HUMAN GROWTH CURVE.

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1. Statement of Problem.

The fascinating changes in the velocity of development, as well as in proportion of parts, that the growing child shows have long been watched with interest by parents but have only lately been made the subject of scientific analysis. Quetelet (1870) was perhaps the first to measure children at each year of age; but his subjects were few in number (ten to each year), strictly, but not always wisely, selected. Then came the measurements of great numbers of school children by Bowditch (1875) in Boston. This work was followed by a host of similar investigations whose results are summarized by Baldwin (1921) and in my 1926 paper.

The first attempt to interpret the course of human development on a chemical basis was made in the same year by W. Ostwald and by T. Brailsford Robertson, the latter of whom has published a remarkable series of papers since 1908. Robertson early concluded that there are three maxima in the curve of growth of man; one intrauterine, a second that reaches its greatest velocity at about the 6th year, and a third which, in the male, occurs at about the 16th year. This view of a triple set of growth cycles is still adhered to by Robertson who discusses them fully in his book Chemical basis of growth and senescence (1923) and later papers. Robertson's conclusions have been largely based on the data published by Quetelet, and this selection has not been altogether fortunate. Brody has extended Robertson's methods of analyzing the growth curve; but recently (1926) he has found the human growth curve to be of a different order from the growth curve of other mammals and he has been led to abandon, for the present, attempts at its interpretation. In view of the unsatisfactory condition of the analysis of the human growth curve it has seemed desirable to reattempt it, using the best available data. This is the excuse for the present paper.

2. *Methods and Material.*

The curve of development of weight from conception to maturity (Fig. 1) is based on data drawn from various sources. For the antenatal portion the data of Streeter (1920) have been utilized. For postnatal weights, up to 6 years, the data of Woodbury (1921) have been used. For later years various sources, chiefly Nordic males as given in Table B of my Human metamorphosis (1926), were used.

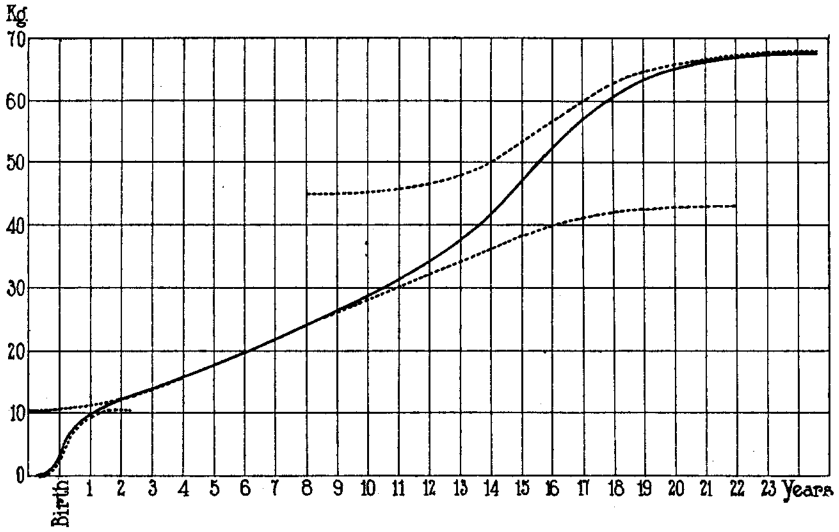

FIG. 1. Analysis of the developmental curve of body weight (full line) into two auto-catalytic curves (dotted line at top and bottom) and a residual curve (dotted line in the middle). Human Nordic stock, males. The autocatalytic and residual curves drawn in free-hand. Abscissæ, time in years; ordinates, body weight in kilos.

For annual increments in weight (Fig. 2) the same sources have been used, together with my Table D (1926) for Nordic males.

The dotted curves of Fig. 1 were put in free-hand to indicate the location of possible autocatalytic curves. The dotted curves of Fig. 2

