

# Lung function in white children aged 4 to 19 years: I—Spirometry

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## Abstract

**Objective**—A study was performed to produce reference standards for spirometric lung function in white children and to calculate standard deviation scores adjusted for gender and pubertal stage.

**Methods**—A cross sectional study was made of 772 white children aged 4.6 to 18.8 years (455 male) tested on an OHIO 840 spirometer and assessed anthropometrically and pubertally.

**Results**—Before puberty there was a linear increase in all lung function measurements with height. During puberty a sudden increase occurred, but subsequently the relationship was again linear. No simple single equation described this pattern. Advanced puberty in younger children conferred a respiratory advantage, whilst delayed puberty resulted in the converse. Girls had poorer volumes per unit height, but young girls had superior airflow/unit lung volume. In both sexes lung volumes and flows bore a constant relationship to external thoracic dimensions.

**Conclusions**—Puberty has a dramatic effect on lung function. Regression equations for predicted values of lung function measurements and for calculation of standard deviation scores are given (with pubertal correction factors) for each gender.

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At least 118 reference standards for lung function in white children have been published since 1950.<sup>1</sup> From some of these summary equations have been derived.<sup>2</sup> It is 13 years since the last standards on UK schoolchildren were published<sup>3</sup> but, as with other quoted UK standards,<sup>4,5</sup> potential drawbacks exist. Difficulties in data interpretation may arise because of modest sample size (<400) which may account for the lack of differences between the sexes,<sup>4</sup> the use of linear regression only to derive summary equations,<sup>5</sup> the possibility that distributions may be non-normal, and the lack of reported assessment of possible trends in the standard deviation of a lung function variable with height—that is, whether the spread of results about the predicted mean changes with increasing height.

Now that children with progressive lung conditions such as cystic fibrosis survive into adolescence, longitudinal monitoring becomes even more important but requires lung function reference data in which puberty is a variable.<sup>6</sup> It has been shown that a single power curve for forced expired volume in one second (FEV<sub>1</sub>) cannot be used from early childhood to late adolescence,<sup>7</sup> although some groups continue to do so.<sup>8</sup> Most studies, including those in the UK, have predominantly assessed younger prepubertal children,<sup>3-5,9</sup> whilst none have shown the original data from which the validity of the summary equation might be judged. In current clinical practice summary equations are used to calculate "percentage predicted results" ((actual result/predicted result) × 100%), but these do not indicate the centile position of such a result nor how they are distributed about the quoted regression line.

We therefore performed a cross sectional study of lung function in healthy schoolchildren to reassess reference standards throughout childhood and puberty. A small portion of these data has previously been used for the assessment of vital capacity in patients with severe scoliosis on the basis of hand and foot size.<sup>10</sup>

## Methods

One thousand and seven children were initially recruited from 12 London schools. Informed consent was obtained from all parents who also completed a detailed questionnaire concerning the family's smoking history, the child's antenatal and postnatal history, and any previous respiratory symptoms. Twenty seven children were excluded because they had either had an acute respiratory illness in the three weeks before testing or, despite initial screening before recruitment, they had symptoms strongly suggestive of chronic respiratory disease. A further 208 children were not of white UK origin and were also excluded. The results are thus based on 772 children, 455 of whom were male.

Auxology was performed by a single trained anthropometrist (SB) and included measurements of height (Harpender stadiometer), weight (Harpender Balance scales), left triceps and subscapular skinfold thicknesses (Holtain calipers), chest circumferences and depths at maximum inspiration and expiration measured at the fourth inter-

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costal space (Harpenden anthropometer), hand and foot lengths, head circumference, and biacromial and bi-iliac diameters.

Consent was obtained from both the children and their parents to pubertally stage 81% of girls aged 8 years or more and 61% of boys aged 10 years and more, according to the method of Tanner.<sup>11</sup>

Spirometric variables measured were FEV<sub>1</sub> (l), forced vital capacity (FVC, l), peak expiratory flow (PEF, l/s), maximum expiratory flow at 50% and 25% of FVC (MEF<sub>50</sub>, MEF<sub>25</sub>, l/s respectively), and peak inspiratory flow (PIF, l/s). A 12 litre dry rolling seal spirometer (OHIO 840) with a frequency response of 10 Hz was used to obtain the maximum flow-volume loops of three to six efforts. A minimum of two technically satisfactory results were required. Each child was asked to breathe in to total lung capacity (TLC), subsequently blow out as hard and as fast as possible to residual volume (RV), and then similarly to breathe in back to TLC. End expiration was detected by back tracing the start of inspiration to the expiratory curve to detect the point of zero flow. The data were downloaded to a BBC computer sampling at 100 Hz via a 12 bit analogue digital converter. The use of a mercury column barometer and a thermocouple in the spirometer allowed the body temperature and ambient pressure (BTPS) correction to be made. The protocol conformed to both US and European standards<sup>12-14</sup> in terms of exclusion criteria for study entry, accuracy of equipment, and performance of the test, except that the FVC with the highest FEV<sub>1</sub> was chosen provided the FVC was technically satisfactory. In practice this conforms to the "best loop" requirement of the maximum sum of FEV<sub>1</sub> and FVC.<sup>14</sup>

STATISTICAL ANALYSIS

For each spirometric measurement the results were grouped in either 5 cm blocks so that 150 cm represented children of standing height 147.6–152.5 cm inclusive, or 2.5 cm blocks for sitting height. For each spirometric variable and height block the Shapiro-Wilks and Lilliefors tests<sup>15 16</sup> for departures from normality were performed together—for example, for each variable with 21 height blocks, 42 tests were performed in boys and 36 in girls. If fewer than 10% of the tests departed from normality the variable was deemed empirically to have a normal distribution. If the variable conformed to normality the Tukey weighted mean<sup>15</sup> (using 4.685 as the weight) was calculated for each height group to reduce the disproportionate effects of outliers on unweighted means. Weighted means were plotted and regression equations fitted. The coefficient of variation (CV), (standard deviation (SD)/Tukey weighted mean) was calculated for each height block within each variable and plotted against height to detect any trends. If none was found—that is, the SD was a fixed proportion of the mean—an SD score could be calculated thus (Equation 1):

Actual result - Predicted result from regression equation using height  
Fixed fraction × (Prediction of mean from same regression equation using height)

On the other hand, if a significant trend existed a second height based regression equation was derived to represent this trend so that, under these circumstances, an SD score could be calculated thus (Equation 2):

Actual result - Predicted result from regression equation using height  
(Fraction calculated from a second equation using height) × (Predicted result from equation using height)

In both these instances the only information required for the calculation of an SD score was the actual result and the child's height. Using these equations each result for each variable was converted to an SD score so that, for any variable, the mean of the entire sample was 0 with an SD of 1. The independent effects of puberty on lung function were assessed using the child's SD score by one way analysis of variance (ANOVA) with Duncan's correction for multiple contrasts.

