THE JOURNAL OF PEDIATRICS

SEPTEMBER 1985 Volume 107 Number 3

SPECIAL ARTICLE

Clinical longitudinal standards for height and height velocity for North American children

Longitudinally-based height and height velocity charts for North American children are presented. Centiles are given for early, middle, and late maturers. The shape of the curves is taken from a review of longitudinal studies, and the prepubertal and adult centiles for height attained are taken from National Center for Health Statistics data. The charts are suitable for following an individual child's progress during observation or treatment throughout the growth period, including puberty.

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IN 1956 Bayley[1-3] produced charts for height and weight growth that, for the first time, took into account whether a child was an early or late developer. Her work derived from the classic studies of growth *tempo* by Boas[4,5] (who coined that term) and by Shuttleworth.[6,7] As standards, however, Bayley's charts lacked practicality, because they were based on very small numbers of subjects. Thus, although they indicated the average heights and height velocities to be expected in boys and girls maturing relatively early and relatively late, they did not give the population centiles necessary in judging whether a child's growth is abnormal.

Ten years later, Tanner et al[8] combined large-scale cross-sectional studies of a population (London County Council schoolchildren) with small-scale longitudinal studies (The Harpenden Growth Study and the International Children's Centre London Study) to produce longitudinal standards suitable for clinical use. These British-based height and height velocity and weight and weight velocity charts have been widely used, and remain valid for the contemporary British population.[9] In North America, however, children grow at a slightly faster tempo and are, on average, taller. There is a need, therefore, for clinical longitudinal standards for North America, based on the principles of the 1966 British Standards but using an American population survey and American data on growth tempo. We supply such standards for height and height velocity.

NCHS	National Center for Health Statistics
PHV	Peak height velocity

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Submitted for publication Nov. 27, 1984; accepted May 13, 1985.

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The three-color charts are available through Serono Inc., 280 Pond St., Randolph, MA 02368, or direct from Castlemead Publications, Swains Mill, 4A Crane Mead, Ware, Hertfordshire, SG12 9PY, England. They are printed in two formats: research (large) and clinic (A4 size).

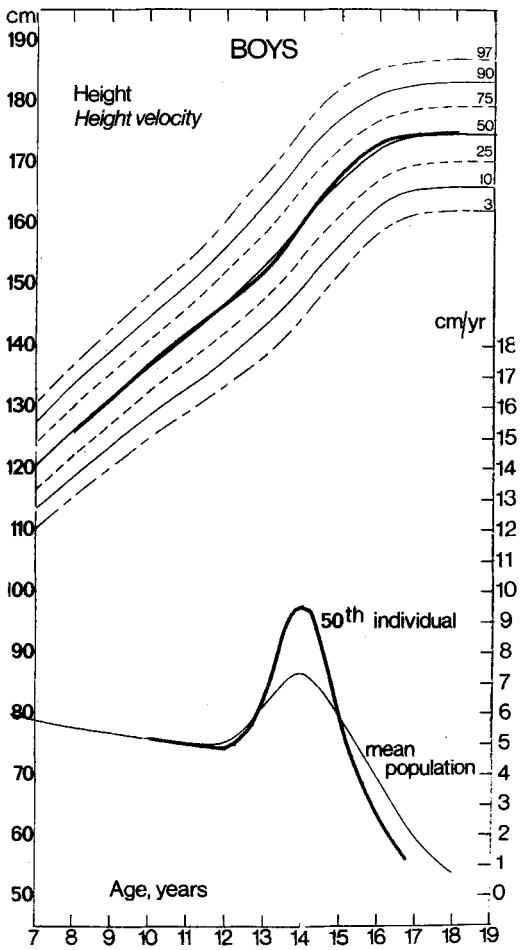

Fig. 1. Comparison of longitudinal individual and cross-sectional population standards. British longitudinal 50th centile individual curve (mean size, mean tempo) plotted *(heavy line)* on British population curves from London survey.[8] *Top,* height attained; *bottom,* height velocity. (From Tanner JM: The uses and abuses of growth standards.' In: Faulkner F, Tanner JM, eds: Human growth, ed 2. New York: Plenum, 1985, in press.)

These standards are an advance on the British standards in that the use of color printing enables them to carry more information. The British charts for height attained give simply the centiles characterizing the cohort of boys or girls with average growth tempo.[10] Only in the height velocity charts are the centiles for early and late maturers also displayed. In the American height-attained charts, however, it has been possible to indicate not only the 50th centile for children with their pubertal growth spurts at the average time but also the 50th centile for children 2 SD of age early and 2 SD of age late. In addition, the 95th centile for height attained in a 2 SD early child and the 5th centile for height attained in a 2 SD late child are shown. Incidence of children on these centiles is about one in 1000 population.

