their time of maximum velocity. (From Tanner (1962), *Growth at Adolescence,* with the permission of Blackwell Scientific Publications)

Bolton Growth Standards

Examination of the Broadbent *et al*. (1975) atlas also shows a small consistent increase in the magnitude of facial dimensions in both males and females with no significant growth spurts evident (Slide 24). However, the authors do point out on page 68:

> "It is well known that periods of acceleration and deceleration occur in an individual's developmental progress, particularly in relation to the pubertal growth spurt. However, the occurrence of these changes in velocity takes place at different chronologic ages in different individuals. Consequently, the method of averaging tracings that has been used to resolve the Standards into one outline tracing has obliterated these individual variations, so that the Standards demonstrate an essentially uniform incremental pattern. The point, then, should be constantly kept in mind that, although the Bolton Standards demonstrate almost complete uniformity of progression, the individual is a variable entity and will present changes of growth magnitude at varying times in his or her own developmental growth progress."

Slide 24. Male Bolton Standards. These are superimposed tracings at three year intervals and indicate the symmetrical and uniform growth pattern when registered on R point with the Bolton planes (Na–Bo) parallel. (From Broadbent *et al*. (1975), *Bolton Standards of Dentofacial Developmental Growth*.)

King's College London Growth Standards

The King's College London Growth Study at the Dental School at Denmark Hill was started in 1952 by Professor Barry Leighton, and continued by Suren Bhatia culminating in a *Manual of Facial Growth* (Bhatia and Leighton, 1993). Five hundred and twenty-eight British subjects of Caucasian origin were examined at birth, six months and annually thereafter. Longitudinal cephalometric growth data from the age of four to twenty years based on 121 subjects in the study was subsequently published in the *Manual.*

Compared to the University of Michigan manual there are significant differences between the two as far as the recorded linear measurements are concerned (Slide 25). For example, for boys aged 12 years, the mean mandibular distance Co–Gn is 119.7 ± 4.5 mm in the Michigan Study, and 104.9 ± 4.7 mm in the King's Study. This is because in the Michigan Study an x–ray distance of 152.25 cm was used and all the linear measurements in the atlas are subject to a 12.9 percent enlargement, which does not make the atlas particularly user friendly. In the King's Study the x–ray distance was 183 cm and a factor of 0.928 (equivalent to an enlargement of 7.76 percent) was used to adjust all linear dimensions to natural size. Another advantage of the King's College manual, having been produced 20 years later than the Michigan and Bolton Standards, is the inclusion of linear dimensions expressed in the form of velocity curves (Slide 26), although they are averages and not *tempo-conditional*.

Slide 25. Growth curves showing cumulative changes in the mandibular linear dimension condylion–gnathion (Co–Gn) of participants in the King's College London Growth Study. A small spurt in mandibular growth during puberty is evident in the male sample, less so in the female; (From Bhatia and Leighton (1993), *A Manual of Facial Growth*)

Slide 26. The same data as in Slide 25 for the mandibular linear dimension Co–Gn expressed in the form of growth velocity curves. A small but detectable spurt in mandibular growth starting at the age of 12 is evident in the male sample and age 10 in the female sample. (From Bhatia and Leighton (1993), *A Manual of Facial Growth*)

Manuals of craniofacial growth standards should be regarded as historical documents, and not be used as controls in clinical investigations of treatment outcome. They are no substitute for contemporaneous controls in which the participants are matched for ethnic background – the subjects enrolled in the Bolton, Michigan and King's College growth studies were all of Caucasian ethnicity and date back many years. Nevertheless, it is important they are preserved because the records they hold are unlikely to be repeated. The most productive use they could be put to in the future would be to document the changes in dentofacial growth of the individual participants. After all that is what longitudinal studies were designed for in the first place. It made absolutely no sense to spend years and large sums of money collecting longitudinal data on numerous individuals and then analyzing the data cross-sectionally.

How reliable are mandibular growth measurements?

