Height and age adjustment for cross sectional studies of lung function in children aged 6–11 years

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Accepted 3 March 1992

Abstract

Background No standard exists for the adjustment of lung function for height and age in children. Multiple regression should not be used on untransformed data because, for example, forced expiratory volume (FEV_1), though normally distributed for height, age, and sex, has increasing standard deviation. A solution to the conflict is proposed.

Methods Spirometry on representative samples of children aged 6·5 to 11·99 years in primary schools in England. After exclusion of children who did not provide two repeatable blows 910 white English boys and 722 girls had data on FEV_1 and height. Means and standard deviations of FEV_1 divided by height were plotted to determine whether logarithmic transformation of FEV_1 was appropriate. Multiple regression was used to give predicted FEV_1 for height and age on the transformed scale; back transformation gave predicted values in litres. Other lung function measures were analysed, and data on inner city children, children from ethnic minority groups, and Scottish children were described.

Results After logarithmic (ln) transformation of FEV_1 standard deviation was constant. The ratios of actual and predicted values of FEV_1 were normally distributed in boys and girls. From the means and standard deviations of these distributions, and the predicted values, centiles and standard deviation scores can be calculated.

Conclusion The method described is valid because the assumption of stable variance for multiple regression was satisfied on the log scale and the variation of ratios of actual to predicted values on the original scale was well described by a normal distribution. The adoption of the method will lead to uniformity and greater ease of comparison of research findings.

(*Thorax* 1992;47:707–714)

Despite the considerable amount of published work on lung function in children there seems to be no consensus on the appropriate method of adjustment for height and age in cross sectional studies, although there now seems to be agreement that both variables should be taken into account. The problem arises both in the construction of reference centiles and in the analysis of lung function in relation to respiratory illness, passive smoking, or other effects, and a method needs to found that is appropriate for both situations.

Some authors have used multiple regression of untransformed lung function on age and height, for each sex separately, sometimes apparently without question.[1 2] However, many authors have considered this inadequate, some including quadratic or even cubic terms in height or age,[3 4] but rather more log transforming lung function and height and other independent variables if used.[5–8] Some have used complex models in a mixture of transformed and untransformed variables,[9] while others have constructed indices of lung function for height.[10]

Although not stated, it can be assumed that authors who analysed untransformed lung function did so because they found their measures to be approximately normally distributed for height, age, and sex of children. Those choosing the log transformation noted that this stabilised the variance of lung function, which increases with height and age if untransformed,[8] but have ignored the non-normality of the transformed variables. The conflict between normalising and variance stabilising transformations seems to exist at least for peak expiratory flow rate (PEFR), forced vital capacity (FVC), and forced expiratory volume in one second (FEV_1), but no previous author has addressed this conflict.

Although achieving homoscedasticity—that is, stabilising variance—is more important than normalising distributions for analysis of variance and regression analysis, it is desirable, at least for centile estimation, to use the normal distribution. In theory the problem of centile estimation could be dealt with by dividing children into age and height subgroups, estimating means and standard deviations on the scale giving a normal distribution, and then smoothing the means and standard deviations using some suitable function of age and height before deriving the centiles. This works well for height itself,[11] for which only age need be taken into account, but would require far more data on lung function than are likely to be available. Achieving homoscedasticity is therefore important for centile estimation as it enables centiles to be estimated relative to the predicted value for height and age from a single distribution. If normality can be achieved it provides simple and efficient estimation of centiles.

Bland *et al* considered the problem of constructing centiles of birth weight, which is normally distributed for a given gestational age but shows increasing variance with gestational age.[12] They found that if log(birth weight) was regressed on gestational age the back transformed (antilogged) residuals were both homoscedastic and normally distributed. We used the method in relation to FEV_1 in children and report results for FVC and forced expiratory flow rate over the mid portion of the curve (FEF_{25-75}) and for FEF_{75-85}, which enables centiles for these measures to be calculated. Calculation of predicted values for ethnic minority groups is discussed.

