GROWTH AND DEVELOPMENT

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Contents

1. Adolescent Growth

Growth at adolescence is characterized by the presence of an adolescent, or pubertal, growth spurt.

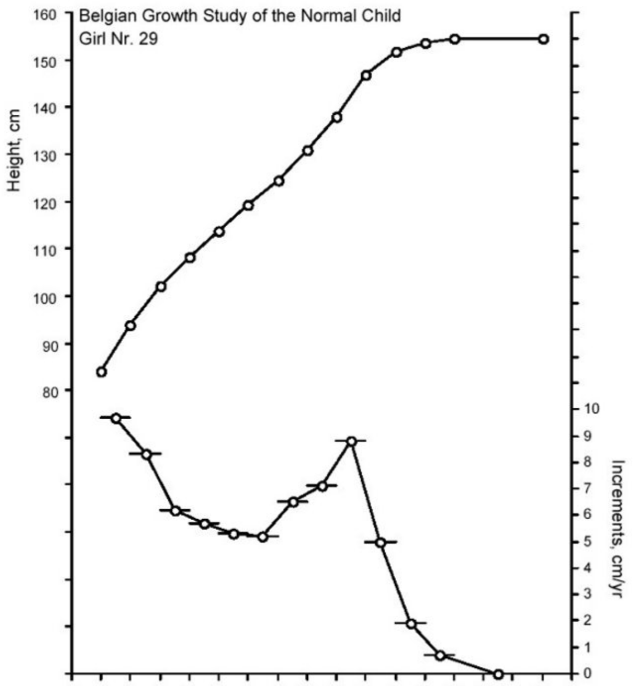

Figure 1. Growth in height of a girl between 3 and 18 years of age. The upper part

shows a plot of the height-for-age data (distance curve), while the lower part shows the yearly increments in height (velocity curve). The horizontal bars indicate the length of the intervals. Source: Belgian Growth Study of the Normal Child: Graffar *et al*. 1962; Wachholder and Hauspie 1986; Hauspie and Wachholder 1986.

Figure 1 shows a typical example of the growth in height of a girl between 3 and 18 years of age. The upper part is a plot of the height-for-age data (distance curve), while the lower part shows the increments in height over one-year intervals, i.e. a proxy for velocity in growth. Actually, yearly increments reflect average velocity in the considered interval while, strictly speaking, the term 'velocity' refers to instantaneous velocity, i.e. the first derivative of a smooth distance curve. Despite this, the terms 'increments' and 'velocities' are, such as in this text, often used intermixed. The horizontal bars in the graph indicate the length of the intervals over which the increments were calculated. It is common practice to calculate increments from measurements not less than 0.85 years and not more than 1.15 years apart, and to convert them to whole-year increments by taking the ratio of the difference between the two measurements and the length of the interval. Increments calculated over shorter periods reflect seasonal variation and are relatively more affected by measurement error.

The growth pattern in height is characterized by a gradually decreasing (sometimes more or less constant) velocity during childhood, which is, in many children, interrupted by one or more small pre-pubertal (or mid-childhood) spurts. The age at minimal velocity before puberty, i.e. age at take-off (TO), is considered as the onset of the pubertal growth spurt. The age at take-off varies considerably, between populations, between individuals (Standard Deviation (SD) equals about 1 year) and between sexes, boys being in average 2 years later than girls in starting off their adolescent spurt. Maximum velocity in height (or peak height velocity) is reached within 3 to 3.5 years after the onset of the spurt. The difference in age at take-off and age at peak velocity (PV) can be used as a measure of the duration of the adolescent spurt. After having reached a peak, the growth velocity rapidly decreases, inducing the end of the growth cycle at full maturity, i.e. around 16-17 years for girls and 18-19 years for boys in Western populations. There is a wide variation between populations, between individuals and between the two sexes as to the attained size at each age, the timing of events such as adolescent growth spurt and the age at which mature size is reached. The growth curve of height shown in Figure 1 is typical for all post-cranial skeletal dimensions of the body.

Growth in weight has a different pattern in the sense that the start of the adolescent growth spurt in weight does not correspond with the age of minimal increment in weight before puberty. Most children show the lowest annual increase in weight in late infancy or early childhood, i.e. around 2 to 3 years of age. Thereafter, growth in weight slowly, but steadily, accelerates until the onset of puberty when there is a sudden rapid increase in weight velocity. The growth pattern of weight and weight velocity shown by the data of the girl in Figure 2 illustrates these typical features very well. In this example, the sudden change in growth velocity of weight between childhood and puberty can be identified at 11.5 years of age. The precise location of the onset of the adolescent growth spurt is generally more problematic and subjective for weight than it is for height.

