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RESEARCH PAPER

A chart to predict adult height from a child's current height

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Background: A child's adult height is commonly predicted using their target height, based on mid-parent height. However, if no growth disorder is suspected, the child's current height is a far better predictor of their adult height.
Aim: To develop a chart to predict a child's adult height from their current height, adjusting for regression to the mean.
Subjects and methods: Data from the First Zurich Longitudinal Growth Study provided correlations between child height and adult height by age and sex, for use in a regression model predicting adult height centile from child height centile. The model was validated using data from the British 1946 and 1958 birth cohorts.
Results: The chart is illustrated superimposed on the British 1990 boys height chart. The predicted height has a standard error of 4–5 cm for ages from 4 years to puberty in both sexes. The regression adjustment partially compensates for biased predictions in early and late developers in puberty. A simplified version of the chart for restricted age ranges is also shown, as used on the UK-WHO 0–4 years growth charts.
Conclusion: The height prediction chart should be of value for parents, and indirectly professionals, to predict adult height in their children.

Keywords: Height, chart, child, adult, prediction

INTRODUCTION

Ever since Francis Galton introduced the concept of the mid-parent height in 1886 (Galton 1886; Cole 2000a), it has been the cornerstone of methods to assess the normality of height growth in children relative to their parents. The conventional target height assessment involves two distinct predictions of adult height: the target height based on the parents' heights, and the adult height corresponding to the child's current height centile. Of these, the better predictor will be the one that correlates most highly with the child's future adult height, although using the parents' heights is important if the child is believed to have a growth disorder (van Buuren et al. 2004).

The correlation between mid-parental target height and adult height is theoretically 0.7 based on genetic arguments, but reported values are lower, 0.4–0.55 (Himes et al. 1981; Cole 2000b) and broadly independent of the child's age (Cole 2000b). In contrast the correlation between child height and adult height changes with the child's age—low at birth, rising through childhood and reaching one in adulthood. Several longitudinal growth studies have published child–adult correlations over a range of ages, for example the First Zurich Longitudinal Growth Study (Molinari et al. 1995).

The British 1990 reference height chart (Freeman et al. 1995) includes a box for plotting the mid-parental target height range, along with instructions for deriving it. Despite this it has not been widely used as it is fiddly to do and easy to get wrong; it also requires the heights of both parents to calculate mid-parent height and cannot be calculated if either is unknown. Furthermore its statistical basis is unsound as the prediction does not include an adjustment for regression to the mean (Wright and Cheetham 1999; Hermanussen and Cole 2003). Statistically the more correct approach is to adjust the child's current height for parental height using regression analysis and a chart for this purpose has been published (Cole 2000b).

An alternative approach is to predict adult height from the child's current height. Tanner et al. (1975; 1983) used height and bone age to predict adult height, but the methods were complex and focused on puberty. This paper revisits the process of predicting adult height, with the aim of improving and simplifying the assessment for community use. The result is a graph that can be added to a height centile chart and a simplified look-up is already in use on the UK-WHO 0–4 years chart (Wright et al. 2010).

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METHODS

The charts to be described here make use of the Zurich Growth Study correlations, which were based on slightly smoothed height data from 120 boys and 112 girls (Molinari et al. 1995). Figure 1 shows the child–adult height correlations for this cohort by age and sex. The correlation is ~ 0.4 at birth, similar to that for mid-parental target height, but it rises steeply through infancy and by 2 years reaches 0.65 in girls and 0.75 in boys, appreciably higher than for target height. The correlation rises more gradually through childhood, but is interrupted by a fall during puberty due to increased variability at that time. Thus, at all ages past infancy current height is better than mid-parental target height for predicting adult height.

These correlations can be used to make individual predictions of adult height. Height is converted to an SD score z using the formula

$$z = \frac{Height - Mean}{SD} \tag{1}$$

where Mean and SD are constants for age and sex, here obtained from the British 1990 reference (Freeman et al. 1995). The SD score can optionally be converted to a centile using Normal distribution tables. Formula (1) applies to heights for all ages from birth to 23 years. For growth references such as the British 1990, constructed using the LMS method (Cole and Green 1992), Mean corresponds to the M value in the LMS tables and SD is the product $M \times S$ (where S is the coefficient of variation). The values at age 20 are $M = 177.3$, $SD = 7.0$ cm for males and $M = 163.6$, $SD = 6.0$ cm for females.

