PREDICTION OF ADULT HEIGHT USING MATURITY-BASED CUMULATIVE HEIGHT VELOCITY CURVES

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Objective To validate and demonstrate how adult height can be predicted by using reference values obtained from maturity and sex-specific cumulative height velocity curves.

Study design Serial height measurements were taken on 224 boys and 120 girls. Individuals were classified as early, average, or late maturers, depending on their age of peak height velocity. Maturity and sex-specific cumulative height velocity curves were developed for early, average, and late maturers, and the area under these curves were used to develop reference values to predict adult height.

Results This method can predict adult height within ±5.35 cm 95% of the time in boys and ±6.81 cm 95% of the time in girls.

Conclusions The technique is a valid, nonintrusive, inexpensive, and simple method of predicting adult height in adolescent children, free of growth limiting diseases. ***(J Pediatr 2005;147:508-14)***

Growth in stature is known to have a distinct and measurable end point; however, children differ greatly in the rate at which they pass through the various phases of growth. Some children have a rapid tempo of growth and attain adult stature at a relatively early age, whereas others have a slow tempo and finish growing relatively late.[1] Thus, an accurate method of estimating adult height needs to incorporate an indicator of biological maturity.

Previous methods have incorporated measures of secondary sex characteristics[2] and age at menarche.[2,3] These methods, however, have restricted applicability. Age of menarche is limited to girls who have attained menarche; an event that occurs, on average, fairly late in adolescence.[4] Secondary sex staging techniques lacks precision as an indicator of maturity as the time it takes to move through the stages can be lengthy and vary considerably between individuals.[5,6]

The most popular predictive equations of adult height are the Bayley and Pinneau method,[7] the Roche-Wainer-Thissen method,[8,9] and the Tanner-Whitehouse method.[10,11] These methods all include assessment of skeletal age (or bone age) to account for variation in biological maturity. The assessment of skeletal age, however, is costly and requires exposure to radiation.

In an effort to develop a nonintrusive and inexpensive method of predicting adult height, the modified Roche-Wainer-Thissen method[12] and the Khamis-Roche method[13] were developed. These methods estimate adult stature from current age, stature, weight, and mid-parent stature (adjusted mean height of the parents). However, these nonintrusive methods do not include a measure of biological maturity. Although the inclusion of midparent height has been shown to reduce error in the prediction,[14-16] the heights of both parents are not always available.

Recently, a method of assessing biological maturity has been developed that requires chronological age of an adolescent and a measurement of height, sitting height, and weight.[17] The timing of leg length velocity and sitting height velocity is used to predict years from peak height velocity (PHV [the adolescent growth spurt in height]), which is an indicator of somatic maturity. This is a nonintrusive, inexpensive and simple way of assessing biological maturity and has the potential to be incorporated into methodologies for predicting adult stature.

It is known that during adolescence, early-maturing individuals of both sexes are closer to their adult height than average and late-maturing individuals of the same chronological age. This is due to their earlier attainment of PHV. This phenomenon is illustrated for male subjects in Figure 1, *A*. Compared with average and late maturers,

LLTS	Leuven longitudinal twin study	SGDS	Saskatchewan growth and development study
PBMAS	Pediatric bone mineral accrual study		
PHV	Peak height velocity		

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early maturers stop growing in height first. By full maturity, no difference in adult height between maturity groups exist.[18] In addition to the differential timing of PHV among maturity groups, early-maturing individuals also attain a greater magnitude of growth at PHV. This is evidenced when maturity group velocity curves are aligned on the common benchmark of PHV (Figure 1, *B*). To date, the techniques of predicting adult stature have predominantly used linear regression. We present a novel approach using cumulative height velocity (area under the velocity curve) for early-, average-, and late-maturing male and female subjects to predict the distance an individual has left to grow to adult height. If the present height of an individual is known and an estimation of height left to grow before reaching adult stature is predictable, then adult height can be ascertained. The purpose of this paper is to validate and then demonstrate how a child's adult height can be predicted by using reference values obtained from maturity and sex- specific cumulative height velocity curves.

METHODS

Subjects

Subjects were drawn from three longitudinal growth studies: the Saskatchewan Growth and Development Study (SGDS) (1964 to 1973; 1998 and 1999),[19] the Saskatchewan Pediatric Bone Mineral Accrual Study (PBMAS) (1991 to 1998; 2002 to 2004),[20] and the Leuven Longitudinal Twin Study (LLTS) (1985 to 1999).[21] Data from the SGDS and PBMAS were used to develop reference data to predict adult height, and data from the LLTS were used to test the accuracy of the prediction method.

