Prediction of adult height from height and bone age in childhood

A new system of equations (TW Mark II) based on a sample including very tall and very short children

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SUMMARY A new series of equations is presented for predicting the adult height of a child given present height and bone age. These equations (TW height prediction, Mark II) which replace the ones given in 1975 (TW height prediction, Mark I) are based on larger numbers of normal children, and more importantly on a sample that includes, for the first time, numbers of very tall, very short, and very growth-delayed children. In addition, equations are given for use when the increment of height or bone age, or both, over the previous year is known. These variates improve the prediction at most ages over 8 years in girls and 11 years in boys. The previously given parental allowance has been dropped.

Typically 95% of the predictions lie within ± 8 cm of the real value for boys aged 10 years, falling to ± 6 cm for boys aged 15 years, or ± 4 cm if their previous height increment is known. For premenarcheal girls the predictions lie within about ± 6 cm at age 8 years; a figure which diminishes little till 13 years unless height and bone age increments are known, when it reaches ± 4 cm at 13 years. For postmenarcheal girls the predictions are substantially more accurate.

The prediction of adult height is a useful part of the therapeutic armamentarium of the paediatrician—particularly of the paediatric endocrinologist. In small, growth-delayed boys an accurate prediction is a powerful reassurance and an essential monitor if anabolic steroids are given. In tall girls the prediction is an important element in the decision whether or not to give oestrogens.

Yet all current methods of prediction¹⁻³ suffer from a crucial fault in precisely these two situations. They are based exclusively on samples of normal children, selected more or less at random from the community, and followed from preschool days to adulthood. These samples include scarcely any very tall, very short, or very delayed children. Thus, applying the standard prediction equations to such children represents an extrapolation into areas where they may not continue to be valid—in fact, in clinical practice, we have been struck by the frequency with which rather large errors occur, especially in the case of (untreated) tall girls.

We have therefore revised our 1975 height prediction equations,² this time including numbers of

very tall and very short children in the standardising group. Such children, followed in the Growth Disorder Clinic to adulthood, were not available in 1975. In addition, we have examined afresh the range of possible predictor variables and have improved the predictions at certain ages by including more than one measurement of height and of bone age, where these are available.

Subjects

The standardising groups were as follows:

Random sample boys. Sixty nine boys of the Harpenden growth study (HGS)⁴⁻⁸ and 41 boys of the International Children's Centre London longitudinal growth study (ICC)⁹⁻¹⁰ who had been followed till growth in height had virtually stopped were included. Our minimum criterion for this was an increment of less than 1 cm between two successive measurements taken a year or more apart. Some boys grow 1 cm or, rarely, 2 cm beyond this.¹¹ Most of our random sample boys, however, were

followed well beyond the minimum increment point, and their final height represents a value obtained by drawing a smooth curve through a succession of practically constant measurements. All 110 boys were healthy at all times of measurement and their average adult height was 174.6 cm, exactly at the 50th centile of the British standards.⁵

Growth Disorder Clinic boys. This group comprised 34 boys referred to the Growth Disorder Clinic at the Hospital for Sick Children, Great Ormond Street, for short stature. All had growth delay, genetic short stature, or both; all were healthy, and none had any treatment. Five were measured by us at final adult height, just like the 'random-sample' boys, but 29 had themselves measured at home according to our written instructions, and sent the result to us. Average final height was 167.2 cm.

Random sample girls. Fifty two girls from the HGS, 41 girls from the ICC, and 57 girls from the Royal Ballet training school, whose height had been measured for professional reasons, were included. All these were measured under the same conditions as the 'random sample' boys, except that final heights on the ballet school series were obtained by measurements done at the ballet school or at home. Average final height was 162.9 cm—again at the 50th centile of the British Standards.

Growth Disorder Clinic girls. Nineteen girls were referred to the clinic because of excessive stature and 10 were referred because of short stature. All were healthy and none reported here had had any treatment. Seven were measured by us at final adult height and 22 had themselves measured at home. Average final height of the tall girls was 179.8 cm and of the others, 154.0 cm.

The HGS children entered the study at various ages from 3 to 10 years; they were measured at 6 monthly intervals till puberty, 3 monthly intervals during puberty, and yearly intervals thereafter. The ICC children entered the study at birth and from age 2 were measured at annual intervals. These two sets of children are those on whom the 1975 predictions were based (less 6 boys and two girls). The ballet school girls were exceptional in being measured once only as children, at ages between 9 and 12 years. The Growth Disorder Clinic children entered at various ages (mostly between 12 and 16 years in boys, 9 and 13 years in girls) and were measured at intervals of 6 months, one year, or two years.