The short answer is not very. Changes in the growth velocity of the various facial dimensions discussed above are based on measurements of the linear distance between two cephalometric landmarks. As far as measurements of a dimension such as the anterior cranial base (S–N) are concerned this does not present a problem, but when considering the growth of the mandible, the use of a linear dimension such as condylion–gnathion (Co–Gn) or articulare–gnathion (Ar–Gn) to measure growth changes in an angular bone has considerable potential for error. In addition to problems arising from the anatomy of the mandible, conventional cephalometric methods assume a constancy of the facial pattern that in reality does not occur. Another problem is that condylion, obscured as it is by the petrous temporal bone and the basiocciput, is notoriously difficult to identify accurately in conventional cephalometric radiographs, although there has been some improvement with the introduction of digital films. An additional radiograph taken with the mouth wide open will provide a satisfactory image of the condylar head for most purposes, but unlikely to be approved by Ethical Committees these days.

Quantifying condylar growth

When Björk superimposed mandibular profiles on implants (Björk, 1955), he found that the longitudinal growth of the mandible was confined to the head of the condyle, and that the direction of condylar growth was highly variable (Björk, 1963; Slide 27). The linear dimension Co–Gn or Ar–Gn will thus be influenced by the condylar growth direction of the subject being measured. In the 1963 paper Björk also reported the measurement of condylar growth rate in 45 boys from the age of 5–22 years, and found a clear difference between the average growth rates for the juvenile and pubertal periods (Slide 28). Annual mean growth during the juvenile period was fairly even at about 3 mm; during the pubertal period, condylar growth accelerated to an average of about 5 mm/annum, although there was marked individual variation in all ages throughout the observation period. Remarkably, none of the mandibular growth studies or growth standards published subsequent to Björks's paper has taken mandibular growth rotation into account.

Slide 27. Illustration of the wide variability in condylar growth direction (revealed by superimposition of Cephalometric tracings on mandibular implants at 3 year intervals) in 12 boys and 9 girls over a 6 year period in relation to the ramus line (RL). The growth in most cases followed a path that curved forwards and was strongly correlated with rotation of the mandible; in case 4 there was a backward curvature of 13° and in case 2 of 15°. (From Björk (1963), *Journal of Dental Research*)

Slide 28. Annual growth rate of mandibular condyles in 45 boys measured in the direction of condylar growth. The 209 points represent annual observations marked at the middle of the year of observation. The curve represents the mean annual growth. (From Björk (1963), *Journal of Dental Research*)

The scientific method: based on changes in condylion

To address this problem, Hägg and Attström (1992) quantified differences between conventional cephalometric methods for estimating mandibular length, and what they called a scientific method based on changes in the position of condylion on cephalograms orientated by metallic implants. They found that (1) the amount of growth estimated by the distance Co–Pog was on average 3.3 mm less than the scientific method, (2) the distance Ar–Pog was on average 3.9 mm less than the scientific method, and (3) the amount of growth estimated by the maximum length of the mandible was on average 2.3 mm less than the scientific method (Slide 29). By any criteria these are significant differences. Mandibular growth curves based on standard cephalometric methods, and clinical investigations of the effects of treatment on mandibular growth, which consistently underestimate the growth of the condyle are therefore not valid (Slide 30).

Slide 29. Pronounced vertical condylar growth pattern in a girl from the Copenhagen Growth Study. (A) Localization of the landmarks used to estimate mandibular growth by the scientific method (condylion) and for two of the standard cephalometric methods (condylion–pogonion and articulare–pogonion). (B) Points used for the estimation of maximum mandibular length. It also shows the three locations of pogonion which were transformed to the tracing of the mandible.(From Hägg and Attström (1992), *American Journal of Orthodontics and Dentofacial Orthopedics*)

Pancherz analysis

The Pancherz analysis (Pancherz, 1982) has been used in a number of prospective clinical trials designed to test the ability of a variety of functional appliances to significantly alter dentofacial growth. This analysis also fails to take into account individual variation in condylar growth direction, and as a consequence, will significantly underestimate both condylar and mandibular growth (Slide 31).