Individual group results are presented as

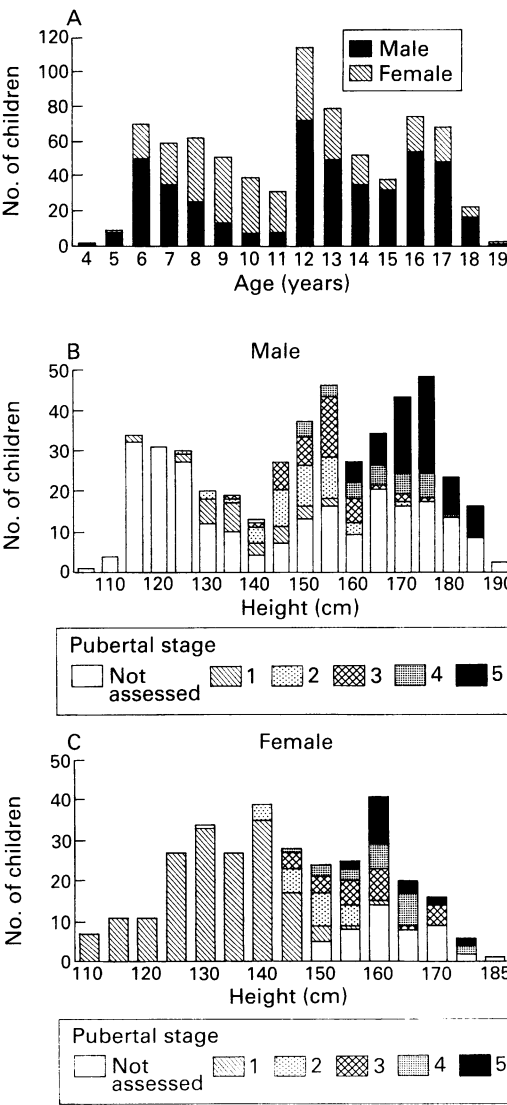


Figure 1 Distribution of children's age by (A) sex, (B) male height by pubertal stage, and (C) female height by pubertal stage.

mean and 95% confidence intervals unless otherwise stated.

Results

The height, age, and pubertal stage distributions of the 772 children comprising the data set are shown in fig 1A–C. Technically unsatisfactory results were obtained from 1.3% of boys and 0.6% of girls with respect to FEV<sub>1</sub> and FVC, 5.9% of boys and 4.7% of girls with respect to PEF, MEF<sub>50</sub> and MEF<sub>25</sub>, and 6.2% of boys and 6.9% of girls with respect to PIF. Most of these failures occurred in children less than 125 cm in height. With the exception of MEF<sub>25</sub> in boys taller than 162.5 cm in which a logarithmic transformation was necessary, all other measurements in both sexes did not depart from normality.

Figure 2A and B shows the scatterplot results for FEV<sub>1</sub> in boys and girls against standing height. Figure 2C and D shows the same scatterplot but the results are grouped into 5 cm height blocks. There is a sudden discontinuity in values in boys between 160 and 165 cm and in girls between 150 and 155 cm which is not immediately apparent in the

data in fig 2A and B. Figure 2E and F show the Tukey weighted FEV<sub>1</sub> mean (2SD) for each height block together with the fitted regression lines for the mean (2SD) above and below the discontinuity. For FEV<sub>1</sub> the CV was constant across the height range, therefore the fitted SD lines were calculated on the basis of Equation 1 (see analysis). This pattern of discontinuity was duplicated for all the other spirometric variables in an identical manner and the raw and fitted mean (2SD) are summarised in fig 3A–F for boys and fig 4A–F for girls.

The same method of analysis was performed with sitting height. In this case the height blocks were 2.5 cm each. Figure 5A and B show the scatterplot results for FEV<sub>1</sub> in boys and girls with no obvious discontinuity.

Tables 1 and 2 show the regression equations for the predicted spirometric variable and standing height (table 1) or sitting height (table 2) as the independent variable, together with their calculated SD scores, either as a fixed fraction or as a second regression equation. For worked examples the reader is referred to the Appendix.