The number of subjects at each age is shown in Table 1. Each child had his measurement referred to the nearest half year point (6.0, 6.5 etc.) from age

Table 1 *Numbers of children at each age*

Age (years)	Boys			Girls		
	Random sample	Growth clinic	Total	Random sample	Growth clinic	Total
6.0	66	0	66	59	0	59
6.5	31	0	31	28	1	29
7.0	66	0	66	69	0	69
7.5	32	0	32	35	1	36
8.0	76	0	76	73	0	73
8.5	36	0	36	35	1	36
9.0	75	0	75	69	0	69
9.5	44	3	47	36	3	39
10.0	80	1	81	76	4	80
10.25	66	0	66	15	2	17
10.50	46	1	47	49	5	53
10.75	1	2	3	24	4	28
11.0	82	0	82	78	4	82
11.25	18	2	20	34	3	37
11.50	47	0	47	46	8	54
11.75	20	0	20	41	2	43
12.0	72	1	73	69	4	73
12.25	52	2	54	23	2	25
12.50	51	0	51	44	4	48
12.75	50	2	52	43	2	45
13.0	74	1	75	65	4	69
13.25	57	1	58	46	5	51
13.50	47	1	48	39	3	42
13.75	44	2	46	29	5	34
14.0	66	5	71	45	4	49
14.25	43	2	45	27	5	32
14.50	42	3	45	25	4	29
14.75	35	9	44	14	3	17
15.0	55	4	59	33	3	36
15.25	17	5	22	3	1	4
15.50	31	3	34	13	3	16
15.75	4	11	15	1	2	3
16.0	61	8	69	16	3	19
16.25	12	10	22	4	3	7
16.50	16	2	18	2	1	3
16.75	1	7	8	1	3	4
17.0	55	2	57	4	0	4
17.25	8	5	13	1	3	4
17.50	4	2	6	0	1	1
17.75	2	5	7	1	3	4
18.0	19	3	22	0	1	1
18.25	5	5	10	0	1	1
18.50	2	1	3	0	2	2
18.75	0	3	3	0	0	0
19.0	0	2	2	0	3	3
Adult	110	34	144	150	29	179

6.0 to 10.0 years and the nearest quarter year point (10.25, 10.5, 10.75 etc) from age 10 years onwards. For purposes of age classification (see below) the child was deemed to be at that point, but in the equations themselves his or her exact age was used (in the case of the random sample children this was always very close to their age-point, since the studies were set up that way). As not all children were present on all occasions the series is a mixed longitudinal one.¹² In both sexes the most populated age-point is 11.0 years. There were not many gaps in the longitudinal runs of the HGS and ICC children, but a few occurred by virtue of missed radiographic examinations since we excluded any childhood height measurement that was not accompanied by a radiograph for bone age.

Methods

Height measurement. All height measurements were taken using a Harpenden Stadiometer, with the technique of gentle upward pressure applied under the mastoid processes to stretch the child to maximum stature.^{13 14} Measurements on the HGS children were done by R H Whitehouse; on the ICC children, with a few exceptions, by J M Tanner or W A Marshall; on the ballet girls by Glynis Sharp; and on the Growth Disorder Clinic children by R H Whitehouse or N Cameron.

Bone age. Radiographs of the left hand and wrist were taken and rated according to the TW2 system.² Ratings were done by R H Whitehouse, W A Marshall, or N Cameron. Comparison of these raters showed that discrepancies greater than ± 0.7 years occurred in less than 10% of cases. We are concerned here only with the RUS score of the TW2 system, derived from rating radius, ulna, metacarpals, and phalanges: we have previously shown that ratings of the carpal bones contribute nothing useful to the prediction equations.²

Statistics. Standard multiple regression techniques were used, implemented with the programme BMD P2R. Adult height was estimated from various linear and non-linear combinations of childhood height and bone age (see below). The distributions of the residuals were examined graphically.

We have constructed equations, firstly for each of the age points listed in Table 1 and secondly (because of the small numbers present at some age points and the potential convenience to the user) for whole year 'bands' (that is for age 10+ years, which includes the data for 10.0, 10.25, 10.50, and 10.75; age 11+ years, and so on). Since most subjects entered more than once in such a classification, and this is undesirable in establishing the standard errors of estimate, we have included only one value for each individual in each whole year age 'band', the value being chosen by computer, using a pseudo-random number generator, from among the two, three, or four values present. We have run a number of replicates to assess the differences made by successive random selections. Differences in the standard errors of estimate averaged around 2% and rose as high as 5% in a few cases. In this whole-year series the subject's exact chronological age entered the estimation equation, which thus included linear and non-linear combinations of height, bone age, and exact chronological age.

Each series (point-year, whole-year) generates a series of equations with coefficients for height, bone age etc that change from one age to the next. In order to smooth the age progression, specifically in the whole-year series, we calculated equations for overlapping whole-year ages, that is 9.0+ (9.0, 9.5), 9.5+, (9.5, 10.0) 10.0+ (10.0, 10.25, 10.5, 10.75) 10.25+ (10.25, 10.5, 11.0) years etc. In each whole-year group we selected only one value for each individual child, as described above.