Slide 31. The Pancherz analysis. A. Linear measurements of sagittal skeletal and dental changes are made from the reference line OLp (occlusal line perpendiculare), a line perpendicular to the occlusal line (OL) through sella. Mandibular length is represented by Pg/OLp plus Co/OLp. (Redrawn from Pancherz (1982), *American Journal of Orthodontics*.) B. The Pancherz method for measuring mandibular length will underestimate the contribution of condylar growth (Co/OLp), compared to a direct measurement from Co^1 to Co^2 or Co^3. The difference will be less significant the more horizontal the growth pattern of the condyles. However, if the patient grows vertically to Co^3, the difference between the direct and indirect measurements will be considerable.

Condylar growth velocity curves

In a pioneering and important study, Buschang *et al.* (1999) produced sex-specific growth charts for the incremental growth of the mandibular condyle. The data was based upon a mixed–longitudinal sample of 113 male and 108 female French-Canadian children from the Human Growth Research Centre, University of Montreal, who had been followed annually from 6 to 16 years of age. Mean yearly velocities of condylar growth for males ranged from 2.1–3.1 mm/year with a pubertal peak at 14.3 years; for females mean condylar growth ranged from 2.0–2.7 mm/year, with a pubertal peak at 12.2 years (Slide 32). As can be seen from the percentile curves, there was substantial individual variation in condylar growth. This will have a significant impact on treatment outcome in patients with skeletal discrepancies. For a male patient on the 90th percentile, for example, condylar growth will average 5 mm/year, while for another on the 25th percentile the annual increment will be as little as 1–2 mm.

Slide 32. Growth velocity curves for the mandibular condyle (corrected for magnification) based on the movement of condylion on serial mandibular tracings superimposed on natural reference structures (Björk's structures). Percentiles were used to describe individual variation and the growth curves were drawn by plotting growth rates at each age and smoothing the lines between them. (Redrawn form Buschang *et al*. (1999), *European Journal of Orthodontics*.)

Growth of the ageing craniofacial skeleton

Growth of the face and head does not cease on reaching physical maturity. Small but measurable increases in both cranial and facial dimensions can be detected in hard and soft tissue landmarks beyond the age of twenty years (Hunter and Garn, 1969). The first workers to investigate the effects of ageing on physical characteristics such as stature and head size were anthropologists and anatomists. One who studied the problem extensively was Aleš Hrdlička (1936), who also reviewed the literature from the time of Quételat (1842) and added some observations of his own. He concluded from the available evidence that growth does not cease completely in all individuals by 22–24 years, but that on average it proceeds slowly in some features to the fourth decade (increase in stature), in others the fifth (skull and face), and in a few even later (size of nose, length of ears, width of mouth). However, as in every other human characteristic there was considerable individual variation.

Other well-known figures such as T Wingate Todd and Milo Hellman carried out cross-sectional studies on skulls, reporting that the calvaria increased in thickness up to the seventh decade (Todd, 1924), while the face continued to grow in height and width until old age (Hellman, 1927b). Lasker (1953) found a tendency for head breadth and bizygomatic diameter to increase with age in both males and females in adult Mexicans. And in a study to analyze size changes in the head and face during the third decade of American military personnel (age range 19–33 years), Baer (1956) found a significant increase in total facial height, nose height and bizygomatic width in the male sample. However, all these studies involved craniometric measurements made through soft tissues.

The advent of cephalometry enabled the effects of ageing on skull dimensions to be measured more accurately. In a cross-sectional study of 165 Finnish women aged 20–81 years, Tallgren 1957) found that facial height (N–Gn), showed an average increase from the 20–29 age group (117.6 ± 0.72 mm) up to the oldest age group, 50–81 years (121.86 ± 0.81 mm); the highest mean value, however, was found in the 30–39-year-olds (123.3 ± 1.16 mm). In a longitudinal study of 71 Caucasian males aged 22–34 years of age Thompson and Kendrick (1964) found that during a one year interval small increases in the vertical dimensions of the skull could be measured. Although statistically significant, the mean differences in total skull height (vertex–menton) and total facial height (nasion–menton) amounted to 0.46 mm and 0.57 mm respectively. The topic was investigated at length by Israel using subjects from the Fels Research Institute (Israel, 1968, 1971, 1973). He found that the skull increased in thickness (0.5 ± 0.25 mm) in both sexes by approximately 6 percent after the age of 24 years over a mean period of 18 years (Slide 33). Both surface and sutural deposition were implicated in the enlargement. Israel also found a consistent 5–7 percent enlargement in overall mandibular size and contrary to a long-standing dogma, neither age nor dental status had any effect upon the gonial (mandibular) angle. Longitudinal radiographic studies of the mandible do not support the view popularized by textbooks that the gonial angle increases with age or edentulism.