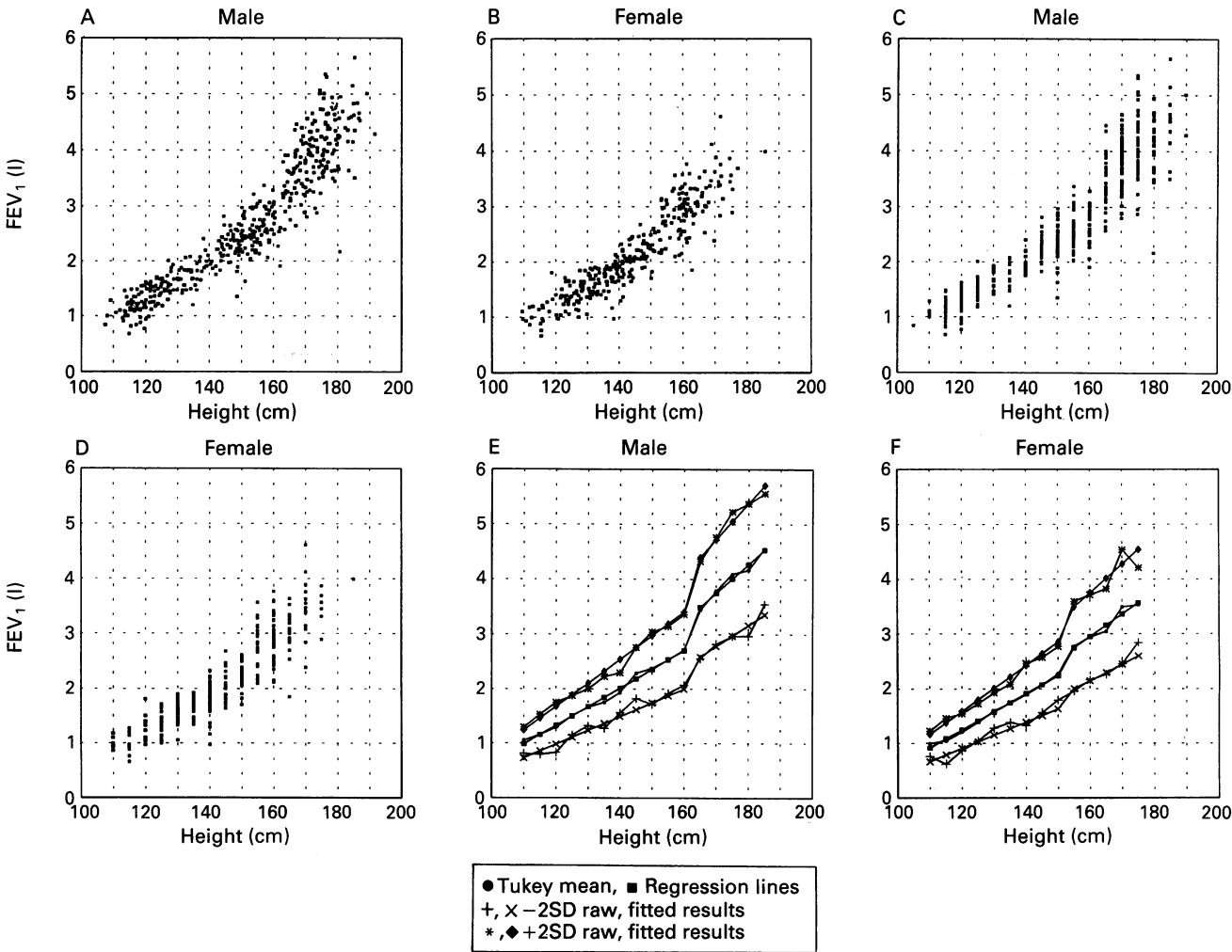


Figure 2 Raw data for FEV<sub>1</sub> in (A) males and (B) females against exact standing height, or (C) males and (D) females grouped in 5 cm height blocks (note the discontinuity in values at 165 cm in males and 155 cm in females), Tukey mean (2SD) for each height block with the fitted mean and SD lines derived from table 2 in (E) males and (F) females.