Further smoothing of the coefficients was done by plotting each successively against age and smoothing graphically. When one coefficient had been smoothed the resulting values were used to recalculate the regression, for each age, and the next coefficient was then smoothed; finally the constant term was smoothed. This whole cycle of smoothing was repeated a second time for the boys' equations and some of the girls': the second cycle resulted in only minor changes in the coefficients (mostly <5%), however, and first cycle values are the ones presented here.

Results

A series of multiple regressions were examined where:

- Y = Final adult height.
- H = Height at time of measurement.
- RUS = Bone age at time of measurement.
- CA = Exact chronological age at time of measurement.
- ΔH = Increment in height during the year before measurement (in practice during a time between 0.88 and 1.12 years before measurement, adjusted to the annual rate).
- ΔRUS = Increment in bone age during the year before measurement (in practice, as for height).

The equations were of the form:

- (i) Y a function of H, CA, RUS, and interactions (H $\times$ RUS etc).
- (ii) Y a function of H, CA, RUS, ΔH , and interactions.
- (iii) Y a function of H, CA, RUS, ΔRUS , and interactions.
- (iv) Y a function of H, CA, RUS, ΔH , ΔRUS , and interactions.

In girls aged 11 and over the equations were calculated separately for premenarcheal and postmenarcheal subjects. The equations were computed both for the age-point groups given in Table 1, and for whole-year age groups. In the former case, CA

was omitted in the calculation since the range of exact CA at each age-point was very small.

Equation (i). In the whole-year age groups the inclusion of the CA term was essential at all ages. The RUS term improved considerably the prediction, beginning at age 8 years in boys and 6 in girls. It became progressively more important at older ages, and from 13 years onwards in boys and 10 onwards in girls it contributed more to the prediction than did CA. The interaction terms ($H \times RUS$), ($CA \times RUS$), and ($H \times CA$) did not contribute significantly at any age.

The distributions of the residuals (actual less predicted adult height) were examined at each age. None departed grossly from normality or homoscedasticity. The residual SDs were on average no larger in the whole-year series than in the age-point series, so the inclusion of the CA term in the whole-year series compensated adequately for the broadening of the age categories. The correlation coefficients were on average a little higher in the whole-year series.

Two related equations were also examined— Y a function of H , H^2 , CA , and RUS ; and $\log Y$ a function of H , CA , and RUS —to see if either improved significantly the average prediction or the distribution of the residuals. They did not.

Equation (ii). In this series of equations ΔH , the increment of height during the previous year, was included. It improved the prediction significantly at ages 12 and 13 years in the boys, and at 8, 9, 10, and 11 years in the girls. In postmenarcheal but not in premenarcheal girls, it also improved the prediction at 12, 13, 14, and 15 years. The decrease of the residual SD was of the order of 5% in the premenarcheal girls and 30% in the postmenarcheal.

Equation (iii). The inclusion of ΔRUS , the bone age increment during the previous year, failed to improve the prediction at any age in boys. In girls it caused an appreciable lowering of the residual SD; in premenarcheal girls at ages 13 and 14 years and in postmenarcheal girls at ages 12 and 13 years. The reduction amounted to about 15%.

Equation (iv). The effects of including ΔH and ΔRUS in girls were independent of one another so that including both gave the best combination among all the equations examined. In some age groups the diminutions of the residual SD using equation (iv) compared with equation (i) were striking. In 13 year old premenarcheal girls the residual SD diminished from 2.84 cm to 2.33 cm and

in 13 year old postmenarcheal girls from 1.73 cm to 1.22 cm.

Menarche. The separation into pre- and postmenarcheal makes a large difference to the accuracy of prediction in that the final height of postmenarcheal girls is much more accurately predicted than that of premenarcheal girls of the same chronological age, or even of the same bone age. This remains true even when ΔH and ΔRUS are included: at age 14 years for example, using equation (iv), the residual SD for premenarcheal girls still remains 2.0 cm ($R=0.94$), whereas for postmenarcheal girls it is 0.9 cm ($R=0.99$).

We have investigated whether adding in the actual number of years since menarche further improved the already good prediction for postmenarcheal girls. There was no notable improvement when equation (iii) or (iv) was used, but in cases where ΔRUS and ΔH were not available, years after menarche decreased the residual SD at ages 13 and 14 years.

Final equations. The equations finally chosen were:

(1) Adult height = $a_1 H + b_1 CA + c_1 RUS + k_1$: for use when there is no record of an earlier height or bone age, or when a boy is less than 11.0 years old or a girl less than 8.0 years.

(2) Adult height = $a_2 H + b_2 CA + c_2 RUS + d_2 \Delta H + k_2$: in boys from 11.0 upwards where ΔH is available; and in girls from 8.0 years upwards where ΔH but not ΔRUS is available.

(3) Adult height = $a_3 H + b_3 CA + c_3 RUS + d_3 \Delta H + e_3 \Delta RUS + k_3$: in girls over 8.0 years when ΔH and ΔRUS are available.