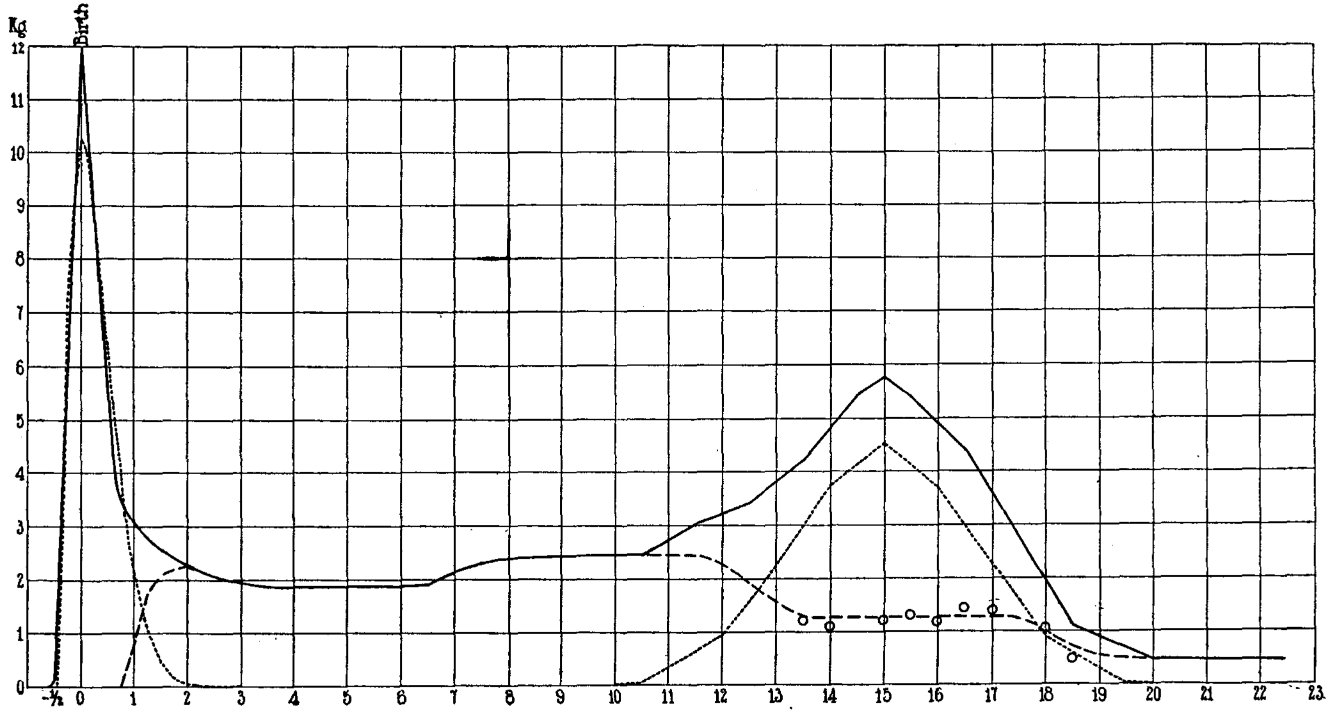

FIG. 2. Full line, the curve of annual increment rate of total body weight, male Nordic stock (see text). Dotted line to left, theoretical skew curve corresponding to increments of circumnatal growth cycle. Dotted line to right, theoretical "normal" curve of increments corresponding to adolescent growth cycle. Dash line, 0.75 to 2.25 years, full line 2.25 to 10.5 years, dash line 10.5 to 20 years, and full line beyond 20 years indicates the residual growth increments. Abscissæ, time in years; ordinates, annual rate of increments in weight in kilos. Small circles between 13 and 19 years indicate the precise points upon which is based the position of the dash line, which is smoothed between these years.

were drawn after careful computations, as described below. All statistical work was checked.

The curves are plotted on arithmetical paper, instead of logarithmic paper as is frequently done. The justification for the latter practise is found in the theoretical conception, clearly expressed by Minot (1891): "The increase of weight depends . . . . upon the amount of body substance or, in other words, of growing material present at a given time." As I pointed out many years ago (1897)[1] not all the body substance is "growing substance." During early development much water is imbibed which adds to the weight of the body, and although it may accelerate growth is not itself "growing material." During later development "body substance" is being laid down as formed substance that has primarily a mechanical or sustentative function and is not growing material. Indeed, a consideration of the complex processes of growth leads to the conclusion that to plot growth on logarithmic paper leads to just as great a distortion of the facts as to plot it on arithmetical paper. Since the latter method of plotting has the merit of simplicity, I am adopting it in this paper and suggest its uniform adoption until the advantages of some other method of plotting growth curves shall have been demonstrated.

3. RESULTS.

The arithmetical curve of growth, as plotted in Fig. 1, begins near 0 kilos at the time of fertilization of the egg. It increases slowly at first, then with ever accelerating velocity, until at birth it is shooting upward at its steepest angle. After birth the angle of slope gradually diminishes to the age of 2 or 3 years. It runs upward at a tolerably uniform rate until 7 or 8 years of age, then begins to rise more rapidly again; reaches a second maximum of slope at 14 or 15 years and then gradually approaches the horizontal.