Methods

SUBJECTS

Data on lung function were collected in a subsample of areas that took part in the national study of health and growth in 1987 and 1988.[13] This is a surveillance study of schoolchildren aged 5 to 11 years in which data are collected from a representative sample of English children in even years, from inner city and ethnic minority children in odd years, and from a representative sample of Scottish children over both years. For pragmatic reasons lung function testing was carried out only in areas in which time was available during regular fieldwork and therefore, with some exceptions, in the areas of smaller sample size. The main analysis reported in this paper was carried out on data from white children in the English representative sample, of whom 2486 were eligible for inclusion. The English inner city sample contained 1895 eligible children, who were subdivided into white, Afro-Caribbean, Urdu, Gujarati, Punjabi speaking, other Indian subcontinent, or other, according to the language spoken at home and the fieldworker's assessment.[13]

MEASUREMENTS

Only children in classes in which the majority were aged 7 years or more at the start of the school years had their lung function measured, which was carried out using a spirometer (Vitalograph Model S) with spirogram and digital printout. After calibration of the machine, instruction was given by a trained fieldworker to the children in small groups with a demonstration. Each child tried three times without wearing a noseclip and with a minimum exhalation time of 1·5 s, and the results were recorded unless the fieldworker judged a blow to be in error from the spirogram. Limitations on time for fieldwork precluded further attempts. A child was not measured if the teacher informed the fieldworker that the child had a bad heart or was otherwise severely ill. In this analysis data for a child with asthma who had used an inhaler that morning were excluded. All measurements were made in May, June, or autumn and no correction at body temperature and ambient temperature was applied.

FEV_1 from the best blow, defined as the greatest sum of FVC and FEV_1, was analysed in all children satisfying the above criteria, as well as in the smaller number in whom the two best ($FVC + FEV_1$) measurements agreed to within 5%; only the results in those having two best ($FVC + FEV_1$) measurements within 5% agreement are reported in detail. The definition of best blow accords with the American Thoracic Society recommendation for FEF_{25-75} and FEF_{75-85}.[14]

Height was measured on a Holtain Stadiometer to the last complete 0·1 cm, as described by Tanner *et al*,[15] and 0·05 cm added before analysis.

ANALYSIS

Only the analysis of FEV_1 is described in detail. To determine whether FEV_1 satisfied the criterion for log transformation boys and girls were divided into 5 cm height groups. Most (98·9%) of the children fell in the nine groups from ≥115 cm to ≥155 cm, which ranged in size from 10 children to 288 children, but only the 155+ cm groups had fewer than 40 children. Mean and standard deviation were calculated for FEV_1 within each group and plotted against each other to check that standard deviation was proportional to mean value. Multiple regression of $\ln(FEV_1)$ on ln(height) and ln(age) was used to determine equations for predicted $\ln(FEV_1)$ in boys and girls, where ln denotes logarithm to base e. The distributions of the residuals—that is, differences between actual $\ln(FEV_1)$ and its predicted value for each child—were found and re-examined after antilogging each residual to determine which distribution was the more normally distributed. Means and standard deviations of the antilogged residuals were calculated, providing a method of calculating centiles and standardised scores. A similar procedure was carried out for FVC, FEF_{25-75}, and FEF_{75-85}, which were taken from the best curve as defined.

Participation, defined as the child providing at least one useful blow, was analysed by logistic regression in relation to age and sex using the generalised linear interactive modelling (GLIM) program,[16] as was ability to perform a repeatable blow. Ability to perform a useful blow was additionally analysed in relation to wheeze and asthma as reported on a self administered questionnaire, usually completed by the child's mother.

