

Seminar 8

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Growth at adolescence

An understanding of human growth and development, particularly at adolescence, is an essential part of clinical orthodontic practice. A close association between peak height velocity in stature and the pubertal growth spurt in facial dimensions is well established, and can be of value in timing certain types of orthodontic treatment. Furthermore, although we are treating more adults, orthodontics remains a predominantly paediatric specialty and we need to be able to focus our attention on more than just the patient's dentition. Parents frequently enquire about the growth of their children, particularly where they appear short in stature compared to other children of the same age and sex. Clinicians with a hospital practice may also be involved in the management of children with endocrine problems and/or growth disorders.

Adolescence [*L. adolescentia*] is the transitional period between childhood and maturity in human development which begins with the appearance of the secondary sex characteristics and ends with the cessation of somatic growth – from about 10 to 20 years of age. Puberty [*L. pubertas*] is the period during which the secondary sex characteristics begin to develop and the capacity for sexual reproduction is attained. Although the terms have been used interchangeably in the literature, in the following discussion the acceleration in growth that occurs during adolescence will be referred to as the pubertal rather than the adolescent growth spurt. The chapter heading is taken from the title of Tanner's classic text *Growth at Adolescence*, first published in 1955 and essential reading. James Mourilyan Tanner (1920–2010) was Professor of Child Health and Growth at the Institute of Child Health, University of London, and the Hospital for Sick Children, Great Ormond Street, London. In 1948 Tanner took over a childhood growth study started during the war at an orphanage at Harpenden in Hertfordshire, and together with Reginald Whitehouse measured the children and recorded their stages of sexual maturation at monthly intervals from 1948 to 1971. With data from other European surveys Tanner and Whitehouse's work led to the development of the modern growth chart.

Human growth studies

Man has been formally measuring the height of man for just over three hundred years. In the eighteenth and nineteenth centuries, such studies were undertaken for purposes of army recruitment and to measure social inequality. Tall soldiers were regarded as being preferable to short ones, and a regiment of tall household guards was a matter of prestige for numerous European rulers (Tanner, 1981). During the Industrial Revolution, growth was used to monitor social conditions, and identify groups whose children showed signs of delay in growth and/or shortened stature. The aim was to quantify height differences arising from social class and how they might be remedied by social reform. In 1837 the mean height of boys aged 16 working in factories in the Manchester–Leeds area was 5 feet (Horner, 1837), very small by present day standards. Very few investigations were undertaken out of pure intellectual curiosity; the study of Count Montbeillard on his son discussed later was one.

The growth of few children had been followed from birth to maturity. Little information was available regarding the extent to which individual variation should be regarded as normal, and whether any observed variation was due to heredity, or to a rapid or slow rate of growth which may depend upon the environmental conditions (Boas, 1932). Franz Boas (1858–1942), Professor of Anthropology at Columbia University in New York, was a pioneering German American anthropologist born in Minden, Westphalia. He applied the scientific method to the study of human cultures and societies, as well as changes in body form including height, cranial measurements and other physical characteristics.

These deficiencies in knowledge were remedied during the last century, with the emergence of a child welfare movement in the United States devoted to the study of child development that provided the impetus for a number of longitudinal growth studies. A well-designed growth study is a powerful tool with which to monitor the health of a population, since a child's growth rate reflects perhaps better than any other single index his/her state of health and nutrition (Eveleth and Tanner, 1990).

The first growth study to be established was the Iowa Child Welfare Research Station (later called the Institute of Child Behaviour and Development) at the University of Iowa in 1917. Others included the Harvard Growth Study (1922), the Child Research Council at the University of Colorado (1927), The Fels Research Institute for the Study of Human Development at Antioch College in Ohio (1929), The Brush Foundation at Western Reserve University (1928) and the Berkeley Growth Study at the University of California, Institute of Child Welfare (1928). There were many more (see Tanner, 1948). European growth studies were slower off the mark and most did not appear until after World War II. The better known were the Oxford Child Health Survey (1943) and The Harpenden Growth Study in Hertfordshire (1948). Much of the data collected by these investigations was reported in the literature during the period 1930–1970 in the USA, and 1950–1980 in Europe.

In contrast to orthodontics, the influence of research on human growth in the therapeutic rather than the epidemiological sense is comparatively recent in medicine. It dates from the 1950s and the realization by paediatricians of the usefulness of growth as a guide to restored health. The development of paediatric endocrinology as a speciality, has also led to the establishment of clinics for the treatment of children with growth disorders resulting from endocrine and other causes. (See Tanner (1981), *A History of the Study of Human Growth* for a comprehensive review of the historical background)

Methodology

There are three ways in which to obtain growth data; (1) cross-sectional; (2) longitudinal or serial, and (3) mixed-longitudinal (Slide 3). In a cross-sectional study, a child is measured only once. Cross-sectional studies are concerned with growth at the population level (with means and variability), rather than the growth pattern of the individual, and are used to provide information at one point in time. Since it is not possible to measure everyone, a cross-sectional survey is limited to a sample or subset of the population chosen at random, which means that overall population sampling can be done in a relatively short time. To construct national standards of the type shown in slide 7, a random sample upwards of 1000 boys and 1000 girls at each age group would be required. The cross-sectional method provides general information, and when applied to a child will tell only where he or she stands with reference to other children.

Longitudinal studies involve the measurement of the same individual over a number of years. The disadvantage of a longitudinal study is that it may take several years to complete, and is therefore time consuming and expensive; some participants will inevitably drop out of the programme. However, the data they provide is necessary to construct growth velocity standards (Slides 13, 14) and to identify individual variation in growth rate. Individual difference or variation is the normal condition in nature.

A third type of growth study is the mixed-longitudinal. This is a combination of cross-sectional and longitudinal methods in which children enter and leave a study at different ages giving different degrees of longitudinality (Eveleth and Tanner, 1991). In practice, this means that subjects of different age levels are studied longitudinally for shorter periods (say 3–4 years), which can then be added to each other to cover a much longer time scale. The Bolton Study was originally set-up as a mixed-longitudinal investigation. Groups of children were started at 3 months, 6 months and 3, 6, 9, 12, 15 and 18 years of age.

Count Montbeillard and his son

The first longitudinal study of human growth was made by Comte Philibert Guéneau de Montbeillard (1720–1785), who measured the height of his son from birth to eighteen years of age (Slide 4). This was undertaken at the request of his close friend and neighbour George-Louis

Leclerc, Comte de Buffon (1707–1788) the leading French naturalist of the day, and published in the fourth supplement to Buffon's *Histoire Naturelle* issued in 1777. Sadly, Montbeillard's and Buffon's sons were both casualties of the French Revolution during the Terror of 1793-94, when France became a republic under Maximilian Robespierre; during this 14-month period both were guillotined along with an estimated 17,000 others.