Reversing formula (1) expresses height in terms of SD score z:

$$Height = SD \times z + Mean. \tag{2}$$

Conventionally a child's likely adult height is predicted from their current height on the assumption that their height SD score (and centile) will remain the same from child to adult. Thus, if subscript c indicates 'child' and a denotes 'adult' then the assumption is that

$$z_a = z_c. \tag{3}$$

It follows from (2) that

$$\begin{aligned} Height_a &= SD_a \times z_a + Mean_a \\ &= SD_a \times z_c + Mean_a \end{aligned} \tag{4}$$

So predicted adult height in equation (4) is a linear function of the child's SD score z_c and constants from the growth reference.

The key assumption here is equation (3), that the predicted adult SD score is equal to the child SD score. However, since this is a prediction it is improved using regression. The regression equation predicting adult SD score from child SD score can be written formally (Cole 1995) as

$$z_a = r \times z_c \tag{5}$$

where z_c and z_a are the SD scores for the child now and as an adult, and r is the child–adult correlation from Figure 1 for the child's age. In words this prediction 'shrinks' the child SD score towards the mean by an amount corresponding to the correlation, and the smaller the correlation the greater the shrinkage. It leads to a predicted adult height analogous to equation (4),

$$\begin{aligned} Height_a &= SD_a \times z_a + Mean_a \\ &= SD_a \times r \times z_c + Mean_a \end{aligned} \tag{6}$$

with a standard error (Cole 1995) given by

$$SE(Height_a) = SD_a\sqrt{1 - r^2}. \tag{7}$$

Formula (6) again consists of mean adult height, $Mean_a$, plus a term proportional to the child's SD score z_c, so it is feasible to include the prediction in the height centile chart.

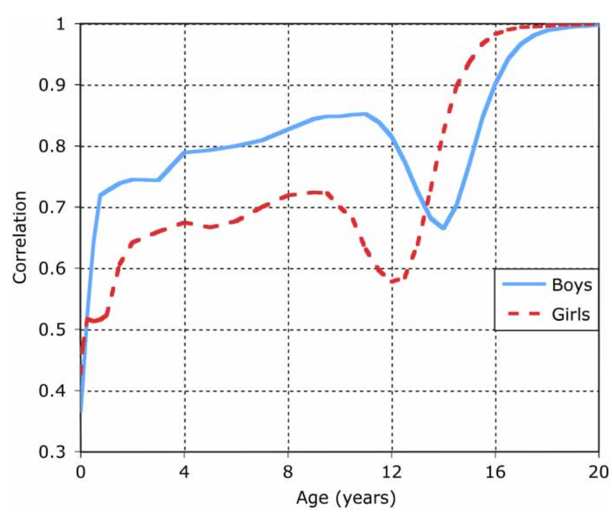

Figure 1. The correlation between a child's current height and their adult height, by age and sex (Molinari et al. 1995).

Validation

The accuracy and precision of this prediction (6) was tested using subjects from the 1946 and 1958 British birth cohorts, whose heights were measured in adulthood and at several ages in childhood, allowing the observed and predicted adult heights to be compared. The 1946 cohort, consisting originally of 3562 subjects recruited at birth in a single week in 1946 (Wadsworth et al. 2006), were measured at 2, 4, 6, 7, 11, 15 and 20 years. The 1958 cohort, consisting originally of over 17 000 subjects recruited at birth in a single week in 1958 (Power and Elliott 2006), were measured at 7, 11, 16 and 23 years. The heights at age 20 in the 1946 cohort and age 23 in the 1958 cohort were treated as adult height. All the heights were converted to SD scores relative to the British 1990 reference (Freeman et al. 1995) and predicted heights obtained using formula (6). The prediction errors are