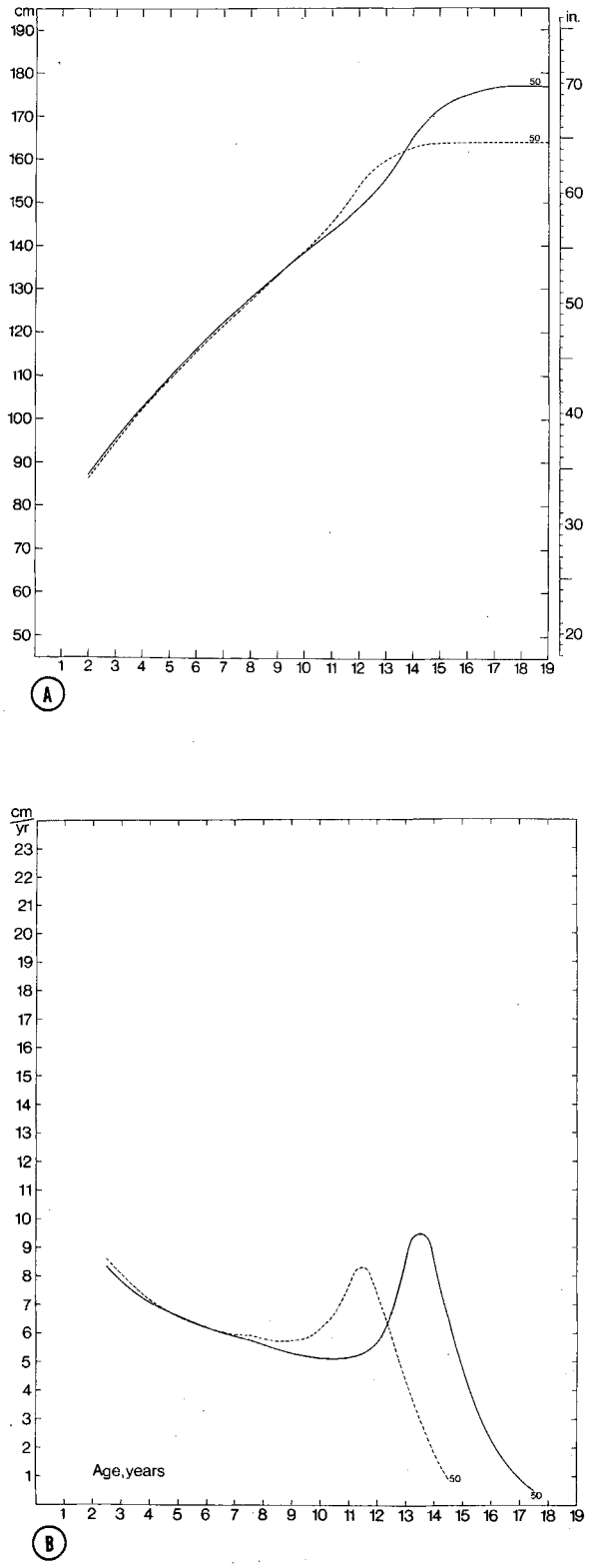

Fig. 2. The 50th centile curves for American boys *(solid lines)* and girls *(dashed lines)* of average growth tempo (that is, peak height velocity at average age). **A,** Height attained. **B,** Height velocity.

Table I. The 50th centile values for height and whole-year height velocity for boys and girls with peak height velocity at average times (13.5 and 11.5 years, respectively)

	Boys		*Girls*	
Age (yr)	*Height (cm)*	*Height velocity (cm/yr)*	*Height (cm)*	*Height velocity (cm/yr)*
2.0	87.0		86.0	
		8.3		8.6
3.0	95.3		94.6	
		7.4		7.6
4.0	102.7		102.2	
		6.8		6.8
5.0	109.5		109.0	
		6.4		6.4
6.0	115.9		115.4	
		6.0		6.1
7.0	121.9		121.5	
		5.8		5.9
8.0	127.7		127.4	
		5.4		5.7
9.0	133.1		133.1	
		5.2		5.8
10.0	138.3		138.9	
		5.1		6.7
11.0	143.4		145.6	
		5.3		8.3
12.0	148.7		153.9	
		6.8		5.9
13.0	155.5		159.8	
		9.5		3.0
14.0	165.0		162.8	
		6.5		0.9
15.0	171.5		163.7	
		3.3		0.1
16.0	174.8		163.8	
		1.5		
17.0	176.3			
		0.5		
18.0	176.8			

INAPPLICABILITY OF CROSS-SECTIONAL STANDARDS TO CHILDREN OLDER THAN 9 YEARS IN THE CLINICAL SETTING

There is much literature, stretching back to the nineteenth century, to point out the fallacy of using cross-sectional population curves such as those of the National Center for Health Statistics to follow the growth of individual children once puberty has begun.[11-13] The difficulty is that the 50th centile line derived from cross-sectional data is not actually followed by any individual child and is not the correct shape for a growth curve. This is most easily seen in terms of height velocity (Fig. 1, *lower curves*). The actual growth velocity in a child who is at the 50th centile for both size and tempo is compared with the curve of "velocity" obtained from the differences of successive cross-sectional population means. The pseudo-velocity curve has a peak that is at about the 3rd centile for real individual peaks and is wider than any individual peak would be. Even in the height-attained, or "distance" formulation (Fig. 1, *upper curves*), although graphically the effect looks small, the cross-sectional means overestimate the 50th centile height of the average individual by 2 cm at age 13 years and underestimate it by 2 cm at age 15 years. These comparisons refer only to children with average growth tempo; in early and late maturers the discrepancy between longitudinal and cross-sectional standards is even greater. Thus there is a need for standards of the type that Boas, Shuttleworth, and Bayley recommended—standards that, in modern jargon, are said to be *conditional on tempo.*[13]

LONGITUDINAL STANDARDS

Average tempo child. The details of how the standards were constructed are given in the Appendix. It suffices to