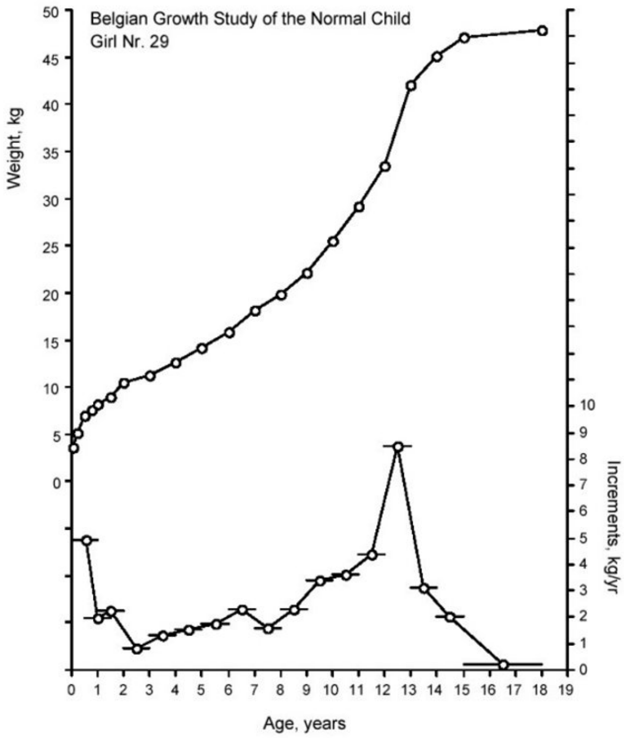

Figure 2. Growth in weight of a girl between 3 and 18 years of age. The upper part shows a plot of the weight-for-age data (distance curve), while the lower part shows the yearly increments in weight (velocity curve). The horizontal bars indicate the length of the intervals.

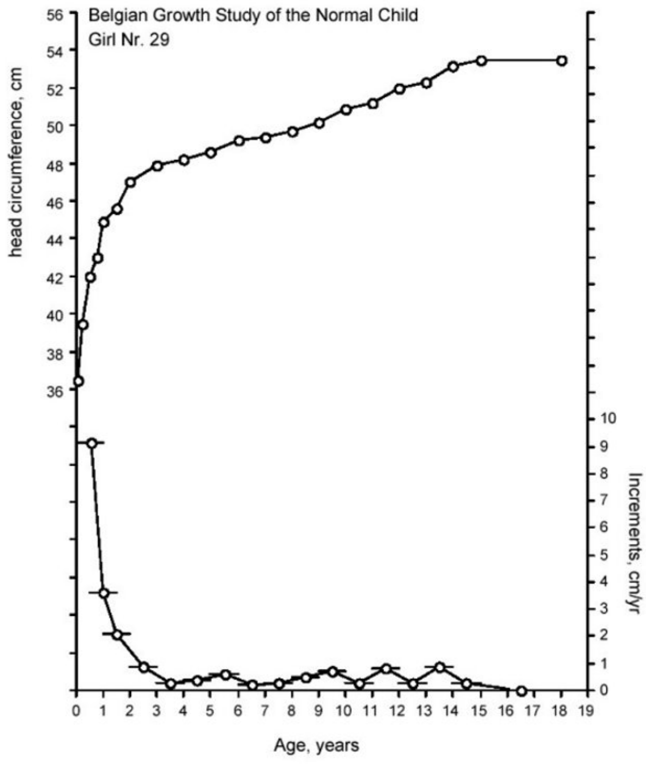

Figure 3. Growth in head circumference of a girl between 3 and 18 years of age. The

upper part shows a plot of the head circumference-for-age data (distance curve), while the lower part shows the yearly increments in head circumference (velocity curve). The horizontal bars indicate the length of the intervals.