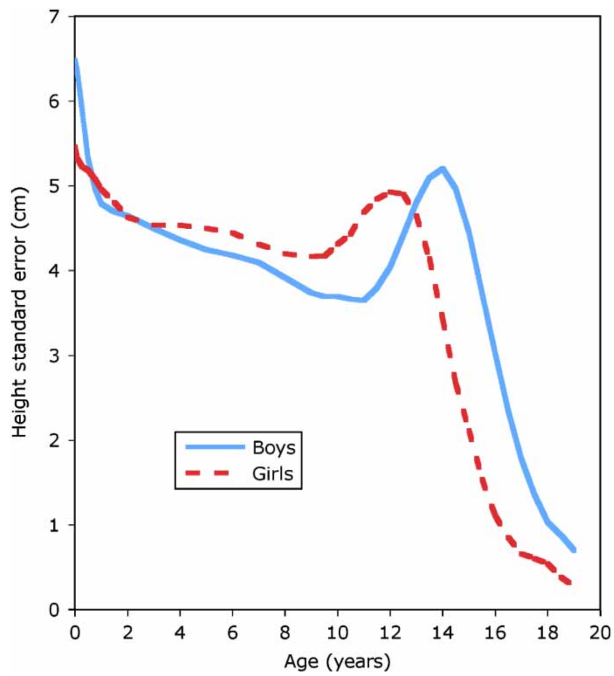

Figure 2. The standard error of the height prediction from equation (7), by age and sex.

summarized as the mean and SD of the residuals (i.e. observed height − predicted height).

Age 0–20 years chart

The correlations in Figure 1 were used to construct a set of height predictor centile curves for age 0–20 years, illustrated with the British 1990 height chart (Freeman et al. 1995). This chart is in nine centile format with centiles spaced two-thirds of an SD apart (Cole 1994). From (6) the predictor median curve (i.e. for $z_c = 0$) is a horizontal straight line across the chart at height Mean_a (177.3/163.6 cm for boys/girls) and the other predictor centile curves are above or below it by an amount $\text{SD}_a \times r \times z_c$. Because r changes with age, these spacings are not constant and the predictor centiles (apart from the median) are curved not straight.

As an example consider the 98$^{\text{th}}$ predictor centile at 3 years, where r is 0.764 for boys and 0.660 for girls (Figure 1) and the 98$^{\text{th}}$ centile corresponds to $z_c = +2$ (Cole 1994). The predicted adult height for a child aged 3 on the 98$^{\text{th}}$ centile is above the median by

$$\begin{aligned} SD_a \times r \times z_c &= 7.0 \times 0.764 \times 2 = 10.7\,\text{cm} \\ &= 6.0 \times 0.660 \times 2 = 7.9\,\text{cm} \end{aligned} \tag{8}$$

for boys/girls, giving predicted adult heights (6) of 188.0/171.5 cm. Similar calculations at other ages make up the 98$^{\text{th}}$ predictor centile curve and similarly for the other predictor centiles. This description should become clearer with the example.

Illustrative growth data

Heights collected opportunistically for one boy through childhood were used to illustrate the chart. He was measured standing barefoot against a wall with head in the Frankfort plane; a square ceramic tile held vertical, perpendicular to the wall and with one edge pressed against it was lowered onto his head, the level of the lower edge was marked on the wall, and this height was measured and recorded in a book.

Age 2–4 years chart

A simplified chart based on equation (6) is included in the UK-WHO charts (Wright et al. 2010), the 2–4 years height chart of the Personal Child Health Record (PCHR). The correlations in Figure 1 change little from 2–4 years so the height predictor centiles at 3 years are used. They are presented at the top right of the height chart as ‘ladders’ of centiles where the rungs are the nine centiles and the uprights are the corresponding adult height scales in metric and imperial units.

To test this height predictor, a total of 78 NHS staff in seven focus groups were given a hypothetical child’s age and height and asked to predict their adult height and range using the chart (Wright et al. 2011). In addition 15 parents in three focus groups were shown the predictor and asked for their comments.