Results

RESPONSE

A small number of non-white children were omitted from the English representative sample because ethnic group differences were expected, leaving a total of 2486 children aged from 6·5 to less than 12 years eligible for lung function in this sample. The number of children excluded for reasons of no lung function, use of inhaler, or leak in the Vitalograph tube are given for each sample in table 1. Children who gave only one valid blow or whose two best blows differed by 5% or more (table 1) were omitted from the results given in detail. In the Scottish representative sample and English inner city samples a greater proportion of

Table 1   Response to lung function in English representative, English inner city, and Scottish representative samples. Values are numbers (percentages of children)

	English representative sample (1988)*	English inner city sample (1987)	Scottish representative sample (1987+1988)
Reasons for no lung function result:			
Refusal	0	4	1
Absence	133	115	23
Bad heart or severely ill	5	4	4
No valid blow	47	142	46
Total	185 (7·4)	265 (14·0)	74 (11·7)
Reason why valid blow excluded:			
Inhaler used	60	32	7
Bad heart or severely ill	2	0	0
Leak in tube	0	0	54
Total	62 (2·5)	32 (1·7)	61 (9·6)
Only one valid blow	98 (3·9)	138 (7·3)	27 (4·3)
Best two blows differed by ⩾5% in (FVC+FEV$_1$)	458 (18·4)	407 (21·5)	104 (16·4)
Acceptable lung function but no height data	1	3	0
Included in analysis	1682 (67·7)	1050 (55·4)	368 (58·0)
Total eligible	2486 (100)	1895 (100)	634 (100)

*White children only.

children were excluded for reasons of absenteeism or failure to provide a valid blow. A leaky Vitalograph tube caused a problem in one Scottish area, and a greater proportion of inner city children gave non-repeatable blows. There remained 55·4% of inner city children and 58·0% of Scottish children with data meeting the criteria for inclusion in the analysis, compared with 67·7% in the English representative sample. The main analysis here reported is of the data on the English representative sample, 1682 children (910 boys and 772 girls).

Useful participation, defined as giving at least one valid blow, increased with age (p < 0·001) and varied significantly between study areas (p < 0·001). The same was true when analysis was confined to those whose data were not rejected for reasons of illness or use of inhaler— that is, ability to perform a useful blow increased with age. Within area and adjusted for age ability to perform a useful blow was lower in children with persistent wheeze than in children with no symptoms (p < 0·05).

Means and standard deviations of FEV$_1$ by sex and age group are shown in table 2 for the English representative sample. Increasing variance with age was found for boys and girls.

TRANSFORMATION OF LUNG FUNCTION

The standard deviations of FEV$_1$ within 5 cm height groups is shown plotted against mean value in figure 1. The standard deviations increased with mean value and could be assumed to proportional to the mean value as

the intercept of the regression line did not differ significantly from zero (p > 0·1) in boys or girls. This suggested the need for logarithmic transformation to stabilise variance[17]; figure 2 shows little relation between standard deviation and the mean of ln(FEV$_1$).

RELATION TO HEIGHT AND AGE

Ln(FEV$_1$) is shown plotted against ln(height) in figure 3, the relation being reasonably smooth and linear. FEV$_1$ was significantly (p < 0·001) related to ln(height) and to ln(age) (p < 0·001) in girls but not boys. Non-linearity, as assessed by quadratic and cubic terms in ln(height) and ln(age), was not significant (p > 0·05). The regression equations are given in table 3.

DISTRIBUTIONS OF RESIDUALS

Distributions of residuals on the ln scale were negatively skewed, as shown for FEV$_1$ in boys in figure 4. Antilogging the residuals produced greater symmetry, as illustrated in figure 5. The means and standard deviations of the antilogged residuals, which are ratios of actual to predicted FEV$_1$, are given in table 3. The information in table 3 can be used to calculate centiles of FEV$_1$ for height and age or standard deviation scores for individual children, which

Table 2   Distribution of FEV$_1$ (l) for white children in English representative sample by sex and age