The SGDS used a pure longitudinal design for the boys and a mixed longitudinal design for the girls. The boys were 7 years old at study entry and the girls were 7, 8, or 9 years old at study entry. The PBMAS used a mixed longitudinal design. Boys and girls were incorporated into eight age cohorts. The cohorts were between 8 and 15 years of age at study entry. The LLTS used a pure longitudinal design for the boys and girls, and all participants were 10 years old at study entry. One hundred percent of the SGDS and LLTS participants were white, and more than 98% of the PBMAS participants were white, with Aboriginal, Asian, and African accounting for the remaining 2%.

The studies received approval from the University and Hospital Advisory Committee on Ethics in Human Experimentation. Written informed consent was obtained from parents/guardians and their children. For inclusion in the present analysis, subjects required a measure of adult height and serial measures of stature around the attainment of PHV; 224 boys and 120 girls from the SGDS and the PBMAS fulfilled these requirements. The LLTS subjects required at least one measurement occasion during adolescence and a measurement of adult stature. One member of a subset of same-sexed twin pairs was used, which resulted in data from 28 boys and 24 girls.

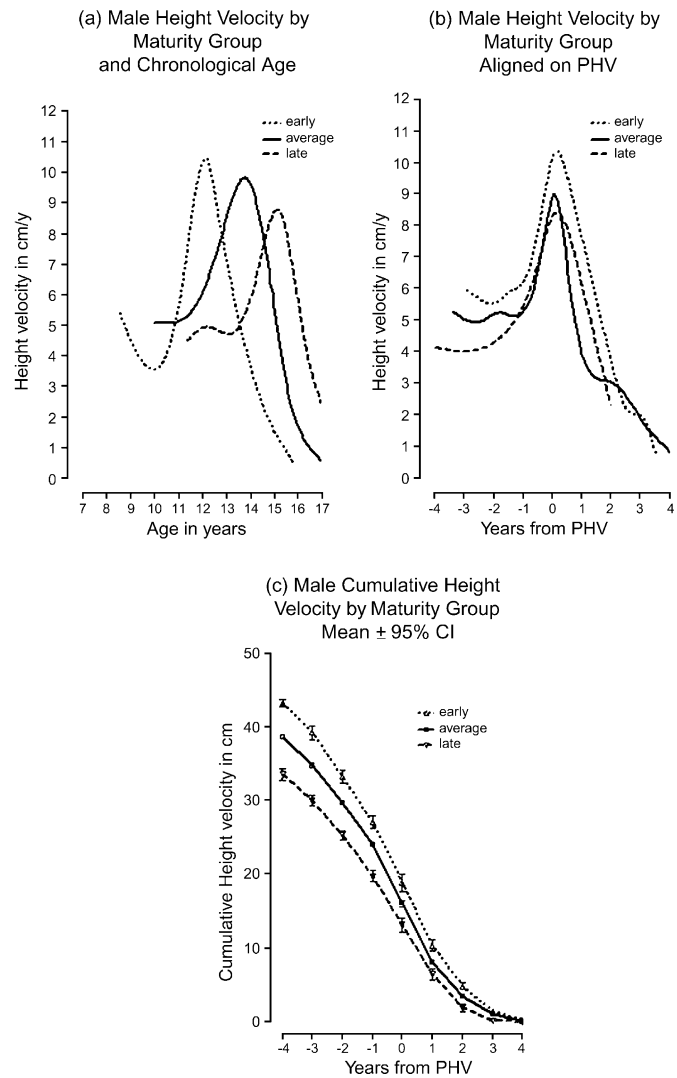

Figure 1. **A**, Height velocity aligned to chronological age. **B**, Height velocity aligned to peak height velocity (PHV). **C**, Cumulative height velocity curves aligned to PHV for early- (n = 35), average- (n = 156), and late-maturing (n = 33) boys (SGDS and PBMAS data).

Anthropometric Assessment

All of the studies longitudinally assessed stretched height (cm). Individuals enrolled in the SGDS were assessed on an annual basis, and individuals enrolled in the PBMAS and LLTS were assessed on a semiannual basis. The LLTS also assessed stretched sitting height (cm) and weight (kg). Sitting height was subtracted from standing height to provide an estimate of leg length in the LLTS sample. Two measurements were taken for standing stature, sitting stature, and body mass. A third measure was required if the two measures differed by more than 4 mm for standing stature and sitting stature and 0.4 kg for body mass.[19,20] The average of the two closest readings was used.[22]

Peak Height Velocity

Peak height velocity was identified in the SGDS and PBMAS samples. Standard whole-year velocity calculations

