

Seminar 9

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Cephalometric radiography

Cephalometric radiography or cephalometry is the technique of using orientated radiographs of the head for the purpose of measuring the dimensions of the face and skull; cephalometry is measurement of the living head. It originated with a thesis entitled *Roentgen Anthropometry of the Skull*, awarded the Leonard Research Prize by the American Roentgen Ray Society in 1921 and published the following year (Pacini, 1922). It thus evolved from craniometry, a term traditionally reserved for anatomical and anthropological studies of dried skulls. Standardized cephalometric radiography was subsequently developed independently by Broadbent in the USA and by Hofrath in Germany (Broadbent, 1931; Hofrath, 1931). The technique represented a significant advance over craniometry, in that accurate longitudinal studies of craniofacial growth could be undertaken on living subjects for the first time. It also became possible to accurately determine the effects of orthodontic treatment on tooth movement and craniofacial growth. A vast clinical and research literature has accumulated since 1931, and several textbooks have been published devoted entirely to the subject, of which those edited by Athanasiou (1995) and Jacobson (1995) are among the most recent. The aim in this Seminar is to provide the basics.

Origins of cephalometry

The measurement of the dimensions, shape and proportions of the human body, are generally recognized to have originated during the Renaissance with the work of Leonardo da Vinci and Albrecht Dürer. These were undertaken to provide general and objective rules for portraying the human form in painting, drawing and sculpture. Such studies were part of a search for a utopian ideal of physical beauty based on geometric relationships, and on the harmony of the parts of the human body. These ideals or canons are time-linked, cultural and subjective; the ideals of ancient Greeks, Renaissance Europeans, and modern Western Societies are not the same (Moorrees, 1995).

During the latter half of the eighteenth century the motivation for measuring skulls was anatomical and marked the origin of physical anthropology; the study of the external characteristics of man. Natural historians became interested by questions related to evolution and man's place in Nature. For example, what are the morphological characteristics that distinguish humans from the rest of the animal world, and in particular from non-human primates? And what is the basis and/or significance of the variations in facial form between different ethnic groups of humans? Only the analyses introduced by Camper and von Spix from this period are described here. For the contribution of such notable anatomists as Johann Friedrich Blumenbach (1752–1840), Georges Cuvier (1769–1832) and Etienne Geoffrey Saint-Hilaire (1772–1844) to the measurement of facial proportions, see Gysel (1996).

Leonardo da Vinci

Leonardo da Vinci (1452 –1519) needs no introduction, a man of endless curiosity and inventive imagination; one of the greatest painters of all time. During the late 1480s he embarked on a series of extensive studies of the anatomy and physiology of the human body. In 1489 he began a book entitled *On the Human Figure* (a project that was never completed) in which he made systematic studies of two young men. Leonardo then compared the results of these anthropometric studies with the only surviving theory of proportions from antiquity, the Vitruvian Man. Vitruvius, a Roman architect and engineer had written a treatise on architecture entitled *De Architectura* (prior to AD 27), which included in its third book a description of the complete measurements of the human body. These led Vitruvius to conclude that a man with legs and arms outstretched would fit into a square and a circle (Slide 4). As part of his anatomical

studies at this time, Leonardo also made several pen and ink drawings of the human head and skull, including the one shown in [Slide 5](#), in which a coordinate or grid system is projected onto the head of a man. The principle of coordinates to study human proportions was in common use by artists in the fifteenth and sixteenth centuries.

Slide 4. *The Proportions of the Human Figure* by Leonardo da Vinci (circa 1490). Probably the best known of all his drawings, Leonardo re-interpreted the ancient teachings of Vitruvius on the proportions of the human body. According to Vitruvius if the figure of a man with legs and arms outstretched was shown within a square (*homo ad quadratum*) and a circle (*homo ad circulum*), then the centre of the human body would coincide with the navel. Pen, ink and watercolour over metalpoint. Original 344×245 mm. (Gallerie dell Accademia, Venice)

Slide 5. *Study for Man's Head in Profile* by Leonardo da Vinci (circa 1490). A proportional analysis of the face has been made using a grid system of horizontal and vertical lines. According to the marginal notes the head has been divided into seven parts by eight horizontal lines; the eye is situated midway between the crown of the head and the chin. Leonardo's drawings represent the first scientific studies of the human body. Silverpoint worked over in ink on blue prepared paper. Original 213×153 mm. (Royal Library, Windsor Castle, Windsor)

Albrecht Dürer

Albrecht Dürer (1471–1528) a German painter and printmaker from Nuremberg whose prints established his reputation across Europe when he was still in his twenties; regarded as the greatest artist of the Northern Renaissance. During his final years he concentrated on writing treatises including his great work on symmetry and human proportions (*De Symmetria Partium*), published posthumously in 1528. Dürer used a rectilinear coordinate system to demonstrate the characteristics of different facial types, and continued to search for a mathematical canon that would describe and set out the classical rules for beauty. The illustrations in [Slide 6](#) are from a French translation of 1557. To anyone familiar with Dürer's work as an artist, painter and engraver, they hardly do justice to his creative genius.

Slide 6. Woodcuts from *Les Quatre Livres d'Albert Dürer* (1557). Left: A proportional analysis of straight, convex and concave facial profiles has been made to illustrate the variations in facial form. Original 150×60 mm. From *Proportion de l'Homme, Livre III*. (Courtesy of the Syndics of Cambridge University Library.) Right: proportional analysis of a dolichocephalic (narrow) and brachycephalic (broad) head has been made using a rectilinear coordinate system. This shows that difference in facial type is only a difference of scale. Original 120×150 mm. (Courtesy of the Syndics of Cambridge University Library)

The facial angle of Petrus Camper

Petrus Camper (1722–1789) was a Dutch polymath who lived in Amsterdam. He held a chair of anatomy and surgery at the Athenaeum Illustre, forerunner of the University of Amsterdam and in 1762 the chair of medicine at the University of Groningen. One of the first to interest himself in comparative anatomy and palaeontology, he was also a talented artist and sculptor, as well as a conservative politician. He wrote a series of works on human and comparative anatomy, but his major work in which he attempted to give a scientific basis to physical anthropology was published posthumously by his son in 1794. Camper's treatise is remembered today for defining the facial angle, which measures the relative protrusion of the jaws to the cranial vault, originally described in two lectures he gave in Amsterdam in 1770 to art students on beauty and portraiture. ([Slides 7, 8](#)). The facial angle is the traditional beginning of craniometry and used to quantify variation in facial features between different ethnic groups. Human races were ranked in hierarchical fashion, with Europeans on top. For a discussion of the racial implications of the facial angle and Camper's original purpose which was principally artistic (he had observed that Africans portrayed in classical paintings had the facial features of Europeans) see Gould (1991).

Slide 7. Plate I from *The Works of the Late Professor Camper* (1794), showing the increase in facial angle of a monkey (Fig. I) an orangutan (Fig. II) an African (Fig. III) and a Kalmuck (a Mongolian people of Asia and Russia). Camper orientated the skulls on a horizontal reference line connecting the anterior nasal spine to the upper edge of the external auditory meatus (the line N–C). He then constructed the facial line from the incisor teeth to the most prominent point on the forehead (the line S–T). The facial angle is the intersection

of the two lines; a low angle indicates prognathism of the jaws. Original 210×300 mm. (Courtesy of the Syndics of Cambridge University Library)

Slide 8. Plate V from *The Works of the Late Professor Camper* (1794), showing a series of skulls and facial profiles with a progressive increase in the facial angle. In IV (a Grecian head) the facial angle exceeds 90 degrees and the cranial vault projects in front of the jaws. Original 210×300 mm. (Courtesy of the Syndics of Cambridge University Library)

The facial angle of Johann-Baptiste von Spix

Johann-Baptist Ritter von Spix (1781-1826) was a German naturalist. During his 1817 expedition to Brazil and the Amazon basin he collected a large variety of plants, insects, mammals, birds, amphibians and fish, which formed the basis of the National Zoological Collection in Munich. In his study of the comparative anatomy of the skull throughout the animal kingdom entitled *Cephalogenesis* (1815) von Spix compared the morphology of the skulls of man, apes, reptiles and birds, and proposed his own facial analysis as an improvement on that of Camper. The analysis incorporates several planes and angles and has a rather modern look about it (slide 9). Instead of orientating the skull on a reference line from the anterior nasal spine (acanthion) to the upper edge of the external auditory meatus (porion), von Spix used a line from the lowest point of the occipital condyle to the anterior point of the alveolar process between the central incisor teeth (prosthion). The facial line joins prosthion to the frontonasal suture (nasion) and the angle between the horizontal reference line and the facial line represent the facial angle. This can open or close depending on the species or the individual.