RESULTS

Variability of the adult height prediction

Figure 2 shows the theoretical standard error of the height prediction by age and sex as derived from equation (7). The error is largest in infancy, then close to 4.5 cm during mid-childhood, higher again in puberty and then falling to 0 as adulthood approaches.

The corresponding errors of prediction as observed in the 1946 and 1958 British birth cohorts at each age are summarized in Tables I and II. After age 4 the SDs are broadly below 5 cm, but at younger ages they are somewhat higher, particularly for boys at age 2. The mean biases are all less than 2 cm. Thus, after age 4 the observed and predicted standard errors of 4.5–5 cm are broadly in

Table I. 1946 cohort: summary statistics for error in predicting height (cm) at age 20.

Age	Sex	n	Mean error	SD of error
2	Boys	1551	1.1	8.5
	Girls	1419	0.3	6.6
4	Boys	1683	0.7	6.0
	Girls	1575	−0.3	5.2
6	Boys	1605	1.6	5.0
	Girls	1504	0.5	4.6
7	Boys	1647	1.4	4.9
	Girls	1577	0.4	4.5
11	Boys	1622	1.2	4.6
	Girls	1546	0.1	4.9
15	Boys	1557	1.9	5.2
	Girls	1434	1.2	3.4

Table II. 1958 cohort: summary statistics for error in predicting height (cm) at age 23.

Age	Sex	n	Mean error	SD of error
7	Boys	5102	0.4	5.1
	Girls	5127	−0.4	4.8
11	Boys	4884	0.4	4.8
	Girls	4929	−0.6	5.1
16	Boys	4465	1.1	4.4
	Girls	4435	0.6	2.5

agreement and the mean biases are appreciably smaller than the SDs.

For parents' use the chart needs to present a confidence interval for the height prediction that is wide enough to cover most children, but not so wide as to devalue the prediction. The compromise chosen was to quote on the chart instructions an 80% confidence interval, corresponding to ± 1.28 SDs or ∼ ± 6 cm. However, in light of the results in Table I this ought to be larger at age 2–4.

Age 0–20 years chart

Figure 3 shows the nine adult height prediction centiles for boys on the British 1990 0–20 years height chart (Freeman et al. 1995). The shape of each prediction centile curve reflects the shape of the correlation curve (Figure 1), with a low correlation in early life, rising to a peak at age 11 before the pubertal dip, then rising again to one in adulthood.

The chart is used as follows:

(1) Plot the child's height on the height chart and read off the height centile; and
(2) Plot this centile at the same age on the adult predictor centile curves and read off the predicted adult height.

To illustrate the method, 68 height measurements from 3–20 years for one boy are plotted on the boys chart (Figure 3). (The method would normally be applied one age at a time, but plotting the measurements together shows how the prediction varies with age.) The heights are first plotted on the centiles in the usual way (dots), showing a tall boy with heights between the 91st and 99.6th centile, an early puberty with the peak centile at 13 years and a final height of 188.6 cm (shown with a larger dot). The regression-adjusted adult predictions in equation (6) are plotted above the observed heights using the adult prediction centile curves (and shown as filled triangles), so that for example the first two measurements, just before age 3, are respectively above and below the 91st centile and they predict an adult height of 184–185 cm. (It is unfortunate that the chart label obscures the prediction centiles before age 6). In addition the corresponding unadjusted adult predictions (equation 4)