Slide 4. Graph illustrating the growth of the son of Comte Philibert Guéneau de Montbeillard from birth to eighteen years (1759–1777). The height in the original old French units of linear measure is placed on the right margin of the graph and their equivalents in the metric system on the left. Montbeillard's son was very tall, ending above the 97th percentile of modern standards; he also had a marked adolescent growth spurt with a peak velocity of 12.1 cm/year and a total gain from beginning to end of about 31 cm (Tanner, 1981). Figure from (From Scammon (1927), *American Journal of Physical Anthropology*)

The figure shows four rather definite stages: (1) a period of rapid increase during infancy and early childhood; (2) a middle period extending from about 3 to 12 years in which growth is slow but constant; (3) a period of marked acceleration around puberty from about 12 to 15 years; and (4) a terminal period of slow increase thereafter (Scammon, 1927). This four phased or general type of growth is common not only to the external linear dimensions of the body but also to many internal organs, musculature and skeleton.

In addition to establishing the existence of the pubertal growth spurt, Montbeillard's study also showed that there was a seasonal change in growth rate and confirmed the occurrence of shrinkage in height during the day. The practical significance of this is that height measurements should be undertaken in the morning. Surprisingly, it took almost 100 years for the pubertal growth spurt to be recognized for what it was because it was commonly confused with catch-up growth, the abnormally rapid growth that occurs following a period of growth retardation due to illness or starvation (Tanner, 1981). Even the Belgian mathematician and sociologist Lambert Adolphe Jacques Quételet (1796–1874), who carried out the first cross-sectional human growth study, and the first mathematical analysis of growth data, failed to recognize its significance in *A Treatise on Man and the Development of his Faculties* (1842).

Patterns of human growth

No discussion of human growth is complete without an illustration of Scammon's growth curves (Slide 5). Richard Everingham Scammon (1883–1952), was Professor of Anatomy at the University of Minnesota and the Institute of Child Welfare, another early centre for the study of child development founded in 1925 with funding from the Rockefeller Foundation. In order to understand the various patterns of postnatal growth, in a famous illustration in *The Measurement of Man* (1930), Scammon reduced the growth of the human body to four basic curves of systematic and organic growth: general, neural, lymphoid and genital.

Slide 5. Scammon's growth curves for the various parts and tissues of the body. The curves are drawn to a common scale and plotted as the size attained in percent of the total postnatal growth from birth to 20 years of age, *i.e.* they have 100 percent of their value at the age of 20 years, starting at birth with zero percent. (From Scammon (1930), *The Measurement of Man*)

These four types comprise the most frequent modes of increment observed postnatally and are characteristic of the majority of organs and tissues of the body. The general type follows a sigmoid or S-shaped curve and includes practically every linear dimension of the body, the respiratory system and weights of a number of viscera, plus the musculature and skeleton as a whole. The brain and its membranes, the spinal cord, the eye and associated ocular muscles, plus the cranial vault are characterized by what Scammon termed neural growth, *i.e.* an initial phase of rapid growth following birth and infancy followed by a slower terminal one.

The majority of organs composed chiefly of lymphoid tissue show a rapid rise in infancy and early childhood, followed by a continued but slower increase to an apex at puberty and a decline thereafter—the so-called lymphoid type of growth. The reduction from 200 to 100 percent is achieved mainly by involution of the thymus, which loses much of its function and reverts to connective tissue (Krogman, 1972). Wilton Marion Krogman (1903–1987) was an important figure in orthodontics and cephalometry with his studies of the jaws, facial structure and the

dynamics of craniofacial growth. First, at Western Reserve University in Cleveland, Ohio with T Wingate Todd, and from 1947 at the University of Pennsylvania, where he founded the Philadelphia Center for Research in Child Growth. The genital type of growth which includes the genital organs and secondary sex traits is characterized by a slight increase in infancy, a latent period of approximately a decade, followed by rapid growth at puberty.

Growth standards and growth curves

Standards for height and weight are available for many populations worldwide. They were developed as a clinical tool to determine if the physical growth of a child is within normal limits for age, sex, population and social class. Height and weight charts are cross-sectional and constructed from the measurements of a large number of individuals of each sex at given ages measured once only. They provide an important tool for evaluating the growth of children in clinical and research settings. The frequency distribution of height and weight is then converted into a percentile ('centile') plot, which is smoothed to produce the familiar growth curves (Wales, 2002; Slide 6). Most growth charts are expressed in percentile lines rather than standard deviation (SD) but the exact percentiles used may vary. Both the original Tanner-Whitehouse charts and the newer UK90 reference charts use similarly spaced percentile lines. The mean is represented by the 50th percentile and the space between adjacent percentile lines is approximately 2/3 of a standard deviation. This results in lines equivalent to the 25th and 75th (± 0.66 SD); the 9th and 91st (± 1.32 SD) and; the 2nd and 98th (± 2.0 SD) percentiles around the mean. The extremes of normality for height are set at less than 0.4th or greater than the 99.6th percentile (1 in 250 children will fall outside these limits).

Slide 6. Height is normally distributed throughout the population to form the familiar bell-shaped or Gaussian curve. Percentiles are calculated and related to the SD as shown on the lower scale. The percentile plots are then rotated by 90 degrees to provide one age/percentile distribution and the process repeated for each age group to produce the charts shown in slides 7 and 8. (From (Wales, 2002), *Clinician's Guide to Growth Disorders*, with permission of Arnold, Hodder Headline Group)

Height and weight charts

In the United Kingdom most clinicians will be familiar with the Tanner-Whitehouse growth charts first published in 1966. The data which formed the basis for these growth charts came from (1) a sample of about 80 children of each sex followed longitudinally at the Child Study Centre, London, from birth to 5½ years; (2) The London County Council Survey of 1959 which measured a random sample of 1000 boys and 1000 girls at each year of age from 5½-15½; and (3) 30 children from the Harpenden Growth Study that had been studied up to the age of 20 (Tanner *et al.*, 1966). However, because of the well-recognized secular trend towards earlier maturity and increasing height at all ages, the original Tanner-Whitehouse growth standards are now obsolete and should not be used. The Buckler-Tanner (1995) update of the Tanner-Whitehouse standards (Buckler and Tanner, 1997) does allow for the secular trend and is very similar to the UK90 growth charts now recommended for use on contemporary British children (Wright *et al.*, 2002).

UK90 growth curves

In view of the concerns regarding the Tanner-Whitehouse standards, a project was begun to produce new reference curves for stature and weight for the United Kingdom, using up-to-date data that were as nationally representative as possible. The data for the construction of the reference curves were taken from seven sources; all measurements were made between 1978 and 1990 from over 25,000 children (for details see Freeman *et al.*, 1995). Slides 7 and 8 show the resultant height and weight percentile curves for boys and girls (now referred to as the UK90 growth curves). Weight is not normally distributed in both male and female charts as there are more heavy individuals in a given population, a situation that is likely to get progressively worse with the alarming increase in obesity in the Western World, and increasingly in Asia associated with fast food.