Each of these equations was computed for each whole year of age. The coefficients for H , RUS etc do not change entirely smoothly from age to age, and there are problems of prediction at the junctions of one age and another. Thus a boy aged 10.9 years will be predicted on the 10 year old equation (actually 10.5, see below) and a month later, at 11.0, on the 11 year old equation. The two predictions should clearly give the same result apart from inevitable measuring errors in height and, more importantly, in bone age.

The coefficients of the equations were smoothed by two successive devices as described in Methods. Firstly, we calculated equations for successively overlapping whole-year age groups so that at least half the children in one group were also present in the previous group, thus giving stability to the coefficient; and then we smoothed each series of coefficients graphically. This resulted in equations for each half year up to age 10 years, and each quarter year thereafter. Contiguous quarter year

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Table 2.1 Coefficients of adult height prediction (3 variates), boys. (All boys under 11.0 years and boys over 11 years with no height increment available)

Age (yr)	Height (cm)	Chronological age (yr)	Bone age (RUS) (yr)	Constant	Residual SD (cm)	r
6.0—	+1.28	-7.5	-0.12	75	4.7	0.82
6.5—	+1.25	-7.1	-0.13	75		
7.0—	+1.24	-6.6	-0.32	73	4.6	0.82
7.5—	+1.28	-6.2	-0.67	69		
8.0—	+1.30	-5.8	-1.00	66	4.1	0.87
8.5—	+1.27	-5.4	-1.25	68		
9.0—	+1.16	-5.0	-1.30	79	4.1	0.87
9.5—	+1.13	-4.7	-1.25	80		
10.0—	+1.12	-4.4	-1.27	79	4.0	0.87
10.5—	+1.12	-4.0	-1.50	77		
11.0—	+1.11	-3.6	-1.85	78	3.8	0.89
11.5—	+1.09	-3.2	-2.37	82		
12.0—	+1.07	-2.8	-2.90	86	3.8	0.89
12.5—	+1.04	-2.4	-3.45	92		
13.0—	+1.01	-2.1	-3.90	99	3.7	0.89
13.5—	+0.98	-1.7	-4.25	104		
14.0—	+0.94	-1.4	-4.42	107	3.5	0.90
14.5—	+0.87	-1.0	-4.17	108		
15.0—	+0.81	-0.8	-3.65	109	3.2	0.91
15.5—	+0.80	-0.6	-3.07	98		
16.0—	+0.85	-0.4	-2.65	80	2.9	0.93
16.5—	+0.90	-0.3	-2.27	64		
17.0—	+0.94	-0.2	-2.02	51	2.0	0.97
17.5—	+0.96	-0.1	-1.90	43		
18.0—	+0.98	-0.0	-1.90	38	1.4	0.99
18.5—	+0.98	-0.0	-1.90	37		

Table 2.2 Coefficients of adult height prediction (4 variates), boys. (Boys over 11.0 years, with height increment available)

Age (yr)	Height (cm)	Chronological age (yr)	Bone age (RUS) (yr)	Increment of height during previous year* (cm)	Constant	Residual SD (cm)	r
11.0	+1.19	-3.1	-1.50	-0.3	59	3.8	0.89
11.5	+1.20	-2.7	-1.92	-1.4	62		
12.0	+1.15	-2.3	-2.73	-1.5	73	3.2	0.93
12.5	+1.09	-1.9	-3.03	-1.3	81		
13.0	+1.03	-1.6	-3.57	-1.0	91	3.1	0.93
13.5	+0.99	-1.4	-4.17	-0.6	100		
14.0	+0.95	-1.1	-4.73	-0.5	109	3.1	0.92
14.5	+0.92	-0.8	-4.82	-0.4	110		
15.0	+0.89	-0.7	-3.68	-0.2	95	2.5	0.94
15.5	+0.83	-0.5	-2.58	-0.1	84		
16.0	+0.78	-0.4	-2.25	0	84	2.8	0.91
16.5	+0.85	-0.4	-2.07	0	69		
17.0	+0.93	-0.4	-1.90	0	54	1.6	0.97
17.5	+0.99	-0.3	-1.45	0	38		
18.0	+1.01	-0.3	-0.55	0	14	0.7	0.99

* ± 5 weeks (0.83 to 1.12 years) adjusted to annual rate.

coefficients were averaged to give tables based on half years for practical use.

Finally, we examined the predictions at each age for each child, comparing the results of each equation, and also of the old TW Mark I method, with the actual final height. This resulted in a few further small adjustments of the (by now rounded) coefficients.

Boys' equation 1. Table 2.1 shows the coefficients for equation 1 for boys, together with the residual SDs and correlation coefficients. At ages 13.0 and 13.5 years combined the residuals (actual less estimate) range from +10 to -8 cm; at age 14 and 14.5 years

from +9 to -9 cm, at ages 15.0 and 15.5 years from +6 to -7 cm, and at ages 16.0 and 16.5 years from +7 to -7 cm. The Growth Disorder Clinic patients did not have larger residuals than the random sample subjects at any of these ages. At each age the range amounts to just about five times the standard deviation, as expected.