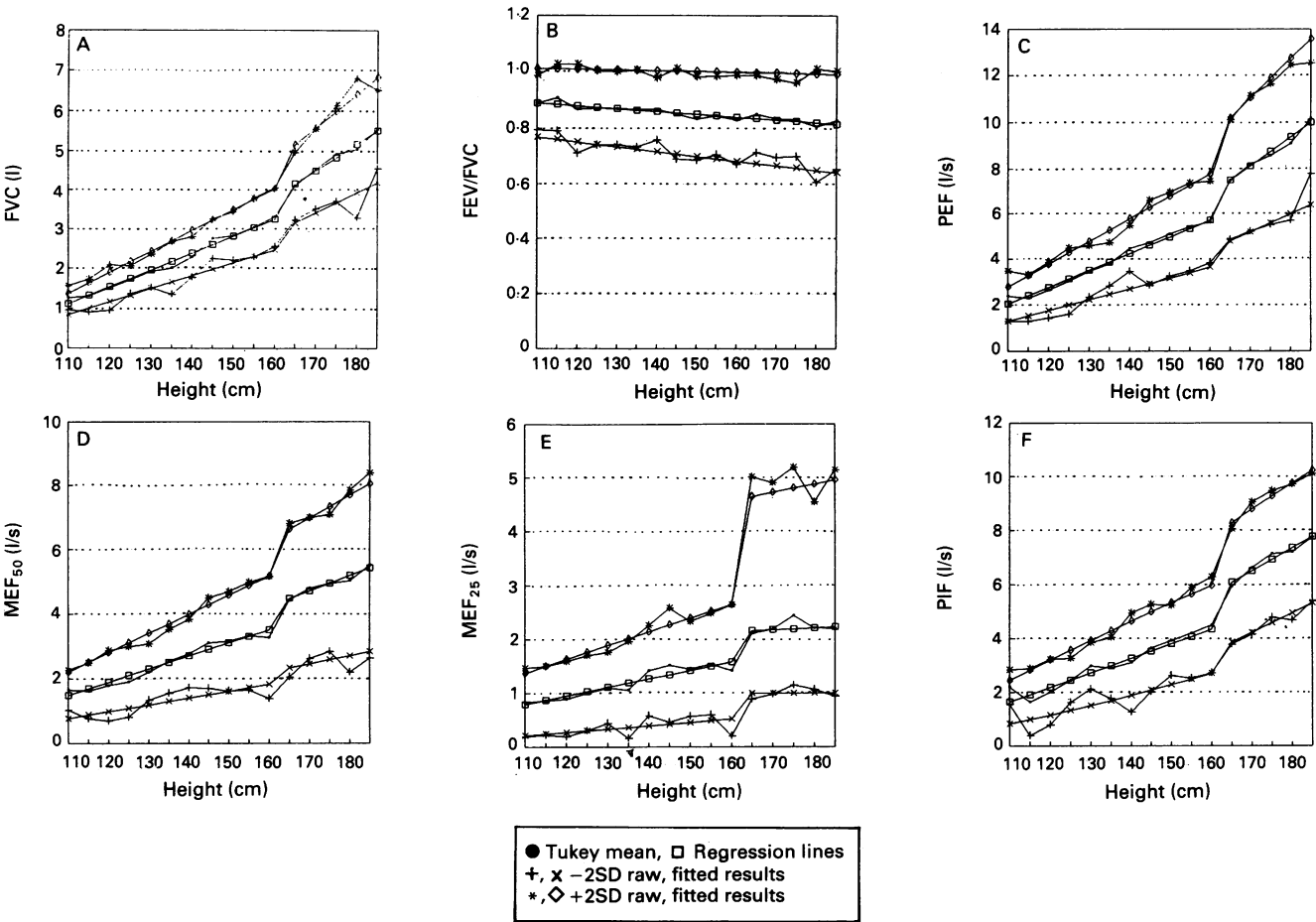


Figure 3 Tukey mean (2SD) results in males together with the fitted mean and SD lines derived from table 2. (A) FVC, (B) FEV/FVC, (C) PEF, (D) MEF<sub>50</sub>, (E) MEF<sub>25</sub>, (F) PIF.

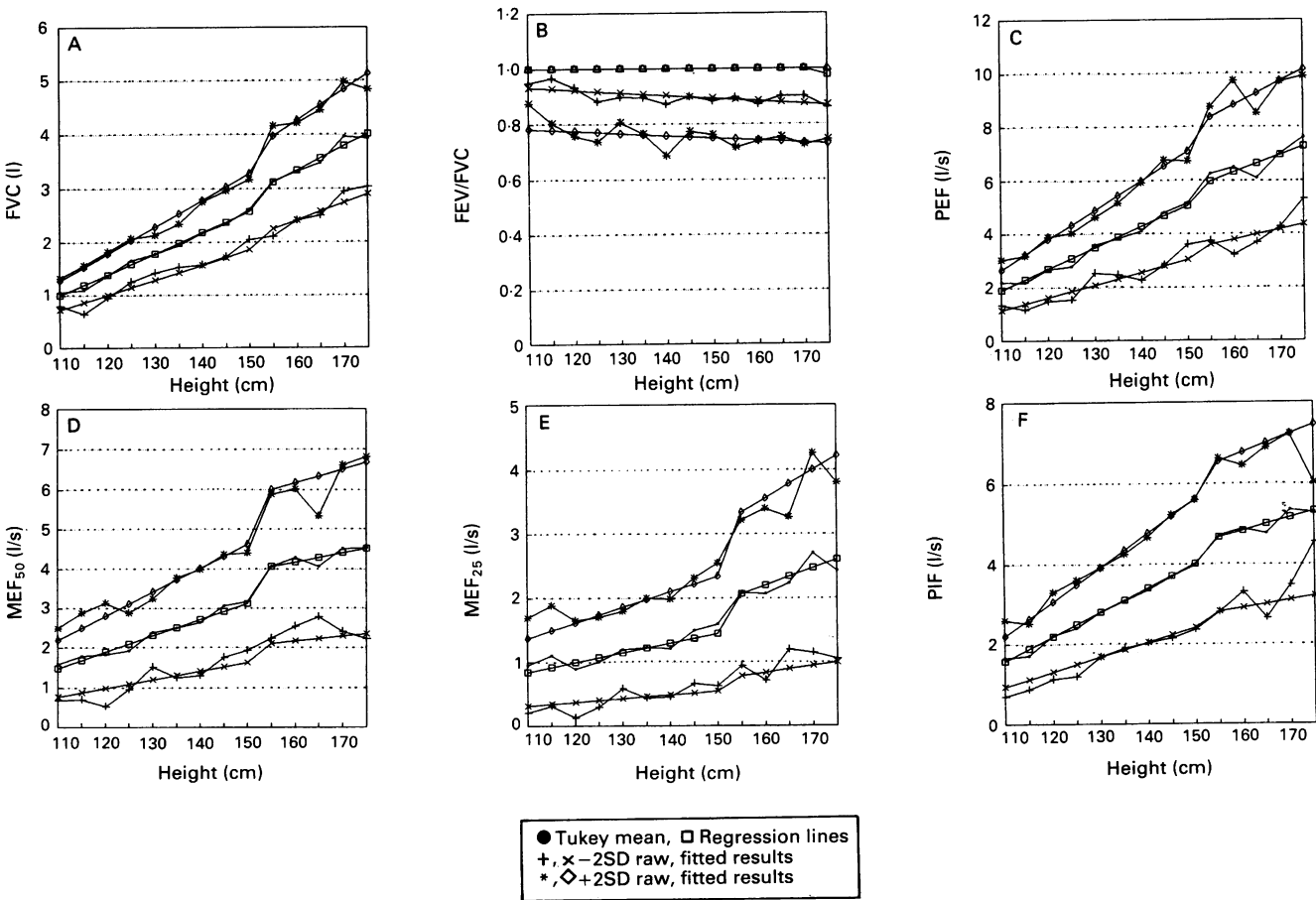


Figure 4 Tukey mean (2SD) results in females together with the fitted mean and SD lines derived from table 2. (A) FVC, (B) FEV/FVC, (C) PEF, (D) MEF<sub>50</sub>, (E) MEF<sub>25</sub>, (F) PIF.

EFFECT OF PUBERTY

The sudden change in spirometric lung function seen in each sex (figs 2 and 3) would appear to coincide with the pubertal growth spurt observed in Tanner's charts.<sup>11</sup> Table 3 summarises the Tukey weighted mean SD scores calculated for each sex and pubertal stage in the six height blocks around the discontinuity. In boys 147.6–162.5 cm in height, early puberty (stages 2 and 3) resulted in lower lung function at a given height than prepuberty (stage 1). For example, average PEF in stage 1 boys was 0.77 SD higher than those in stage 3, whilst stage 2 was intermediate. This situation pertained to all other variables except FVC. In taller boys (162.6–177.5 cm) early puberty (stage 3) resulted in a considerably lower lung function (FVC excepted) compared with late puberty (stages 4 and 5). The difference between pubertal stages 3 and 5 varied from 1.27 SD (0.1–2.44) for MEF<sub>50</sub> to 2.37 SD (1.2–3.54) for FEV<sub>1</sub>.