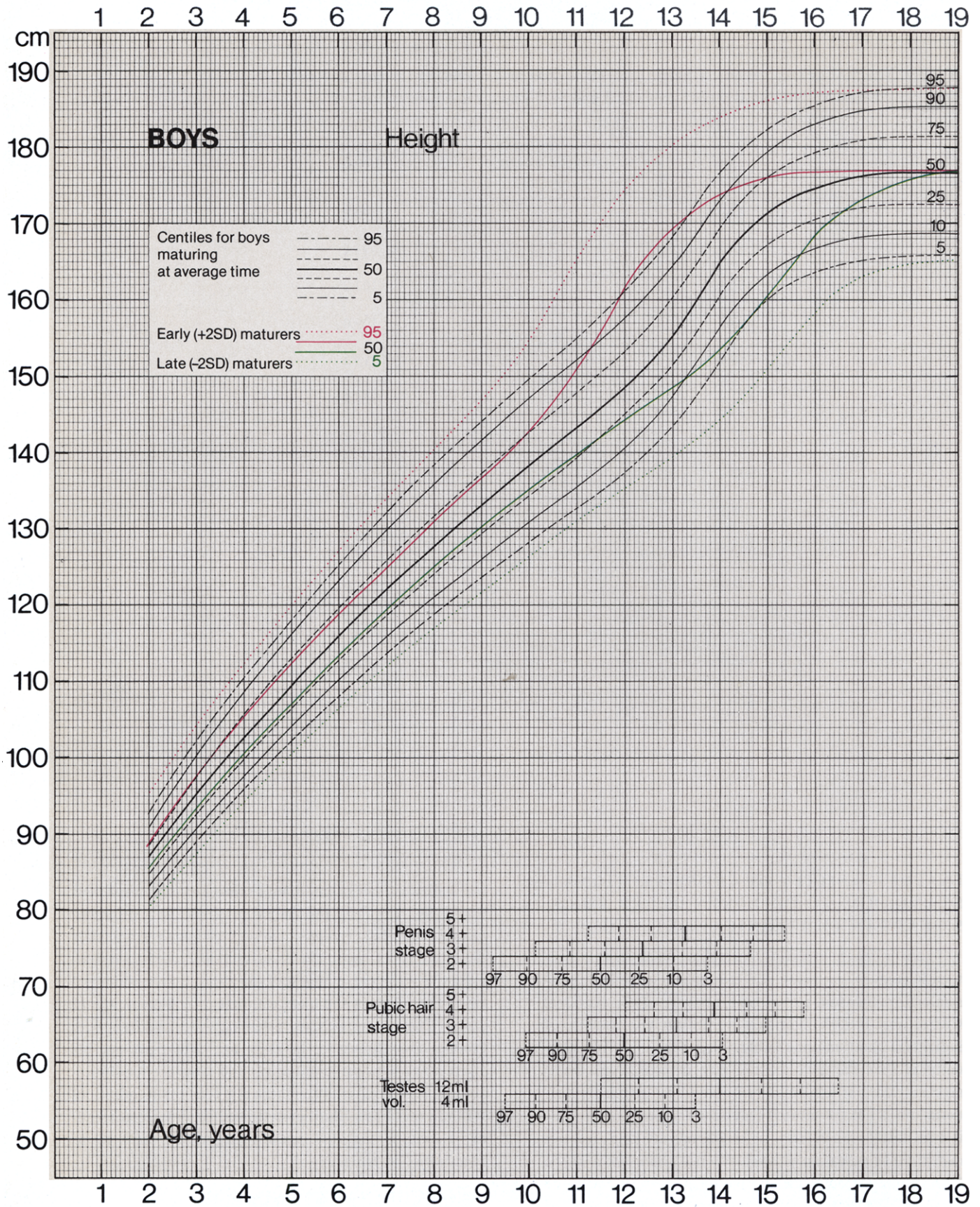

Fig. 3. Height attained for American boys. *Red lines*, 50th centile *(solid)* and 95th centile *(dashed)* for boys 2 SD of tempo early; *green lines*, 50th centile *(solid)* and 5th centile *(dashed)* for boys 2 SD of tempo late.

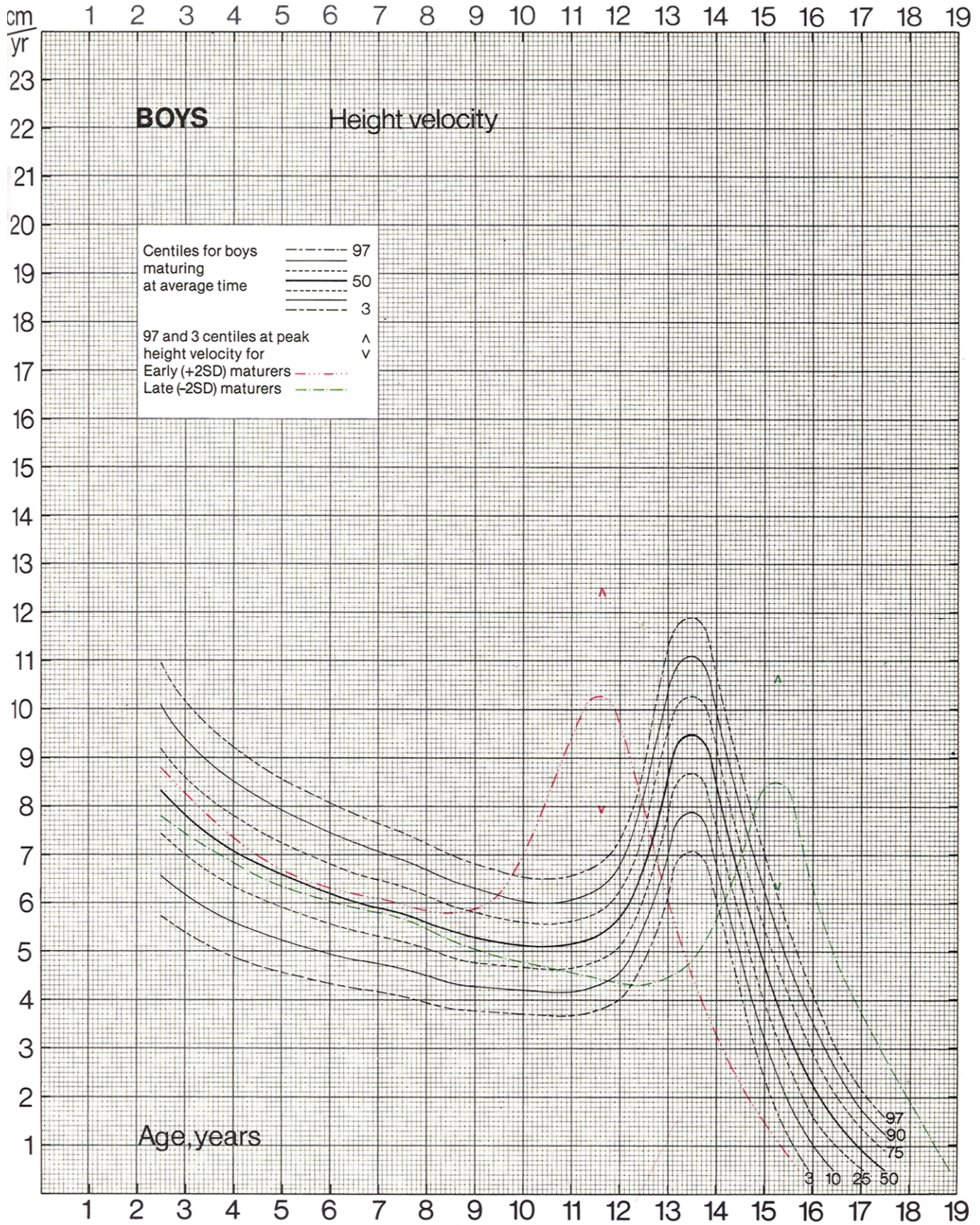

Fig. 4. Height velocity for American boys. *Red line*, 50th centile for boys 2 SD of tempo early; *green line*, 50th centile for boys 2 SD of tempo late. ∧ and ∨, The 97th and 3rd centiles for peak velocities of early and late maturers, respectively.