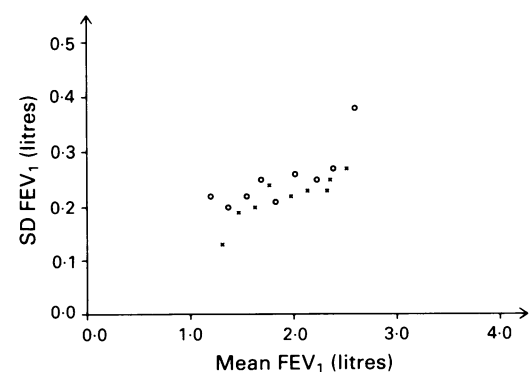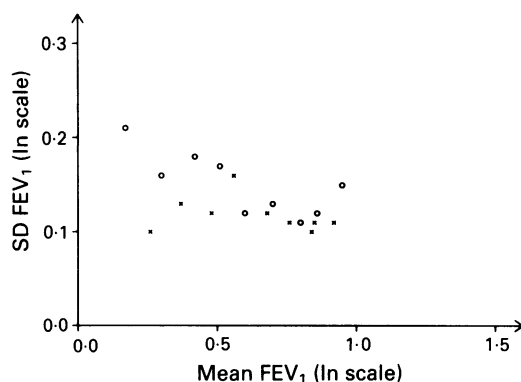| Age (years)	Boys (n=910)		Girls (n=772)	
	n	Mean (SD)	n	Mean (SD)
⩾6	11	1·38 (0·20)	6	1·42 (0·17)
⩾7	97	1·54 (0·24)	85	1·46 (0·23)
⩾8	209	1·71 (0·27)	182	1·59 (0·28)
⩾9	236	1·94 (0·32)	179	1·78 (0·27)
⩾10	225	2·07 (0·29)	179	1·97 (0·30)
⩾11	132	2·25 (0·36)	141	2·23 (0·38)

Figure 1   Standard deviations of FEV$_1$ plotted against mean values for white boys (×) and girls ( ) in English representative sample.

Figure 2 Standard deviations of ln(FEV₁) plotted against mean values for white boys (×) and girls ( ) in English representative sample.

Figure 3 Mean ln(FEV₁) (boys ————, girls — — — — —) plotted against mean ln(height), for white children in English representative sample, in 5 cm height groups.

can be used in subsequent analyses as the appropriate measure of height and age adjusted lung function. This is described in the appendix.

FEV, FEF$_{25-75}$, AND FEF$_{75-85}$

Outlying values of FEF$_{25-75}$ above 6·5 l/s and FEF$_{75-85}$ above 4 l/s were omitted, leaving data for 908 boys and 771 girls for FEF$_{25-75}$ and 888 boys and 767 girls for FEF$_{75-85}$. FVC and FEF$_{75-85}$ for boys and girls had standard deviations proportional to mean value. For FEF$_{25-75}$ the relation was linear but not proportional. Logarithmic (ln) transformation was therefore optimal for FVC and FEF$_{75-85}$ and preferable to no transformation for FEF$_{25-75}$. The regression equations to obtain predicted ln(value) and mean and standard deviation of antilogged residuals are shown in table 4.

Discussion

The main aim of this paper was to demonstrate a method that can be used to analyse lung function data in children without violating the assumptions of regression analysis and analysis of variance, the main tools of practical data analysis. A secondary aim was to provide the means of calculating reference centiles and standard deviation scores for children aged 6·5 to 11·99 years.