Slide 9. Figure 1 from *Cephalogenesis* by von Spix (1815). The skull is orientated by (1) a horizontal line from *prosthion* (p) to the occipital condyle (q); (2) a line (Sr) is constructed parallel to the horizontal line passing through the vertex. (3) The basilar line joins point q of the occipital condyle to the frontonasal suture (u) and (4) the fourth line joins prosthion to the frontonasal suture (nasion); this is the facial line. From this two angles are obtained, the facial angle (τ) and the cerebral angle (μ) which can open or close depending on the species or individual. The height of the skull is measured from the vertex line to the horizontal line; von Spix did not regard the mandible as being part of the skull. Original 200×195 mm. (Courtesy of the Syndics of Cambridge University Library)

The transition from craniometry to cephalometry

Prior to the development of cephalometric radiography, physical anthropologists and others interested in craniofacial growth had to rely on measurements carried out on dried skulls largely of an uncertain age. These could be carried out very accurately using a craniostat or skull holder. The problems associated with this method, however, were (1) the extent to which the measurement of the skulls of dead children could be regarded as a record of normal growth, and (2) only cross-sectional data could be obtained; serial growth analysis was not possible. Longitudinal studies of growth required measurements to be carried out on living children, but these were hampered by difficulties in measuring hard tissue landmarks through the skin and soft tissues. What was needed was a standardized technique for measuring the living head as accurately as anthropologists could survey the dead skull. It was this requirement that led Broadbent to design a roentgenographic craniostat, forerunner of the Broadbent-Bolton Cephalometer introduced to the dental profession in 1931 (Broadbent, 1931).

Broadbent's study of craniofacial and dental development in the growing child was part of the Brush Inquiry into human development. This had been established in 1928 under the direction of T Wingate Todd, head of the Institute of Anatomy, Western Reserve University Medical School. (Seminar 8). Broadbent's work at the Institute was financed by Mrs Chester Bolton and her son Charles and became known as the Bolton Study. (The records of the Brush Inquiry and the Bolton Study are housed in the Bolton-Brush Growth Study Center at Case Western Reserve University, Cleveland, Ohio.) Hofrath, an oral surgeon in Düsseldorf did not follow-up his original paper, although he did foresee the advantages of cephalometry in orthodontic diagnosis, growth studies and surgical planning. However, he did not have Broadbent's advantage in being an active member of an established growth study. Although Broadbent and Hofrath both published in 1931, priority of invention belongs to Broadbent. In 1930 he had presented the Bolton technique

at both the *Conference on Adolescence* held in Cleveland, and the *White House Conference on Child Health and Protection* in Washington, DC (Broadbent, 1930a, b).

Craniometric and cephalometric landmarks

At the risk of stating the obvious, accurate cephalometry is dependent on a thorough knowledge of craniofacial osteology and the precise location of the points or landmarks used for calculating measurements. These are almost exclusively sited on bone and most have been borrowed from craniometry (slide 10) and it is important to remember that absolute reliability in locating anatomical landmarks in cephalometric radiography is not possible. Furthermore, unlike adult skulls that are largely growth static, in growing skulls such points are intrinsically variable or growth dynamic (Krogman and Sassouni, 1957). The standard reference manual for craniometric definitions, *Lehrbuch der Anthropologie* by Martin and Saller (1957).

Slide 10. Left. Anterior view of the skull showing the major craniometric landmarks. For definitions see text. 1, frontal bone; 2, orbital plate of frontal bone; 3, lesser wing of the sphenoid bone; 4, greater wing of the sphenoid; 5, lacrimal bone; 6, nasal bone; 7, nasal septum; 8, middle turbinate (concha) bone; 9, inferior turbinate; 10, zygomatic (malar) bone; 11, maxilla; 12, nasal process of the maxilla; 13, body of the mandible; 14, ramus of the mandible.

Right. Lateral view of the skull showing the major craniometric landmarks. The Frankfort horizontal plane has been used to orientate the skull. 1, frontal bone; 5, lacrimal bone; 6, nasal bone; 10, zygomatic (malar) bone; 11, maxilla; 12, nasal process of the maxilla; 13, body of the mandible; 14, ramus of the mandible; 15, greater wing of sphenoid (alisphenoid); 16, temporal bone; 17, parietal bone; 18, occipital bone. (Original photograph kindly provided by Dr Barry Berkovitz, King's College London)

Definitions of anatomical landmarks

Bregma (Bg) [Gr. *bregma*]. Point at the intersection of the sagittal and coronal sutures.

Metopion (M) [Gr. *metopon*, forehead]. Mid-point of the line joining the two frontal bosses.

Glabella (Gl) [L. *glaber*, smooth]. The most anterior point on the frontal bone.

Nasion (N) [L. *nasus*, nose]. The most anterior point of the frontonasal suture in the midline. The frontonasal is an overlapping suture and moves upwards and forwards during growth; this affects vertical more than horizontal measurements (Scott, 1956).

Acanthion (Ac) [G. *akanthion*, thorn, prickle]. A point at the tip of the anterior nasal spine. Corresponds to the cephalometric point **ANS** (anterior nasal spine). The point is not anatomically or radiographically stable.

Subspinale (Sp). The deepest midline point on the maxillary alveolar profile between *acanthion* and *prosthion*. First used as **point A** in cephalometrics by Downs (1948). Point A is subject to remodelling during growth and orthodontic treatment.

Prosthion (Pr) [Gr. *prosthios*, the foremost]. The most anterior point on the alveolar process of the premaxilla between the upper central incisor teeth.

Incision Superius (Is). Tip of the crown of the most anterior maxillary central incisor.

Incision inferius (Ii). Tip of the crown of the most anterior mandibular central incisor.

Infradentale (Id). The most anterior point of the alveolar process situated between the mandibular central incisors.

Supramentale (Su) [L. *mentum*, chin]. The deepest point in the concavity between infradentale and pogonion. Synonymous with **point B** (Downs, 1948) in cephalometry.

Pogonion (Pog) [Gr. *pogon*, beard] The most prominent or most anterior point of the bony chin.

Gnathion (Gn). [Gr. *gnathos*, face]. Defined in craniometry as a point on the lower margin of the mandible in the median sagittal plane where the anterior curvature becomes confluent with the base. In

cephalometry it is a point on the chin determined by bisecting the angle formed by the facial (N-Pog) and mandibular planes (Craig, 1951).

Menton (Me). In craniometry menton (the French point mentonnière) is defined exactly the same as gnathion. To resolve this problem in cephalometry, menton is defined as the lowest point on the symphyseal shadow and gnathion defined as above.

Ethmoidale (Et) [Gr. *ethmos*, sieve + *eidōs*, form]. Point on the cribriform plate of the ethmoid midway between the greater wings of the sphenoid.

Sella (S) [L. *sella*, seat, saddle]. The mid-point of the sella turcica as determined by inspection. The sella turcica grows along with the rest of the cranial base so that the point S is not necessarily as stable as assumed.

Basion (Ba) [Gr. *basis*, base]. Craniometrically the median point on the anterior margin of the foramen magnum in the mid-sagittal plane.

Opisthion (Op) [Gr. *opisthion*, rear, posterior]. The most posterior point of the foramen magnum.

Inion (In) [Gr. *inion*, back of head]. Most prominent point on the external occipital protuberance in the midline.

Bolton point (Bo). Introduced by Broadbent (1931). Located as the most superior point in the profile of the bicondylar notches on the occipital bone.

Posterior Nasal Spine (PNS). The tip of the posterior spine of the palatine bone in the hard palate.

Pterygomaxillary fissure (PTM). Inverted teardrop-shaped radiolucency; point located where the two edges merge inferiorly.

Gonion (Go) [Gr. *gonia*, angle]. Craniometrically the point on the mandible at which the basal and posterior margin of the ramus are confluent; the most inferior, posterior point on the angle of the jaw. In cephalometry the point on the bony contour of the gonial angle located by bisecting the angle formed by the mandibular base line and the ramal line (Björk, 1947).