If one contemplates this curve of growth one is struck by the resemblance of its two ends to the autocatalytic curve, to whose importance for growth Robertson has so forcefully called the attention of biologists. I have drawn in, free-hand by dotted lines, such approximate autocatalytic curves. But the growth curve, as a whole, is very

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[1] Davenport (1897), pp. 82 and 83.

far from being merely one, two, or three autocatalytic curves. The analysis of the curve may be made more readily if we transform it into a curve of growth velocities, and this is done in Fig. 2, which also is drawn on the arithmetical scale. The curve thus drawn is an instructive one. Starting at the zero base line the velocity of increments in weight rises, at first slowly, them more and more quickly, to a striking peak which corresponds with the moment of birth. At this time the child is increasing at the rate of 12 kilos per annum. The absolute velocity of growth at this period is greater than at any other time during life.

After birth the velocity of growth proceeds to diminish just as rapidly as it had increased before birth. This leaves out of account the cessation of growth that is well known to occur during the 2 or 3 days after birth, since to consider it would unnecessarily complicate the main result. The curve of velocity of growth in weight runs nearly on a level from 3½ to 6½ years. It then rises very gradually for a year or two, remains constant from 8½ to about 10 years, and then proceeds to climb up to a second peak which it reaches at 15 years (in the male), at which time there is an annual growth increment of about 5.75 kilos per annum. After this peak is reached the velocity of growth diminishes to 20 years and then continues at an annual rate of slightly less than 0.5 kilos to middle life. The curve does not reach zero, on the average, because the population of adult males in the United States gains about 1 pound a year from 22 to 26 years and ½ pound thereafter until about 45 years and about ⅓ pound from then until 55 years of age.

Our velocity curve brings out clearly the fact that growth is not one autocatalytic process. It suggests the hypothesis that there are two autocatalytic cycles; one that we may call the circumnatal and the other the adolescent. The circumnatal cycle begins at fertilization of the egg; reaches a maximum at birth and probably ends at between 2 and 3 years. An attempt to fit a theoretic curve to this cycle has been made. The best fit is given by a skew curve of Pearson's (1895) Type I. Its formula is:

$$y = 854.9\left(1 + \frac{x}{5.221}\right)^{0.985}\left(1 - \frac{x}{38.876}\right)^{7.334}$$

This curve is plotted by a dotted line in Fig. 2. Its standard deviation is only 5.17 months. The y_0 value is 854.9 gm. per month or 10.259 kilos per year. This falls short of the empirical value of 12 kilos per annum partly because smoothed values were used in computing the theoretical curve. The modal velocity of 12 kilos at birth is based on Zangemeister's data (1911), which are at least conservative in respect to velocity of growth at birth.

The circumnatal curve of velocity is, as stated, a skew curve of Pearson's Type I. The index of skewness is 0.31. In the formula given above the denominator of the fraction in the second factor gives the range in months of that part of the curve that lies between birth and conception. It is 5.22 months. The denominator of the fraction in the third factor gives the range in months of that part of the curve that lies between birth and the end of the circumnatal growth spurt, amounting to 38.88 months. The theoretical range to the left of the mode is thus only 5.2 months, while, actually, development begins at 9 months before birth. However, at the end of the 6th month before birth increments in weight are only just becoming considerable (10 gm. monthly) so that the calculated curve agrees here fairly well with the observed curve. The other end of the curve is at about 39 months, at which age the observed curve of increments has nearly reached the bottom of its first peak. Thus the theoretical and observed curves are in close agreement.

The adolescent spurt is probably measured by a normal frequency polygon, whose mode at 15 years in the male corresponds with that of the total increment curve. It seems to start at about the 10th birthday and ceases at the 20th. The adolescent episode of growth thus extends over 10 years or from 10 to 13 per cent of the full span of life.

The theoretical normal curve that most clearly accords with the observed adolescent curve is shown at the right of Fig. 2 in the dotted line. There is assumed a substratum of generalized growth which, after 12 years of age, gradually declines from 1.9 kilos per annum to 0.5 kilos. The theoretical curve is drawn in accordance with the formula

$$y = \frac{n}{\sigma\sqrt{2\pi}} e^{-1/2\left(\frac{x}{\sigma}\right)^2}$$

where n = 19,000 kilo-years; σ = 1.70 years, and y_0 = 4.47 kilos.