Slide 33. Increase in skull thickness and diameter over an 18 year period demonstrated by aligning the occipital tables. (From Israel (1968), *Archives of Oral Biology*)

In a longitudinal study, growth changes in 39 men and 32 women (average age 24 years) who had been students at the Faculty of Odontology in Stockholm were recorded after 5 and 10 years (Forsberg, 1976). Small but statistically significant increases in vertical facial height (N–Gn) were detected; these were of very small magnitude, however, amounting to on average only 0.35 mm in men and 0.37 mm in women; these changes had occurred during the period 24–29 years and were thought to result from posterior mandibular rotation. Since these represent average values, not all individuals recorded an increase in vertical facial height; biological variation was such that 8 male and 3 female participants exhibited negative values, while 6 individuals did not show any vertical change at all.

Contrary to the generally accepted assumption that periosteal deposition of new bone ceases at or shortly after skeletal maturity (about age 20), histological studies of sections through the human rib and femur have shown that increases in the transverse dimensions of these bones continues well past the age of 40 years (Trotter *et al.,* 1960; Sedlin *et al.,* 1963; Smith and Walker, 1964). Conclusive evidence that periosteal bone deposition can continue after attaining skeletal maturity was provided by Epker and Frost (1966), who analyzed over 400 mineralized cross-sections of ribs from ninety-two metabolically normal individuals, whose bones had been labelled *in vivo* with tetracycline on one or more occasions. Of the children under 10 years of age, 92 percent had tetracycline labelling of the subperiosteal circumferential lamellae. With increasing age there was a significant decline in the percentage with periosteal tetracycline labelling from 70 percent at age 20–29, but even in the seventh decade 33 percent of individuals had labelled bone surfaces. At no age were 100 percent of the periosteal surfaces labelled, reflecting variability in the ongoing remodelling activity of bone surfaces (Slide 34).

Behrents (1985) in a well-known investigation recalled some of the participants in the original Bolton Study, and of these 113 were selected for in-depth analysis. Superimposition of serial headfilm tracings indicated that growth had occurred at older ages than previously thought (Slides 35, 36). And although the changes noted were in the main small, they did suggest that the craniofacial skeleton underwent growth and remodelling changes throughout life. (One criticism of Behrent's study is that because of the length of the time-scale between radiographs, it is not possible to pinpoint exactly when the changes had occurred.) Cephalometry was also able to show in detail the well-known alterations in the soft tissues of the ageing face, as well as sexual dimorphism in both osseous and soft tissue landmarks. Soft tissue glabella moved forwards and downwards with time and soft tissue nasion showed similar adjustments. The nose continued to enlarge and the upper lip lengthened; soft tissue pogonion and menton followed a progressive forward and downward movement (Slides 35, 36).

Slide 34. A. Superimposition of the headfilm tracings of a female subject at 17 (dotted line) and 21 years (solid line). B. Superimposition at 21(dotted) and 57 years (solid line). Changes in the soft tissue profile during this period are quite marked, although it is not possible to be certain exactly when during the 36 year interval these changes took place. (From Behrents (1985), *Growth in the Aging Craniofacial Skeleton*)

Slide 35. A. Superimposition of the headfilm tracings of a male subject at 17 (dotted) and 20 years (solid line). The changes in both osseous and soft tissue landmarks are marked. B. Superimposition at 20 (dotted) and 55 years (solid line) showing further growth adjustments. (From Behrents (1985), *Growth in the Aging Craniofacial Skeleton*)

Changes in the dimensions of the head with age reported previously, can therefore be attributed to the continued subperiosteal deposition/remodelling of new bone during the life of an individual. Cephalometric landmarks in the adult are therefore not growth static as originally thought. Surface growth and remodelling may significantly alter the position of osseous anatomical landmarks that will affect both linear and angular measurements, particularly those of facial dimensions involving nasion and the various mandibular landmarks.