Slide 7. Growth curves for boys' height and weight currently recommended for use in the UK. These are based on cross-sectional data collected between 1978 and 1990 (Freeman *et al.*, 1995). There are nine height percentile lines equally spaced approximately two thirds of a standard deviation apart. (With permission of the Child Growth Foundation, 1996)

Slide 8. Growth curves for girls' height and weight currently recommended for use in the UK. Weight is not normally distributed in both the male and female charts as there are more heavy individuals in a given population; the nine percentile lines are therefore unequally spaced. (With permission of the Child Growth Foundation, 1996)

For boys' stature, the 1990 50th percentile is greater than that of the Tanner-Whitehouse standards at all ages, the smallest difference being 0.8 cm at age 16 and the greatest 1.7 cm at age 18 (Slide 9). As far as weight was concerned overall there was an increase compared to the Tanner-Whitehouse data. The 50th percentile for UK90, for example was greater than Tanner-Whitehouse at all ages apart from age 2 with a difference at age 18 of 3.2 kilograms.

Slide 9. (A) Comparison of the UK90 height percentile (boys) with the comparable Tanner-Whitehouse cross-sectional data. The solid line represents the 1990 data and the dotted line Tanner-Whitehouse. (B) Comparison of the UK90 weight percentile (boys) and Tanner-Whitehouse cross-sectional data. (From Freeman *et al.*, (1995), *Archives of Disease in Childhood*, with permission from the BMJ Publishing Group)

CDC 2000 growth charts

In the United States growth charts were developed in 1977 by the National Center for Health Statistics (NCHS) and were based on a cross-sectional growth study that measured children from 1 to 17 years of age from 1971 to 1974 and reported by Hamill *et al.* (1977). They were subsequently adopted for international use by the World Health Organisation. These NCHS data were also used by Tanner and Davies (1985) to construct growth velocity standards for US children. The 2000 CDC (Center for Disease Control and Prevention) growth charts represent the revised version of the 1977 NCHS growth charts. The data used to construct these charts comes from the National Health and Nutrition Examination Survey (NHANES), which has collected height, weight and other health information on the American population since the early 1960s, can be downloaded from the NCHS website (Slides 10, 11) and are very similar to the UK90 growth curves.

Slide 10. Growth charts for boys' height and weight currently recommended for use in the USA. At 17 the average height (50th percentile) is 175 cm compared to 176 cm in UK90; the average weight at 17 is 65 kg compared to 64 kg in UK90. (Developed by the National Center for Health Statistics in collaboration with the National Center for Chronic Disease Prevention and Health Promotion, 2000)

Slide 11. Growth charts for girls' height and weight currently recommended for use in the USA. At 17 the average height (50th percentile) is 163 cm compared to 164 cm in UK90; the average weight is 55 kg compared to 57 kg for UK90. (Developed by the National Center for Health Statistics in collaboration with the National Center for Chronic Disease Prevention and Health Promotion, 2000)

Height velocity charts

While the percentile curves on height charts are useful for evaluating the cumulative or attained height of a child at a given age in the population at large, they do not reveal the distinctive features of pubertal growth. The dynamics of pubertal growth are best represented by height velocity charts rather than by standard growth charts (Abbassi, 1998). Height velocity charts are constructed from longitudinal observations conducted on a relatively small number of individuals by plotting the increase in height per annum against age in years (Slide 12). Since such time-consuming and costly longitudinal studies are no longer in fashion, the data on which the currently available growth charts in the UK are based was collected by Tanner and Whitehouse from the Harpenden Growth Study in the 1950s. It consisted of measurements of height on 49 healthy boys and 41 healthy girls that had been followed for a sufficient period before, during and after puberty to give a clear indication of the course of their pubertal growth spurt (Tanner *et al.*, 1966). Because of the secular increase in height that has occurred since that time (approximately 1.7 cm for boys), this difference spread over 18 years is unlikely to produce a significant change in the Tanner-Whitehouse (1976) height velocity charts, making them still broadly applicable to the UK population (Wales, 2002).

The pubertal growth characteristics that can be quantified from height velocity charts include age at takeoff (onset of growth acceleration), age at peak height velocity, peak height velocity, duration of puberty, and the contribution of the pubertal growth spurt to final adult height (Abbassi, 1998). Table 1 shows the pubertal growth characteristics from four major United States longitudinal growth studies. Age at peak height velocity was 13 years for boys and 11 years for girls (a difference known as sexual dimorphism) and the data is based on measurements of children made prior to 1950. The likely explanation for the difference in average height between the California, Denver, Fels and the Harvard data is the socio-economic background of the participants. All were of European ancestry but drawn from the lower middle (Harvard) and upper middle classes (California, Denver, Fels), reflected in the fact that the Harvard sample averages about 2 cm shorter for both males and females.

Table 1. Pubertal Growth Characteristics in Four US Longitudinal Studies

	University California Berkeley	Denver Child Research Council	Fels Research Institute	Harvard School of Public Health
Girls				
Age at peak height (y)	11.01 (0.83)	11.01 (0.91)	10.96 (0.80)	11.13 (0.87)
Height at takeoff (cm)	141.79 (7.60)	137.25 (6.64)	138.57 (7.44)	140.83 (7.19)
Adult height (cm)	168.12 (6.23)	168.23 (6.69)	168.02 (5.15)	165.75 (5.07)
Pubertal gain (cm)	26.33 (5.69)	30.98 (4.04)	29.45 (6.80)	25.43 (5.64)
Boys				
Age at peak height (y)	13.06 (1.08)	13.31 (1.08)	12.99 (0.93)	12.90 (0.94)
Height at takeoff (cm)	150.60 (6.98)	149.42 (7.14)	149.95 (7.03)	147.39 (5.72)
Adult height (cm)	180.74 (6.58)	180.40 (5.41)	180.85 (5.79)	175.56 (6.11)
Pubertal gain (cm)	30.14 (5.43)	30.98 (4.66)	30.90 (4.34)	28.17 (5.51)

Values are mean ± standard deviation (SD).

From Abassi (1998); based on data from Thissen *et al.* (1976).

Peak height velocity

The duration of the spurt is the same for both sexes at about 5 years and irrespective whether the child is short or tall, the tendency is to progress towards maturity at the same rate. Peak height velocity (PHV) is the largest annual increase in height during the pubertal growth spurt and on average occurs 2.5 years after its onset. In English children, based on Tanner/Whitehouse data, PHV in boys occurred at a mean age of 14 years with a range of 0.3 years and in girls at a mean age of 12 years with a range of 0.5 years (Tanner and Whitehouse, 1976). In the US children grow at a slightly faster tempo; in the US growth velocity standards constructed by Tanner and Davies (1985), peak height velocity occurred at a mean age of 13.5 years for boys and 11.5 years for girls. A child with the peak of his/her spurt at the average time follows one of the percentile curves. If he/she has an earlier or a later spurt the curve will follow the same shape but will be in one of the shaded areas. If the peak velocity lies in the left shaded area the pubertal spurt is abnormally early, and if in the right, abnormally late (Eveleth and Tanner, 1991; Slides 13, 14).