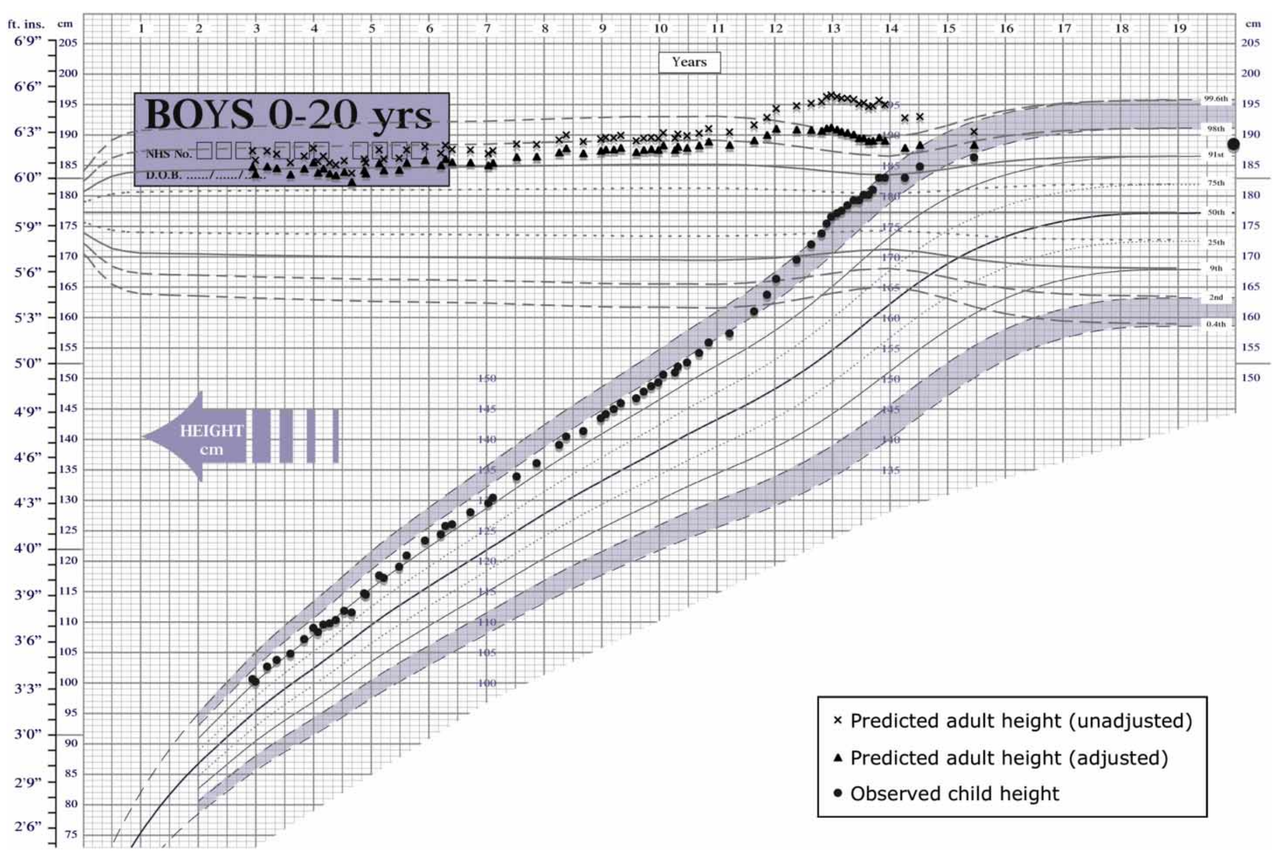

Figure 3. A composite height chart for boys containing British 1990 reference centiles (Freeman et al. 1995) and adult prediction centiles. The measured heights are plotted as dots, the unadjusted height predictions (equation 4) as crosses and the adjusted predictions (equation 6) as triangles.

are plotted above the observed heights (as crosses), the predictions being the heights at age 20 whose centiles correspond to the centiles at each age. Note that these latter points would not normally be plotted and they are included only for comparison purposes.

The unadjusted predictions range from 184–196 cm (mean 190.1 cm) and 15 of the 67 (22%) differ from adult height by more than 6 cm, all after age 12. In contrast the adjusted predictions range from 182–191 cm (mean 187.3 cm) and just one (1.5%) is outside the ± 6 cm range. Figure 3 illustrates how the shrinkage works—the unadjusted values are too high in puberty between 12–14 years due to the boy's early puberty, but this is at a time when uncertainty in the timing of puberty makes the correlation relatively low, so that the regression adjustment compensates partially for the exaggerated height prediction.