Summary

- Prior to cephalometric radiography, most clinicians believed the dogma of the Angle School; malocclusion of the teeth and jaws was the consequence of inadequate bone growth, which could be corrected by orthodontic treatment. In other words, orthodontic appliances could stimulate the growth of bone.

- Following the investigations of Broadbent and Brodie, this was replaced by a new dogma. First, facial growth occurred in and orderly consistent manner. Second, orthodontic treatment was limited to dentoalveolar remodelling, and tooth movement alone. Some clinicians still believe this.

- Small but detectable spurts in facial growth, and the pubertal growth spurt have been well documented, although the timing may be asynchronous.

- Volumes of facial standards should now be regarded as historical documents. Facial growth curves are useful if one wishes to know the average growth for a given population sample, but like growth curves for height they reveal little about the growth dynamics of pubertal growth, or growth of an individual patient. And after all, as clinicians that is what we are interested in.

- The King's College London manual being the most recent has adressed some of the shortcomings of the Michigan and Bolton standards. However, none are substitutes for contemporaneous controls in clinical investigations of clinical outcome.

- Measurements of mandibular growth based on linear measurements that do not take into account variability in the amount and direction of condylar growth, or mandibular growth rotation, are not valid.

References

Angle EH (1907). *Treatment of Malocclusion of the Teeth*. *Angle's System*. Seventh edition, The SS White Dental Manufacturing Company, Philadelphia, Pennsylvania.

Angle EH. The latest and best in orthodontic mechanism. *The Dental Cosmos*: December (1928) **70**, 1143–1156; February (1929) **71**, 164–174; March (1929) **72**, 260–270; April (1929) **73**, 409–421. Founded in 1859, in 1936 *The Dental Cosmos* merged with *The Journal of the American Dental Association*, itself founded in 1913.

Baer MJ (1956). Dimensional changes in the human head and face in the third decade of life. *American Journal of Physical Anthropology* **14**, 557–575.

Bambha JK (1961). Longitudinal cephalometric roentgenographic study of face and cranium in relation to body height. *Journal of the American Dental Association* **63**, 776–799.

Behrents RG (1985). *Growth in the Aging Craniofacial Skeleton*. Monograph 17 Craniofacial Growth Series, Center for Human Growth and Development, University of Michigan, Ann Arbor.

Bergersen EO (1972). The male adolescent facial growth spurt: its prediction and relation to skeletal maturation. *The Angle Orthodontist* **42**, 319–338.

Bhatia SN, Leighton BC (1993*). A Manual of Facial Growth. A Computer Analysis of Longitudinal Cephalometric Growth Data*. Oxford University Press, Oxford.

Bishara SE, Jamison JE, Peterson LC, DeKock WH (1981). Longitudinal changes in standing height and mandibular parameters between the ages of 8 and 17 years. *American Journal of Orthodontics* **80**, 115–135.

Björk A (1947). The face in profile. An anthropological X-ray investigation on Swedish children and conscripts. *Svensk Tandläkare-Tidskrift* **40** (Supplement 5B). pp. 1–180. Second printing (1972), Odontologisk Boghandels Forlag, Copenhagen.

Björk A (1955). Facial growth in man studied with the aid of metallic implants. *Acta Odontologica Scandinavica* **13**, 9–34.

Björk A (1963). Variations in the growth pattern of the human mandible: a longitudinal radiographic study by the implant method. *Journal of Dental Research* **42**, 400– 411.

Brash JC (1924). The growth of the jaws and palate. Lectures on *The Growth of the Jaws, Normal and Abnormal, in Health and Disease*. Dental Board of the UK, London. pp. 23–66.

Broadbent BH (1937a). The face of the normal child. *The Angle Orthodontist* **7**, 183–208.

Broadbent BH (1937b). Bolton standards and technique in orthodontic practice. *The Angle Orthodontist* **7**, 209–233.

Broadbent BH Sr, Broadbent BH Jr, Golden WH (1975). *Bolton Standards of Dentofacial Developmental Growth.* The C V Mosby Company, St. Louis, Missouri.