Prepubertal girls between 137.6 cm and 152.5 cm in height had lower lung function (PEF, MEF<sub>50</sub>, MEF<sub>25</sub>) than those in stage 3 (approximately 1SD) while stage 2 was again intermediate. No comparison could be made in taller girls (152.6–167.5 cm) as they were all in late puberty.

A pubertal correction factor can thus be applied (table 3) for a particular variable in these height ranges. Outside these height ranges the overwhelming number of children

Table 1 Calculation of the predicted mean of a spirometric variable using a linear equation of intercept A and slope B × standing height in cm. R<sup>2</sup> represents the variance predicted by the linear equation and D represents the standard deviation expressed as a fraction of the predicted mean. For worked example, see Appendix.

	Sex	Height	A	B	R <sup>2</sup>	D
FEV <sub>1</sub> (l)	M	<162.6	-2.780	0.03425	99	0.13
	M	>162.5	-5.108	0.0521	97	
	F	<152.6	-2.734	0.03316	99	0.136
	F	>152.5	-3.680	0.04112	93	
FVC (l)	M	<162.6	-3.619	0.0429	98	0.12
	M	>162.5	-7.038	0.0678	98	
	F	<152.6	-3.311	0.03918	99	0.139
	F	>152.5	-3.881	0.04512	92	
PEF (l/s)	M	<162.6	-5.98	0.073	98	0.18
	M	>162.5	-13.14	0.125	97	
	F	<152.6	-6.79	0.079	97	0.20
	F	>152.5	-3.94	0.064	68	
MEF <sub>50</sub> (l/s)	M	<162.6	-2.91	0.040	96	0.24
	M	>162.5	-3.38	0.048	93	
	F	<152.6	-3.03	0.041	97	0.24
	F	>152.5	0.49	0.023	63	
MEF <sub>25</sub> (l/s)	M	<162.6	-0.948	0.0158	87	0.43-0.0006 × Ht
	M	>162.5 <sup>1</sup>	0.218 <sup>1</sup>	0.00074 <sup>1</sup>	6	0.50 <sup>1</sup>
	F	<152.6	-0.807	0.015	79	0.56-0.0018 × Ht
	F	>152.5	-2.12	0.027	63	
PIF (l/s)	M	<162.6	-4.31	0.054	94	0.38-0.0012 × Ht
	M	>162.5	-7.96	0.085	95	
	F	<152.6	-5.14	0.061	99	0.47-0.0019 × Ht
	F	>152.5	-0.379	0.0326	74	
FEV/FVC	M		1.00	-0.001	83	0.012 + 0.0005 Ht
	F		1.04	-0.00098	47	0.08

FEV<sub>1</sub>—forced expiratory volume in one second; FVC—forced vital capacity; PEF—peak expiratory flow; MEF<sub>50</sub>, MEF<sub>25</sub>—maximum expiratory flow at 50% and 25% of FVC; PIF—peak inspiratory flow.

<sup>1</sup>This equation calculates the SD score based on the log<sub>10</sub> (MEF<sub>25</sub>).

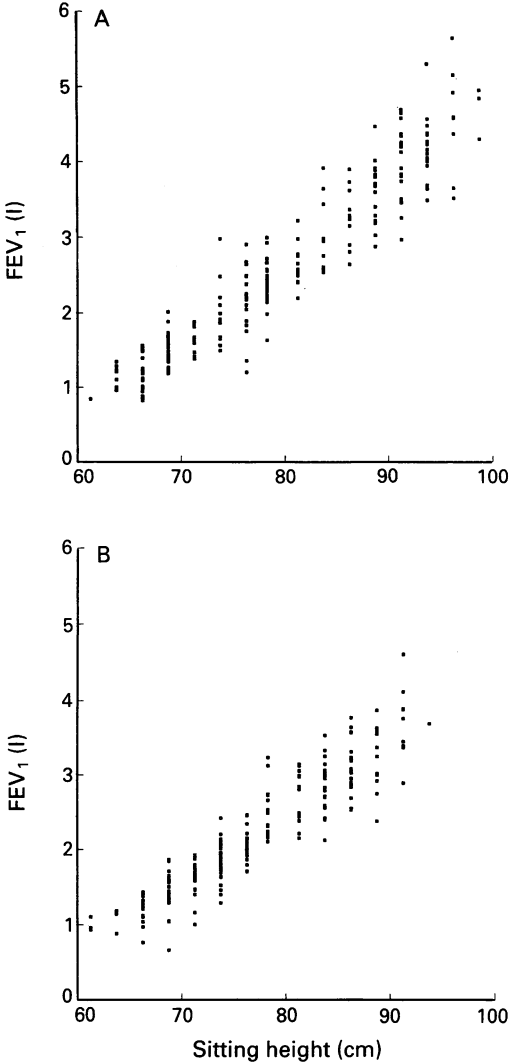


Figure 5 Raw FEV<sub>1</sub> results for (A) boys and (B) girls against sitting height. Note the lack of discontinuity in the results.

are either prepubertal (stage 1) or postpubertal (stage 5) and hence no correction is likely to be necessary.

EFFECT OF GENDER

In children under 152.6 cm in height there was no difference in PEF, MEF<sub>50</sub>, MEF<sub>25</sub>, and PIF between the sexes. There were, however, small but significant differences in FEV<sub>1</sub>, FVC, and FEV/FVC. In boys of the same height these were 6% (5.8–6.3%), 8.5% (8.3–8.7%), and 2.4% (2.3–2.55%) higher than girls respectively. This difference was uniform over the height range 107.6–152.5 cm. The results for FEV<sub>1</sub> are shown in fig 6.

Between heights of 152.6 cm and 162.5 cm when girls typically have their pubertal growth spurt, all female spirometric variables were higher than males with the exception of FVC. FEV<sub>1</sub> was 7.4% (3.4–11.4%, p = 0.0001), PEF 7.4% (0.08–14.6%, p < 0.07), MEF<sub>50</sub> 19% (11–27%, p = 0.0001), MEF<sub>25</sub> 36% (24–48%, p < 0.0001), and PIF 7.6% greater in girls (1.1–14%, p < 0.02). After 162.5 cm, a time when boys typically have their pubertal growth spurt, male spirometry results were significantly higher than female values, the difference increasing with height.