Slide 13. Longitudinal standards for height velocity (boys). The left shaded area represents the percentiles for boys with a PHV occurring 2 SDs before the mean age (approximately 2 years early). The right shaded area represents the percentiles for boys with a PHV occurring 2 SDs after the mean age (approximately 2 years late). The shaded areas thus enclose all velocity curves within the 3rd – 97th percentile limits for age and PHV. 3rd, 50th and 97th percentiles for early and late maturing boys are indicated by arrowhead and diamond symbols. (From Tanner and Whitehouse (1976), *Archives of Disease in Childhood*, with permission from the BMJ Publishing Group and Castlemead Publications)

Slide 14. Longitudinal standards for height velocity (girls). For explanation see Slide 13. Peak height velocity in girls from the Harpenden Growth Study occurred at a mean age of approximately 12 years. This is 2 years earlier than in boys (Slide 13), and indicates sexual dimorphism in the timing of the pubertal growth spurt. (From Tanner and Whitehouse (1976), *Archives of Disease in Childhood*, with permission from the BMJ Publishing Group and Castlemead Publications)

Early versus late maturation

Growth in height is closely related to the rate of physical maturation and although most children mature and grow according to much the same pattern, healthy normal children differ greatly in size and may be accelerated or retarded from the average in their rates of maturing (Bayer and Bayley, 1959). Early maturing boys and girls are on average taller than their late-maturing peers from early childhood to about the age of 15 years in girls and 17 years in boys, but it has been reported that on average there is no difference in final stature for either sex (Bayley, 1956; Tanner, 1962; Lindgren, 1978; Tanner and Davies, 1985). Growth in standing height will on average cease at about 17.5 years in girls and 20 years in boys, but late-maturing girls will not cease growing in height before 21–22 years of age and late-maturing boys before 23–24 years (Roche and Davila, 1972; Roche, 1989; Taranger and Hägg, 1980).

Comparisons of final stature between early-, average- and late-maturers in the above studies, however, are uncertain because the participants had not been followed for a sufficiently long period of time. To address this deficiency, Hägg and Taranger (1991) followed the growth of a sample of 183 Swedish urban children (103 boys and 80 girls) who were grouped into early-, average- and late-maturers on the basis of their age at PHV. In girls there were significant differences in height between the maturity groups from 5 to 14 years of age, but the final height did not differ between the groups. The early-maturing boys were taller than late-maturers from 12 to 15 years; from 17 onwards, however, late-maturing boys became taller, the difference in final height (at 25 years) being 6.5 cm. Average maturing boys were taller than late-maturers until 18 years, when late-maturing boys became taller with a final difference in height of 4.2 cm. On average final heights were 177.5, 179.8 and 184 cm in early-, average- and late-maturing boys (Hägg and Taranger, 1991). Or in plain English, on average, late maturing boys end up being taller.

The secular trend

In this context secular refers to changes occurring over a long period of time. The term secular trend refers to the fact that over the last 100–200 years, children have been getting taller and growing to maturity more quickly. The main determinants are socioeconomic and are related to (1) improvements in prenatal care; (2) better nutrition with the intake of more protein and calories during infancy; (3) better hygiene and living conditions; and (4) reduction of disease with the availability of public health services. The occurrence of a secular increase in height and weight has been documented for nearly all European countries, and a similar trend reported for the USA, Canada, Australia and Japan (Meredith, 1976).

In the industrialized world the trend has effectively come to an end (Greulich, 1976; Chinn *et al.*, 1989). Measurements of the height of 85 males from four-generation families of Old American descent (defined as a person with four grandparents born in the USA) measured at Harvard between 1870 and 1965, suggest that the secular increase in height had ended amongst economically favoured American men by the 1960s (Damon, 1968). Although the numbers were small there was a significant increase in height (2.63 cm) between generation I (mean birthdate 1858) and generation II (1888), a small increase (1.14 cm) to generation III (1918), and none at all to generation IV born in 1941.

In Norway, the physical growth of children in Oslo has been systematically measured every 5th year since 1920 (Brundtland *et al.*, 1980; Liestøl and Rosenberg, 1995). Changes in height for the period 1920–1975 are shown in Slide 15; for ages between 8 and 14 the mean height increased by about 4 cm per decade for both sexes between 1920 and 1940. A drop of about 1.5 cm occurred during World War II, resulting from food shortages in German-occupied Norway, followed by a rapid catch-up after 1945. An update for girls from 1980–1985 (Liestøl and Rosenberg, 1995), suggested that the post-war increase in height has plateaued.

Slide 15. Mean height of different age groups of boys and girls in Oslo from 1920 to 1975. The ages 8 to 13 cover the total population of schoolchildren in Oslo. The increase in height at all ages was interrupted for 1940–1945 during World War II (a drop of about 1.5 cm occurred), followed by a rapid period of catch-up growth. An update for girls from 1980–1985 (Liestøl and Rosenberg, 1995), suggests that the slow but steady post-war increase in height appears to have plateaued. (From Brundtland *et al.* (1980), *Annals of Human Biology*, with permission)

The secular trend for Dutch and Swedish girls has also plateaued with the mean heights for all three countries lying between the 50th and 75th percentiles of the NCHS (1977) growth charts for girls in the USA (Ulijaszek, 1998). This difference is likely to be a reflection of the mixture of northern and southern Europeans in US growth data. South Europeans including the Spanish and Italians are on average shorter in childhood than their north European counterparts (Ulijaszek, 1998). Much of the trend in children's heights is due to their maturing earlier and is best shown by statistics on age at menarche (Tanner, 1989). The secular trend in age at menarche is shown in [Slide 16](#) and from 1880–1970 averaged a reduction of 3–4 months per decade. During the last 10 years the trend has slowed down or even stopped in most European countries.

Slide 16. Secular trends in age at menarche from 1860–1970. The earlier data are all based on recollected age, but the general trend is clear, and from 1880–1970 averaged 1–4 months per decade. In recent years the trend has slowed down in most European countries. (From Tanner (1989), *Foetus into Man*, with the permission of Castlemead Publications)

The importance of socioeconomic factors in determining growth in prosperous first world countries even today is highlighted by the Swedish evidence. Socioeconomic differences in the growth of Swedish children have been studied since 1883. Up until 1950, children from upper socioeconomic groups were shown to be significantly taller and heavier than those from lower socioeconomic backgrounds. No significant differences in height and rate of maturation were present in children born in 1955 (Lindgren, 1976), but in a nationwide sample of children born in 1967, there was an indication that the difference in height might be coming back; girls of lower socioeconomic status were an average 1 cm shorter than the rest at 7 years of age (Lindgreen, 1988). These differences were interpreted as mirroring socioeconomic conditions in Swedish society, and have been confirmed by a more recent 1980 birth cohort study (Lindgren *et al.*, 1994).