Articulare (Ar) [L. *articularis*, pertaining to a joint]. Introduced as a strictly cephalometric landmark by Björk (1947). The point of intersection of the dorsal contour of the mandibular condyle and the lower contour of the basiocciput.

Condylion (Co) [Gr. *kondylion*, knob]. The most posterosuperior point on the condylar head.

Porion (Po) [Gr. *poros*, pore]. The highest point on the osseous margin of the external auditory meatus (anatomical porion). In cephalometry the location of porion is a function of the positioning of the ear rods in the cephalostat (machine porion) and subject to considerable error.

Key Ridge (KR). The radiopaque line formed by the zygomatic process of the maxilla.

Orbitale (Or) [L. *orbitale*, pertaining to the orbit]. Lowermost point on the inferior margin of the orbit.

Slide 12. Lateral skull radiograph showing the principal cephalometric landmarks. Landmark identification being subjective lacks precision and is an important source of error in cephalometry. N, nasion; ANS, anterior nasal spine; A, point A; Pr, prosthion; Is, incision superioris; Ii, incision inferioris; Id, infradentale; B, point B; Pog, pogonion; Gn, gnathion; Me, menton; Et, ethmoidale; S, sella; PTM, pterygomaxillary fissure; Ar, articulare; Co, condylion; Po, porion (anatomical); Or, orbitale.

Orientation of the head

To properly assess the facial profile or facial type of a patient (whether they are prognathic, mesognathic, or retrognathic), the head should be orientated in the natural or free-postural position. This holds for both the clinical examination and cephalometric analyses of skeletal structure. For comparative purposes orientation of the head is dependent upon a craniofacial reference plane with a relatively constant relationship to either the true horizontal or to the vertical plane (Solow and Tallgren, 1971). In this section two common methods for orientating the head will be discussed, Frankfort horizontal and natural head position.

Early studies of cranial morphology orientated skulls on a variety of largely horizontal reference lines. Camper (1794) used a line connecting acanthion (anterior nasal spine) to porion, while von Spix (1815) drew a line from prosthion to the occipital condyles, from which an additional horizontal line was constructed passing through the vertex of the skull. With the development of craniometry as a major branch of physical anthropology, it became clear that a standardized method for orientating skulls was required, and at the Craniometrical Conference in Frankfurt am Main (1884), what became known as the Frankfort horizontal plane was adopted. This passes through porion and orbitale and was a modification of the line originally used by von Ihering (1872), in which the midpoint of the external auditory meatus had formed the posterior landmark. The advantage of the Frankfort plane was that porion and orbitale could be easily identified on skulls and it coincided reasonably well with natural head position (Slide 13).

Following the introduction of cephalometric radiography, Frankfort horizontal continued to be used to orientate the head in the cephalostat and in cephalometry. However, porion and orbitale are difficult to locate accurately on headfilms bringing into question its reproducibility. (One way of minimizing this problem in the analysis of serial radiographs is to orientate subsequent tracings on the original Frankfort horizontal plane.) An additional problem is the normal variation that occurs in the position of anatomical landmarks between individual patients. Having observed discrepancies between cephalometric facial typing and photographic facial typing, Downs (1956) compared Frankfort horizontal (FH) to true horizontal in 100 children; he found the mean position of FH to be an upward tip of 1.3 degrees with a standard deviation of 5 degrees. In a similar study on 35 subjects aged 22–36 years, Bjerin (1957) found the mean deviation between FH and true horizontal to be a downward tip of 1.8 degrees with a standard deviation of 4.6 degrees. This means that in a normal sample of the population (mean \pm 2 SD), one can expect the Frankfort plane to deviate by as much as 10 degrees up or down from the true horizontal position.

An alternative to the Frankfort horizontal plane is to use natural head position (Slide 14). This also has its origin in 19th century craniometry and was defined by Broca (1862) as follows... 'When a man is standing and when his visual axis is horizontal, he [his head] is in the natural position' (Moorrees and Kean, 1958). The methods used for determining natural head position vary, but most studies have reported good reproducibility (Bjerin, 1957; Moorrees and Kean, 1958; Solow and Tallgren, 1971; Siersbæk-Nielsen and Solow, 1982). Other assessments of reproducibility have been more critical (Luyk *et al.*, 1986; Bister *et al.*, 2002), and suggest that in practice the use of natural head position is no more accurate than Frankfort horizontal, which continues to be used by the majority of orthodontists. Although it is as well to be aware of the problem, it seems to me to have been somewhat exaggerated. Most competent clinicians can tell by looking at the patient whether the head is tipped up or down.

Slide 14. Headfilm tracing of a radiograph taken in the natural head position, with the lines and landmarks used by Solow and his co-workers. The true vertical line (VER) was projected onto the film by a 0.5 mm lead wire suspended in front of the cassette. s, sella; n, nasion; sp, anterior nasal spine; pm, pterygomaxillary fissure; Gn, gnathion; NSL, nasion–sella line; NL, nasal line; ML, mandibular line; RL, ramus line; OPT, odontoid process tangent; CVT, cervical vertebrae tangent; HOR, true horizontal line, perpendicular to VER. (From Solow and Tallgren (1971), *Acta Odontologica Scandinavica*)

Cephalometric analyses

Given the importance of cephalometry to current orthodontic practice, both in terms of diagnosis and treatment outcome, it is perhaps surprising to find that in its early years there was a good deal of resistance to the use of cephalometrics by practising orthodontists. It was perceived by many to be a research tool for academics with little relevance to everyday clinical practice (Steiner, 1953, 1959). It is also clear that some of the high expectations that accompanied the development of cephalometric radiography as a clinical diagnostic technique failed to be realized. (For reviews see Graber, 1954; Salzmann, 1964; Hixon, 1972.) First, it soon became apparent that cephalometrics had little or no value in predicting craniofacial growth and limited value in providing meaningful treatment goals; and second, comparing the cephalometric values of the individual with the normative values for a given population for deciding treatment objectives had

no scientific justification. (It is a curious feature of orthodontic diagnosis that we still persist in comparing the cephalometric values of an individual patient to an artefactual mean or norm derived from a small sample of the population, which for all practical purposes is meaningless clinically.)

Nevertheless, while not wishing to seem too iconoclastic, one can say that a cephalometric analysis is an important diagnostic aid, particularly for the novice clinician, to establish variation in dentofacial relationships and to identify areas of significant deviation. Cephalometric radiography besides permitting accurate evaluation of growth in the individual patient is also indispensable for distinguishing between growth and the dentofacial changes brought about by orthodontic treatment. Cephalometry demonstrates the effectiveness of treatment as well as its shortcomings and as such ultimately benefits our patients. The answer to the question whether one cephalometric analysis is superior to another is almost certainly no. In 1957 Krogman and Sassouni carried out an appraisal of the 45 craniometric and cephalometric analyses published up to that time. All were found to have strengths and weaknesses and many more have been published since then. Most university orthodontic departments will teach an analysis based on habit and historical precedent, and will contain measurements that have been cannabilized from the numerous eponymous analyses published in the literature. The following list includes some of the better known ones, but is not meant to be exhaustive, and is included to give the student some idea of the background and how this very important clinical tool evolved. Most are now of historical interest only, and not meant to be memorized!

The Downs' analysis

The first clinically tested and widely used cephalometric analysis was developed in the graduate Department of Orthodontics at the University of Illinois, Chicago and published in 1948 by William Downs. William B Downs (1899–1966) graduated DDS from the University of Illinois in 1926, and joined the first postgraduate orthodontic class at Illinois under its newly-appointed director Dr Allan Brodie. A member of the faculty at Illinois, in 1948 he reported his work on developing a pragmatic approach to analyzing headfilms at a meeting in Columbus, Ohio, the first of its kind, which became known as the Downs' analysis. The paper remains the gold standard against which to compare all subsequent analyses. It was based on measurements of a small sample of 20 white individuals, aged 12–17, and equally divided by sex and all with clinically excellent occlusions (Slide 16). The aim was to determine the variation in dentofacial pattern one might expect to find in the normal individual, and whether any clinically useful correlations existed in such normals. What the study showed was that even individuals with clinically excellent occlusions show considerable differences in skeletal and dental relationships. Downs recognized that single readings are not important; what counts is the manner in which they fit together. Its importance was that it moved cephalometrics out of the research laboratory and served as a catalyst for further developments towards clinical applications.