Age 2–4 years lookup

The adult height predictor ladders on the PCHR 2–4 years height chart are shown in Figure 4 for the two sexes. The instructions for use are as follows:

(1) Plot the child's height on the height chart and read off the height centile; and
(2) Plot this centile on the adult height predictor ladder and read off the predicted adult height. Four-fifths of predictions are within ± 6 cm of the true value.

In the focus group validation 63/67 (94%) of the NHS staff testing the chart predicted a height within 1 cm of the

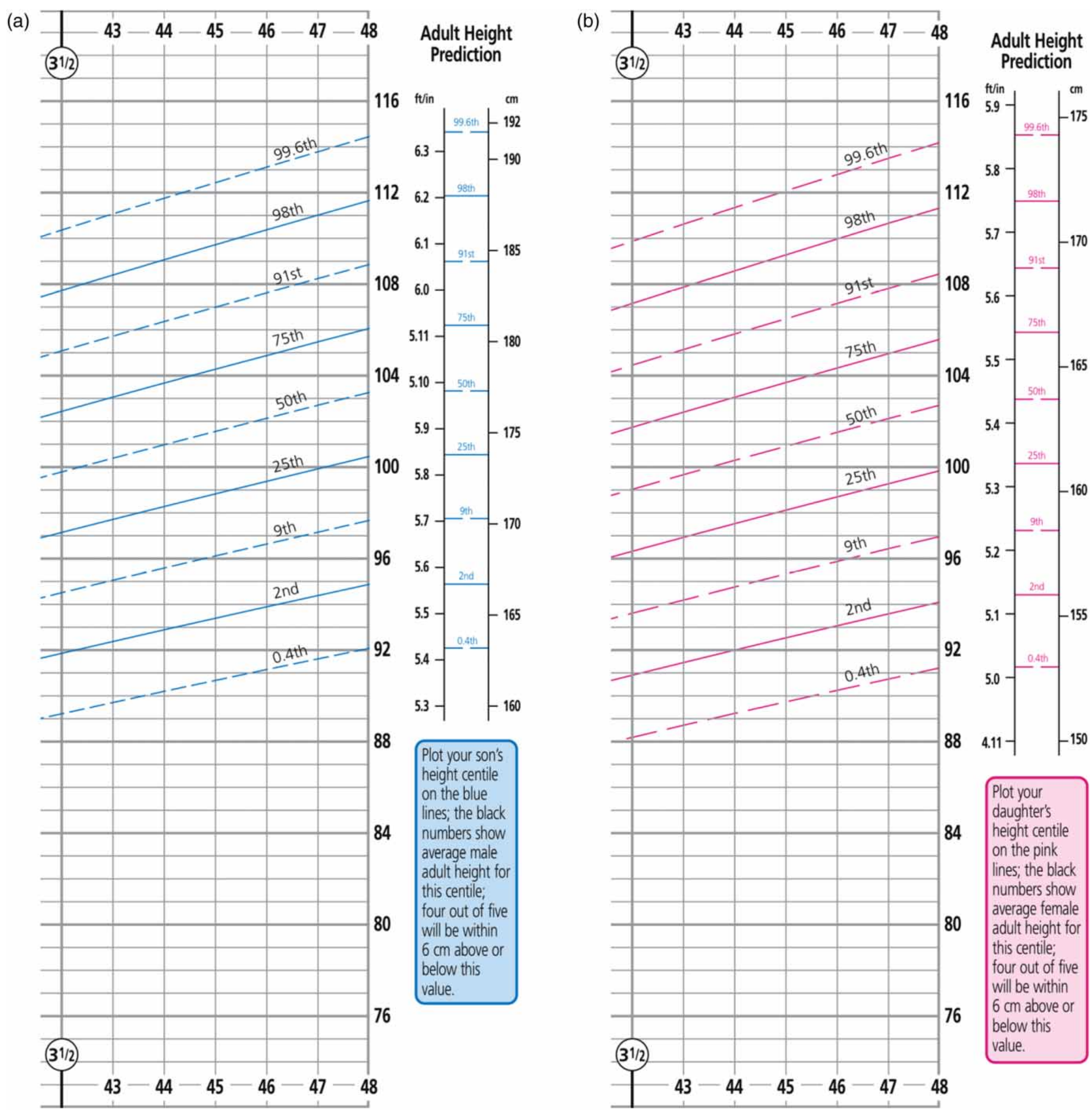

Figure 4. The adult height predictor in the UK-WHO 2–4 years height chart, for boys (left) and girls (right).