Boys' equation 2. Table 2.2 shows the coefficients for equation 2, in which Δ height is included. Since there seemed no advantage to be gained at ages before 11.0 years, the table starts at that age. It has to be remembered that the number of subjects having a valid Δ height was less than the number

Table 3.1a *Coefficients of adult height prediction (3 variates), premenarcheal girls. (All girls under 8.0 years and girls over 8.0 years with no height increment available)*

Age (yr)	Height (cm)	Chronological age (yr)	Bone age (RUS) (yr)	Constant	Residual SD (cm)	r
5.0-	+0.89	-3.7	-0.80	90	3.7	0.78
5.5-	+0.89	-3.5	-1.00	90		
6.0-	+0.89	-3.3	-1.15	89	3.5	0.80
6.5-	+0.89	-3.1	-1.25	89		
7.0-	+0.89	-2.9	-1.33	87	3.5	0.82
7.5-	+0.89	-2.6	-1.50	85		
8.0-	+0.89	-2.2	-1.73	84	3.4	0.85
8.5-	+0.90	-1.9	-2.00	82		
9.0-	+0.92	-1.7	-2.40	81	3.6	0.85
9.5-	+0.92	-1.6	-2.83	83		
10.0-	+0.91	-1.6	-3.03	86	3.3	0.87
10.5-	+0.91	-1.7	-3.13	88		
11.0-	+0.91	-1.7	-3.33	90	3.0	0.90
11.5-	+0.93	-1.7	-3.68	91		
12.0-	+0.96	-1.7	-3.90	89	3.0	0.90
12.5-	+0.96	-1.6	-3.55	84		
13.0-	+0.94	-1.4	-3.15	79	2.9	0.94
13.5-	+0.92	-1.0	-3.43	79		
14.0-	+0.90	-0.6	-3.65	79	2.4	0.95
14.5-	+0.88	-0.1	-3.88	79		

Table 3.1b *Coefficients of adult height prediction (3 variates), postmenarcheal girls. (Girls with no height increment available and age at menarche unknown)*

Age (yr)	Height (cm)	Chronological age (yr)	Bone age (RUS) (yr)	Constant	Residual SD (cm)	r
11.5-	+0.98	-2.2	-1.05	49	1.9	0.96
12.0-	+1.00	-1.4	-1.15	38	1.8	0.96
12.5-	+1.00	-0.8	-1.35	32		
13.0-	+1.01	-0.2	-1.50	26	1.8	0.97
13.5-	+1.02	-0.1	-1.45	21		
14.0-	+1.04	0.0	-1.25	15	1.4	0.98
14.5-	+1.08	0.0	-1.00	5		
15.0-	+1.05	0.0	-0.70	4	0.9	0.99
15.5-	+1.02	0.0	-0.75	10		
16.0-	+1.00	0.0	-1.35	22	1.1	0.99
16.5-	+1.02	0.0	-1.95	28		

entering into equation 1 so the standard errors of the coefficients in Table 2.2 are somewhat higher than those of the coefficients in Table 2.1. Comparison of the actual final heights with those predicted by equations 1 and 2 did show a small advantage for equation 2 from age 11.5 years onwards. In the age range 11.5–14.5 years inclusive, 59% of cases were

better predicted by equations 2, and in the range 15–17 years, 67% of cases were better predicted.

Girls' equation 1. Tables 3.1a and 3.1b show the coefficients for equation 1 for girls; separately for those who are premenarcheal at the time of examination (Table 3.1a) and those who are postmenarcheal

Table 3.1c *Coefficients of adult height prediction (3 variates plus age at menarche), postmenarcheal girls. (Girls with no height increment available but age at menarche known)*

Age (yr)	Height (cm)	Chronological age (yr)	Bone age (RUS) (yr)	Age at menarche (yr)	Constant	Residual SD (cm)	r
11.5–	+1.05	–4.4	–0.12	+2.0	+29	1.9	0.96
12.0–	+1.02	–3.5	–0.23	+1.6	+29	1.7	0.96
12.5–	+0.98	–2.8	–0.60	+1.4	+34		
13.0–	+1.01	–2.2	–0.90	+1.3	+28	1.7	0.98
13.5–	+1.05	–1.5	–0.68	+1.4	+7		
14.0–	+1.09	–0.8	–0.47	+1.3	–11	1.2	0.99
14.5–	+1.12	–0.4	–0.48	+1.2	–20		
15.0–	+1.08	–0.2	–0.65	+0.7	–8	0.9	0.99
15.5–	+1.02	0.0	–1.05	+0.1	+12		
16.0–	+1.00	0.0	–1.50	0.0	+24	1.1	0.99
16.5–	+1.03	0.0	–2.00	0.0	+29		

Table 3.2a *Coefficients of adult height prediction (4 variates), premenarcheal girls. (Girls aged 8 years and over with height increment but no bone age increment available)*