Brodie AG, Bercea MN, Gromme EJ, Neff CW (1937). The application of the principles of the edgewise arch in the treatment of Class II division 1 malocclusion. (A discussion of the paper of Charles H Tweed, DDS, published under the above title in Vol VI, No 3 of *The Angle Orthodontist*). *The Angle Orthodontist* **7**, 1–14.

Brodie AG (1940). Some recent observations of the growth of the face and their implications to the orthodontist. *American Journal of Orthodontics and Oral Surgery* **26,** 744–757.

Brodie AG (1941). On the growth pattern of the human head from the third month to the eighth year of life. *American Journal of Anatomy* **68**, 209–262.

Brodie AG, Downs WB, Goldstein A, Myer E (1938). Cephalometric appraisal of orthodontic results. *The Angle Orthodontist* **8**, 261–351.

Brown T, Barrett MJ, Grave KC (1971). Facial growth and skeletal maturation at adolescence. *Tandlaerebladet (Danish Dental Journal)* **75**, 1211–1222.

Buschang PH, Santos-Pinto A, Demirijan A (1999). Incremental growth charts for condylar growth between 6 and 16 years of age. *European Journal of Orthodontics* **21**, 167–173.

Dewey M (1914*). Practical Orthodontia*. CV Mosby Company, St Louis.

Epker BN, Frost HM (1966). Periosteal appositional bone growth from age two to age seventy in man. A tetracycline evaluation. *Anatomical Record* **154**, 573–577.

Forsberg C-M (1976). *Growth Changes in the Adult Face. A longitudinal roentgen cephalometric investigation on men and women in early adulthood*. Doctoral Thesis, Faculty of Odontology, Karolinska Institute, Stockholm, Sweden.

Goldstein MS (1936). Changes in dimension and form of the face and head with age. *American Journal of Physical Anthropology* **22,** 37–86.

Hägg U, Attström K (1992). Mandibular growth estimated by four cephalometric measurements. *American Journal of Orthodontics and Dentofacial Orthopedics* **102**, 146–152.

Hellman M (1927a). Changes in the human face brought about by development. *The International Journal of Orthodontia, Oral Surgery and Radiography* **13**, 475–515.

Hellman M (1927b). A preliminary study in development as it affects the human face. *Dental Cosmos* 69, 250–269.

Hrdlička A (1936). Growth during adult life. *Proceedings of the American Philosophical Society* **76**, 847–897.

Humphry GM (1866). On the growth of the jaws. *Transactions of the Cambridge Philosophical Society* **11**, 1–5.

Hunter J (1778). *The Natural History of the Human Teeth*. Second edition. J. Johnson, St. Paul's Churchyard, London.

Hunter CJ (1966). The correlation of facial growth with body height and skeletal maturation at adolescence. *The Angle Orthodontist* **36**, 44–64.

Hunter WS, Garn SM (1969). Evidence for a secular trend in face size. *The Angle Orthodontist* **39**, 320–323.

Israel H (1968). Continuing growth in the human cranial skeleton. *Archives of Oral Biology* **13**, 133–137.

Israel H (1971). *The Impact of Aging upon the Adult Craniofacial Skeleton.* Dissertation for the PhD degree, University of Alabama, Birmingham, Alabama.

Israel H (1973). Recent knowledge concerning craniofacial aging. *The Angle Orthodontist* **43**, 176–184.

Johnson AL (1940). Constitutional factor in skull form and dental occlusion. *American Journal of Orthodontics and Oral Surgery* **26**, 627–663.

Keith A Sir, Campion GC (1922). A contribution to the mechanism of growth of the human face. *Dental Record* **42**, 61–88. Also published (1922) in the *International Journal of Orthodontia, Oral Surgery and Radiography* **8**, 607–633.

Lande MJ (1952). Growth behaviour of the human bony facial profile as revealed by serial cephalometric roentgenology. *The Angle Orthodontist* **22**, 78–90.

Lasker GW (1953). The age factor in bodily measurements of adult male and female Mexicans. *Human Biology* **25**, 50–63.

Lewis AB, Roche AF (1972). Elongation of the cranial base in girls during pubescence. *The Angle Orthodontist* **42**, 358–367.