Table 2 Calculation of a predicted result of a spirometric variable using sitting height (cm) where A,B,C,E,F and G represent the coefficients of a fifth power polynomial, R<sup>2</sup> represents the percentage of variance predicted by the equation and D represents the standard deviation expressed as a fraction of the predicted result. (For full explanation and worked example, see Appendix.)

	Sex	A	B	C	E	F	G	R <sup>2</sup>	D
FEV <sub>1</sub> (l)	M	10.107	−0.39891	0.0050266	−0.000015303	0	0	99	0.25 − (0.0014 × SITHT)
	F	−1158.963	77.71608	−2.072198	0.027452762	−0.00018054902	4.717225 × 10 <sup>−7</sup>	100	0.12
FVC (l)	M	31.255	−1.26559	0.0166057	0.000064885	0	0	99	0.30 − (0.0022 × SITHT)
	F	−3092.658	208.193	−5.578967	0.074372456	−0.00049302353	1.3003603 × 10 <sup>−6</sup>	100	0.32 − (0.0025 × SITHT)
PEF (l/s)	M	3362.180	−219.8179	5.70878	−0.073621	0.00047169616	−0.0000012006367	99	0.35 − (0.0021 × SITHT)
	F	−5229.425	357.2533	−9.700325	0.130816026	−0.00087574816	0.0000023284273	99	0.30 − (0.0014 × SITHT)
MEF <sub>50</sub> (l/s)	M	9.2997	−0.3455	0.004199	−0.0000010288	0	0	98	0.24
	F	−2496.402	162.3742	−4.188856	0.053552587	−0.00033896110	0.00000084951565	98	0.35 − (0.0019 × SITHT)
PIF (l/s)	M	50.131	−2.057	0.027276	−0.000109053	0	0	99	0.70 − (0.0061 × SITHT)
	F	−1299	91.00096	−2.527663	0.03479060	−0.00023693800	0.0000006385803	99	0.54 − (0.0045 × SITHT)

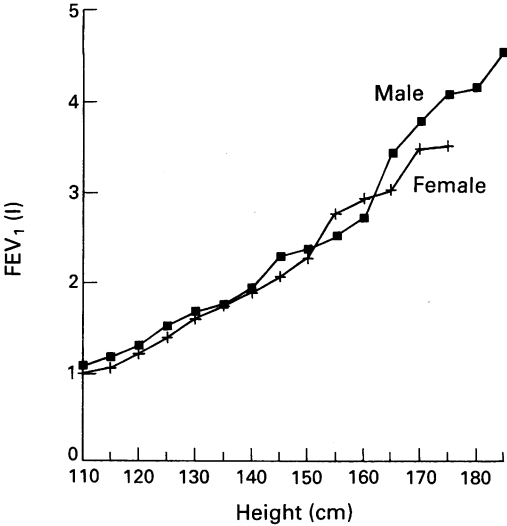
SITHT—Sitting height (cm). For other definitions see footnote to table 1.

Table 3 Mean SD scores for each variable and pubertal stage for standing heights 15 cm above and below the discontinuity. Significant differences are marked where p < 0.05 (see footnote). 95% confidence limits for the difference between significant means are also shown. (For worked example, see Appendix.)

<i>Pubertal stage</i>	<i>FEV<sub>1</sub></i>	<i>FVC</i>	<i>PEF</i>	<i>MEF<sub>50</sub></i>	<i>MEF<sub>25</sub></i>	<i>PIF</i>
Males 147.6–162.5 cm inclusive						
1	0.15* <sup>(-0.2, 1.04)</sup>	0.14	0.6* <sup>(0.21, 1.33)</sup>	0.38* <sup>(0.03, 1.35)</sup>	0.33* <sup>(0.33, 1.49)</sup>	0.67* <sup>(0.33, 1.67)</sup>
2	0.07***	0.05	-0.1**	-0.33	0.09***	0.01**
3	-0.27	-0.16	-0.17	-0.31	-0.58	-0.33
4	-0.17	0.18	0.36	-0.28	-0.01	0.93††
5	Insufficient numbers					
Males 162.6–177.5 cm inclusive						
1	Insufficient numbers					
2	Insufficient numbers					
3	-1.83† <sup>(1.2, 3.54)</sup>	-0.09	-1.17† <sup>(0.58, 2.82)</sup>	-0.84† <sup>(0.1, 2.44)</sup>	-2.14† <sup>(1.22, 2.46)</sup>	-1.35† <sup>(0.54, 2.84)</sup>
4	-0.35††	-0.24	-0.27	-0.23	-0.17	-0.1
5	0.54††† <sup>(0.42, 1.36)</sup>	0.20††† <sup>(-0.04, 0.96)</sup>	0.53††† <sup>(0.33, 1.27)</sup>	0.43††† <sup>(0.18, 1.14)</sup>	0.2††† <sup>(-0.1, 0.84)</sup>	0.34††† <sup>(-0.03, 0.91)</sup>
Females 137.6–152.5 cm inclusive						
1	-0.42	0.21	-1.12* <sup>(0.73, 2.47)</sup>	-0.79* <sup>(0.48, 2.26)</sup>	-0.33* <sup>(0.05, 1.83)</sup>	-0.36
2	0.03	-0.2	0.12	0.33	0.53	-0.15
3	0.33	0.13	0.48	0.58	0.61	0.15
4	Insufficient numbers					
5	0.81	0.94	0.60	0.35	0.61	0.15
Females 152.6–167.5 cm inclusive						
1–5	No pubertal effect noted					

\*(a,b)—Pubertal stage 1 differs from pubertal stage 3; \*\*\*(a,b)—pubertal stage 1 differs from pubertal stage 2; \*\*\*(a,b)—pubertal stage 2 differs from pubertal stage 3; †(a,b)—pubertal stage 3 differs from pubertal stage 5; ††(a,b)—pubertal stage 3 differs from pubertal stage 4; †††(a,b)—pubertal stage 4 differs from pubertal stage 5; (a,b)—95% confidence interval for the difference between the means tested. For definition of other abbreviations see footnote to table 1.