In 1938 the first cephalometric appraisal of orthodontic treatment was published in the *Angle Orthodontist* by Brodie, Downs, Goldstein and Meyer and Downs had been assigned to analyze the changes that took place during the treatment of Class II cases. Over the following decade he continued to analyze records, motivated in part by Brodie's annoying habit of eyeballing a film – information that could not be readily transmitted to students and others, and in 1948 in Columbus, Ohio presented his findings entitled "Variations in facial relationships: their significance in treatment and analysis," which became the Downs' analysis (McGonagle, 1975)

Slide 16. Landmarks and planes used in the Downs' analysis. Frankfort horizontal (FH) was used as a plane of orientation and the Bolton triangle (the shaded area bounded by N–S–BP) and its registration point R for superimposing serial tracings. BP, Bolton point; GN, gnathion; N, nasion; O, orbitale; OP, occlusal plane; P, pogonion; S, sella (From Downs (1948), *American Journal of Orthodontics*)

The Skeletal pattern

Downs used five parameters to assess the skeletal pattern (Slide 17; Table1). (1) A line from sella to gnathion was used as an expression of the direction of growth and called the Y axis (Slide 17A). The angular relationship between the Y axis and Frankfort horizontal was used to measure the anteroposterior/downward position of the chin and is complementary to the facial angle. (2) The facial angle was used to measure the degrees of protrusion or retrusion of the chin and is determined by constructing a line from nasion to pogonion; this is the facial plane. The internal angle formed by its intersection with the Frankfort horizontal is the facial angle (Slide 17B). This differs from the facial angles of Camper and von Spix. (3) The angle of convexity is a measure of the protrusion or retrusion of the maxilla to the facial profile. The angle is formed by the intersection of two planes; nasion–point A and pogonion–point A (Slide 18A). (4) The A–B plane is a measure of the anterior limit of the denture (apical) bases to the facial plane (Slide 18B). It permits an estimation of the difficulty in achieving the correct incisal relationships and axial inclination of the incisor teeth. (5) The mandibular plane angle is the angle between the mandibular plane (Go–Gn) and Frankfort horizontal (Slide 18C). Downs found that as the mandibular plane angle increased the facial angle decreased.

Table 1. Parameters used by Downs to determine the skeletal pattern

	Mean	Standard deviation	Range
Facial angle	87.8	± 3.57	82–95
Y axis	59.4	± 3.82	53–66
Angle of convexity	0	± 5.09	–8.5 to 10
A–B plane to facial plane	–4.6	± 3.67	–9 to 0
Mandibular plane angle	21.9	± 3.24	17–28

Data based on 20 white individuals aged from 12 to 17 years, about equally divided by sex and with clinically excellent occlusions. All are angular relationships expressed in degrees.

Slide 17. A. Measurements used to assess the skeletal pattern in the Downs' analysis. The Y axis is the line from sella (S) to gnathion (GN); the angular relationship between the Y axis and FH was used to measure anteroposterior/vertical position of the chin and is complementary to the facial angle. B. The facial angle is an expression of the degree of retrusion or protrusion of the chin and is the internal angle formed by the intersection of the facial plane (N–P) with Frankfort horizontal (FH). (From Downs (1948), *American Journal of Orthodontics*)

Slide 18. A. The angle of convexity is formed by the intersection of the planes N–P and A–P. B. The A–B plane to the facial plane. This plane was found to range from 0° or parallelism to a posterior position of B of –9°. C. The mandibular plane angle is the angle formed by the mandibular plane (Go–Gn) and Frankfort horizontal (FH). (From Downs (1948), *American Journal of Orthodontics*)

The dental pattern

These relationships were of particular significance to Downs because they contained the structures that responded directly to orthodontic treatment. He selected five parameters which he felt were of the greatest clinical importance (Table 2). (1) The cant of the occlusal plane. The angular relationship between Frankfort horizontal and the occlusal plane; the latter defined as a line bisecting the first molar cusp height and the incisal overbite (Slide 19A). He observed that Class II facial types generally have a relatively steep occlusal plane (Class II division 2 malocclusions will be an exception), while in Class III types the plane become more horizontal. (2) The interincisal angle (Slide 19B) is a measure of the degree of procumbency or proclination of the incisor teeth. (3) Lower incisor to mandibular plane (Slide 19C). The values for this angle will differ between studies depending on the method of locating the mandibular plane. Downs used gonion–menton. (4) Lower incisor to occlusal plane (Slide 20A) was included for the reason that the incisors are then being related to their functioning surface, the occlusal plane. (5) Maxillary incisors to A–P (Slide 20B) is measured in mm from the incisal edge of the maxillary central incisor to the A–P line and is a measure of maxillary dental protrusion.

Table 2. Parameters used by Downs to determine the dental pattern

	Mean	Standard deviation	Range
Cant of occlusal plane	9.3	± 3.83	1.5–14.0
Interincisal angle	135.4	± 5.76	130.0–150.5
Lower incisor to mandibular plane	91.4	± 3.78	–8.5 to 7.0 ^a
Lower incisor to occlusal plane	14.5	± 3.48	3.5–20.0
Upper incisor to A-Pog	2.7 mm	± 3.05	–1.0 to 5.0 ^b

a. As the average relationship of the lower incisors to the mandibular plane was approximately 90°, Downs denoted a labial tip as the number of degrees in excess of 90 (a positive value) and a lingual tip as the number of degrees less than 90 (a negative value). b. A negative value indicates that the incisal edge is behind A–P, a positive reading in front.

Slide 19. A. Cant of the occlusal plane. Angular relationship between Frankfort horizontal and the occlusal plane. B. The interincisal angle will be reduced in bimaxillary protrusion and increased in patients with a Class II division 2 incisor relationship. C. Lower incisor to the mandibular plane measures the axial inclination of the mandibular incisor teeth. (From Downs (1948), *American Journal of Orthodontics*)

Slide 20. A. Lower incisor to the occlusal plane. The inferior inside angle was read and the plus or minus deviation from a right angle recorded. The range was from + 3.5 to +20 with a mean of +14.5 degrees. Downs felt this measurement was of value in checking and interpreting the incisor–mandibular plane angle. B. Maxillary incisors to the line A–P is read in mm and is a measure of maxillary dental protrusion. (From Downs (1948), *American Journal of Orthodontics*)

The Downs' polygon

In 1951 Vorhies and Adams from the University of Indiana applied to the Downs' analysis, the method introduced by Hellman (1937) to express a large number of anthropometric readings graphically. This took the form of a polygon or 'wiggle'. The vertical centre line through the cephalometric polygon represents the mean values; those to the left are below average, those to the right are above average (Slide 21). By plotting the values for a given individual graphically, any deviation from the means and ranges of a representative sample with excellent occlusions, is available immediately at a glance.

Slide 21. The cephalometric polygon, a graphic portrayal of the Downs' analysis. The upper part of the polygon represents the skeletal pattern and the lower half the dental pattern. Note that the values for lower incisor to mandibular plane are represented as the number of degrees ± 90. The mean value of 91.4° is therefore represented as 1.4 degrees; a lingual tip is a minus number. The dotted line is the Downs' analysis of a patient with a Class II division 1 malocclusion. This shows that although there is considerable variation of the skeletal pattern from the normal range, the facial angle and the Y axis are just within normal limits. As far as the dental pattern is concerned the position of the maxillary incisors 8 mm in front of the A–Pog indicates protrusion of the maxillary denture. (From Strang and Thompson (1958), *A Text-Book of Orthodontia*)

The Riedel analysis

Richard Anthony Riedel (1922–1994) graduated DDS from Marquette University, Wisconsin and MSD in orthodontics from Northwestern University in Chicago. He moved to Seattle in 1949 to join the faculty of the newly founded University of Washington's School of Dentistry, eventually succeeding Alton Moore as chairman of the Department of Orthodontics. The first to use the angles SNA and SNB to relate the maxilla and mandible to the cranium it was based on the research for his MSD thesis at Northwestern University (Riedel, 1952). The sample consisted of (1) 52 adults (18–36 years of age) with excellent occlusion, (2) 24 children (7–11 years of age) with excellent occlusion, and (3) 38 individuals with a Class II division 1 malocclusion (Slide 22). No attempt was made to evaluate the groups on the basis of race or sex. Riedel made five skeletal and six dental measurements, but only SNA, SNB and their difference ANB will be discussed. No

significant difference in SNA could be found between patients presenting with excellent occlusion and those with malocclusion. However, there was a tendency for the maxilla to become more prognathic with growth (Table 3). The anteroposterior relation of the mandible to the cranial base (SNB) was found to be significantly different in patients with excellent occlusion and those with malocclusion; this was particularly marked in Class II division 1 cases where the mandible was retrognathic. Again, there was a tendency for the mandible to become more prognathic with growth (Table 3). The beauty of the angles SNA, SNB and ANB was their simplicity; they rapidly became incorporated into most cephalometric analyses and despite some shortcomings still remain the standard method for determining the skeletal pattern.