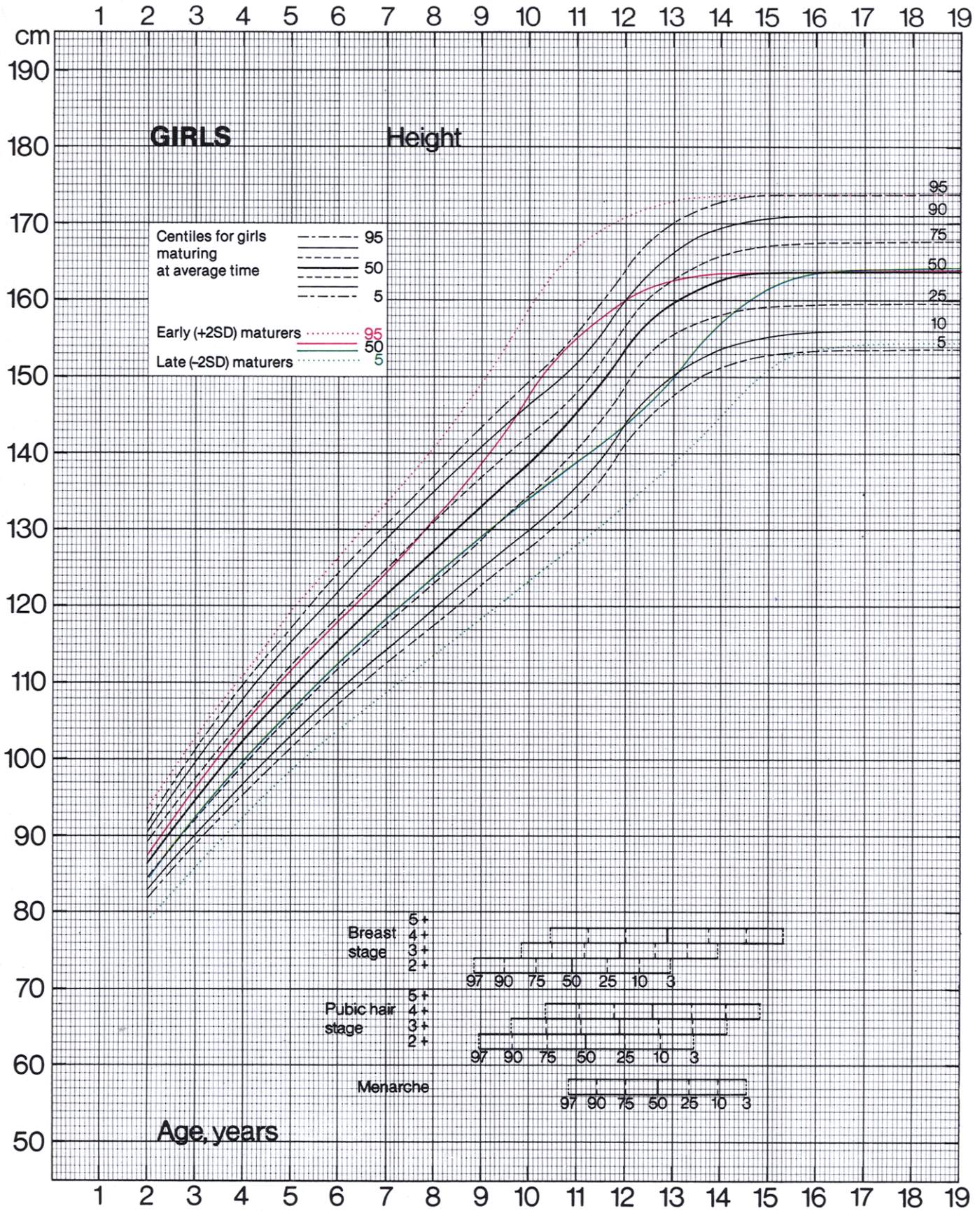

Fig. 5. Height attained for American girls. *Red lines*, 50th centile *(solid)* and 95th centile *(dashed)* for girls 2 SD of tempo early; *green lines*, 50th centile *(solid)* and 5th centile *(dashed)* for girls 2 SD of tempo late.