Evidence for a secular trend in skull dimensions

The existence of a secular trend in body height has been well documented and found to be accompanied by secular changes in skull dimensions. Although the measurement of heads has an unfortunate association with eugenics and theories of racial purity, studies by respected physical anthropologists suggest that coincident with the secular change in size, there has been a progressive brachycephalization of the skull worldwide (Weidenreich, 1945; Abbie, 1947). Franz Weidenreich (1873–1948), German anatomist and physical anthropologist. Professor of Anatomy at the University of Heidelberg and later Anthropology at the University of Frankfurt, in 1934 he left Hitler's Germany for the University of Chicago. His reconstruction of human remains including Peking man (*Homo erectus pekinensis*) and Java man (*Homo erectus*) brought him to pre-eminence in the study of human evolution.

In a Japanese study, for example, it was found that present day males had larger heads and bodies than their predecessors 50 years earlier (Morita and Ohtsuki, 1973), and that the change in the cephalic or skull index (maximum width/maximum length x 100) was due to a distinct increase in the breadth of the head (6.8 mm), not to a decrease in length. One weakness of these data is that they are based on cross-sectional methods. Whether these changes are real and have occurred in more genetically diverse populations is unclear, but having observed the wide variation in skull morphology of one's fellow *Homo sapiens*, does leave some room for doubt. It is also fairly obvious if one looks at basketball players that their heads are not getting bigger in comparison to increase in body size!

There is little recent data on this topic, but in 1969 Hunter and Garn measured facial dimensions from lateral cephalograms of a sample of adult parents and their adult children in 37 families from Ann Arbor, Michigan. They concluded that it was reasonably certain that there is a secular trend in face size such that 25-year-old children have faces that are already larger than those of their 55-year-old parents ([Slide 17](#)). In common with the secular trend in stature, improving nutrition, living conditions and absence of disease are likely to have been the principal causative factors. Stanley Marion Garn (1922–2007) was a Professor of Anthropology and Nutrition at the University of Michigan. In 1952 he joined the Department of Physical Growth and Genetics at the Fels Research Institute in Yellow Springs, Ohio where he studied human growth and maturation,

population differences in epidemiological risk, and family line studies. In 1968 he joined the University of Michigan Center for Human Growth and Development.

Slide 17. Facial polygons based on mean dimensions for fathers (N=31) and their sons (48), and for mothers (27) and their daughters (38). Mandibular growth in offspring exceeds that of parents, although Ar-Go was not consistent with the trend. Facial height was significantly less for daughters than for mothers producing quite different facial polygons. (From Hunter and Garn (1969), *The Angle Orthodontist*)

Secular changes in skull morphology and dimensions of the dental arches over a period of 160 years were analysed cephalometrically in 312 Swedish army conscripts (average age 18.7 years), and compared to the skulls of 60 soldiers aged 18–25 who had died in west Sweden during a typhus epidemic in 1810 (Ingervall *et al.*, 1972). Body height calculated from the long bones of the limbs suggested a mean height for the soldiers of 168 cm. Body height in the conscripts was on average 179 cm. The cranium was found to be larger in the conscripts in both anteroposterior and lateral dimensions; the cranial base angle (N-S-Ba) was reduced in the conscripts, but the gonial angle (ML/RL) was increased compared to the skull material (Table 2). The dental arches were wider (between the first molars) but the length shorter in the skull material. These results confirm that parallel to the secular increase in body height there has been secularization of the morphology of the cranium, including changes in the cranial base involving both length and angulation.

Table 2. Secular changes in skull morphology in Swedish men between 1810 and 1970

Variable	1810			1970			Difference
	N	mean	SD	N	mean	SD	
N – S	(57)	68.40	3.32	(310)	74.86	3.54	6.26 mm***
S – Ba	(57)	45.21	3.18	(249)	49.24	3.74	4.03 mm***
Eur–Eur	(59)	152.90	5.57	(310)	156.98	5.81	4.08mm***
Ms–Ms	(42)	110.87	5.94	(312)	118.49	5.18	7.62mm***
Go–Go	(40)	101.63	10.16	(312)	105.85	6.12	4.22mm*
N–S–Ba	(57)	133.23	7.02	(247)	131.18	5.46	-2.05degrees*
ML/RL	(31)	118.11	7.11	(254)	121.48	6.99	3.37degrees*

Data derived from Ingervall *et al.* (1972). *Eur*, euryon, the point on either side of the greatest transverse diameter of the skull; *Ms*, mastoidale, lowest point on the mastoid process. ML/RL represents the gonial angle of the mandible with the number of observations is in parentheses. * $P < 0.05$, *** $P < 0.001$.

The assessment of skeletal age

The existence of early-maturing as well as late-maturing individuals makes for a wide difference in the onset of puberty (Slides 18, 19). It is therefore difficult to determine the development status of a child solely on the basis of chronological age. Chronological age is a poor indicator of the amount of progress a child has made towards physiological maturity (Greulich and Pyle, 1959).

Slide 19. Differing degrees of puberty in three boys of the same chronological age. Upper row, boys all aged 13 years to 13 years 3 months; lower row, boys all aged 14 years 0 months. At each age the left-hand boy is pre-pubertal, and the right-hand boy approaching maturity. (From Tanner (1962), *Growth at Adolescence*)

The most commonly used indicator of physiological maturity has been the skeletal age (Baldwin *et al.*, 1928; Cattell, 1934; Todd, 1937; Falkner, 1958; Greulich and Pyle, 1959), a measure of how far along the bones of the hand and wrist are in the course of development as recorded by their x-ray appearance. The skeletal age is assessed by comparing a given patient radiograph with a set of standards and there are two ways in which this can be done (reviewed by Gilli, 1996; Cameron, 1998). (1) The atlas or inspectional method in which the radiograph is matched to a published set of standards arranged in order of maturity (Todd, 1937; Greulich and Pyle, 1959). (2) The bone-specific method based on skeletal maturity indicators. A series of standard stages

through which each hand and wrist bone passes has been established and each bone of the given radiograph is matched with these stages and given a numerical score (Acheson, 1957; Tanner *et al.*, 1975, 2001). This will be discussed briefly for completeness but is too complicated for routine clinical purposes.

Atlas of skeletal maturity

In 1928 a long-term investigation of human growth and development under T Wingate Todd at Western Reserve University (now Case Western Reserve University) School of Medicine in Cleveland, Ohio, was started with the financial backing of the Brush Foundation. Thomas Wingate Todd MB, BCh, FRCS (1885–1938) an English-born anatomist was appointed Henry Wilson Payne Professor of Anatomy at Western Reserve University in 1912, and was instrumental in founding the Bolton Brush inquiry to investigate the longitudinal growth and development of children. His aim was an exact X-ray record of the growth changes in the bones – from birth to maturity. One important side-issue of this enquiry related to the growth of the face, and opened up a new field of investigation – Todd perceived that if orthodontic treatment was to become effective, it must be based on knowledge of the normal and disordered growth of the face in childhood (Keith, 1939). The result was the Bolton Study, that became possible when Mrs Chester Bolton financed craniofacial x-ray studies of healthy children from infancy to adulthood in 1929, under B Holly Broadbent Sr DMD, MSD (1894–1977). Broadbent pioneered cephalometric radiography at WRU with the cephalometer, a head positioning device to accurately position a patient's head in relation to the x-ray source, and helped assemble the world's largest collection of serial cephalometric radiographs. Together the Brush Inquiry and the Bolton Study collections form the Bolton–Brush Growth Study, comprising the world's most extensive source of longitudinal human growth data. Both are generally referred to as the Bolton–Brush Growth Study.