Age (yr)	Height (cm)	Chronological age (yr)	Bone age (RUS) (yr)	Increment of height during previous year (cm)*	Constant	Residual SD (cm)	r
8.0–	+0.80	–3.4	–1.80	+1.1	99	3.2	0.87
8.5–	+0.90	–3.2	–1.95	–1.0	98		
9.0–	+0.95	–2.9	–2.15	–2.0	96	3.2	0.87
9.5–	+0.97	–2.7	–2.30	–1.8	92		
10.0–	+0.94	–2.4	–2.35	–1.6	92	3.2	0.87
10.5–	+0.89	–2.2	–2.40	–1.3	95		
11.0–	+0.91	–1.9	–2.45	–1.3	90	2.9	0.92
11.5–	+0.94	–1.7	–2.90	–1.3	88		
12.0–	+0.96	–1.4	–3.55	–0.9	86	3.0	0.81
12.5–	+0.98	–1.2	–3.80	–0.4	80		

*±6 weeks (0.88–1.12 years) adjusted to annual rate.

Table 3.2b *Coefficients of adult height prediction (4 variates), postmenarcheal girls*

Age (yr)	Height (cm)	Chronological age (yr)	Bone age (RUS) (yr)	Increment of height during previous year (cm)*	Constant	Residual SD (cm)	r
11.5–	+0.99	–1.5	–0.00	+0.6	20	1.5	0.96
12.0–	+1.05	–1.1	–0.00	+0.8	5	1.1	0.98
12.5–	+1.02	–0.7	–0.00	+1.0	6		
13.0–	+1.00	–0.5	–0.00	+1.0	6	1.2	0.98
13.5–	+0.99	–0.2	–0.00	+1.0	3		
14.0–	+1.00	–0.1	–0.00	+0.9	1	0.8	0.99
14.5–	+1.01	–0.1	–0.15	+0.8	2		
15.0–	+1.03	–0.0	–0.50	+0.6	3	0.5	0.99
15.5–	+1.07	–0.0	–0.90	+0.1	4		
16.0–	+1.10	–0.0	–1.30	+0.0	5	0.4	0.99

*±6 weeks (0.88–1.12 years) adjusted to annual rate.

Table 3.3a Coefficients of adult height prediction (5 variates), premenarcheal girls (Girls aged 10.0 years and over with height and bone increment available)

Age (yr)	Height (cm)	Chronological age (yr)	Bone age (RUS) (yr)	Increment of height during previous year (cm)*	Increment of bone age in the previous year (yr)*	Constant	Residual SD (cm)	r
10.0—	+0.92	-2.4	-2.50	-1.6	+0.3	+95	3.0	0.87
10.5—	+0.92	-2.3	-2.75	-1.4	+0.8	+94		
11.0—	+0.91	-1.8	-2.95	-1.3	+1.2	+93	2.7	0.89
11.5—	+0.87	-1.5	-3.20	-1.1	+1.6	+95		
12.0—	+0.85	-1.1	-3.60	-0.8	+1.9	+96	2.6	0.89
12.5—	+0.88	-0.7	-3.90	-0.5	+2.1	+89		
13.0—	+0.97	-0.5	-4.15	-0.3	+2.2	+74	2.1	0.93
13.5—	+1.09	-0.3	-4.35	-0.2	+2.5	+54		
14.0—	+1.21	-0.1	-4.55	-0.1	+2.6	+35	1.8	0.95
14.5—	+1.31	-0.0	-4.75	-0.1	+2.7	+19		

*±6 weeks (0.88—1.12 years) adjusted to annual rate.

Table 3.3b Coefficients of adult height prediction (5 variates), postmenarcheal girls

Age (yr)	Height (cm)	Chronological age (yr)	Bone age (RUS) (yr)	Increment of height during previous year (cm)*	Increment of bone age in the previous year (yr)*	Constant	Residual SD	r
11.5—	+1.11	-0.0	-0.50	+0.7	+2.2	-14	1.2	0.98
12.0—	+1.07	-0.0	-0.40	+0.7	+1.5	-7	1.1	0.98
12.5—	+1.03	-0.0	-0.40	+0.8	+0.9	-1		
13.0—	+1.00	-0.0	-0.25	+0.8	+0.5	+3	1.1	0.98
13.5—	+0.99	-0.0	-0.20	+0.8	+0.3	+4		

*±6 weeks (0.88—1.12 years) adjusted to annual rate.

(Table 3.1b). In the latter group the prediction may be improved slightly by adding an extra term in the regression equation to represent the actual time elapsed since menarche (presented simply as age at menarche; Table 3.1c).

Girls' equation 2. Tables 3.2a and 3.2b show the coefficients for equation 2, in premenarcheal and postmenarcheal girls respectively. In premenarcheal girls the advantage of equation 2 over equation 1 began at age 8.0 years and was clearest at age 9 years; at ages 13 and 14 years equation 2 performed worse than equation 1, so Table 3.2a extends only from 8.0 to 12.5 years inclusively. In postmenarcheal girls the addition of the height increment term resulted in a better prediction at all ages.