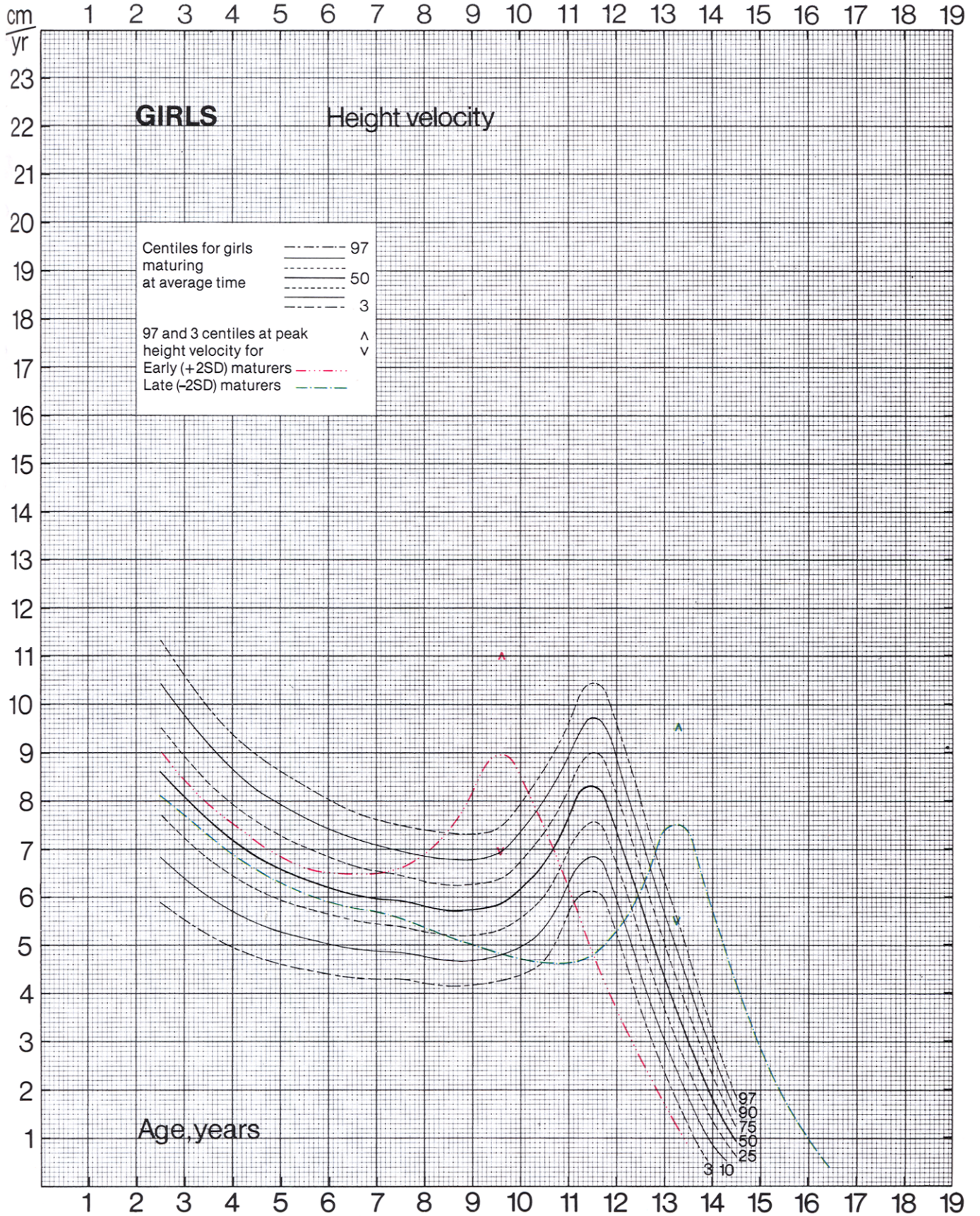

Fig. 6. Height velocity for American girls. *Red line,* 50th centile for girls 2 SD of tempo early; *green line,* 50th centile for girls 2 SD of tempo late. ∧ and ∨, The 97th and 3rd centiles for peak velocities of early and late maturers, respectively.

Table II. The 50th centile height and height velocity values for boys and girls with peak height velocity 2 SD (1.8 yr) early and 2 SD (1.8 yr) late

	Boys				*Girls*			
	2 SD early		*2 SD late*		*2 SD early*		*2 SD late*	
Age (yr)	*Height (cm)*	*Height velocity (cm/yr)*	*Height (cm)*	*Height velocity (cm/yr)*	*Height (cm)*	*Height velocity (cm/yr)*	*Height (cm)*	*Height velocity (cm/yr)*
2.0	88.4		85.6		87.6		84.4	
		8.8		7.8		9.0		8.1
3.0	97.2		93.4		96.6		92.5	
		7.8		7.1		7.9		7.3
4.0	105.0		100.5		104.5		99.8	
		7.0		6.6		7.2		6.5
5.0	112.0		107.1		111.7		106.3	
		6.5		6.2		6.6		6.1
6.0	118.5		113.3		118.3		112.4	
		6.2		5.9		6.5		5.8
7.0	124.7		119.2		124.8		118.2	
		6.0		5.7		6.6		5.6
8.0	130.7		124.9		131.4		123.8	
		5.8		5.2		7.4		5.2
9.0	136.5		130.1		138.8		129.0	
		6.2		4.9		8.9		4.9
10.0	142.7		135.0		147.7		133.9	
		8.2		4.7		7.4		4.7
11.0	150.9		139.7		155.1		138.6	
		10.3		4.5		4.9		4.8
12.0	161.2		144.2		160.0		143.4	
		8.0		4.3		2.7		6.1
13.0	169.2		148.5		162.7		149.5	
		4.5		4.8		0.9		7.3
14.0	173.7		153.3		163.6		156.8	
		2.3		6.9		0.1		4.4
15.0	176.0		160.2		163.7		161.2	
		0.8		8.1				2.0
16.0	176.8		168.3				163.2	
				4.7				0.5
17.0			173.0				163.7	
				2.8				
18.0			175.8					
				1.0				
19.0			176.8					

say that the 50th centiles for average tempo growth were based on the observed values of the NCHS from age 2 to 11 years in boys and from age 2 to 9 years in girls. Adult values (176.8 cm for men and 163.8 cm for women) were also taken from the NCHS data. From 11 years on in boys and 9 years on in girls, the height attained and height velocity curves have the shape characteristic of the growth of the typical individual. For reasons given in the Appendix, the age at peak velocity was taken as 13.5 years in boys and 11.5 years in girls, and the (whole-year) velocity at PHV as 9.5 cm/yr in boys and 8.3 cm/yr in girls.

These 50th centile curves, for the boy and girl of both average height and average tempo, are illustrated in Fig. 2. The values for height and height velocity are given in Table I.

Early and late maturing children. We next determined the 50th centile curves for boys and girls who had their peak height velocities 2 SD of age early and 2 SD of age late. The SD of age at PHV is a little less than 1 year in nearly all published series; we have taken the value 0.9 years. The 2 SD early maturing boys therefore have average PHV at 11.7 years, the 2 SD late maturing at 15.3 years. The equivalent values for girls are 9.7 and 13.3 years, respectively.

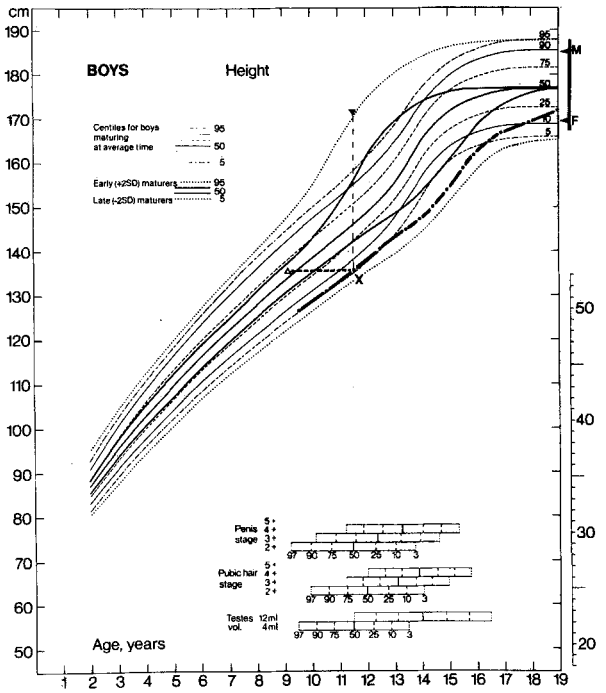

Fig. 7. Height curve of boy with constitutional growth delay. Bone age (△) and adult height prediction (▼) shown at age 11.6 years. *F* and *M*, father's and mother's height centiles; *heavy vertical line*, target height range. Height runs at about 15th centile for 2 SD late maturers until last point.