We have reported results for children with at least two repeatable blows in this paper, in line with many published reports—that is, for 67·7% of the English white representative sample. However, the method, which was suggested by Bland et al,[12] worked equally well on the data for the 90·0% with at least one valid blow. The method depends for its validity on a proportional relation between standard deviation and mean value as well as a normal distribution of lung function for fixed height
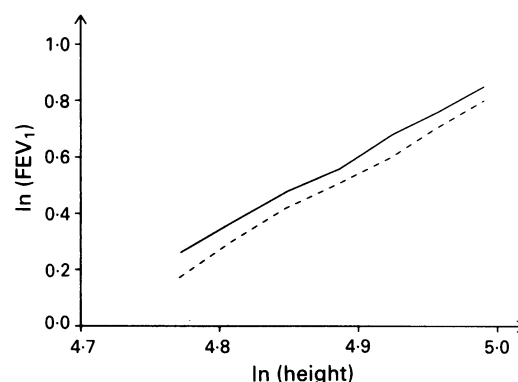
and age. These two properties are not unique to our data: Strang showed a regression line of FEV₁ on height with symmetric 95% range at each height but increasing variance[18] and Lunn commented that centiles bore a constant relation to the median, a consequence of the two properties.[19] Others have used the natural logarithmic transformation to stabilise variance,[8] but no other authors have combined this with the normal distribution. The need for a recommendation for the analysis of lung function in children is clearly shown in a recent paper in which, despite figures showing increasing variance of FVC and FEV₁ and a curvilinear relation with height, the author gave multiple regression equations for untransformed lung function on height and age.[20] When data have the two properties of normal distribution and standard deviation proportional to the mean then the method described here should be used, or a statistically more sophisticated equivalent.

Comparison of response rates with those of other authors is difficult, as many report only the percentage of acceptable spirometric results among those tested, rather than the response rate in those eligible to take part, which is the relevant figure in epidemiological studies. However Kauffman et al reported that 70% of children provided acceptable forced time-volume curves.[21]

Although the standard deviation of FEF$_{25-75}$ increased with mean value, the relation was not proportional, the transformation ln(FEF$_{25-75}$ + 0·3) being preferable[22] to ln(FEF$_{25-75}$). However, use of natural logarithmic transformation is preferable to no transformation.

Table 3 Multiple regression of ln(FEV₁) on ln(height) and ln(age) in white children in the English representative sample

	Regression coefficients			Multiple correlation coefficient (R²)	Distribution of exp(residual)*	
	Intercept	ln(height) (SE)	ln(age) (SE)		Mean	SD
ln(FEV₁)	−11·137	2·365 (0·089)	*Boys (n=909)* 0·071 (0·089)	0·65	1·0078	0·1129
ln(FEV₁)	−10·755	2·212 (0·104)	*Girls (n=772)* 0·209 (0·054)	0·64	1·0107	0·1243

*Lung function ÷ predicted lung function.

Figure 4 Distribution of residuals of $\ln(FEV_1)$ for white boys in English representative sample, with fitted normal curve of same mean and standard deviation.

Figure 5 Distribution of antilogged residuals of $\ln(FEV_1)$ for white boys in English representative sample, with fitted normal curve.

The important features of the analysis are, firstly, the logarithmic transformation before multiple regression analysis and, secondly, the antilogging of the residuals, or equivalently taking the ratio of actual to predicted lung function; predicted lung function is found by antilogging the predicted value from the multiple regression. We have used logarithms to base e, partly because they are natural in this context[22] and partly because of their use by most of the authors cited. However, base 10 can equally be used as results differ by only a multiplicative constant factor. Which terms are included in the prediction equation in addition to ln(height) are less important. We included ln(age), because although it explained a small proportion of the variation in lung function unaccounted for by height in our data, its importance increases with a wider age range. Quadratic and cubic terms in age were significant ($p < 0.05$) for some of the lung function measurements, but the extra variation explained was less than 1%. There is slightly greater justification for inclusion of ln(weight) and ln(triceps skinfold thickness), which showed positive and negative relations respectively with both FVC and FEV_1, in line with the finding of Cotes et al[23] of a positive relation of lung function with fat free mass/stature[2]. However, these two variables explained only 1% of the additional variation, and data on these two variables are unlikely to be available for routine use.