After subtracting the two special curves from the general curve of increments there remains a residual curve. This begins at somewhere about 9 months after birth; rises to the level of the total curve, and coincides with it during the period from 3 to 10 years. That the residual curve does not start at conception would not justify the conclusion that there is no basal growth occurring, independent of the circumnatal spurt, but indicates only that the circumnatal spurt is of such high velocity and that of basal growth is of such low velocity that the latter is quite obscured by the former. From 3½ to 6 years growth is apparently entirely residual and it is very steady and constant, at about 1.85 kilos per annum. There is a slight rise during the 7th year of life to a new constant velocity of growth of 2.4 kilos per annum. This rate of growth continues until 11.5 years is reached at which time the adolescent spurt has already started. The basal increment now diminishes rapidly as the adolescent spurt speeds up. It remains at about the 1.225 kilo level of annual increment from 13.5 to 17.5 years of age and then falls away to the constant rate of 0.45 kilos per year which is reached at 19 years. Statistics gathered by insurance companies (Medical Actuarial Mortality Investigation (1912)) indicate that weight increases, in the male of average stature, about 1 pound a year from 20 to 26 years and then about ½ pound yearly to 45, as stated above.

4. DISCUSSION.

The early optimism as to the possibility of resolving the total growth curve of man into three "growth cycles" superimposed upon one another (Robertson (1923)[2]) has given way to the recognition of the great complexity of this growth curve. Thus Brody (1926)[3] states that "the smoothed time curve of growth in weight [presumably of mammals, in general] is sigmoid, but the point of inflection, or rather region of inflection, is not in its center but where slightly over one-third of the mature weight is reached. The growth curve of man is the only exception encountered." Now our data show two points of inflection that clearly approximate the logistic curve. One occurs at birth and one at 15 years, in the male. Our data do not reveal the S-shaped

[2] Robertson (1923), p. 446.

[3] Brody (1926), p. 235.

curve at "the third, fourth and fifth years" which Robertson finds (1923)[4], and we fail to find in Robertson's or Brody's papers any sufficient evidence of this third or "juvenile" cycle. (Compare my discussion of this matter (1926).[5])

What do the facts, as revealed in the curve of velocity (Fig. 2), show clearly? Besides the circumnatal and adolescent growth cycles there is a mass of growth of irregular velocity from 2 to 10½ years, in the male, which tails away toward 20 years but continues on to 50 years of age, or later. This residual curve does not fall into any autocatalytic cycle. The existence of growth outside of "the three growth cycles" has been recently recognized by Robertson (1926)[6] who introduces the idea and the term of "linear increment." In the mouse he conceives this to begin at about 10 weeks after birth and to increase in arithmetical fashion to 140 weeks, or later. This "linear increment" conception was forced from the fact that growth of mice "continues very slowly for long after the attainment of sexual maturity and dimensions which might readily be supposed to be 'adult' and, therefore, maximal. It is possible that in other animals also a similar linear accretion is occurring, and has escaped attention for lack of data concerning the late growth of the animals."

Now I suspect that the residual curve indicated by the dash line and, in part, by a full line in Fig. 2, corresponds to Robertson's "linear accretion," inasmuch as it continues past maturity; but in detail it is entirely different from Robertson's "linear accretion" since it is not a straight line at all.

One may propose a hypothesis as to the meaning of this residual curve. One may base it on the probability that besides the natal and adolescent growth accelerators there are other growth processes of particular organs or of the body as a whole. These constitute the substratum of growth of which the natal and the adolescent cycles are especially activated or accelerated episodes. Indeed, it is plain from such studies as Riddle (1925) has made on the growth of organs in the pigeons and which Scammon (1925, 1926, *a*, *b*) is making on the growth of organs in man, that the total growth is, as it were,

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[4] Robertson (1923), pp. 445 and 446.

[5] Davenport (1926), pp. 210–212.

[6] Robertson (1926), pp. 469–473.

the summation of growing parts or organs, each following a more or less independent law. Not until we understand the changes in weight of the different parts of the body from the beginning of development to maturity shall we be enabled to give an adequate interpretation of the growth curve. When that happens we shall first be in a position to direct and modify the form of the developmental curve.

To illustrate, merely, the view of an important substratum of growth apart from the cycles I may refer to the findings in respect to the rate of development of three or four human organs in comparison with the growth of the body as a whole.

Thus Starkel and Wegrzynowski (1910) and E. Thomas (1911) find that the suprarenals grow rapidly in the fetus, attaining, at or about birth, a weight of 3 gm. After birth the weight falls, absolutely, to about 1.5 gm. at about 12 months of postnatal life. It then increases very slowly to about 3 gm. at about the end of 5 years. Thomas shows that the degeneration after birth affects, especially, the deeper layers of the cortex. Scammon (1926, *b*)[7] shows, in addition, that in the suprarenals there is no extraordinary prenatal acceleration of growth but only a postnatal involution. A similar postnatal retardation of growth-velocity occurs in the cerebellum (Scammon and Dunn (1924)).