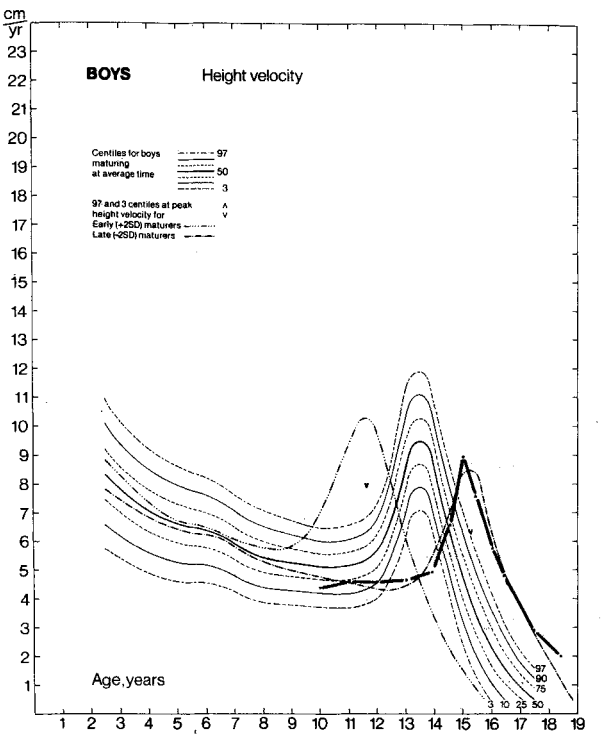

Fig. 8. Height velocity curve (same boy as in Fig. 7). Average curve for 2 SD late maturer is approximated throughout.

Although early and late maturing children on average attain the same adult height,[14-16] their growth data begin to diverge quite early, the 2 SD early boys at age 5 years averaging about 5 cm taller than the 2 SD late boys; in girls the difference is about 5.5 cm. Early maturers have a higher PHV than do late maturers, and we have estimated the value of the 2 SD early peak at 10.3 cm/yr and the 2 SD late peak at 8.5 cm/yr in boys; the respective values are 9.0 and 7.6 cm/yr in girls (*see* Appendix).

The resulting curves are illustrated in Figs. 3 through 6; the values are given in Table II. Figs. 3 and 5, the suggested height attained standards, also give the 95th, 75th, 25th, 10th, and 5th centiles for the cohorts of average maturers. The adult and prepubertal values of these centiles (the latter slightly smoothed) are those of the NCHS. The NCHS gives the 5th and 95th as outside centiles, rather than the more usual 3rd and 97th, and we have retained this feature.

Also in Figs. 3 and 5, we give the 95th centiles for the cohorts of 2 SD early maturing boys and girls and the 5th centiles for the cohorts of 2 SD late maturing boys and girls. The adult and prepubertal values were estimated on the basis of no relationship between tempo and final size, hence a similar SD of height in early and late maturers when fully grown, and also approximately before puberty. Because of this independence, these outside lines set limits outside which only 5% × 2.5% = 0.125%, or about one in 1000 boys or girls, are situated. Intermediate centiles, both for tempo and for size at given tempo, can be readily approximated by eye, but are not included in Figs. 3 and 5 in order to avoid confusion.

Age standards for puberty stages[14] are also given on these charts; by convention, 97th centile indicates early and 3rd centile late.

Figs. 4 and 6 give the velocity standards for boys and girls. The centiles (outside limits 97th and 3rd centiles) are those for the median tempo cohorts; also given are the 50th centiles for the 2 SD early and 2 SD late cohorts, with accents (∨ and ∧) at 97th and 3rd centile peaks for the accompanying centiles.

Strictly speaking, these charts refer to *whole-year* velocities converted from increments that should be taken over not less than 0.85 years and not more than 1.15 years. Velocities calculated over shorter periods reflect seasonal

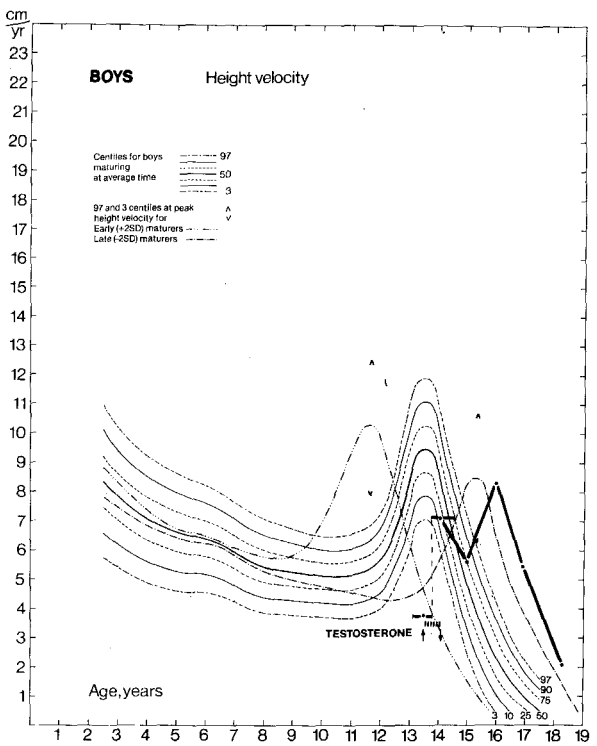

Fig. 9. Height velocity curve for boy with constitutional growth delay treated for 6 months with low doses of testosterone (50 mg enanthate each month).

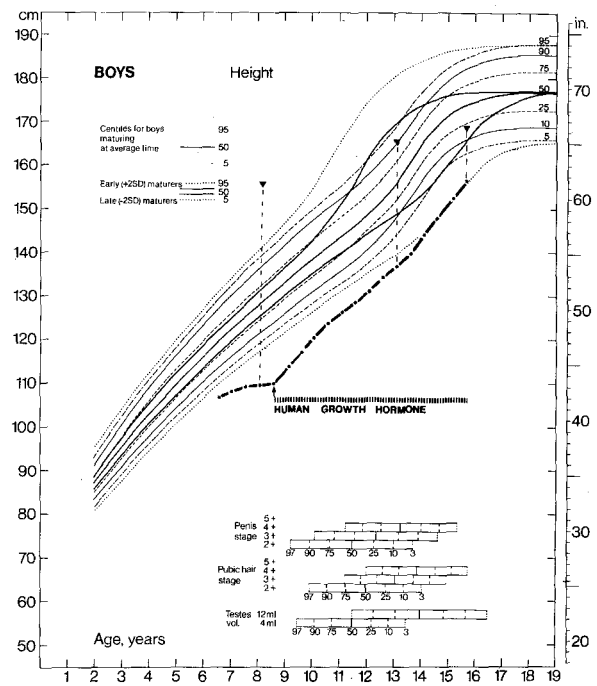

Fig. 10. Height curve of boy with growth hormone deficiency, treated with human growth hormone (15 IU/wk). Adult height predictions at three ages are illustrated.