Girls' equation 3. Tables 3.3a and 3.3b show the coefficients of equation 3, where the last year's increment of bone age is taken into account as well as the last year's increment of height. In the premenarcheal girls there was a clear diminution of the residual standard deviation at ages 12, 13, and 14 years, with a more questionable improvement at 10 and 11 years. In postmenarcheal girls there was an improvement at 11.5, 12, and 13 years, but none at 14 or 15 years.

Discussion

This paper presents equations for predicting adult height which are intended to supplant those given in 1975.^{2 15} They have two advantages. Firstly, the sample of children from which they are derived has been enlarged by the addition of a number of very tall and very short children so that it represents better, though by no means perfectly, the population of patients in which predictions are made in the clinic. Secondly, we have gained in precision by adding in at certain ages the changes in height and in bone age during the year before the prediction. Since these are only known in some instances, a number of equations have to be given; two for boys, three for premenarcheal girls, and four for postmenarcheal girls. The user should find little difficulty in selecting the appropriate equations. The Figure is a guide.

All the equations are simple linear ones. Various non-linear combinations of height, bone age etc were examined but proved no better. The division into premenarcheal and postmenarcheal among the girls does, however, make a large difference. The residual SD for postmenarcheal 12 year olds is 1.7 cm compared with 3.0 cm for premenarcheal 12 year olds; for 13 year olds the figures are 1.7 cm and 2.9 cm, and for 14 year olds 1.2 cm and 2.4 cm.

BOYS	
Under 11·0 years	Table 2.1
11·0 years and over	Table 2.1
No height increment available	Table 2.2
Height increment available	
GIRLS	
Under 8·0 years	Table 3.1a
8·0 years and over	
Premenarcheal	
No height increment available	Table 3.1a
Height increment but <i>not</i> RUS increment available	
Ages 8·0–12·5 years	Table 3.2a
Ages 13·0–14·5 years	Table 3.1a
Height increment <i>and</i> RUS increments available	
Ages 10·0–14·5 years	Table 3.3a
Ages 8·0–9·5 years	Table 3.1a
Postmenarcheal	
No height increment available	
Age at menarche known	Table 3.1c
Age at menarche unknown	Table 3.1b
Height increment but <i>not</i> RUS increment available	Table 3.2b
Height <i>and</i> RUS increments available	
Ages 11·5–13·5 years	Table 3.3b

Figure Choice of prediction equation.

In comparison with the 1975 (TW Mark I) system, the multiple correlations are generally higher since the range of the variates is greater, but the standard errors of prediction are about the same or on occasion larger. This is partly because the standard deviation of the predicted variate is greater and partly because this time, as opposed to 1975, we used each subject once only in each age band. The present standard errors are therefore preferred.

Older children. The last age entries in the tables for boys are 18·5 years for Table 2.1, (three variates) and 18·0 years for Table 2.2 (four variates). Boys with growth delay may be older than this with epiphyses still unfused. Their predictions are made using the last row in the appropriate Table.

In the case of girls the same applies for postmenarcheal subjects over the age of 16·5 or 17·0 years who are still growing; they are looked up under age 16·5 years in Table 3.1b or 16·0 years in Table 3.2b. Premenarcheal girls over the age of 15·0 years present a problem because we had so few in our standardising group. Probably using the 14·5 years row in Table 3.1a or 3.3a would be best, but this is not certain. There is a similar problem for girls who are postmenarcheal before age 11·5 years. Probably the postmenarcheal 11·5 line is best used, but the premenarcheal value at the correct age should also be consulted.

In the 1975 predictions we have subsidiary tables for older subjects, to be entered under bone age rather than chronological age. We think these should now be dropped.

Application in pathological cases. The new equations

are designed to apply to tall, short, and delayed children, but children who have specific pathological disorders are another matter. There is no particular reason why the equation should be valid in cases of precocious puberty or achondroplasia, for example; their applicability there must depend on empirical tests. In growth hormone deficiency we have enough experience to say with confidence that—whether or not the equation applied at diagnosis predicts accurately final height in the absence of treatment—certainly the prediction increases as treatment progresses and indeed is a good guide to its success or failure.

Allowance for parents' heights. In the TW Mark I version we suggested, we now think unwisely, that an allowance be made for parental heights. Clearly such an allowance must depend on the child's age. When the child has reached 95% of adult height and has tall parents, adding on 4 or 5 cm to the prediction is scarcely sensible. Users have tended to ignore this. In any case most of the covariance of parents' and offsprings' heights has already been expressed in the offspring by about the time of puberty and it now seems to us unlikely that parents' heights would add much to the accuracy of prediction, even if we had been able to include them in our standardising equations.

Applicability to other populations. In principle, regression equations derived from one population should be applied to another, only with considerable caution. It is questionable whether the British derived predictions apply to other European children, to children in North America, or children in

Japan, On average, American children are taller and more advanced, and Japanese are shorter and more advanced than British children. Do these differences in mean values affect the applicability of the equations to individuals?