Table 3. Relationship of the maxilla and mandible to the anterior cranial base

	Children (7-11 years)		Adults (18-36 years)	
	Mean	SD	Mean	SD
SNA	80.79	± 3.85	82.01	± 3.89
SNB	78.02	± 3.06	79.97	± 3.69
ANB	2.77	± 2.33	2.04	± 1.81

Data from Riedel (1952).

The Steiner analysis

As Cecil Steiner was the first to admit, many of the measurements included in his analysis were derived from the work of Downs, Riedel, Wylie (1947) and others (Steiner, 1953, 1959). To these Steiner made additions, the most original being the method he used to orientate the upper and lower incisors to their basal bone. (How Steiner arrived at the standards used in his analysis is not stated, but legend has it they were derived from the tracings of one Hollywood starlet!) The location and axial inclination of the upper incisors were determined by relating the teeth to the line N-A. Ideally the most mesially placed point of the crown of the maxillary central incisors should be 4 mm in front of N-A, with an axial inclination to N-A of 22 degrees (Slide 23). Similarly, the lower central incisor was related to the line N-B, the ideal being that the most mesial point on the crown is 4 mm in front of N-B, and with an axial inclination to N-B of 25 degrees. He also introduced a novel method of expressing the data visually, the so-called Steiner chevrons (Slide 24). These standards were not meant to dictate treatment objectives, but were designed to act as guides to the judgement of those with limited experience and of assistance to all in reaching a decision. Steiner played a significant part in popularizing cephalometry in everyday clinical practice. He lectured widely and his papers extol the virtues of cephalometrics as a diagnostic and analytical tool, with numerous exhortations to his colleagues to embrace the technique.

Slide 23. Average measurements used by Steiner to represent a normal average American child of average age. The advice was that these figures should be varied for the use of those who have a different concept of what constitutes a 'good face'. The tracing shows the measurement of the upper incisor to the line N-A (4 mm) and the lower incisor to the line N-B (4mm). (From Steiner (1959), *The Angle Orthodontist*)

Slide 24. The Steiner chevrons. On the left is the ideal relationship of the upper and lower incisors when the ANB angle is 2°. If the ANB angle is increased (as shown here) or decreased, then compromises will have to be made in the inclination of the teeth to compensate for the jaw discrepancy. (From Steiner (1959), *The Angle Orthodontist*)

The Tweed diagnostic triangle

This is not a comprehensive analysis being based on just three measurements. It was developed by Charles Tweed as a diagnostic and treatment planning guide to enable less experienced clinicians achieve pleasing facial aesthetics and decide whether extractions were indicated (Tweed, 1954). Charles Henry Tweed (1895-1970) was in the last student to graduate from the Angle School of Orthodontia and worked closely with Angle on the development of the edgewise appliance, discussed later (Seminar 15). The Tweed triangle is constructed from (1) the

Frankfort horizontal, (2) the mandibular, and (3) the lower incisor planes to form three angles: the Frankfort–mandibular plane angle (FMPA); the lower incisor–mandibular plane angle (IMPA); and the Frankfort–mandibular incisor angle (FMIA) (Slide 25). Tweed attached great importance to the inclination of the lower incisors and aimed for an angulation of 90 ± 5 degrees. This was based on his observation that patients with normal occlusion and pleasing facial balance had an IMPA very close to 90 degrees, confirming the findings of Margolis (1943). If the FMPA is increased, then the IMPA and FMIA will have to decrease to make 180° for the triangle. The facial triangle formed the conceptual basis of the Tweed edgewise technique course held at the Tweed Foundation in Tucson, Arizona.

Slide 25. The Tweed diagnostic facial triangle. The planes of the triangle are formed by (1) the Frankfort horizontal plane, (2) an extension of the mandibular plane from menton to the gonial angle, and (3) by extending the long axis of the mandibular central incisor to the mandibular plane and the Frankfort plane. FMA, Frankfort–mandibular plane angle; IMPA, incisor–mandibular plane angle; FMIA, Frankfort–mandibular incisor angle. (From Tweed (1966), *Clinical Orthodontics*)

The mesh analysis

The mesh analysis is an adaptation of the rectilinear grid system developed by Albrecht Dürer and used by D'Arcy Thompson (Scottish natural historian and zoologist, 1860–1948), in his book *On Growth and Form* (1917). In orthodontics transformation of a mesh coordinate system was first advocated by de Coster (1939). Under Coenraad Moorrees at the Forsyth Dental Center in Boston, the method was developed to graphically convey the essential aspects of facial development for orthodontic diagnosis (Moorrees, 1953; Moorrees *et al.*, 1976).

The mesh diagram is constructed by first drawing a core rectangle to which additional vertical and horizontal lines are added (Slide 26). Examples of the method in action are shown in Slide 27. In its clinical application the vertical and horizontal landmarks in the mesh diagram on the patient's lateral skull are compared to the location of the corresponding landmarks for male and female normative data (Moorrees *et al.*, 1976). The mesh coordinates are then distorted to display differences in the proportionate location of each landmark in the individual mesh. (The procedure for mesh distortion and the use of the mesh diagram for clinical diagnosis are discussed at length in Moorrees *et al.*, 1995.) However, despite its impeccable pedigree, the mesh method has been little used in practice. Compared to numerical analyses the mesh diagram is difficult to produce as well as being time-consuming and is less able to convey information as readily as numerical data and I can't imagine anyone using it out of choice.

Slide 26. Construction of a mesh diagram. This involves constructing a vertical line through nasion, parallel to an extracranial vertical reference line (radiographs are taken in natural head position) and two horizontal lines at right angles to the vertical, one at nasion and the second through ANS. The rectangle is completed with a vertical line through sella. Additional vertical and horizontal lines are added to the core rectangle; the face is thus inscribed in a rectilinear coordinate system of 24 small rectangles. (From Moorrees *et al.*, (1976), *American Journal of Orthodontics*)

Slide 27. A. Mesh analysis of a patient with a moderate Class II division 1 malocclusion. There are only minor deviations from the norm with slight maxillary prognathism and upright maxillary incisors; the mandible is orthognathic, *i.e.* average or ideal. B. Severe Class II division 1 malocclusion characterized by mandibular retrognathia, short vertical ramus and increased mandibular plane angle. (From Moorrees *et al.*, (1976), *American Journal of Orthodontics*.)

The Eastman analysis

The Eastman analysis was developed in the Department of Orthodontics under Professor Clifford Ballard at the Eastman Dental Hospital in London (Ballard, 1956), with modifications by Mills (1970). Clifford Frederick Ballard (1910–1997) Professor of Orthodontics, University of London (1956–72) was a commanding figure in British dentistry and in particular orthodontics. In 1948 he was appointed to the newly formed Department of Orthodontics at the Institute of Dental Surgery part of British Postgraduate Medical Federation, which attracted a large number of postgraduate students from around the world, particularly the former colonies of the Empire including the present author. Ballard became an authority on the aetiology, diagnosis, prognosis

and treatment of orthodontic problems with a special interest in the action of the musculature on the form and function of the jaws. The aim was to produce an analysis for clinical use that did not incorporate too many measurements. The normative values were based on a random selection of 250 patients and rounded to the nearest degree. However, the age, sex and occlusal status of these patients were not documented. Like the Steiner analysis it incorporates features of the Margolis (1943), Herzberg and Holic (1943), Tweed (1944), Downs (1948) and Riedel (1952) analyses. The analysis was widely used in the United Kingdom.