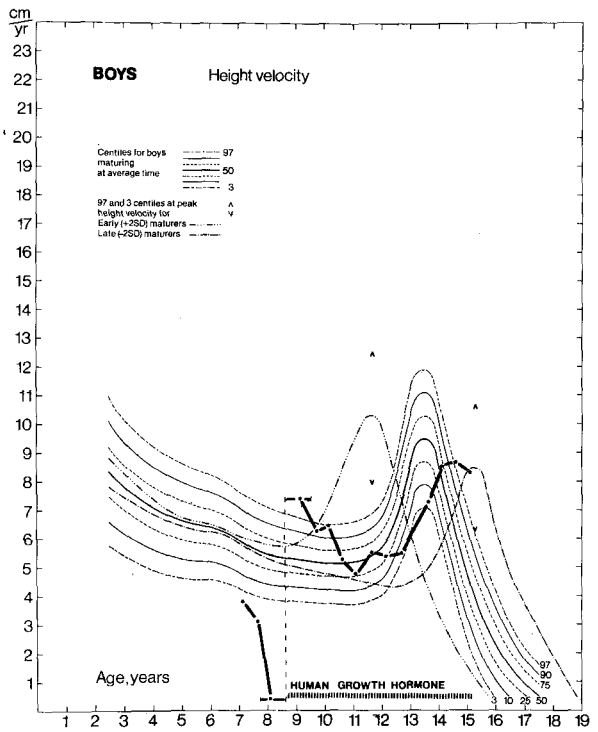

Fig. 11. Height velocity curve (same boy as in Fig. 10).

effects (most children grow faster in the spring and slower in the fall) and are relatively more affected by the unavoidable errors in measurement (which should not exceed 3 mm). Hence, for 6-month periods, rate rounded to centimeters per year, the centiles are wider; roughly speaking the 6-month 90th and 10th centiles are located at the 1-year 97th and 3rd centiles.

Use of charts. We give two examples of the use of the charts. In the first example, constitutional growth delay is followed in two boys, one without medication and the other given short-term low-dose testosterone. In the second, the effect of human growth hormone on the growth of a boy with growth hormone deficiency is charted.

Figs. 7 and 8 show the height and the height velocity in a boy with growth delay first seen at age 9.6 years. Bone age[17] is plotted as shown for the visit at 11.6 years; the length of the horizontal line gives the retardation in years, and the plot (Δ) itself displays the height for bone age. Adult height prediction[18] is plotted at the termination of the vertical line erected at x. These two determinations were, of course, repeated at intervals during the ensuing years, but further points are omitted in the interests of clarity. Also indicated are parental height centiles (mother's height plus 13 cm) and the target height for the child, that is, the range of heights within which 95% of sons of these parents should fall as adults (average of father's and

mother's centiles ±10 cm).[12] The whole-year velocities follow the 2 SD late maturing curve quite closely (Fig. 8). (During 6-month visits they are calculated each time for the whole preceding year.) Velocities are plotted at the center point of the period covered.

In this patient only reassurance was given, based specifically on the charts, which were explained to the boy and his parents. Bone age, adult height prediction, and target height are the key elements, together with the ability of the pediatrician to say exactly how much growth will occur in the next year, the year following, and so on. When parents of a 13-year-old boy complain that he has not grown for the last year or so, they can be reassured, on these bases, that the adolescent spurt is about to begin, that growth next year will be about 6 cm, and the year after that 8 or 9 cm. Often such reassurance suffices. In Fig. 9 is shown the growth curve for a boy given testosterone enanthate, with a careful check on the change in height prediction. The effects of such treatment are best followed in the velocity chart. In this particular boy the treatment was discontinued after 6 months, and the growth velocity fell until the normal pubertal growth spurt (in this instance the rule of whole-year plotting cannot but be broken, with suitable caution in interpreting velocity). When a treatment has been initiated at the beginning of a period, we thicken the vertical line joining the two periods, rather than joining up the adjacent velocities as we did in Fig. 8.

In Figs. 10 and 11 the effect of human growth hormone is shown. The catch-up growth (or velocity above that normal for age) is well seen in the first few years. The steadily increasing prediction of adult height is indicated by the three illustrative occasions plotted.

Examples of many such plots for both normal and abnormal children will be found in Tanner and Whitehouse.[19]

We thank Dr. Isabelle Valadian for making available the data from the Harvard School of Public Health Longitudinal Studies, Ms. Jan Baines for assembling the manuscript, and Castlemead Publications for doing the artwork.

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Appendix

CONSTRUCTION OF 50TH CENTILE CURVE FOR AVERAGE TEMPO

Boys. From ages 2.0 to 11.0 years, the values for height follow the observed NCHS 50th centiles of Hamill et al.[1] (Table 6, p 28), slightly smoothed graphically to fit with the shape of the height velocity curve, which takes into account the slight decrease in deceleration occasioned by the mid-growth spurt.[2-4] Values taken for 1-year velocities at ages 5 to 6, 6 to 7, and 7 to 8 years had regard to the observed NCHS cross-sectional mean differences, the actual mean annual increments seen in the large-scale London County Council 1-year longitudinal study of Tanner and Cameron,[2] and the increments seen in the small-scale longitudinal studies of Largo et al.[5] and Karlberg et al.[6] (p 7). In every yearly point, our smoothing fits the observed values of the NCHS better than (7 points) or as well as (3 points) the smoothing procedure adopted by Hamill (Table 13, p 37). At 11.0 years the observed NCHS value was 143.5 cm, our value 143.4 cm.