A third major type of growth pattern is seen in the dimensions of the head. The growth pattern for head circumference, between 1 month and 18 years of age, is again exemplified in Figure 3. The growth of the head is very rapid during the first postnatal year, but growth velocity steeply falls down to levels below 1 cm/year by the age of 2 years. Thereafter yearly increments in head circumference fluctuate between a few millimeters and 1 cm per year and no spurt is noticeable at puberty. In the given example, 89% of the girls' adult head circumference is reached by the age of 3 years. This value is very close to the mean percentage of adult head circumference reached at 3 years of age in most populations. Very similar patterns are observed for other head dimensions such as head length and head width in both boys and girls. The fact that growth velocity of head dimensions is fairly small beyond the age of 3 years and is very much corrupted by measurement error as studies of growth and growth charts concerning the head and face are usually restricted to the period of infancy.

2. Mathematical Description of the Growth Process

Most of our knowledge on the shape of the human growth curve comes from longitudinal growth data, i.e. sequential measurements of size taken at regular intervals on the same subject, such as shown in Figures 1 to 3. Serial measurements of height, for instance, form a basis for estimating the supposed underlying continuous growth curve of stature. However, recent studies have shown that frequent measurements of size (at daily or weekly intervals) with high precision techniques (such as knemometry with a measurement error of about 0.1 mm) recently showed that the underlying growth process is, at micro-level, not as smooth as we usually assumed (Hermanussen 1998; Lampl 1999). Nevertheless, for the description of the general shape of the growth curve in height, based on body measurements taken with classical techniques at intervals varying between several months and one year, we can readily assume that the growth process is continuous.

Various mathematical models have been proposed to estimate a smooth growth curve on the basis of a set of discrete measurements of growth of the same subject over time. An interesting review of various approaches in modeling human growth has been given by Bogin (1988). More than 200 models have been proposed to describe part or all of the human growth process. Only a small number of them have proved to be of practical use. The possibilities and limitations of commonly-used mathematical functions for analyzing human growth have recently been discussed by Hauspie *et al* (1991) and by Hauspie and Chrzastek-Spruch (1999). We will only emphasize here on the Preece Baines model I (PB1) which has been proven to be a very robust model to describe the adolescent growth cycle on the basis of growth data covering the period from 2 - 5 years of age up to full maturity (Preece and Baines, 1978). Whenever longitudinal data from birth to adulthood is at hand, one can better estimate the whole growth curve by means of the triple logistic function (Bock and Thissen, 1980) or the JPA-2 function (Jolicoeur *et al* 1992), for instance.

The mathematical expression of Preece Baines Model I (PB1) is:

$$y = h_1 - \frac{2(h_1 - h_\theta)}{e^{s_0(t-\theta)} + e^{s_1(t-\theta)}}$$

with y = height in cm, t = age in years, and h_1, h_θ, s_0, s_1, θ the five function parameters. Parameters of non-linear growth models usually allow some functional interpretation of the growth curve. In the case of PB1, parameter h_1 is the upper asymptote of the function and thus corresponds to an estimate of mature size. θ is a timing parameter controlling the location of the adolescent growth spurt along the time axis. θ is very highly correlated with age at peak velocity. h_θ is the size at age θ. Parameters s_0 and s_1 are rate constants controlling respectively pre-pubertal and pubertal growth velocity.

The parameter estimation of non-linear growth functions like the PB1 curve are usually obtained by non-linear least-squares techniques based on numerical minimization algorithms such as the simplex (Nelder and Mead, 1985), Marquardt (1963) and Gauss (Bard, 1974) method. Most statistical and several graphical software packages now offer the possibility of non-linear regression analysis of user-entered functions.

The outcome of modeling an individual's serial growth data is a set of values for the function parameters (five in the case of PB1). Hence, growth modeling (or curve fitting) is a technique by which longitudinal growth data can be summarized in a limited number of constants which have the same meaning for all subjects, thus allowing easy comparison between individuals.

Figure 4 shows a plot of the PB1 function fitted to the distance data for height of the same girl as in previous Figures. The lower part of Figure 4 shows a plot of the yearly increments together with the instantaneous velocity curve obtained as the mathematical first derivative of the fitted distance curve.

Besides producing a smooth continuous curve for growth and growth velocity, and summarizing the growth data into a limited number of constants, the main goals of mathematical modeling of human growth data are:

- to estimate growth between measurement occasions (interpolation);
- to estimate milestones of the growth process (the so-called biological parameters), such as age, size and velocity at take-off and at peak velocity, for instance, and
- to estimate the 'typical average' curve in the population by means of the mean-constant curve (see below).