Table 1. The average age at peak height velocity (years) and the height velocity (cm/year) of early, average and late maturing boys and girls

		Boys			Girls		
Variable	**Maturity**	**N**	**Mean**	**S.D**	**N**	**Mean**	**S.D**
Age at PHV (years)	Early	35	12.33	0.47	18	10.30	0.40
	Average	156	13.85	0.65	85	11.58	0.65
	Late	33	15.26	0.44	17	12.92	0.38
	Total	224	13.82	1.01	120	11.58	0.92
Height Velocity at PHV (cm/year)	Early	35	10.3	1.16	18	9.3	1.06
	Average	156	9.8	1.27	85	8.1	1.03
	Late	33	8.8	1.35	17	8.0	0.86
	Total	224	9.7	1.33	120	8.3	1.08

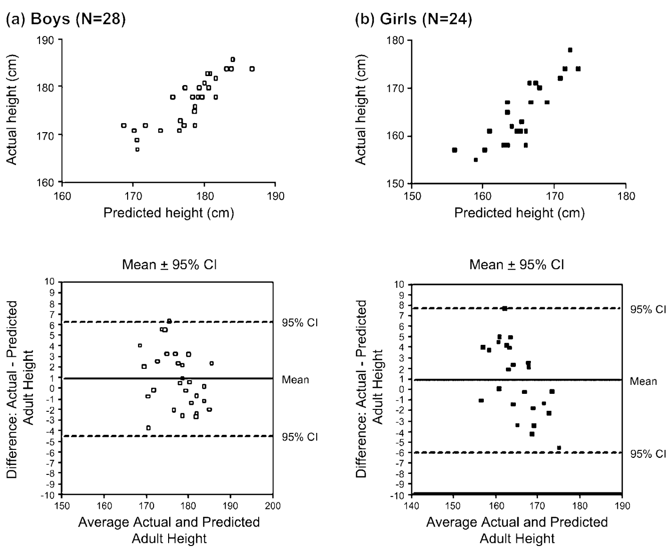

Figure 2. Scatterplots and Bland Altman procedure for LLTS in **A**, boys, and **B**, girls.

were applied to height distance measurements for each individual. The velocity age center for each velocity value represented the mid-point between two measurement occasions. A cubic spline (GraphPad Prism version 3.00 for Windows, GraphPad Software, San Diego, Calif) was applied to the individual velocity values and an age of PHV identified. A more detailed discussion of the cubic spline procedure has been published elsewhere.[23]

Individuals were aligned on their PHV (biological age). This was done by subtracting the chronological age at time of test from the chronological age at PHV. Thus, a continuous measure of biological age was generated. Biological age groups were constructed using 1-year intervals such that the −1 PHV age group included observation between −1.49 and −0.50 years from PHV.

In the LLTS sample, age at PHV was predicted by using a sex-specific regression equation.[17] The equation consists of chronological age, leg length, weight, and trunk length and was used to predict the number of years from PHV. Subtracting years from PHV from age at test gave a predicted age at PHV. The LLTS were categorized as early-, average-, and late- maturing, depending on age of PHV. Early maturers were defined as preceding the average age of PHV (12.0 years of age in girls and 14.0 years of age in boys; for discussion, see Reference 24)[24] by 1 year; average maturers were ±1 year from PHV; and late maturers were >1 year after PHV.

Cumulative Height Velocity

Average velocity values around PHV were calculated for the SGDS and PBMAS sample. Each individual velocity curve was aligned on zero, and general mean cumulative velocity curves were calculated for early, average, and late maturers. With the use of using GraphPad Prism, the area under the cumulative velocity curve for early, average, and late maturers was calculated by using the trapezoid rule for each 0.1-year interval.[25]

Accuracy of Prediction

The accuracy of the area under the cumulative velocity curve tables developed was assessed by predicting the adult height of boys and girls from the LLTS at one time point during adolescence. The testing point used in each individual was selected at random. Predicted years from PHV were used to estimate height left to grow for each individual using the maturity specific cumulative velocity curves. Height left to grow was added to height at time of test to provide a predicted adult height for each individual. Statistical difference between actual and predicted height was estimated using dependent *t* tests, and correlation coefficients were computed. Statistical significance was set at $P < .05$. (SPSS version 11.5, SPSS Inc, Chicago, Ill). Predicted adult height was compared against actual adult height according to the procedure described by Bland and Altman.[26]

Table II. Distance (cm) left to grow in height for early, average and late maturing males and females at different biological ages (years from PHV)