Lewis AB, Roche AF (1974). Cranial base elongation in boys during pubescence. *The Angle Orthodontist* **44**, 83–93.

Lewis AB, Roche AF, Wagner B (1982). Growth of the mandible during pubescence. *The Angle Orthodontist* **52,** 325–342.

Lewis AB, Roche AF, Wagner B (1985). Pubertal spurts in cranial base and mandible: comparison within individuals. *The Angle Orthodontist* **55**, 17–30.

Lischer BE (1912). *Principles and Methods of Orthodontics. An Introductory Study of the Art for Students and Practitioners of Dentistry*. Lea and Febiger, Philadelphia.

McCoy JD (1922). *Applied Orthodontia. An Introductory Text for Students and Practitioners of Dentistry*. Lea and Febiger, Philadelphia.

McCoy JD (1931). *Applied Orthodontia. An Introductory Text for Students and Practitioners of Dentistry*. 3rd Edition. Henry Kimpton, London.

Moore RN, Moyer BA, DuBois LM (1990). Skeletal maturation and craniofacial growth. *American Journal of Orthodontics and Dentofacial Orthopedics* **98**, 33–40.

Nanda RS (1955). The rates of growth of several facial components measured from serial cephalometric roentgenograms. *American Journal of Orthodontics* **41**, 658 – 673.

Pancherz H (1982). The mechanism of action of Class II correction in Herbst appliance treatment. A cephalometric investigation. *American Journal of Orthodontics* **82**, 104–113.

Quételet A (1842). *A Treatise on Man*. W and R Chambers, Edinburgh.

Riolo ML, Moyers ML, McNamara JA, Hunter WS (1974*). An Atlas of Craniofacial Growth.* Monograph 2. Craniofacial Growth Series, Center for Human Growth and Development, University of Michigan, Ann Arbor.

Roche AF, Lewis AB (1974). Sex differences in elongation of the cranial base during pubescence. *The Angle Orthodontist* **44**, 279 – 294.

Sedlin ED, Frost HM, Villanueva AR (1963). Variation in cross section area of rib cortex with bone. *Gerontology* **18**, 9–13.

Shuttleworth FK (1937). Sexual maturation and the skeletal growth of girls aged six to nineteen. *Monographs of the Society for Research into Child Development* **2,** 1–253.

Smith R, Walker R (1964). Femoral expansion in aging women: implications for osteoporosis and fractures. *Science* **145**, 156–157.

Strang RHW (1933). *A Text-Book of Orthodontia*. Lea and Febiger, Philadelphia.

Tallgren A (1957). Changes in adult face height due to ageing, wear and loss of teeth and prosthetic treatment. A roentgen cephalometric study mainly on Finnish women. *Acta Odontologica Scandinavica* **15** (Supplement 24), 1–122.

Tanner JM (1987). Growth at adolescence: an introduction. In *Craniofacial Growth During Adolescence* (eds D S Carlson, D A Ribbens), Monograph 20. Craniofacial Growth Series, Center for Human Growth and Development, University of Michigan, Ann Arbor. pp. 1–21.

Thompson JL, Kendrick GS (1964). Changes in the vertical dimensions of the human male skull during the third and fourth decades of life. *Anatomical Record* **150**, 209 – 214.

Thompson GW, Popovich F, Anderson DL (1976). Maximum growth changes in mandibular length, stature and weight. *Human Biology* **48**, 285 – 293.

Todd TW (1924). Thickness of the male white cranium. *Anatomical Record* **27**, 245–256.

Todd TW (1930). Facial growth and mandibular adjustment. *The International Journal of Orthodontia, Oral Surgery and Radiography* **16**, 1243–1272.

Todd TW (1932). Prognathism: a study in development of the face. *Journal of the American Dental Association* **19**, 2172–2184.

Trotter M, Broman GE, Peterson RR (1960). Densities of bones of white and negro skeletons. *Journal of Bone and Joint Surgery* **42A**, 50–58.

von Kölliker RA (1853). *Manual of Human Histology*. Translation of *Handbuch de Gewebelehre des Menschen* by G Busk, TH Huxley, Volume 1. Sydenham Society, London.