It is not surprising that various equations for height and age adjustment are found in published work,[5 6 8 9] even when ln(lung function) has been used. Firstly, the terms will vary with the age range of the children in the study, as will the total variation explained by the multiple regression. Secondly, with large data sets,

as required for centile estimation, very small departures from linearity can be significant but have negligible effect on predicted values.

We have not followed the recommendations of the American Thoracic Society[14] completely, in that all measurements were taken from the blow with maximum FVC + FEV_1. The recommendation to use maximum FVC and maximum FEV_1 means that for the majority of children the values are taken from the same blow,[14] but for a minority they are from different blows, so that the measurements have a different correlation in the two groups. However, the method of analysis in our study is appropriate to lung function data whichever criterion of selection is used.

Predicted ln(lung function) was calculated for children in the inner city groups and Scottish sample using the equations for the English representative sample. The means and standard deviations of the ratio of actual to predicted values are shown in table 5. The four Indian subcontinent groups (Urdu, Gujarati, and Punjabi speaking and others) did not have significantly different mean values except for FEF_{25-75} in boys ($p < 0.05$) and were combined, but the groups as shown together with the English represenative sample (table 3) had highly significantly different mean values ($p < 0.001$), except for FEF_{25-75} ($p > 0.1$) in boys. All the English inner city groups had lower lung function than the representative sample. The Afro-Caribbean children had the lowest mean values among the boys and the Indian subcontinent group among the girls. Scottish children had greater lung function by all parameters.

Table 4 Regression equations used to adjust $\ln(FVC)$, $\ln(FEF_{25-75})$, and $\ln(FEF_{75-85})$ in white children in the English representative sample

Dependent variable	Regression coefficients			Multiple correlation coefficient (R^2)	Distribution of exp(residual)*	
	Intercept	ln(height) (SE)	ln(age) (SE)		Mean	SD
			Boys			
ln(FVC)	−11·574	2·508 (0·083)	0·016 (0·042)	0·69	1·0084	0·1087
ln(FEF$_{25-75}$)	−8·717	1·802 (0·189)	0·275 (0·096)	0·25	1·0296	0·2427
ln(FEF$_{75-85}$)	−10·816	2·050 (0·329)	0·214 (0·166)	0·12	1·0798	0·3963
			Girls			
ln(FVC)	−10·808	2·267 (0·096)	0·167 (0·050)	0·67	1·0072	0·1162
ln(FEF$_{25-75}$)	−9·269	1·853 (0·212)	0·413 (0·109)	0·30	1·0339	0·2622
ln(FEF$_{75-85}$)	−10·705	1·915 (0·382)	0·482 (0·197)	0·13	1·0841	0·3882

*Lung function ÷ predicted lung function.

Table 5 Distributions of exp(residual) in inner city and Scottish children, with residual taken from model for English representative sample. Values are means (SD)

Ethnic group/sample	FVC	FEV_1	FEF_{25-75}	FEF_{75-85}
		Boys		
Inner city:				
White (n=184)	0·9896 (0·1156)	0·9937 (0·1265)	1·0172 (0·2447)	1·0419 (0·3851)
Afro-Caribbean (n=67)	0·8435 (0·1044)	0·8654 (0·1100)	1·0062 (0·2899)	0·9580 (0·3793)
Indian subcontinent (n=241)	0·8963 (0·1146)	0·9125 (0·1148)	1·0288 (0·3007)	0·9964 (0·3786)
Other (n=67)	0·8968 (0·1632)	0·9017 (0·1548)	0·9846 (0·3019)	0·9325 (0·3593)
Scottish (representative sample) (n=195)	1·0369 (0·1023)	1·0383 (0·1060)	1·0676 (0·2526)	1·1189 (0·4122)
Inner city:		*Girls*		
White (n=195)	0·9771 (0·1217)	0·9851 (0·1262)	1·0303 (0·2639)	1·0534 (0·4212)
Afro-Caribbean (n=71)	0·8937 (0·1058)	0·8994 (0·1121)	0·9751 (0·2824)	0·9307 (0·3471)
Indian subcontinent (n=179)	0·8824 (0·1107)	0·8958 (0·1187)	1·0129 (0·2936)	1·0161 (0·3984)
Other (n=46)	0·9372 (0·1685)	0·9459 (0·1728)	1·0012 (0·2515)	0·9974 (0·3726)
Scottish (representative sample) (n=173)	1·0507 (0·1093)	1·0679 (0·1125)	1·1423 (0·2424)	1·2160 (0·4719)