All the children (more than 4000) recruited into the study were white, free from physical or mental defects and born in the USA of predominantly North European ancestry. They were also from families of above average socioeconomic and educational status and made up what became known as the Research Series (Greulich and Pyle, 1959). Todd developed the radiographic method for assessing skeletal age by noting the shapes, contours, articular surfaces and relative sizes of the diaphyseal–epiphyseal region and other centres of ossification in six areas of the body. These were the shoulder, elbow, hand (including the wrist), hip, knee and foot. Todd found that the hand and wrist with its large number of centres of ossification provided a continuous series of identifiable changes throughout the growth period. This enabled him to make up two series of standards (male and female) for the hand and wrist. These were at three-month intervals during infancy and six-month intervals from three years until growth was completed with closure of the distal radial epiphysis (Bayer and Bayley, 1959). These hand standards were published in 1937 as the *Atlas of Skeletal Maturation (Hand)*, which provided the first practical guide for the clinician to assess skeletal age.

While the Todd *Atlas* of 1937 was based principally on x-ray films of children enrolled in the Research Series, it was also based, in part, on cross-sectional data of children from various public schools and social agencies in the Cleveland area. These children were from less privileged socioeconomic backgrounds and more diverse national antecedents. As a result, the data from the two groups on the rate of skeletal development were not entirely compatible. The Greulich and Pyle *Radiographic Atlas and Skeletal Development of the Hand and Wrist* (1959) which first appeared in 1950 as a revision of the original Todd *Atlas*, was based exclusively on the Research Series and corresponds to the chronological age of the children on whom the standard was based (the standards represent 'central tendencies' or modal level of maturity). On each page facing the standard plate, a bone-specific skeletal age is assigned to each bone together with a description of the corresponding radiographic features. Following the male and female standards an appendix outlines the characteristics of the maturity indicators of individual bones and epiphyses. The purpose of this section is to describe the principal changes that occur in the shape of the various bones and epiphyses of the hand and wrist during postnatal development.

In using the Greulich and Pyle *Atlas* the radiograph to be assessed is compared to the series of standard plates ([slide 22](#)); the plate that fits most closely represents the bone age of the child. It is customary to use radiographs of the left hand. (The International Agreement for the Unification of

Anthropometric Measurements drawn up at the Monaco and Geneva Conferences of Physical Anthropologists in 1906 and 1912, specified that measurements be made on the left rather than the right side of the body.) There are, however, a number of problems associated with the technique. Firstly, the method is prone to subjective error particularly with an inexperienced observer. Secondly, the standards are not applicable to children from different ethnic backgrounds. And thirdly, it presumes a fixed pattern of first appearance and subsequent development of the bones. In practice there is wide variation in the order of ossification of individual bones particularly those of the wrist, and this variation is genetically determined. Children who experience above-average numbers of episodes of ill health do not have greater carpal sequence variability (Garn and Rohmann, 1960). Moreover, the prevalence of sexual dimorphism and sequence polymorphism in hand-wrist ossification is considerable, not one centre having an absolute fixed position in the total order of appearance (Garn *et al.*, 1966).

Slide 22. A. Radiograph of the hand and wrist of a boy with a skeletal age of 12 years and 6 months (male standard 22). The individual carpal bones are numbered in the order in which their ossification usually begins: 1, capitate; 2, hamate; 3, triquetral; 4, lunate; 5, trapezium; 6, trapezoid; 7, scaphoid; 8, pisiform (visible through the shadow of the triquetral). Epiphyses of the wrist: 9, distal epiphysis of the radius; 10, distal epiphysis of the ulna. The skeletal age assigned to each bone in this standard is 12 years 6 months with the exception of the middle phalanges II-V with a skeletal age of 12 years 3 months.

B. Radiograph of the hand and wrist of a boy with a skeletal age of 13 years and 6 months (male standard 24). The ossification centre of the sesamoid bone in the tendon of the adductor pollicis muscle is visible medial to the head of the metacarpophalangeal joint of the thumb (arrow). The skeletal age assigned to each bone in this standard is 13 years 6 months. (From Greulich and Pyle (1959), *Radiographic Atlas of Skeletal Development of the Hand and Wrist*, with the permission of Stanford University Press)

Bone-specific scoring method

In 1962 Tanner *et al.* produced a new method for assessing skeletal maturity (TW1) in which each bone of the hand and wrist was classified separately into 8 or 9 stages to which scores were assigned. These scores were summed to give the skeletal maturity. Being derived from a more solid mathematical basis the aim was to eliminate or at least reduce the errors inherent in the atlas method. In 1975 TW1 was superseded by the TW2 method (Tanner *et al.*, 1975). This assessed the maturity of 20 bones which were examined in the following order:

Radius, ulna, metacarpals I, II, V
Proximal phalanges I, III, V
Middle phalanges III, V
Distal phalanges I, II, V
7 carpal bones (pisiform excluded)

Separate maturity scores were provided for the carpal bones and for the radius, ulna and short bones (metacarpals and phalanges) referred to as RUS. The sum of these scores results in a skeletal maturity score (SMS) rather than a skeletal or bone age. In contrast to a bone age an SMS is independent of such influences as secular growth changes, socio-economic class and ethnic group; it is a quantitative description of the x-ray film, an anthropometric measurement comparable to height or weight (Tanner *et al.*, 2001). The point scores can be combined to give three different SMSs. A 20-bone score, a carpal bone score and the RUS score. The RUS is the score most commonly used by clinicians because the carpal bones are difficult to assess at some stages (Gilli, 1996).