Years from PHV	Growth (cm) left before adult stature is reached					
	Males			Females		
	Early	Average	Late	Early	Average	Late
−4.0	45.29	40.09	34.73	42.61	38.81	34.35
−3.8	44.21	39.08	33.83	41.49	37.67	33.27
−3.6	43.11	38.07	32.94	40.39	36.55	32.20
−3.4	41.99	37.06	32.05	39.30	35.44	31.14
−3.2	40.85	36.05	31.16	38.21	34.34	30.09
−3.0	39.69	35.04	30.27	37.13	33.25	29.04
−2.8	38.52	34.04	29.38	36.04	32.16	27.99
−2.6	37.33	33.05	28.49	34.94	31.04	26.93
−2.4	36.15	32.06	27.60	33.82	29.91	25.87
−2.2	34.97	31.07	26.70	32.68	28.76	24.79
−2.0	33.80	30.06	25.77	31.53	27.58	23.71
−1.8	32.62	29.03	24.79	30.44	26.39	22.63
−1.6	31.44	27.95	23.74	29.36	25.21	21.55
−1.4	30.23	26.83	22.63	28.24	24.03	20.47
−1.2	28.98	25.63	21.45	27.09	22.85	19.37
−1.0	27.66	24.36	20.22	25.87	21.66	18.25
−0.8	26.24	22.99	18.96	24.54	20.44	17.07
−0.6	24.68	21.51	17.68	23.09	19.16	15.81
−0.4	22.96	19.88	16.31	21.50	17.80	14.44
−0.2	21.07	18.09	14.76	19.77	16.33	12.94
0.0	19.04	16.16	13.05	17.94	14.75	11.36
0.2	16.96	14.21	11.32	16.09	13.13	9.81
0.4	14.92	12.35	9.71	14.30	11.56	8.42
0.6	13.01	10.65	8.27	12.64	10.11	7.20
0.8	11.26	9.12	6.94	11.11	8.77	6.12
1.0	9.70	7.78	5.70	9.69	7.52	5.13
1.2	8.33	6.59	4.54	8.39	6.37	4.24
1.4	7.11	5.54	3.51	7.20	5.33	3.46
1.6	6.04	4.62	2.64	6.14	4.42	2.80
1.8	5.10	3.80	1.92	5.19	3.64	2.25
2.0	4.26	3.09	1.35	4.36	2.99	1.82
2.2	3.52	2.48	0.91	3.63	2.45	1.46
2.4	2.86	1.96	0.58	2.99	1.99	1.18
2.6	2.29	1.52	0.32	2.42	1.60	0.94
2.8	1.78	1.16	0.13	1.92	1.26	0.74
3.0	1.34	0.87	0.00	1.47	0.96	0.57
3.2	0.96	0.63	0.00	1.07	0.69	0.41
3.4	0.64	0.43	0.00	0.72	0.46	0.28
3.6	0.37	0.27	0.00	0.43	0.26	0.17
3.8	0.16	0.12	0.00	0.19	0.11	0.08
4.0	0.00	0.00	0.00	0.00	0.00	0.00

PHV=peak height velocity.

RESULTS

The number of SGDS and PBMAS individuals classified as early, average, and late maturers and the average age of PHV and height velocity for each maturity group are shown in Table I. The early-maturing individuals achieved greater magnitude in height velocity compared with late-maturing individuals.

Figure 1 shows (*A*) height velocity aligned to chronological age, (*B*) height velocity aligned to PHV, and (*C*) cumulative height velocity curves for early-, average-, and

Table III. A worked example of predicting years from peak height velocity for a male

Maturity Offset = -9.236 + (0.0002708 * Leg Length & Sitting Height interaction) + (-0.001663 * Age & Leg Length interaction) + (0.007216 * Age & Sitting Height interaction) + (0.02292 * Weight by Height Ratio)

Age	11.25 years
Height	149.4 cm
Weight	40.0 kg
Leg Length	70.4 cm
Sitting Height	79.0 cm
Leg Length & Sitting Height interaction	70.44 * 79.0 = 5561.60
Age & Leg Length interaction	11.253 * 70.4 = 792.21
Age & Sitting Height interaction	11.253 * 79.0 = 888.99
Weight by Height Ratio	(40.0/149.4) * 100 = 26.77

Maturity Offset = -9.236 + (0.0002708 * 5561.60) + (-0.001663 * 792.21) + (0.007216 * 888.99) + (0.02292 * 26.77) = - 2.0 years from PHV

Age at PHV = 11.25 year - -2.0 = 13.25 years = average maturer

Predicted adult height = 149.4 cm+ 30.06 cm (see table II) = 179.46 cm

late-maturing boys from the SGDS and PBMAS samples. Figure 1 provides a visual description of the steps taken to produce the cumulative height velocity curves. The 95% confidence intervals in Figure 1, *C*, indicate a significant difference in cumulative height velocity between early-, average-, and late-maturing male subjects before PHV. Similar steps were taken for girls from the SGDS and PBMAS samples. The area under each of these curves for boys and girls is portrayed in Table II. Table II shows the height left to grow for each fifth of a year from −4 years to +4 years from PHV for early-, average-, and late maturing-boys and girls.