Standard deviation scores for the inner city and Scottish groups can be calculated using the prediction equations in tables 3 and 4 with the means and standard deviations in table 5, as described in the appendix. This assumes that it is appropriate to compare children in these groups with their group mean, rather than assess children relative to a representative sample of the white majority. There is no agreement as yet over whether separate standards should be used for individual assessment of these children,[24] but for analysis of lung function in relation to passive smoking or other environmental influences it is necessary to remove ethnic group differences.

Comparison of mean lung function with other authors is difficult, as existing standards for lung function were published[18 25-27] before the need to take age into account as well as height was recognised, and the studies generally include a greater age range than in the national study of health and growth. One exception is the paper by Dockery et al, which reports results for children aged 6 to 11 years in the United States six cities study.[8] We calculated the differences between ln(FVC) and ln(FEV_1) and their published predictions as functions of height, age, weight, sex, and ethnic group for white children in the English representative sample and antilogged the result to give a ratio for children in the national study of health and growth to lung function of those in the six cities study. The mean ratio was 1·052 (SE 0·004) for FVC and 1·060 (SE 0·004) for FEV_1 in boys and 0·969 (SE 0·004) and 1·000 (SE 0·004) respectively in girls. Our values for white boys in the English representative sample are therefore slightly greater when adjusted for height, age, and weight, but FVC slightly less in girls. Corresponding values for the white inner city sample were 1·030 (SE 0·013) for FVC and 1·044 (SE 0·010) for FEV_1 in boys and 0·938 (SE 0·008) and 0·951 (SE 0·009) in girls respectively—that is, slightly greater for national study of health and growth boys and less for girls than the six cities children. If all children with at least one valid blow were included the white representative sample girls had greater FVC and FEV_1 than the six cities girls.

Published centiles differ in their relation to mean or median because they have been calculated entirely on the untransformed scale or entirely on the log scale. Centiles constructed using Bland's method,[12] although representing variation dependent on height, are symmetric about the median for a given height, unlike those calculated on the log scale. Formulations such as that of Cotes, who quoted a predicted value of the form a(height)[b] with a standard deviation per cent,[27] are equivalent to calculations on the log scale.

We confirm the findings of others that black children have lower lung function for height and age than their white counterparts in inner city areas.[5 6 8] Our differences were 17% for FVC and 15% for FEV_1 in boys, and 9% for each in girls. Patrick and Patel found differences of 13% and 12% for FVC and FEV_1 for children of Indian or Afro-Caribbean origin, but their data for the Afro-Carribbeans were on 82 children only, mainly aged over 12 years.[5] Schwartz et al gave differences in ln(FVC) and ln(FEV_1) of −0·114 and −0·0985 for black American children compared with white children—that is, 11% and 9% less respectively.[6] This was after adjustment for ln(sitting height), which they reported as explaining 16% of the differences, so before the adjustment the differences were of the order of 13% and 11%. Dockery et al gave differences of 12% for FVC and 13% for FEV_1.[12] They also found greater variation in lung function in black children than in white children. The fact that sitting height explains part of the difference between black and white children[6 8] seems to necessitate the use of separate stature and age adjusted standards for black children.