Figure 6 Tukey mean results for FEV<sub>1</sub> in males and females. Note the three phases: 107.6–152.6 cm boys have higher values, 152.6–162.5 cm lower values, and thereafter higher values again.



RELATIONSHIP OF AIRWAY FLOW TO LUNG VOLUME

We examined the data using FVC as the denominator over the age range 4–19 and the results are summarised in table 4. In young children, airflow/FVC was greater in females than males (amounting to an 18% difference for both MEF<sub>50</sub>/FVC and MEF<sub>25</sub>/FVC). However, these differences disappeared by late adolescence although MEF<sub>25</sub>/FVC and PIF/FVC was still significantly greater in 12 year old girls (data not shown). Pubertal stage did not have a significant bearing on the ratio with the exception of PIF/FVC in females where, after breast stage 2, there was a sudden decline (data not shown).

EFFECT OF BODY FRAME

In order to determine its relationship with spirometric variables, thoracic volume was

Table 4 Comparison of the ratio of airflow to forced vital capacity (FVC) in children aged less than 8 years and more than 17 years (mean and 95% confidence intervals)

	Age (y)	Male	Female
PEF/FVC (l/s/l)	<8	1.78 (1.71 to 1.85)	1.90 (1.80 to 2.00)
	>17	1.76 (1.67 to 1.85)	1.71† (1.55 to 1.85)
MEF <sub>50</sub> /FVC (l/s/l)	<8	1.18*** (1.11 to 1.25)	1.40 (1.29 to 1.51)
	>17	1.06 (0.98 to 1.14)	1.13†† (1.01 to 1.25)
MEF <sub>25</sub> /FVC (l/s/l)	<8	0.66** (0.61 to 0.71)	0.78 (0.69 to 0.87)
	>17	0.53 (0.47 to 0.59)	0.56†† (0.50 to 0.62)
PIF/FVC (l/s/l)	<8	1.39* (1.32 to 1.46)	1.53 (1.43 to 1.63)
	>17	1.39 (1.33 to 1.45)	1.36† (1.24 to 1.48)

\*\*\*p < 0.001, \*\*p < 0.01, \*p < 0.05 (comparison between the sexes within age group); ††p < 0.01, †p < 0.05 (comparison between the age groups within each sex). For definitions of abbreviations see footnote to table 1.

estimated from several anthropometric measures. If this estimate is used as the denominator (y) in a function where the spirometric variable is the numerator (x), a constant relationship can be sought—that is, *x/y versus height* is constant. The denominator ought to have a cubic dimension to reflect an estimate of volume. In boys the use of the square of maximum inspiratory chest circumference (an estimate of thoracic area) × sitting height (a better estimate of thoracic length than standing height) to determine y led to *x/y* being a very stable constant across the height range so that one way ANOVA produced no differences between any of the height blocks derived from results on 389 boys in whom inspiratory chest circumference was measured. In girls this relationship bore a positive correlation with height. However, substituting the square of chest depth at maximum inspiration (also a proportional estimate of thoracic area) for chest circumference in the denominator function y also resulted in a constant relationship in girls although measurements were made over a more restricted height range (110–165 cm). The results are summarised in table 5.

Table 5 Mean (95% confidence interval) of the constant ratio of spirometric variables to an estimate of thoracic volume by external thoracic anthropometry

	Sex	Mean (95% confidence interval)	SD
FEV <sub>1</sub>	M	5.46 (5.39 to 5.55)	0.69
FVC	M	6.42 (6.34 to 6.50)	0.78
PEF	M	11.6 (11.4 to 11.8)	2.2
MEF <sub>50</sub>	M	7.0 (6.6 to 7.4)	1.8
MEF <sub>25</sub>	M	3.3 (3.1 to 3.5)	1.3
PIF	M	9.0 (8.8 to 9.2)	1.9
FEV <sub>1</sub>	F	93.7 (89.0 to 97.5)	14.7
FVC	F	107.4 (106.5 to 111.9)	17.8
PEF	F	203 (197 to 211)	45
MEF <sub>50</sub>	F	134 (130 to 142)	36
MEF <sub>25</sub>	F	68 (65 to 71)	22
PIF	F	164 (158 to 170)	39

Males: variable/(chest circumference at maximum inspiration<sup>2</sup> × sitting height) with body dimensions in metres. Females: variable/(chest depth at maximum inspiration<sup>2</sup> × sitting height) with body dimensions again in metres (valid over height range 110–165 cm only). For abbreviations see footnote to table 1.

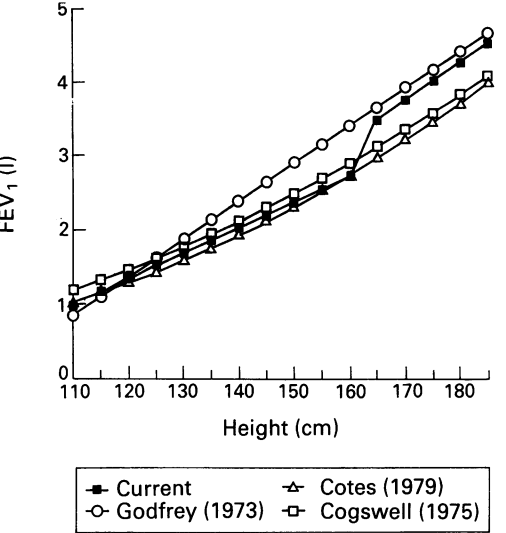


Figure 7 Tukey mean results for FEV<sub>1</sub> in males compared with reference data from Godfrey, *et al.*,<sup>5</sup> Cotes *et al.*,<sup>3</sup> and Cogswell *et al.*<sup>4</sup>

Figure 7 shows the calculated FEV<sub>1</sub> results from this study compared with equations derived from other UK studies.<sup>3–5</sup> The present data show a close approximation to those of Cotes and Cogswell up to a height of 160 cm, after which they deviate sharply and more closely approximate Godfrey’s results.<sup>5</sup>

Discussion

The purpose of this study and its analysis was to derive normative standards for lung function from a local UK, non-hospital based population and to calculate regression equations which not only correctly reflected the “centre” of the reference population, but included an accurate method for determining the dispersion about that centre and thus an SD score. Centile charts will be useful in the longitudinal assessment of children with chronic lung disease, especially around adolescence, but tables 1–3, although appearing complex, will also simplify analysis by permitting easy computer driven calculation of SD scores. As with all predictive equations they are only valid for children aged 4.6–18.8 years and 107.5–192.5 cm in height. Extrapolation to test younger children who are tall for their age or short adults must be done with extreme care as they may be invalid under those circumstances.