The question is most simply approached by considering the bivariate case, for example the regression of adult height on height at age 10 years. For perfect transference from one population to another the within population regressions must be the same. This condition may be split into two subconditions, one of which we can test. (1) The means (adult height, height at 10 years) of the new population must lie on the regression line of the old; and (2) the slopes of the regression must be the same in the new and the old. The multivariate case is a generalisation of this.

The first condition we can test from data in the published reports. If the means lie on the regression line, then the equations will correctly predict mean adult height from earlier mean heights and bone ages. We have applied the equations of Table 2.1 to the mean values from age 8 years upwards of boys in the American NCHS, Boston and Berkeley studies, the Dutch 1971 survey, and the Japanese 1970 school data (values in Eveleth and Tanner).¹⁶ The adult mean value was predicted within 1 cm from each age in each of the American series, given the well attested assumption that these boys were 6 to 12 months more advanced in bone age for chronological age than the British standards. The Dutch boys produced similarly close values on the assumption of bone age equal to the British; and the Japanese also predicted within 1 cm on the assumption of bone age 12 to 15 months advanced and making an appropriate allowance for the secular trend.¹⁷ A similar test in girls is complicated by the division into pre- and postmenarcheal in the Tables. However, the premenarcheal equations of Table 3.1a predict the adult means within 1 cm for the same series, using the same bone age assumptions, up to and including 12.0 years, and the postmenarcheal equations of Table 3.1b predict the means from 14.0 years upwards nearly as well.

This result means that provided, and only provided, the regression coefficients are the same in the various populations, then the constant terms are similar and no constant adjustment should be made to compensate for German adults being taller than British, for example. No satisfactory test of the similarity of the regression coefficients may be made without raw data, so we cannot ourselves pursue this further. Users of the equations in countries other than the UK should, if possible, try them out on a local control group of normal children, including

some at the edges of the distributions. Pending such tests, however, it seems reasonable to use the equations with caution in clinical work in children, at least in industrialised countries.

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References

- 1 Bayley N, Pinneau SR. Tables for predicting adult height from skeletal age: revised for use with the Greulich-Pyle hand standards. *J Pediatr* 1952;41:371.
- 2 Tanner JM, Whitehouse RH, Marshall WA, Healy MJR, Goldstein H. *Assessment of skeletal maturity and prediction of adult height. (TW2 method)* London: Academic Press, 1975.
- 3 Roche AF, Wainer H, Thissen D. Predicting adult stature for individuals. *Monogr Paediatr* 1975;3:1-114.
- 4 Tanner JM. *Growth at adolescence*, 2nd ed. Oxford: Blackwell Scientific Publications, 1962.
- 5 Tanner JM, Whitehouse RH, Takaishi M. Standards from birth to maturity for height, weight, height velocity and weight velocity: British children 1965. *Arch Dis Child* 1966;41:454-71;613-35.
- 6 Marshall WA, Tanner JM. Variations in pattern of pubertal changes in girls. *Arch Dis Child* 1969;44:291-303.
- 7 Marshall WA, Tanner JM. Variations in the pattern of pubertal changes in boys. *Arch Dis Child* 1970;45:13-23.
- 8 Tanner JM, Whitehouse RH. *Atlas of children's growth: normal variation and growth disorders*. London: Academic Press, 1982.
- 9 Moore T, Hindley CB, Falkner F. A longitudinal research in child development and some of its problems. *Br Med J* 1954;ii:1132-7.
- 10 Tanner JM. *A history of the study of human growth*. Cambridge: Cambridge University Press, 1981.
- 11 Roche AF, Davila GH. Late adolescent growth in stature. *Pediatrics* 1972;50:874-80.
- 12 Tanner JM. Some notes on the reporting of growth data. *Hum Biol* 1951;23:93-159.
- 13 Tanner JM, Whitehouse RH, Hughes PCR, Vince FP. Effect of human growth hormone treatment for 1 to 7 years on the growth of 100 children, with growth hormone deficiency, low birthweight, inherited smallness, Turner's syndrome, and other complaints. *Arch Dis Child* 1971;46:745-82.
- 14 Weiner JS, Lourie JA, eds. *Practical human biology*. London: Academic Press, 1981.
- 15 Tanner JM, Whitehouse RH, Marshall WA, Carter BS. Prediction of adult height from height, bone age, and occurrence of menarche, at ages 4 to 16 with allowance for midparent height. *Arch Dis Child* 1975;50:14-26.
- 16 Eveleth PB, Tanner JM. *Worldwide variation in human growth*. Cambridge: Cambridge University Press, 1976. 276, 306, 358.
- 17 Tanner JM, Hayashi T, Preece MA, Cameron N. Increase in length of leg relative to trunk in Japanese children and adults from 1957 to 1977: comparison with British and with Japanese Americans. *Ann Hum Biol* 1982;9:411-24.

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