Table 4. The Eastman Dental Hospital London analysis

	Mean	Standard deviation
SNA	81	± 3
SNB	78	± 3
ANB	3	± 2
Mx-Md plane	27	± 4
SN-Mx plane	8	± 3
Interincisal angle	130	± 10
Upper incisor to Mx plane	109	± 6
Lower incisor to Md plane ^a	93	± 6
Lower facial height ^b	55	± 2 per cent

All measurements are angular measurements expressed in degrees with the exception of the lower facial height. Lower facial height (ANS-menton) is expressed as a percentage of the total facial height (nasion-menton). a. Margolis (1943); b. Herzberg and Holic (1943).

The problem of ANB

The most commonly used measurement for determining the anteroposterior relationship of the jaws (skeletal pattern) is the angle ANB which in normal occlusions is generally 2–3 degrees (Riedel, 1952). Although reliable in most instances there are occasions when this is not the case. This is because ANB will be affected by (1) the extent of maxillary prognathia or retrognathia relative to the anterior cranial base (angle SNA); and (2) the slope or inclination of the anterior cranial base (line S-N). Since the significance of the angle ANB varies according to the size of SNA, several methods have been proposed to measure the anteroposterior jaw relationship more accurately (Slide 28).

The Eastman conversion

The method used in the Eastman analysis consists of adding half a degree to the ANB for every degree the SNA is less than the mean of 81 degrees (and *vice versa*). For example, in the case shown in Slide 29 with an ANB of 6.5, the SNA is 2.5 degrees below 81 degrees and therefore half this value should be added to the ANB which becomes 7.75 degrees; the Class II discrepancy is therefore more severe than it originally appeared. In cases where SNA exceeds 81 degrees half a degree is subtracted from ANB for every degree above 81. In practice this crude calculation works reasonably well. Applied to the case shown in Slide 29 with an SNA of 87 degrees, deducting 3 degrees reduces the ANB from 6 to 3 indicating a Class I skeletal pattern.

Slide 29. Patient with a Class II division 1 malocclusion and an ANB of 6.5 degrees. Because the SNA is less than 81 degrees, the skeletal discrepancy is more severe than suggested by the ANB difference. (From Mills (1982), *Principles and Practice of Orthodontics*)

The Wits appraisal

The Wits appraisal (Wits is an abbreviation for the University of Witwatersrand in South Africa) was introduced as an additional diagnostic aid to the conventional ANB angle, to measure the severity of anteroposterior jaw disharmony independently of cranial reference planes (Jacobson, 1975). It is a linear measurement, not an analysis in itself, and is designed to identify instances where the ANB reading does not accurately reflect the skeletal pattern. In the Wits appraisal perpendicular lines are dropped from points A and B onto the occlusal plane. It was found by Jacobson (1975), that on average in a sample of 21 male and 25 female adults with excellent occlusion, AO and BO (Slide 30) generally coincided in females (mean -0.10, range -4.5 to 1.5), but in males BO was located approximately 1 mm in front of AO (mean 1.17; range -2 to 4 mm). The Wits appraisal is largely dependent on the correct location or representation of the occlusal plane and should only be used in conjunction with other methods for assessing apical base relationships. It has been suggested that to arrive at a more accurate diagnosis of the anteroposterior apical base relationship, both the ANB angle and the Wits appraisal should be used (Bishara *et al.*, 1983). Slide 31 shows the tracings of two patients with identical ANB angles (6 degrees). According to the 'Wits' analysis in tracing A, point BO is 6 mm behind AO indicating a severe Class II skeletal discrepancy. In tracing B, points BO and AO are almost coincident and indicate that this patient has a Class I skeletal pattern.

Slide 30. In the Wits appraisal, perpendicular lines are dropped from points A and B onto the occlusal plane. The Wits reading is measured from AO to BO in mms. In skeletal Class II jaw dysplasias, BO is positioned well posterior to AO (a positive reading), and in Class III cases the reading is negative. (From Jacobson (1975), *American Journal of Orthodontics*)

Slide 31. Tracings of two malocclusions with identical ANB angles of 6 degrees. A. The Wits reading of 6 mm indicates a severe jaw disharmony, whereas in B the Wits of 0 mm indicates a skeletal Class I. (From Jacobson (1975), *American Journal of Orthodontics*)

The McNamara analysis

The analysis reported by McNamara (1984) to differentiate between the skeletal and dentoalveolar components of a malocclusion is derived, in part, from the analyses of Ricketts (1960) and Harvold (1974), with the addition of two new planes, nasion perpendicular and point A vertical. SNA and SNB are not used to relate the maxilla and mandible to the cranial base. The anteroposterior relationship of the maxilla to the cranial base is measured by the linear distance from point A to the nasion perpendicular plane (slide 32). In a sample of adults from Ann Arbor, Michigan with well-balanced faces, point A was in front of the nasion perpendicular by 0.4 mm in females (SD 2.3; n =73) and in males 1.1 mm (SD 1.1; n =38). The relationship of the mandible to the cranial base is determined by measuring the distance from pogonion to nasion perpendicular.

Slide 32. The nasion perpendicular plane is constructed at right angles to the Frankfort horizontal plane. A. This patient has maxillary protrusion since point A is 5 mm in front of nasion perpendicular. B. Patient with maxillary retrusion; point A is 4 mm behind nasion perpendicular. She also has severe mandibular retrognathia. (From McNamara (1984), *American Journal of Orthodontics*)

The lengths of the mandible and the maxilla (or more specifically the midfacial region) are determined by a modification of the method developed by Harvold (1974). The effective midfacial length is measured from condyion to point A; mandibular length is measured from condyion to gnathion (Slide 33). Based on longitudinal data from the Bolton Standards, the Burlington Orthodontic Research Center and the University of Michigan, composite norms have been calculated (Table 5). For example, a mixed dentition subject with a balanced face and an effective midfacial length of 85 mm, will have a mandible of 105 to 108 mm in length (Slide 33).

Slide 33. (A) The determination of effective midfacial length (85 mm) and effective length (105 mm) in a mixed dentition patient with a balanced face. (B) In an adult female. Effective midfacial length is 94 mm and mandibular length 120 mm. (From McNamara (1984), *American Journal of Orthodontics*)

Table 5. Composite norms for midfacial length, mandibular length and lower anterior facial height

Midfacial length (mm)	Mandibular length (mm)	Lower anterior facial height (mm)
80	97-100	57-58
85	105-108	60-62
90	113-116	63-64
95	122-125	67-69
100	130-133	70-74
105	138-141	75-79

The norms represent a geometric relationship between effective midfacial length and effective mandibular length and are not related to the age or sex of the individual subject. Data based on values derived from the Bolton Standards, Burlington and Ann Arbor samples. From McNamara (1984).

Superimposition of cephalometric radiographs

The superimposition of serial headfilm tracings to analyze changes in craniofacial growth and/or orthodontic treatment has been routine since the introduction of cephalometry. Early reports were limited to an overall superimposition registered on the cranial base. The importance of being able to distinguish between growth changes and tooth movement, led subsequently to the introduction of separate maxillary and mandibular superimpositions. All three are indispensable for a proper interpretation of growth and treatment changes.

The overall superimposition

The longitudinal study of dentofacial change requires serial headfilm tracings to be superimposed on stable anatomical landmarks; such stable or fixed reference points within the skull do not exist. Nevertheless, because of its central location at the interface between the cranial and facial parts of the skull, the cranial base has proved to be the most enduring reference area in cephalometry. In his pioneering studies, Broadbent (1931, 1937) used the Bolton–nasion plane and its registration point R for overall superimpositions. Tracings were registered on point R with the Bolton planes (Bo–N) parallel to each other. The Bolton point is difficult to locate accurately so that it became superseded by the anterior cranial base represented by sella–nasion, the most commonly used registration line in clinical practice (Björk, 1947; Riedel, 1952; Steiner, 1953; Houston and Lee, 1985). Nevertheless, there are pitfalls in the use of S–N as a reference line.

Nasion is not a fixed point and moves upwards and forwards due to osteogenesis at the frontonasal suture (Scott, 1956). The pituitary fossa and tuberculum sellae also move upwards during growth as the sphenoid sinus enlarges. Studies of facial growth will therefore give a slightly excessive estimate of vertical growth of the face in comparison with forward growth. Provided that this possibility is realized, there is little practical objection to the employment of S–N, registered at sella, for analyzing the effects of orthodontic treatment on dentofacial growth. Both sella and nasion are located in the mid-sagittal plane, are displaced to a minimum degree by movements of the head and easily identified on most lateral skull radiographs.