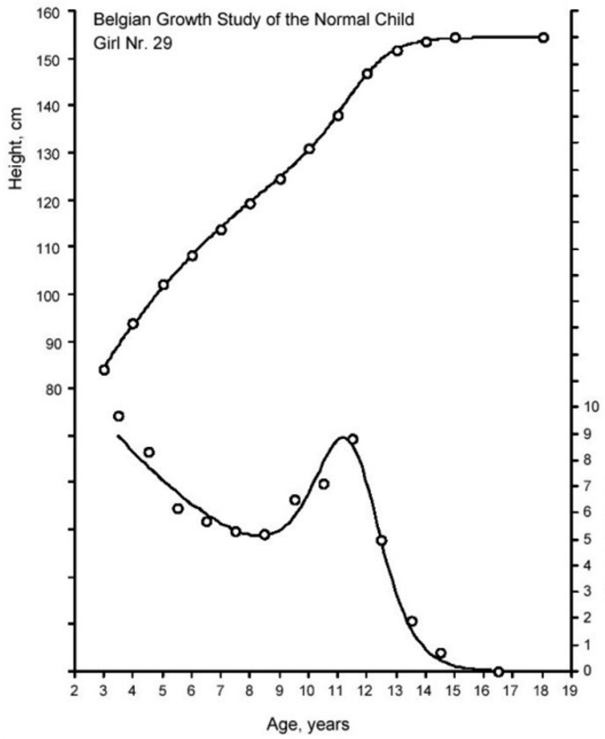

Figure 4. Growth in height of a girl between 3 and 18 years of age. The upper part shows a plot of the height-for-age data together with the Preece-Baines model 1, while the lower part shows the yearly increments in weight with the first derivative of the fitted curve

3. Growth and Maturation

It was the famous American anthropologist Franz Boas who, in the beginning of the twentieth century, stated that 'some children are throughout their childhood further along the road to maturity than others' (see Tanner 1962, 1981). Indeed, individuals do not only vary considerably in size, but also in tempo of growth, i.e. the speed at which they reach mature size. Tempo of growth, also denoted as maturation rate, is correlated with other markers of maturation, such as secondary sexual characteristics and bone age.

Figure 5 shows a theoretical example of the main effects of variation in tempo on the shape of the human growth curve. The Figure shows the distance and velocity curves for stature of typical early, average and late maturing children having the same size at birth and at adulthood. These three theoretical subjects have, so-to-speak, the same potential for reaching a certain mature size, but they considerably differ in height at all ages along their growth period and considerably differ in the shape of their growth pattern. We can see that the early maturer reaches final size earlier and is taller than the average maturer throughout childhood and adolescence. The average maturer reaches adult size earlier and is taller than the late maturer. The effects of differences in tempo of growth on attained height increase with age and are also most apparent in periods where the slope of the growth curve is steepest. Therefore, variation in maturation rate affects attained height mostly during the adolescent period.