With the secular trend in many countries towards more rapid maturation TW2 has been replaced by TW3 (Tanner *et al.*, 2001). The description and manual rating of the bone stages remains unchanged – the RUS scores and the carpal scores are exactly the same, but the 20-bone score has been abolished. TW3 bone ages are about a year ahead of TW2 bone ages from ages 10 or 11 years upwards. The SMS may be plotted on percentile charts for age in the same way as charts for height or weight. However, because clinicians prefer to use bone age the percentile curves for SMS can be used to assign a bone age, which is simply the bone age at which the 50th percentile child has the maturity score of the child under consideration. (For guidance on how the

individual bones are scored the reader should consult Tanner *et al.* (2001), *Appendix 1: The Rating System.*)

Prediction of the pubertal growth spurt

A high degree of association between PHV and a pubertal spurt in facial growth has been well documented and will be discussed further in Seminar 9 (Nanda, 1955; Bambha, 1961; Hunter, 1966; Brown *et al.*, 1971; Bergersen, 1972; Thompson *et al.*, 1976; Fishman, 1982). Being able to predict the onset of the pubertal growth spurt would be of considerable benefit in the timing of certain types of orthodontic treatment, particularly involving growth modification for class II malocclusions (Björk and Helm, 1967). A single height measurement will indicate on which percentile curve a patient lies in comparison to other children, but to determine where they might be on their pubertal growth curve requires serial measurements. In practice this is not usually possible, and the clinician has to rely on a single examination. What would be ideal is a simple marker(s) of skeletal maturation to indicate whether or not the pubertal growth spurt had been reached or passed. As will be seen from the following discussion, accurate prediction of the timing of the pubertal growth spurt remains uncertain.

In paediatrics, hand–wrist radiographs are used mainly for the purpose of comparing physical maturity of the individual child with that of normal children of the same age and sex. In orthodontics, the child’s maturity is evaluated in relation to its own pubertal growth spurt to assess whether pubertal growth is imminent, has been reached or passed (Helm *et al.*, 1971). The use of bone-specific scoring methods requires a good deal of experience and is unnecessarily complicated for orthodontic purposes. However, several groups of investigators have used the timing of certain ossification events in hand–wrist films to evaluate skeletal development.

Studies at the Royal Dental College, Copenhagen

Arne Björk (1911–1996), one of the most important figures in cephalometric research, practiced dentistry in Västerås, Sweden, from 1937 to 1951 until appointed Professor of Orthodontics at the Royal Dental College in Copenhagen, Denmark. His longitudinal cephalometric studies of human postnatal facial growth, carried out with the aid of metallic implants provided new insights into the individual variation of postnatal facial growth patterns, and made possible the development of the structural method of radiographic superimposition. Björk and Helm (1967) found in a longitudinal study of a small number of Danish schoolchildren, that ossification of the ulna sesamoid bone at the metacarpophalangeal joint of the thumb occurred about one year before the occurrence of PHV in both sexes (Slides 23, 24). Their conclusion was that this seemed to indicate fairly reliably that maximal pubertal growth was imminent or had been reached

However, Garn and Rohmann (1962) found a wide range of variability in the timing of ossification of the sesamoid bone in 179 children from the Fels Research Institute Growth Study. It appeared in girls between the eighth and thirteenth year and in boys between the tenth and sixteenth year. The medians were 10.6 and 12.6 years respectively. A sesamoid bone [L. *sesamoides*, like a sesame seed] is one that develops in a tendon. In the hand, sesamoid bones develop in the tendons of insertion of (1) the *adductor pollicis* muscle which is attached to the ulnar side of the proximal phalanx of the thumb (hence its reference as the adductor or ulnar sesamoid), and (2) the *flexor pollicis brevis* muscle which is attached to the radial side of the base of the proximal phalanx of the thumb. In hand and wrist radiographs the radial sesamoid is usually obscured by the first metacarpal.

Slide 23. Ossification stages of the ulna sesamoid bone. Onset of ossification (S) is recorded when ossification is first evident; the error of recording the presence of the sesamoid has been shown to be negligible (Helm *et al.*, 1971). In panels 3 and 4 the radial sesamoid is faintly visible, partially obscured by the head of the first metacarpal. (From Tanner *et al.* (2001), *Assessment of Skeletal Maturity and Prediction of Adult Height (TW3 method)*)

Björk and Helm found that menarche in girls occurred about one year after PHV (Slide 24) and was considered to be a reliable indicator that the pubertal growth spurt had been reached or passed. Dental development in contrast was found to be of little value as a criterion of puberty, since eruption to occlusal level of all canines and premolars, especially for girls, and eruption to

occlusal level of the second molars, especially for boys, could occur several years before or after maximal pubertal skeletal growth. They concluded that ossification of the sesamoid bone by itself was not a reliable indicator of PHV, but an improved estimate could be obtained by supplemental examination of the progressing maturation of the middle phalanx of the third finger (MP3).

Slide 24. Sexual dimorphism in peak height velocity and physical stages of maturation based on a longitudinal study of 20 girls and 32 boys conducted at the Royal Dental College, Copenhagen. H, maximal pubertal growth in body height (peak height velocity); S, ossification of the sesamoid bone; M, age at menarche. (From Björk and Helm (1967), *The Angle Orthodontist*)

University of Adelaide aboriginal study

To establish the relationship of PHV to various ossification events in hand-wrist films, Grave and Brown (1976) analysed the serial records of 88 aboriginal children (52 boys and 36 girls) from the Northern Territory of Australia enrolled in a longitudinal growth study at the University of Adelaide. They found that the accelerative phase of growth was best indicated by the onset of pisiform or hamate (H-1) ossification, or by equality in the epiphyseal and diaphyseal widths of the radius. High associations were found between PHV and sesamoid bone ossification in both boys ($r = 0.83$) and girls ($r = 0.88$).

Evidence from the Stockholm-Göteborg Growth Study

In a similar longitudinal study of 212 randomly selected Swedish urban children, Hägg and Taranger (1980) evaluated skeletal development by the attainment of specific ossification stages (using the TW2 method) of (1) the ulna sesamoid of the first finger, (2) the epiphysis of the middle phalanx (MP3) of the third finger (slide 25), and the distal (DP3) phalanx of the third finger, and (3) the distal epiphysis of the radius. They found that if the sesamoid is not ossified, PHV has not been reached, although in occasional subjects ossification may begin just after PHV. For MP3 if stage FG (an intermediate stage defined by the authors) is attained the subject is in the pubertal growth spurt, most probably the accelerative phase, and if stage G is reached PHV is imminent or has been reached. Fusion of DP3 and the distal epiphysis of the radius indicated that PHV had passed, and growth terminated.

The Harpenden Growth Study

Houston *et al.* (1979) studied the relationship between PHV and the timing of 21 ossification events in hand-wrist radiographs according to the TW2 method; the sample was a mixed-longitudinal one of 64 boys and 49 girls from the Harpenden Growth Study. As we have seen above, skeletal maturity is usually assessed from bone stages; these are arbitrary stages that are defined according to the appearance of the bone on a standardized x-ray. The study of Houston *et al.* was based on ossification events they defined as the change from one bone stage to the next. In **Slide 25** for example, ossification event G occurs between stages F and G. (In my opinion, the distinction seems somewhat Jesuitical.) Based on the standard errors and confidence limits of the timing of PHV and certain ossification events, they concluded that the latter are of limited benefit in the prediction of the timing of the pubertal growth spurt. Coming from an eminent academic orthodontist (Houston) and the doyen of post-war human growth studies (Tanner), these conclusions resulted in a totally negative attitude to the use of hand-wrist films within the UK orthodontic community.