Schoenberg et al derived separate, and in our view unnecessarily complex, equations for black and white subjects aged 7 to 17 years,[9] so comparison is difficult. They stated that differences were greater for FVC than for FEV_1. We support their conclusion that a single "scaling factor", as proposed by Rossiter and Weill,[28] in inappropriate, but mainly on the grounds that it may obscure increased variation.

Data on children of Indian subcontinent origin living in Western society are more scarce. Patrick and Patel studied 166 Indian boys and 108 Indian girls aged from 5 to 16 and found lower FVC and FEV_1 as reported above.[5] Johnston et al found greater lung function in Indian children than in those of African origin, but differences were not significant.[29] However, data on lung function were obtained in only 47 children of African origin and 40 of Indian

origin. Our data on 241 boys and 179 girls are therefore a substantial additon to information. We confirm Johnston *et al*'s suggestion of lung function intermediate between that of white inner city children and that of Afro-Caribbean origin for boys, but not for girls.

Our finding of greater lung function in Scottish children than in the English white representative sample, after height and age adjustment, is so far unexplained, although it may in some way be related to the lower response. The finding was not explained by differences in birth weight because, although we found lung function to increase with birth weight, as reported for adults by Barker *et al*,[30] the relation was weak, and in our sample Scottish boys had lower mean birthweight than English boys in the representative sample.

For centile estimation correct description of residual variation is more important than inclusion of all significant terms in height and age in the prediction equation, but for the purposes of analysis in relation to other factors it is important also to incorporate all potentially confounding variables, including non-linear terms in height and age, and weight and triceps skinfold thickness or other measures of fatness. Effects such as passive smoking are likely to be small, and the potential for bias great.

Two approaches are possible—either to include all terms of interest and confounding variables in the age and height multiple regression equation or to calculate height and age adjusted standard deviation scores as described in the appendix and then carry out multiple regressions of these on the other independent variables. The latter is preferable because significance tests are then performed on a scale on which the residuals can be expected to be normally distributed with equal variance, and it allows the inclusion of groups with differing residual standard deviations, such as ethnic minority groups.

At least for FVC, FEV_1 and FEF_{75-85}, the properties of the data lead to the conclusion that the method of Bland *et al* should be adopted,[12] and it may have application to many measurements in medicine. The method maximises use of the data, as children do not have to be divided into age or height subgroups, and requires estimation of only a small number of parameters. Its adoption for lung function should lead to more uniformity in presentation of results, so enabling authors to compare their results more easily than hitherto.

Appendix

The results showed that FEV_1/predicted FEV_1 is approximately normally distributed, mean 1·0078 for boys, 1·0107 for girls, and standard deviation 0·1129 and 0·1243 respectively (table 3). This can be used to calculate centiles of FEV_1 and standard deviation scores.

For example a boy of height 130 cm, age 9·00 years has predicted $\ln(FEV_1) =$

$-11·137 + 2·365 \ln(130) + 0·071 \ln(9)$

$= -11·137 + 2·365 \times 4·868 + 0·071 \times 2·197$

$= 0·531$

So predicted $FEV_1 = \exp(0·531) = 1·70$ l.

Therefore for centiles of FEV_1 for boys height 130 cm, age 9·00 years

$\dfrac{FEV_1}{1·70}$ is normally distributed,

mean 1·0078, standard deviation 0·1129.

So pth centile for boy height 130 cm, age 9 years, is given by

$$1·70 (1·0078 + 0·1129 \, z_p) ,$$

where z_p is the pth centile of the standard normal distribution.

Thus the 3rd centile is $1·70 (1·0078 - 0·1129 \times 1·8808)$, which is 1·30 l.

To obtain a standard deviation score for an individual child the predicted $\ln(FEV_1)$ is found and antilogged as above. If a boy height 130 cm, age 9, has an FEV_1 of 1·5 then the ratio of FEV_1 to its predicted value of 1·70 is 0·88 and his standard deviation score $= (0·88 - 1·0078)/0·1129 = -1·11$.

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