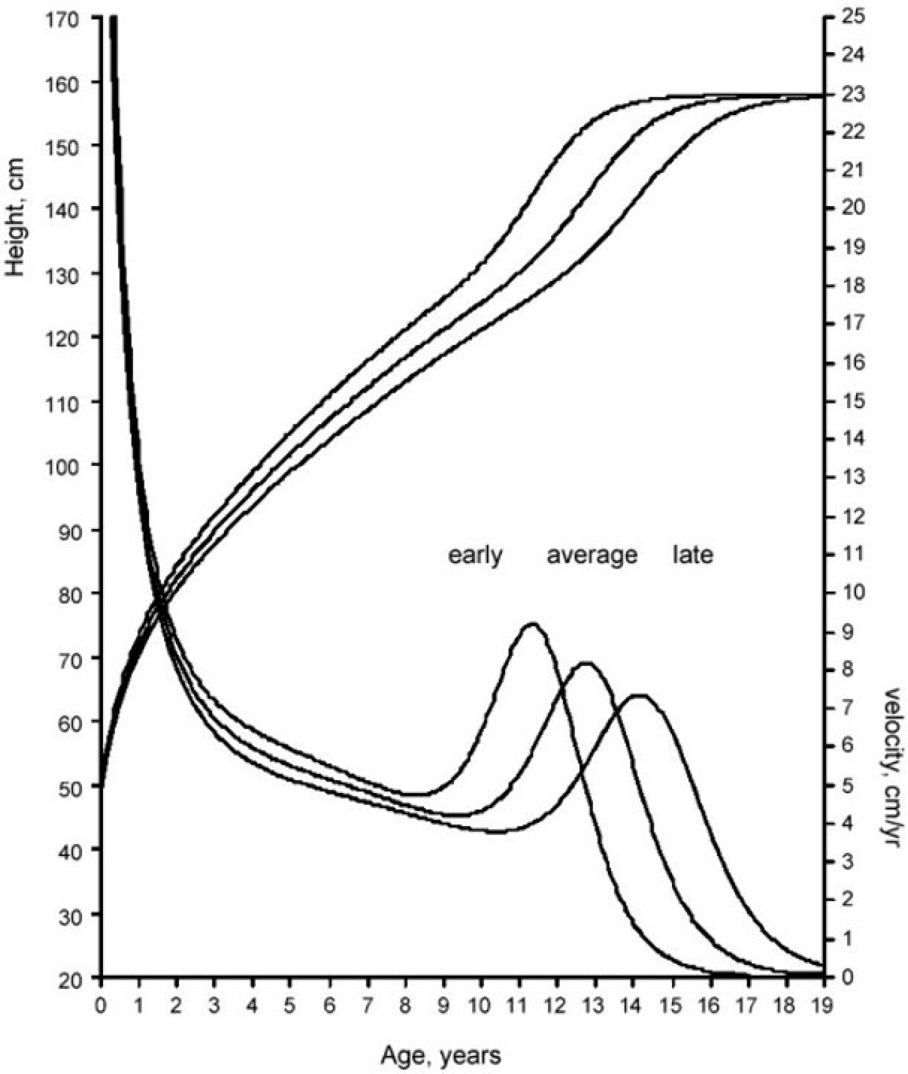

Figure 5. Effect of tempo on the pattern of growth: a theoretical example.

The relationship between the shape of the growth curve and the tempo of growth, as depicted in the theoretical example above, is also reflected in real population data. Longitudinal studies have repeatedly shown that little or no correlation exists between the timing of the pubertal spurt and adult stature, i.e. early, average and late maturing children reach, on average, the same adult height. This is also true for other post-cranial body dimensions, but not for weight. Early maturing children are on average heavier than late maturing children. The shorter growth cycle in early maturers is compensated by a slightly but consistently greater growth velocity during childhood and, particularly, by a more intense pubertal growth spurt. The opposite is seen in late maturing children. This relationship is reflected in the negative correlation between peak velocity and age at peak velocity in height and several other traits.

Studies on longitudinal growth of twin and family data have show that tempo of growth is to a great extent genetically determined. In a recent longitudinal growth study of monozygotic and dizygotic male twins Hauspie *et al* (1994) found a strong genetic component in the variance of various biological parameters characterizing the shape of the human growth curve, and in particular for age at peak velocity, reflecting tempo of growth. Similar findings were reported by Byard *et al* (1993) on the basis of an analysis of familial resemblance in growth curve parameters in the Fels Longitudinal Growth Study. Tanner (1978) suggested that both the growth status and the tempo of growth are under genetic control, but that the genetic factors might be quite different. Despite the strong genetic control over tempo of growth, there is also evidence that the human body can adapt to adverse environmental conditions by a slowing down in developmental growth rate, probably allowing a child to better cope with the physiological and metabolic requirements for a balanced development in sub-optimal situations. If the adverse conditions are reversed, then a child usually restores its growth deficit by a period of rapid growth in order to regain its original 'growth channel'**—**the so-called catch-up growth (Golden 1998; Prader *et al*. 1963; Tanner 1986). If, however, the environmental stresses persist for a long period or throughout the whole growth cycle, the resulting effect on growth may be a pattern which is typical for late maturing children. Typical examples of this were found for children exposed to chronic mild under-nutrition (Hansen *et al* 1971), to chronic diseases such as asthma (Hauspie *et al* 1977), to psycho-social stress (Skuse 1998; Powell *et al* 1967; Widdowson 1951), to socio-economic deprivation (Bielicki 1986), or for children living at high altitude (Malik and Hauspie 1986). Those children tend to be slightly delayed in reaching the adolescent growth spurt, in achieving sexual maturity, and in attaining their final size. Final stature is usually not affected (i.e. is compatible with the population average) unless the long-lasting adverse conditions are too severe.

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