Slide 25. Ossification stages of the middle phalanx of the third finger (MP3). Stage F. The epiphysis is as wide as the metaphysis; Stage G. The epiphysis caps the metaphysis; Stage H. Fusion of the epiphysis and metaphysis has begun; Stage I. Fusion of the epiphysis and metaphysis is completed. (From Tanner *et al.* (2001), *Assessment of Skeletal Maturity and Prediction of Adult Height (TW3 method)*)

Cervical vertebrae as maturational indicators

One of the main criticisms of hand-wrist films to establish the skeletal age is that it requires an additional radiographic exposure; for that reason their use is considered by many to be unjustified in these radioactive conscious days. As a consequence, cervical vertebral staging that can be readily assessed from a headfilm, has been gaining in popularity amongst orthodontists (Lamparski, 1972; O'Reilly and Yanniello, 1988; Hellsing, 1991; Hassel and Farman, 1995; Garcia-Fernandez *et al.*, 1998; Franchi *et al.*, 2000). Actually, cervical vertebral staging is as old as the hand-wrist film and dates back to the time of Todd at Western Reserve University.

The method is based in changes in the morphology of the second, third and fourth cervical vertebrae; specifically (1) the presence or absence of a curvature of the lower border, (2) the shape of the vertebral bodies (trapezoid, square or rectangular), and (3) the width of the intervertebral space. Lamparski (1972) in an unpublished thesis from the University of Pittsburgh was the first to develop specific numerical stages corresponding to 6 different maturational stages (Slide 26). The relationship between cervical vertebral maturation (CVM) stages and mandibular growth has been investigated and suggest that significant increases in mandibular dimensions are associated with the acceleration/transition stages of CVM (O'Reilly and Yanniello, 1988; Franchi *et al.*, 2000).

Slide 26. Developmental stages of the third cervical vertebrae based on changes in the morphology of the third cervical vertebra: Stage 1 and 2, the bone is trapezoid in shape with a flat lower border; Stage 3, a curvature of the lower border is beginning to develop; Stage 4, the bone is square with a concavity of the lower border; Stage 5 and 6, the dimensions are greater vertically than horizontally and with accentuation of the curvature of the lower border. (From Hassel and Farman (1995), *American Journal of Orthodontics and Dentofacial Orthopedics*)

Slides 27–29. These show the cervical vertebral maturation (CVM) stages of three patients: (1) a boy aged 10 years 0 months assessed as being in the acceleration/transitional stage (CVM 2–3) and hence pre-pubertal; (2) a girl aged 15 years 5 months assessed as having entered the deceleration phase (CVM 4); and (3) a girl aged 14 years 2 months assessed as having reached the completion phase (CVM 6) and therefore post-pubertal.

Obesity and the pubertal growth spurt

Obesity is a major public health problem that has grown to epidemic levels in children and adolescents throughout the world. (Individuals are considered obese when their body mass index (BMI; weight in kilograms/height in metres²) exceeds 30 kg/m². It has been known for some time that overweight girls tend to mature earlier than lean girls (Garn and Haskell, 1959), leading to the hypothesis that the degree of body fatness may trigger the neuroendocrine events that lead to the onset of menses (Frisch and McArthur, 1974). Obesity as measured by BMI is significantly associated with early puberty in white girls, but less so in black girls (Kaplowitz *et al.*, 2001). However, obesity may delay puberty in boys (Burt Solorzano and McCartney, 2010). Although the mechanisms are complex and not well understood, orthodontists need to bear in mind that childhood obesity is associated with growth problems such as early puberty, premature adrenarche (an early sexual maturation stage that in humans typically occurs at around 6 to 8 years of age and the most common cause of early pubic hair) and accelerated growth with impaired final height potential (Shalatin and Phillip, 2003).

The finding that obese children have higher levels of leptin than lean children suggested it may be implicated in the early onset of puberty. Leptin, a small polypeptide hormone (*Mr* 16K) coded by the obese (*OB*) gene (Zhang *et al.*, 1994), plays a critical role in the regulation of body weight by inhibiting food intake and stimulating energy expenditure. Leptin circulates in the serum and serum levels correlate with adipose tissue mass, falling in both humans and mice after weight loss (Friedman and Halaas, 1998). The first *ob/ob* mouse arose by a chance mutation in 1949 at the Jackson Laboratory, Bar Harbor, Maine (Ingalls *et al.*, 1950). In homozygous mutant (*Ob*^{-/-}) mice, lack of leptin signalling in the hypothalamus leads to persistent hyperphagia, obesity and diabetes (Slide 30). The discovery that leptin, acts on hypothalamic neurons to suppress appetite and regulate energy expenditure in mice raised hope for an obesity therapy. Obese humans, however, were found to have high serum levels of leptin – unfortunately, this did not suppress their appetite because such individuals have developed leptin resistance.

Slide 30. The mouse on the left is a homozygous mutant (*Ob*^{-/-}) which does not produce leptin. Because the gene is recessive, heterozygous mutant (*Ob*^{+/-}) and wild-type littermates are normal. The first *ob/ob* mouse arose by a chance mutation in 1949 (Ingalls *et al.*, 1950). Mutant mice are phenotypically indistinguishable from unaffected littermates at birth, but are hyperphagic (compulsive overeating) and gain weight rapidly, reaching three times that of unaffected mice; *ob/ob* mice develop high blood sugar despite an enlargement of the pancreatic islets, and increased levels of insulin and diabetes.

Implications for orthodontic treatment planning

In an ideal world, the treatment of patients with jaw discrepancies, particularly Class II malocclusions should coincide with the pubertal growth spurt and ideally peak height velocity. Unfortunately, individuals show unlimited variation in the timing of their pubertal growth spurt and few clinicians enjoy the luxury of monitoring the growth of prospective patients longitudinally to establish PHV before starting treatment. Although there are wide differences in the timing of PHV and pubertal spurts in facial growth, even if PHV has been reached a good deal of growth potential remains. Hägg and Panchez (1988) have shown that the skeletal contribution to orthodontic changes in dental arch relationships from Class II to Class I will be greater in patients treated at the pubertal maximum of growth in standing height or during the succeeding year.

In practice most orthodontists will begin growth modification with headgear or functional appliance treatment when they think it appropriate, bearing in mind the age of the patient at the first consultation, and anticipated levels of co-operation. However, for those orthodontists who wish to use hand-wrist films to assist their clinical judgement, ossification of the ulna sesamoid bone and the maturation stages of the middle phalanx of the third finger (MP3) would seem to be the most practical and reliable guides to the skeletal age. Furthermore, the skeletal stage MP3-FG will indicate that the patient is in an intense period of sagittal condylar growth. In practice the use of hand-wrist films would seem to be cultural; their use is widespread in Northern Europe but rare in the United Kingdom and the United States. The use of cervical vertebral maturation as seen on routine cephalometric radiographs is a practical alternative for assessing skeletal age without exposing the patient to additional radiation.

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