From 11.0 years on, we grafted the NCHS values for prepuber-

tal height, adult height, and age at peak height velocity onto the shape of the height and height velocity curves that characterize the growth of the typical individual. The adult value was taken as 176.8 cm[7] (Table 13, p 37, in agreement with the estimate derived by fitting a Preece-Baines[8] model I curve to the observed values of the NCHS). The age at PHV is approximately 13.5 years if taken from the observed cross-sectional semiannual values of the NCHS (Table 6, p 28), and 13.4 if estimated by fitting a Preece-Baines curve to the observed cross-sectional means. (The smoothed NCHS values, given as Table 13, practically obliterate any pubertal rise and lead to a clearly erroneous age at PHV of about 12.8 years; they are best ignored.) A value of 13.5 years for age at PHV is 0.4 years lower than the age at PHV of the British standards, and agrees well with calculations for girls (see below) and with the differences in bone ages between the two populations.[9]

We also needed a value for PHV itself (not instantaneous PHV, but peak velocity computed over a whole year, because the velocity standards are presented this way). There were a number of empirically determined values, all in fair agreement. Tanner et al.[10] fitted measurements taken every 3 months on each individual by an iterative graphic procedure, starting with the height-attained curve, then plotting the observed velocities against the estimated velocities, smoothing and repeating the cycle a second time. Their mean whole-year PHV was 9.5 cm/yr. Using similar graphic procedures, also on 3-month measurements, Taranger et al.[11] found a mean of 9.9 cm/yr in the Stockholm Longitudinal Study. Lindgren[12] estimated a mean of 9.8 cm/yr in the all-Sweden twin longitudinal study, using 373 singleton (control) boys measured every 6 months. Billewicz et al.[13] obtained a mean of 9.6 cm/yr in 669 boys in Newcastle-upon-Tyne examined at 6-month intervals, but this is the maximum 6-monthly peak velocity and corresponds to about 9.3 cm/yr for the whole-year peak velocity.

Largo et al.[5] fitted cubic splines to 6-monthly height values of boys in the Zurich longitudinal study and found a mean PHV of 9.0 cm/yr. Authors who have fitted parametric curves have found lower values still; for the Berkeley growth study data reported by Tuddenham and Snyder,[14] the Preece-Baines model I curve gives a mean of 8.4 cm/yr (our calculations), and the triple logistic curve a mean of 8.7 cm/yr[15]; these values are for instantaneous peak velocity, which is greater than whole-year peak velocity by approximately 0.8 cm/yr in boys and 0.6 cm/yr in girls.[10] The graphically fitted whole-year peak velocity in these data comes out to 8.9 cm/yr, 1.3 cm above the whole-year peak estimated by the Preece-Baines method (which is 8.4 − 0.8 cm/yr). Thus it seems that parametric curves at present are insufficiently flexible to accommodate the full rise of the observed curves. The Preece-Baines curve, for example, when fitted to the British male standards, underestimates PHV by 1.5 cm/yr. Similarly, when fitted to a subsample of the Tanner[10] data, it produced a value of 8.7 cm/yr compared with the graphic instantaneous value of 10.3 cm/yr. We have relied, therefore, on the empirically derived values, and chosen the midrange figure of 9.5 cm/yr.

Girls. Exactly similar considerations for girls led to the 50th centile curves shown in Fig. 2 and the values given in Table I. For the prepubertal value, at age 9.0 years, we have taken 133.0, the NCHS observed value at this age being 132.7. Our values fit the observed NCHS means better than do the spline-smoothed NCHS values in four of seven cases. For adult height we have taken 163.8, the NCHS observed value being 163.7. We located PHV at 11.5 years, which was the same from the observed NCHS values, the Preece-Baines fit to them, and the NCHS cubic spline fit. This value is confirmed by considering the average difference in time between age at menarche and age at PHV, which is between 1.2 and 1.3 years in nearly all published series. The NCHS value for menarche is 12.77 years.[16]

Whole-year PHV values in the empirically derived data are 8.4,[10] 8.6,[11] and 8.3 cm/yr.[12] There are 6-monthly PHV of 8.0 cm/yr, leading to about 7.8 cm/yr for whole-year for Newcastle,[13] and 8.3 cm/yr, leading to about 8.1 cm/yr for whole-year in the Polish longitudinal study reported by Bielicki.[17] Cubic splines fitted to the Swiss data give a value of 7.1 cm/yr,[5] and Preece-Baines model I curves give instantaneous values of 7.3 cm/yr[18] (Belgians), 7.8 cm/yr[19] (Americans), 7.4 cm/yr (Berkeley Growth Study, our calculations), and 7.7 cm/yr (Harvard School of Public Health Growth Study, our calculations). We have taken the value 8.3 cm/yr.

Early and late maturing children. Values for the difference in height between 2 SD early and 2 SD late boys at age 5 years were derived from the regressions of height at age 5 years on age at PHV, which, using fitted Preece-Baines curves, were −1.1 ± 0.5 cm/yr in the Berkeley data and −1.8 ± 0.4 cm/yr in the Harvard data. For girls the regressions were −1.3 ± 0.6 cm/yr (Berkeley) and −1.9 ± 0.5 cm/yr (Harvard).

The regression of PHV on age at PHV, in boys, in the data of Tanner et al.[10] was −0.8 cm/yr; in the Newcastle data −0.4 cm/yr,[13] in the Polish data approximately −0.6 cm/yr,[17] in the Swedish data −0.5 cm/yr,[20] in the Harvard Growth Study −0.5 cm/yr,[21] and in the Swiss data, using spline fits, −0.5 cm/yr.[5] In the Berkeley data it was −0.6 ± 0.1 cm/yr, and in the Harvard School of Public Health data −0.4 ± 0.2 cm/yr, both using Preece-Baines fits. We have taken −0.5 cm/yr as the value, giving the 50th centile PHV for 2 SD early maturing boys as 9.4 + 0.9 = 10.3 cm/yr and for 2 SD late maturing boys as 9.4 − 0.9 = 8.5 cm/yr.

In girls the regression is a little lower than in boys. Estimates are −0.5 cm/yr (Tanner et al.[10]), −0.4 cm/yr[13] (Newcastle), −0.4 cm/yr[17] (Poland), −0.3 cm/yr[20] (Sweden), −0.5 cm/yr[21] (Harvard Growth Study), −0.4 cm/yr[5] (Swiss children, spline fitted), −0.6 cm/yr (Berkeley data, fitted Preece-Baines curves), −0.4 cm/yr (Harvard School of Public Health, fitted Preece-Baines curves), and −0.1 cm/yr[19] (New England, fitted Preece-Baines curves, but home measured and with very high SD for PHV). We have taken the value −0.4 cm/yr, giving 50th centile PHVs of 9.0 cm/yr for 2 SD early maturing and 7.6 cm/yr for 2 SD late maturing girls.

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