Figure 2, *A* and *B*, illustrates the scatterplots and Bland Altman procedure for the boys and girls from the LLTS sample. Correlations between predicted height and actual height were 0.86 and 0.85 ($P < .05$) for boys and girls, respectively. In the Bland Altman procedure, the averages of the predicted and actual adult height are plotted against the difference between the two values. The mean difference between the two measurements was 0.91 cm, with a standard deviation of 2.72 cm in boys and 0.92 cm, with a standard deviation of 3.47 cm in girls: neither difference was significant ($P > .05$). This method can predict final height ±5.35 cm 95% of the time in male subjects and ±6.81 cm 95% of the time in female subjects.

DISCUSSION

The method of predicting adult stature presented in this communication is simple to use and, unlike other nonintrusive methods, it takes into account the child's biological maturity status (rate of somatic growth). Popular methods to date have used multiple variables within a regression equation to predict biological maturity. The method displayed in this paper predicts adult height by using the area under cumulative height velocity curves for early-, average-, and late-maturing individuals, and, to the authors' knowledge, this is a novel approach. Results show that this new method predicts adult stature with a reasonable degree of accuracy. Previous methods that used skeletal age reported being able to predict adult height anywhere between 5 cm and 8 cm 95% of the time in boys and anywhere between 2.7 cm and 7.8 cm 95% of the time in girls.[2,3,10,27] The error associated with the prediction method presented in this communication falls within this range. However, it should be noted that to obtain this degree of accuracy, correct protocols of measuring sitting height, standing height, and weight need to be followed. If accurate measurements are not ensured, there is a chance that an individual could be placed into the wrong maturity category (ie, an average-maturing individual categorized as late maturing).

To facilitate a better understanding of the practical utility of the methods, we show the following example of predicting the adult height of a boy 11.25 years of age. Sitting height, leg length (subtract sitting height from standing height), weight, and chronological age are entered in to the sex-specific regression equation[17] to predict years from PHV. An example is shown in Table III. The equation estimates that the boy is −2 years from PHV. Age at PHV is calculated by subtracting years from PHV from the boy's chronological age (11.25 to −2.0 = 13.25 years). For a boy, the average age at PHV is approximately 14.0 years,[1,24] so the boy's age at PHV falls within 1 year of this value and thus is categorized as an average maturer. The calculated years from PHV is now used to determine how much growth the boy has left until he reaches his adult and final height. Using Table II, one can determine that an average-maturing boy at −2.0 years from PHV has 30.06 cm left to grow. His present height is 149.4 cm, thus his predicted adult height is 179.46 cm (149.4 + 30.06 = 179.46).

Although methods of predicting adult stature that use skeletal age are the gold standard, this new technique could be useful as a nonintrusive and inexpensive estimate of a child's final height. Although there is a curiosity in the adult height of normal-growing children, the real interest lies in predicting the adult height of children who are abnormally tall or abnormally small. This is of importance because growth problems can have an impact on the child's physical and psychosocial well-being, interfering with school performance, sports participation, and social integration.[28] Prediction of adult height is a useful tool, both in the diagnosis and in the treatment of abnormal growth; however, we strongly suggest that the method presented in this paper only be used in children free of growth-limiting disease. Caution should be taken when using this equation to predict heights of children with abnormal growth (ie, individuals with hyperthyroidism or hypothyroidism, and so forth), as the reference standards and maturity predictive equation presented in this paper are modeled on a population of normal-growing children. Unfortunately, there are limited longitudinal data that document the natural patterning of growth in abnormally tall or abnormally short children to be able to validate the predictive equation presented in this paper. The lack of longitudinal data is primarily because therapeutic interventions are often used in individuals demonstrating abnormal growth, which alters the destined growth of the child. Furthermore, the patterning of growth may be different, depending on the disease; thus, the prediction technique needs to be disease specific. In addition, this prediction method has been developed and validated on primarily Caucasian boys and girls. Future work would need to validate this method by using data from other ethnic populations. A website (http://www.usask.ca/kinesiology/research_index.php) is available in which a child's adult height can be estimated by using the methodology described in the present paper.

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