The length of the uterus in the fetus undergoes extraordinary changes that have been worked out by Scammon (1926, *a*).[8] Thus in the 7th fetal (lunar) month the uterus begins to show an extraordinary spurt in growth, as compared with the body as a whole. At birth the length of the uterus is 35 mm. while, had the spurt not occurred, it would have been only about 23 mm. Within 3 weeks after birth the length of the uterus has fallen to 24 mm; and then increases slightly during the following 5 months. "This suggests," says Scammon, "that the growth of the uterus in the latter fetal months consists of a substrate of typical fetal growth plus a secondary growth increment, which, presumably, is due to an extra stimulus furnished by a hormone of placental or possibly ovarian origin. After birth the organ loses this secondary increment but retains that result-

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[7] Scammon (1926, *b*), p. 809.

[8] Scammon (1926, *a*), p. 690.

ing from the early fetal growth rate." Again, reference may be made to the well known case of the thymus, which, according to Hammar (1921),[9] undergoes a rapid reduction of size and function as adolescence sets in at 11 to 15 years. This involution seems to be determined and controlled by the development of the gonads.

The foregoing interesting studies on variations in the velocity of growth of human organs justify the conclusion that the development of weight in man is the resultant of many, more or less elementary, growth processes. When some special activator of development causes one or more organs simultaneously to increase in velocity of growth to a high degree then a marked maximum occurs in the human growth curve, and this may assume the form of the logistic curve of growth. Two of these episodes are of overwhelming importance. The great number of smaller growth operations are less outstanding, and overlap in time to such a degree as to become submerged in a nearly uniform, high and prolonged wave of growth. It is probable that some of these growth impulses affect not merely one or two organs of the body but are diffused more or less uniformly throughout the entire body. It is this substratum of the growth process which deserves special study and analysis in the future.

Finally, one is led to speculate on the nature of the activators of the two principal special growth accelerations—the circumnatal and the adolescent. There is some ground for entertaining the hypothesis that the adolescent spurt is especially activated by the secretions of the pituitary gland, or anterior lobe of the hypophysis; since preadolescent hypophyseal underactivity results in reduced growth and preadolescent hyperactivity in giant growth.

The tremendous velocity of growth in the circumnatal cycle seems to be activated by something coming into the fetus from the mother through the placenta. Hardly otherwise can we account for the fact that the growth process ceases its acceleration at just the time when the placental connection is broken.

Experiments should throw light on the nature of the special, as well as the general, growth activators at different stages of development.

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[9] Hammar (1921), p. 551.

5. SUMMARY OF CONCLUSIONS.

The human growth curve shows two (and only two) outstanding periods of accelerated growth—the circumnatal and the adolescent.

The circumnatal growth cycle attains great velocity, which reaches a maximum at the time of birth. The curve of this cycle is best fitted by a theoretical skew curve of Pearson's Type I. It has a theoretical range of 44 months and a standard deviation of 5.17 months. The modal velocity is 10.2 kilos per year.

The adolescent growth cycle has less maximum velocity and greater range in time than the circumnatal cycle. The best fitting theoretical curve is a normal frequency curve ranging over about 10 years with a standard deviation of about 21 months and a modal velocity of 4.5 kilos per year.

The two great growth accelerations are superimposed on a residual curve of growth which measures a substratum of growth out of which the accelerations arise. This probably extends from conception to 55 years, on the average. It is characterized by low velocity, averaging about 2 kilos per year from 2 to 12 years. It is interpreted as due to many growth operations coincident or closely blending in time.

Our curve shows no third marked period of acceleration at between the 3rd and 6th years.

The total growth in weight of the body is the sum of the weight of its constituent organs. In some cases these keep pace with the growth of the body as a whole; great accelerations of body growth are due to great accelerations in growth of the constituent organs. In other cases one of the organs of the body (like the thymus gland) may undergo a change in weight that is not in harmony with that of the body as a whole.

The development of the weight in man is the resultant of many more or less elementary growth processes. These result in two special episodes of growth and numerous smaller, blending, growth operations.

Hypotheses are suggested as to the basis of the special growth accelerations.

I take this occasion to acknowledge the valuable assistance of Miss Mary T. Scudder in the calculation of the two theoretical curves of Fig. 2.

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