To avoid errors in superimposition from the instability of nasion, de Coster (1951) proposed the outline of the anterior cranial fossa (anterior contour of the sella turcica, cribriform plate of the ethmoid, frontal cranial outline) that had been used previously in craniometry by Keith and Campion (1922). This was subsequently modified by Alton Moore by adding the twin outlines of the greater wing of the sphenoid bone to the cribriform plate to form the ethmoid triad (Moore, 1959). With closure of the sphenothmoidal suture at the age of 6–7 years, the ethmoid triad represents the most stable reference area for superimposing serial cephalometric radiographs (Nelson, 1960; Elmajian, 1960; Slide 35). Alton Wallace Moore (1916–2007) was the first chairman of the Department of Orthodontics at the University of Washington being appointed in 1948. A graduate of the University of California (DDS 1941), and the orthodontic programme at Illinois under Brodie (MS 1944), where he developed his interest in biological research; together

with Dick Riedel and Dr Benjamin Moffett, an anatomist, the clinical and research programme at Washington developed into one of the world's best.

Slide 35. Tracing of a lateral skull radiograph. For abbreviations see text. The two greater wings of the sphenoid bone, together with the cribriform plate of the ethmoid form the ethmoid triad. Because it eliminates growth changes at nasion and sella, the ethmoid triad and its registration point ethmoidale represents the most stable reference area for superimposing serial cephalometric radiographs. (With kind permission of Professor Alton W Moore)

Maxillary superimposition

The aim of a maxillary superimposition is to quantitate changes in tooth position (dentoalveolar remodelling) relative to the supporting or basal bone of the maxilla. It is complementary to the overall superimposition and is essential to distinguish between changes in tooth position due to orthodontic treatment and those due to growth. Unfortunately, the maxilla may undergo quite extensive surface remodelling during treatment and several methods have been suggested for superimposing maxillary structures. The accuracy of all current methods is compromised to some extent.

The palatal plane (ANS–PNS) registered at ANS was commonly used in early studies (Broadbent, 1937; Brodie, 1941; Moore, 1959), but ANS is difficult to locate and also suffers from anteroposterior remodelling and radiographic burn-out. To minimise changes in ANS, superimposition on the palatal contour, the so-called method of best fit was proposed at the Research Workshop on Cephalometrics in 1960 (Salzmann, 1960) and is the method commonly used by orthodontists (Slide 36). However, the method is characterized by a low degree of validity and only a medium degree of reproducibility (Kristensen, 1989).

Slide 36. Maxillary superimposition. (A) Superimposition on the palatal plane registered at ANS; with growth PTM moves distally. In practice this is very similar to superimposition on the palatal contour (the method of best fit) and in this example, the profiles of the palatal contour are coincident. (B) Superimposition on the palatal plane registered on PTM. (From Moore (1959), *American Journal of Orthodontics*)

The major problem with the method of best fit is growth remodelling of the hard palate. Implant studies have shown that the palate undergoes significant resorptive remodelling on the nasal surface with concomitant deposition on the oral surface (Björk and Skieller, 1977). Björk and Skieller therefore suggested using what is referred to in the literature as the structural method; tracings are superimposed on the anterior contour of the zygomatic process of the maxilla (the key ridge) which is relatively stable after eight years of age (Slide 37). Nielsen (1989) in a study that compared the two anatomical methods, best fit and structural with the implant method, found that during a 4-year interval the best fit method significantly underestimated eruption of the teeth by 30–50 percent (Slide 38). The structural method on the other hand showed no differences in displacement of selected landmarks in comparison with the implant method (38B). Difficulty in identifying the zygomatic process accurately can be a disadvantage and in practice the method does not seem to have been widely adopted.

Slide 37. Three stages in the remodelling of the maxilla between 10 and 21 years in a male subject. Tracings were superimposed on the implant line, with the midpoint of the implants in the zygomatic process as the registration point; anterior implants were inserted into the maxilla below ANS, one each side of the midline. There is little remodelling of the anterior surface of the zygomatic process; the posterior surface is appositional moving downwards and backwards. Change in the inclination of the nasion–sella line indicates rotation of the maxilla relative to the anterior cranial base. (From Björk and Skieller (1977), *British Journal of Orthodontics*)

Slide 38. (A) Mean \pm SD of differences in displacement of skeletal and dental landmarks between implant and best fit superimpositions during a 4-year period (N=18). ANS and PNS show slight upward displacement, with ANS showing twice as much vertical displacement as PNS. For the dental landmarks the best fit method underestimated molar eruption by 30% and incisor eruption by 50%. (B) Mean \pm SD of differences in displacement of skeletal and dental landmarks between structural and best fit superimpositions during a 4-year period (N=18). No statistically significant differences were found

between the structural and implant methods in the vertical plane. (From Nielsen (1989), *American Journal of Orthodontics and Dentofacial Orthopedics*)

Mandibular superimposition

It is clear from the literature that early workers had difficulty in deciding how to superimpose mandibular tracings. Most used the mandibular plane but because of the significant remodelling that occurs at the lower border of the mandible none were particularly accurate. It was the longitudinal study of mandibular growth using the implant method (Björk, 1963), which showed that contrary to previous studies the growth pattern of the mandible was highly variable, and coincidentally, a method for accurately superimposing mandibular tracings. Björk found that the anterior contour of the chin, the inner contour of the symphyseal cortex, the outline of the inferior dental canal and the lower contour of the third molar were relatively stable and could be used as natural reference structures for mandibular superimpositions (Slide 39). These have become known as Björk's structures and are widely used for clinical and research purposes to demonstrate mandibular growth changes and alterations in tooth position.

Studies of tracing errors associated with Björk's mandibular structures have shown that anterior (midline) structures are more reliable than posterior (bilateral) structures, especially in the horizontal direction (Cook and Gravely, 1988). It has been suggested by Cook and Gravely that the tracings should first be superimposed on the anterior contour of the bony chin to establish the horizontal relationship (the chin is the most stable of the structures and therefore most valid for use as a natural reference area). The 'best fit' of the remaining structures is then used to complete the superimposition. They placed greater emphasis on the lower contour of the third molar crypt than the outline of the mandibular canals, which are not always clearly visible (slide 41).

Slide 39. Anatomical structures in the mandible recommended by Björk to assess mandibular dentoalveolar changes. (1) Anterior contour of the symphysis, (2) Internal contour of the symphyseal cortical bone, (3) outline of the inferior dental (mandibular) canal, and (4) lower contour of the third molar tooth germ before the start of root formation. (From Solow (1980), *British Journal of Orthodontics*)

Errors in cephalometric radiography

It is important to realize that in spite of an appearance of mathematical rigour, cephalometric radiography and the quantitative analyses derived from it are subject to many sources of error (Slide 40). These may be grouped into three categories; (1) errors of projection; (2) errors of landmark identification, also referred to as tracing errors; and (3) validity, that is to say, does the measurement actually represent what it is supposed to?

Errors of Projection

These arise from the fact that a 3-dimensional image of the head is projected onto the headfilm as a 2-dimensional shadow. The x-ray beam diverges from a point source resulting in magnification of those structures that are not on the principal axis (the central ray). The image is also distorted and structures that are closer to the film are magnified less than those further from it (Slide 41). Nevertheless, errors arising from obtaining radiographs have been shown to be quite small, provided that due care is given to positioning the patient in the cephalostat correctly, and can be kept to an acceptably low level for most purposes (Björk, 1947; Hixon, 1960; Solow, 1966; Carlson, 1967; Ahlqvist *et al.*, 1986; Houston *et al.*, 1986). Rotation of the head by up to 5 degrees from the proper position results in errors of length measurements of less than one percent (Ahlqvist *et al.*, 1986).

Slide 41. Uneven magnification of left and right structures produces bilateral images. Left-sided structures being closer to the film cassette will be magnified less than right-sided structures. A. Bilateral images of the posterior and lower borders of the mandible. In this radiograph the inferior dental canal is difficult to identify. B. Bilateral images of the greater wings of the sphenoid and the key ridges. In this exposure the images of the PTM are coincident. When tracing bilateral structures one can either trace the left of the two images or split the difference.