The finding that no single linear or power curvilinear relationship correctly describes the relationship between forced ventilatory manoeuvres and height throughout childhood was first noted by Dickman *et al*<sup>6</sup> who found a sudden discontinuity between height and FVC at 60 inches (153 cm) in boys and girls. This is not, however, reflected in currently published summary equations.<sup>2</sup> Although pubertal stage was not assessed in that study, it was nevertheless assumed to be the reason for the discontinuity. Years later Warner related peak flow to pubertal stage and testosterone levels and showed a marked rise in PEF in late puberty (stages 4 and 5).<sup>17</sup> Engstrom *et al*<sup>18</sup> also showed that, at a given

height, older children had a higher vital capacity. Sherrill *et al*,<sup>19</sup> although not recording pubertal stage or thoracic dimensions in a longitudinal study of somatic growth and lung function, found sudden changes in lung function during the adolescent growth spurt different from those before or after this period. In addition, although the maximum changes in lung function coincided with the growth spurt in females in their study, they lagged behind the growth spurt in males by six months for FVC to 18 months for MEF<sub>25-75</sub>. In a further longitudinal study DeGroodt *et al*<sup>20</sup> evaluated thoracic dimensions and standing height and related this to changes in RV and VC. Once more puberty was not formally assessed but they concluded that thoracic width in females hardly changed during adolescence while thoracic length increased twice as fast in males than in females.

The above findings, together with the knowledge that maximum muscle strength (which will contribute to forced manoeuvres) occurs 14 months after peak height velocity,<sup>21</sup> may explain the pubertal discontinuity in both sexes and the apparent “acceleration” in male lung function with increasing height after puberty in our study, evidenced by significant increases in the slopes for FEV<sub>1</sub>, FVC, and PEF in males taller than 165 cm compared with those of 160 cm or less. The significant changes in thoracic dimensions at puberty (greater in males) lead to the discontinuity, with the continuing asynchronous and greater male thoracic *versus* somatic growth and later increase in muscle strength contributing to the continuing divergence of male and female lung function after puberty. The apparently constant relationship of external thoracic dimensions to lung function, where sitting height estimates thoracic length and chest circumference or depth estimates thoracic area, lends support to this. In our study there were insufficient anthropometric measurements in the taller females to draw firm conclusions; nevertheless, in males the change in the square of the chest circumference with somatic growth mirrored the changes in lung function (data not shown).

The finding of superior airflow per unit lung volume in younger girls (an effect which equalises by late adolescence) confirms the findings of Hibbert *et al*<sup>22</sup> suggesting that younger girls have shorter (to account for the reduced lung volumes at a given height in girls) but wider airways than boys. In our study maximal differences were in MEF<sub>50</sub>/FVC and MEF<sub>25</sub>/FVC, suggesting greater differences in the smaller airways.

Using two separate linear equations to describe the relation between height and lung function, especially when monitoring children longitudinally, can lead to potentially spurious changes in relative lung function when the child’s growth requires one to change from one linear equation to the second linear equation necessary for taller children. These spurious changes—for example, the child’s SD score may appear to temporarily fall

although actual lung function continues to improve—can be minimised by correcting for pubertal stage at this time (155–170 cm in males and 145–160 cm in females), with the help of table 3 (see Appendix). An undoubted advantage, however, of linear over power equations for calculating an SD score is the halving of changes in a particular SD score due to height measurement errors.

The methods of analysis described in this paper are based on the same statistical principles recommended by Chinn and Rona,<sup>9</sup> namely ensuring a normal distribution and not assuming equal variances. Their study, however, only dealt with children under 12 thus excluding the pubertal years and, although they were able to recommend a single descriptive equation for spirometric variables, we have shown that this is not possible over a wider age range.

In conclusion, changes in lung function, like somatic growth, have distinct phases that cannot be explained by a single simple relationship. The pubertal state is crucially important when comparing patients, especially those with chronic disease, with their healthy counterparts. We believe the use of centile charts similar to those for growth, or the calculation of SD scores, or both, are the best way of longitudinally monitoring such children. We hope the results of the current study can be used to this end.

Appendix

SD score = 
$$\frac{\text{Actual result} - \text{Predicted result}}{\text{Population standard deviation}}$$

Worked example from table 1  
Male 170 cm, PIF = 5 l/s.

SD score = 
$$\frac{5 - (-7.96 + (0.085 \times 170))}{(0.38 - (0.0012 \times 170)) \times (-7.96 + (0.085 \times 170))}$$
  
= -1.304

If individual is pubertal stage 3 then “corrected” score from table 3 = -1.31 - (-1.35) = +0.04.

If individual is pubertal stage 5 then “corrected” score = -1.31 - (+0.34) = -1.65.

Worked example from table 2  
Female, sitting height 75 cm, FEV<sub>1</sub> = 2.3 l.

Predicted result = 
$$\begin{aligned} &-1158.963 + (77.716 \times 75) \\ &- (2.0721964 \times 75^2) \\ &+ (0.02745276177 \times 75^3) \\ &- (0.0001805490219 \times 75^4) \\ &+ (0.0000004717225 \times 75^5) \\ &= 2.002 \text{ litres} \end{aligned}$$

SD = 0.12 × 2.002 = 0.240 litres

SD score = 
$$\frac{2.3 - 2.002}{0.240} = +1.24$$

NB. (a) Do not round the coefficients especially in polynomial equations as this will lead to significant errors. (b) Do not use outside the height range of the sample population.

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