correct value (Wright et al. 2011). However, only 43/74 (58%) correctly interpreted the range. The mothers shown the chart were enthusiastic about it, some comments being 'fabulous', 'much easier' and 'straightforward, simple and easy to understand'. They were told about the range of uncertainty but their understanding of it was not tested.

DISCUSSION

Adult height prediction allows parents and professionals to predict a child's adult height at any age from birth onwards. Current advice for parents wanting to estimate adult height is to double a boy's height at age 2 or a girl's height at 18 months, but this is both restrictive and biased. So a prediction chart satisfies a real need, providing a simple and unbiased estimate of adult height for children of any age.

The combined height centile chart in Figure 3 offers a way to provide the height prediction most accurately while simultaneously showing the actual height centiles. The adjusted predictions are less biased than the unadjusted predictions and, in particular, the peak height centile in puberty is attenuated by the adjustment.

The standard error of the predictor is ~ 5 cm, as predicted from the correlations (7) and observed in the two British birth cohorts (Tables I and II). This leads to the 80% confidence interval of ± 6 cm quoted for the 2–4 years predictor chart, although in practice a larger interval of ± 7 cm would be more appropriate (see Table I). The equivalent 95% range of ± 8–10 cm is similar to that claimed for mid-parental target height, although the true value for target height is actually ± 10–11 cm (Hermanussen and Cole 2003). For comparison the population 95% range for adult height with the British 1990 reference is ± 12–13 cm (Freeman et al. 1995). This confirms that, after infancy, mid-parental target height is not as good a predictor as the child's current height and both are more precise than unadjusted adult height.

The shapes of the prediction centile curves reflect the way the child–adult correlation changes with age, as estimated from the Zurich Growth Study (Molinari et al. 1995). It is likely that the shape would be broadly similar if other correlations were used instead. One uncertainty is the timing of the pubertal dip, which is centred on the age at peak height velocity and which is earlier now than at the time of the Zurich Study.

Another uncertainty is the difference in the correlation profiles by sex (Molinari et al. 1995). In boys the correlation increases linearly from 9 months to adult apart from the pubertal dip. In girls the correlation increases linearly from 2 years to puberty, but the value at puberty onset is much smaller than for boys (0.72 for girls at age 9 vs 0.85 for boys at age 11). Thus, the degree of tracking in puberty is appreciably less for girls than boys.

The standard error curves in Figure 2 are very similar in shape to the plot of height velocity vs age—high in infancy, low in mid-childhood, higher in puberty and zero in adulthood (Tanner et al. 1966). This implies that height velocity affects the age-changing prediction error and in turn the underlying child–adult correlation—at ages when the velocity is high the child–adult correlation is relatively low and vice versa.

The adult height predictor is designed more for parents than as a clinical tool. The simple version included on the UK-WHO 0–4 years charts has already proved popular and a similar look-up could easily be generated for all pre-pubertal children, since the correlation changes relatively little from 2–10 years (Figure 1). However, to include puberty the full chart is needed to cope with the pubertal dip in correlation (Figure 3). An alternative would be to print the predictor centiles on a wipeable transparent plastic overlay, to be placed on the height chart with the median lined up with median adult height, and this could be used with existing charts and would avoid the need to design a new chart.

For clinicians concerned about possibly abnormal growth the prediction needs to be compared to the parents' heights. Further work is underway to develop a refinement of this approach which would also allow both parents' height centiles to be plotted and compared.

In conclusion, this adult height prediction approach provides a simple yet powerful tool to allow parents to predict their child's adult height at any age during childhood. Further work is needed about how best to incorporate parental heights in the chart for clinical assessment purposes.

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