Errors of landmark identification

Accurate cephalometry is dependent upon the precise location of points or anatomical landmarks. However, the definition of many craniometric/cephalometric landmarks, even those on the surface of the skull often lack precision, including terminology which is liable to subjective interpretation. Supramentale or point B, for example, is defined as the deepest point on the concavity between infradentale and pogonion which leaves plenty of room for error (Slide 42). The problem is further compounded for landmarks that lie within the skull such as condylion, which may be partially obscured by superimposed anatomical structures. Inconsistency in landmark identification is widely recognized as an important source of error in cephalometry and has been widely investigated (Björk, 1947; Hixon, 1956; Richardson, 1966; Mattila and Haataja, 1968; Baumrind and Frantz, 1971a,b; Midtgård *et al.*, 1974). These errors have been shown to be specific to each landmark which has its own characteristic envelop of error (Slide 42); dental landmarks have a low level of reliability.

Slide 42. Hundred-point scattergrams each representing the distribution of errors for a single skeletal landmark around the best estimate for that landmark, each orientated to the S-N line. The scattergrams were derived from 20 headfilms each traced by 5 first -year orthodontic residents at the University of California, San Francisco. Gonion was the least reliable landmark. Landmarks on a sharp curve are easier to identify than points located on broad curves. (From Baumrind and Frantz (1971a), *American Journal of Orthodontics*)

The largest errors in cephalometry arise from landmark identification and attempts to minimize measurement errors should be directed specifically at these (Houston, 1983; Houston *et al.*, 1986). Inter-tracer error is generally higher than intra-tracer error, and the level of error is affected by operator experience and training (Kvam and Krogstad, 1969). But irrespective of who does the tracing calibration is important; the error levels specific to the tracer(s) must be established before the data can be meaningfully interpreted (Gravely and Benzie, 1974). Duplicate measurements are essential. Single measurements of anatomical landmarks on headfilms are characterized by a high degree of error, even when traced by experienced orthodontists. Random errors are reduced if measurements are replicated and averaged, a procedure that is less tedious if the radiographs are digitized directly (Houston, 1982).

Validity of cephalometric measurements

Validity is the extent to which, in the absence of measurement error, the value obtained represents the object of interest (Houston, 1983). This includes not only the accuracy with which dental or skeletal landmarks can be measured, but also the extent to which certain linear and angular measurements are justified on the grounds of anatomical authenticity. A good example of the latter is the way in which changes in mandibular growth have been measured (Slide 43). These have included the linear measurements condylion-gnathion (Co-Gn), articulare-gnathion (Ar-Gn) and gonion-gnathion (Go-Gn), all of which have drawbacks. Ar-Gn and Go-Gn are not valid measurements because they exclude changes at the condyle, and although Co-Gn includes changes at the condyle, it does not take into account condylar growth direction, or its effect on mandibular growth rotation. (This is discussed further in Seminar 10.)

To evaluate the validity of 15 commonly used skeletal and dental cephalometric landmarks, Tng *et al.* (1994) glued steel ball markers to 30 skulls to represent the true anatomical landmarks. The skulls were mounted in a purpose built holder and two X-rays taken; one with and one without the steel balls. Validity was expressed as the difference between the two measurements which were made relative to X (horizontal) and Y (vertical) coordinates, constructed from reference points (steel balls) glued intracranially to the skulls. Their findings were not encouraging; seven out of 10 skeletal landmarks and all five dental landmarks investigated were found to be non-valid along the X or Y axes ($P < 0.05$).

Systematic and random errors

Errors of measurement may be systematic or random. If a particular measurement is persistently over or under-recorded a systematic error is introduced (Houston, 1983). An

important source of systematic error which has been largely ignored in cephalometry is the potential for subjective bias. That is to say the subconscious weighting of results in the favour of one group when two series of measurements are being compared. We would not accept the findings of a drug trial that had not been conducted as a placebo-controlled, double-blind study. And while that is not possible in an orthodontic clinical trial, the least that can be expected is that the films are randomized, the tracer is calibrated, and does not know *a priori* whether the headfilms are from the experimental or the control group. It is extremely rare to find that this has been undertaken in orthodontics studies of treatment outcome (I can't remember ever having read one) casting doubt on the validity of most clinical investigations.

Random errors can arise as a result of variations in positioning the patient in the cephalostat, but the greatest source of random error is difficulty in identifying a particular landmark (Houston, 1983). As discussed above many landmarks are difficult to locate and the observer's opinion about the exact location may vary at random.

Posteroanterior (frontal) radiography

Posteroanterior (PA) radiographs are not taken routinely in orthodontic practice. Normative data for transverse measurements of the face and jaws derived from PA cephalometric radiographs have been published (Athanasίου *et al.*, 1992; Cortella *et al.*, 1997; Basyouni and Nanda, 2002), but have limited clinical utility. PA radiography is, however, indicated in planning the nonsurgical and surgical management of (1) cases with severe dental and/or skeletal asymmetries; (2) patients with maxillary deficiency and associated crossbite and/or airway problems; and (3) patients with cleft lip and palate or other craniofacial anomalies (Slide 44).

PA headfilms are more difficult to interpret than lateral skull radiographs. Landmark identification can be unreliable due to overlying hard and soft tissues, and the absence of well-defined stable structures complicates the superimposition of serial radiographs (Major *et al.*, 1994, 1996). Taking the radiograph shown in Slide 45 as an example, there is a considerable element of guess work and wishful thinking in attempting to identify some of the anatomical landmarks in the middle third of the face. Moreover, the position of the head is more difficult to control in PA radiography and tilting of the head in the cephalostat is a significant source of error. Transverse measurements are least affected by positional errors; PA cephalometric studies of transverse dentofacial growth have been shown to be associated with acceptable method error (Athanasίου *et al.*, 1990; Cortella *et al.*, 1997).

Definitions of posteroanterior anatomical landmarks

Antegonion (Ag) [L. *ante*, before + gonion]. Deepest point on the curvative of the antegonial notch (Solow, 1966).

Ectomaxillare (Em). Point on the lateral contour of the maxilla closest to the median plane (Solow, 1966).

Euryon (Eu) [Gr. *eurys*, wide]. The point on each side of the greatest transverse diameter of the skull.

Mastoidale (Ma) [Gr. *mastos*, breast]. Lowest point of the mastoid process.

Condylar (Cd). The most superior point of the condylar head.

Latero-orbitale (Lo). Intersection of the lateral orbital contour with the innominate line.

Medio-orbitale (Mo). The point on the medial orbital margin closest to the median plane.

Lateral piriform aperture (Lpa). The most lateral aspect of the piriform aperture.

Zygion (Zy) [Gr. *zygoma*, bar]. The most laterally situated point on either zygomatic arch.

Zygomatofrontal suture (Zf). Medial point on the orbital contour of the zygomatofrontal suture.

Slide 45. Posteroanterior radiograph of a girl aged 10 years with mild hemifacial microsomia affecting the right side of the face and marked mandibular asymmetry. Menton is approximately 1 cm to the right of the midsagittal plane. Antegonion is not present on the affected side and the mandibular condyles are difficult to distinguish from the mastoid processes.

Slide 46 . Posteroanterior cephalometric landmarks. Ag, antegonion; Em, ectomaxillare; Eu, euryon; Ma, mastoidale; Cd, condylar; Lo, latero-orbitale; Mo, medio-orbitale; Or, orbitale; CG, crista galli; Lpa, lateral piriform aperture; Zy, zygon; Zf, zygomaticofrontal suture; ANS, anterior nasal spine; Me, menton. (Adapted from Athanasiou (1995), *Orthodontic Cephalometry*.)

Posteroanterior cephalometric analyses.

A number of PA cephalometric analyses have been described in the literature of varying degrees of complexity (Solow, 1966; Letzer and Kronman, 1967; Ricketts *et al.*, 1972; Vig and Hewitt, 1975; Svanholt and Solow, 1977; Grayson *et al.*, 1983; Grummons and Kappeyne van de Coppello, 1987). Since the main purpose of PA cephalometry is to assess facial asymmetry, once the midsagittal plane has been established, linear, angular or proportional measurements of the clinician's choice can then be related to the midline. In most cases, however, visual inspection is sufficient to determine where the abnormality or asymmetry lies. Quantitation is of limited benefit. For those who wish to obtain further details about PA cephalometric analyses, chapter 6 in Athanasiou (1995) is recommended, but the easiest thing to do is make up your own analysis.

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