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Combined body plethysmographic, spirometric and flow volume reference values for male and female children aged 6 to 16 years obtained from "hospital normals"

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Abstract Vital capacity (VC) and its subdivisions (IC and ERV), total lung capacity (TLC), residual volume (RV), peak expiratory flow (PEF), forced vital capacity (FVC), forced expiratory volume in one second (FEV_1), maximum flow volume curve (MEF_{75}, MEF_{50}, MEF_{25}, MMEF, $FEF_{75–85}$), airway resistance (R_{tot}, R_{eff}) and the thoracic gas volume at resting expiratory position (FRC) were measured in 187 girls and 213 boys (hospital normals) aged 6 to 16 years. The measurements were carried out consecutively on the same subjects in the morning using a volume-constant plethysmograph (Master-Lab, E. Jaeger; programs: body plethysmography, spirometry and flow volume). Using multiple regression analysis the best fitting curves for the prediction of normal values for boys and girls were selected. Analyses of covariance were performed to compare the adjusted means of the spirometric and body plethysmographic variables of the male and female subjects. As expected, we found higher static and dynamic (FVC, FEV_1, PEF) lung volumes in boys than in girls relating to height. The flows (MMEF, MEF_{50}, MEF_{25}, $FEF_{75–85}$) were significantly lower in the male than in the female subjects of the same age justifying separate prediction equations, but the same equation for both genders may be used for the resistance variables R_{tot} and R_{eff}. Our results are compared with those of previous studies.

Conclusion Lung volumes and flows differ significantly between girls and boys calling for separate reference values for female and male subjects of the same age.

Key words Body plethysmography · Children · Reference values · Sex-related differences · Spirometry

Abbreviations *A* age · *ERV* expiratory reserve volume · $FEF_{75–85}$ forced late expiratory flow, flow rate between 75 and 85% vital capacity · FEV_1 forced expiratory volume in 1 s · FIV_1 forced inspiratory volume in 1 s · *FRC* functional residual capacity · *FVC* forced vital capacity · *H* height · *IC* inspiratory capacity · *IVC* inspiratory vital capacity · MEF_x maximal expiratory flow at x% of the FVC remains to be expired · *MMEF* maximal mid-expiratory flow · *nlog* natural logarithm · *PEF* peak expiratory flow · r^2 coefficient of determination · *RSD* residual standard deviation · R_{eff} effective airway resistance · R_{tot} total airway resistance · *RV* residual volume · SR_{eff} specific effective airway resistance · SR_{tot} specific total airway resistance · *TLC* total lung capacity · *VC* vital capacity · *VT* tidal volume · *W* weight

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Introduction

Lung function testing by body plethysmography can be easily performed on children aged 5 years and older, but no reliable reference values based on large populations are available. Only a few studies separated boys and girls and also included age and weight of the children in addition to body size [1, 2, 4, 7, 12, 19, 24, 28, 30]. On the other hand, many reference values for static and dynamic lung volumes obtained by spirometry exist and are based on sizeable populations [25]. However, most measurements of the flow volume curves have been carried out only in small groups of children and adolescents. Thus, the results of the studies referring to normal values for maximal expiratory flow (MEF) at varying percentage of the forced vital capacity (FVC) (MEF_{75}, MEF_{50}, MEF_{25}), maximal mid expiratory flow (MMEF) and forced late expiratory flow, flow rate between 75% and 85% of FVC ($FEF_{75–85}$) vary considerably and most of them use rather simple prediction equations [2, 19, 21].

In order to obtain more reliable prediction equations, body plethysmographic, spirometric and flow volume measurements of 400 children and adolescents (hospital normals) have been analysed by regression models that deliver adequate and consistent descriptions of the data. In particular, we considered for which parameters separate prediction equations in boys and girls are justified.

Subjects and methods

Subjects

From January 1989 to July 1993, combined body plethysmographic, spirometric and flow volume tests were carried out on 4714 children during their 6 week stay at the Seehospiz Kaiserin Friedrich, a large rehabilitation centre on Norderney, an island off the coast of Northern Germany. Its intake is primarily for patients suffering from chronic diseases of the respiratory system, the skin or from psychosomatic disorders. A large number of patients are convalescents or subjects suspected of having allergic diseases; however, most of them are healthy subjects tested routinely also by spirometry and body plethysmography. From this subpopulation, 400 (397) subjects, 213 (211) males and 187 (186) females aged 6 to 16 years, were the basis for modelling dynamic lung volumes and flows (or static lung volumes and airway resistance).

The main admission diagnoses (prophylactic cure) of the 400 hospital normals were susceptibility to infection (without underlying chronic illness) (181 patients), psychosocial problems (115 patients), and diseases of the skin (104 patients). All were of Caucasian origin and did not show any signs of respiratory dysfunction on the day of lung function testing. Taking into account the individual medical history the selection criteria were similar to those recommended for epidemiologic studies by the GAP conference [31]. Furthermore, subjects were excluded according to the following statistical criteria: (1) if any of the combined lung function tests were missing; and/or (2) if there were outliers according to standardised residuals below −3.0 or above +3.0 of the regression model.

Body size was measured as standing height in metres, weight was registered in kilogrammes. Age was recorded as the difference between day of measurements and birthday in years. Each age group in Table 1 includes children up to the next highest age, e.g. age group 7 includes children between 6 and 7 years (7th year of age).

Table 1 Distribution of age in females and males

Sex	Year of age											Total
	6	7	8	9	10	11	12	13	14	15	16	
Females	7	15	14	21	18	24	13	18	17	21	19	187
Males	17	17	17	30	24	34	21	15	16	12	10	213

Lung function testing

Body plethysmography and spirometry were performed consecutively on the same subject in the morning using a volume–constant plethysmograph connected to a pneumotachograph and a pressure recorder (completely computerised MasterLab with electronic body temperature pressure saturation compensation, E. Jaeger, Würzburg, Germany). During the breathing manoeuvres the subjects were sitting in an upright position wearing a noseclip. The specific plethysmographic variables, i.e. airway resistance and functional residual capacity (FRC_{box}), were measured first. Immediately after the assessment of FRC an inspiratory capacity manoeuvre (IC) was performed to determine the total lung capacity (TLC = IC + FRC) followed by the measurements of expiratory reserve volume (ERV) and inspiratory vital capacity (IVC). After a short rest, maximal expiratory flow volume curves were recorded. All measurements and curves were stored and the best of them obtained from three to five technically satisfactory manoeuvres were chosen for analysis using a special MasterLab data recording system.

Total airway resistance (R_{tot}) was taken as a slope of the total flow–pressure loop. Furthermore, the effective resistance of the airway (R_{eff}) throughout the respiratory cycle was calculated as $R_{eff} = \int \frac{P_{alv} dV}{\text{flow } dV}$ by computerised analysis [15]. All measurements were carried out by the same technicians.

Statistical analysis

Multiple regression analysis

The stored data were analysed and processed using the SPlus 4.0 statistical software [16]. Multiple regression equations were chosen to predict the reference values. The lung function measurements except forced expiratory volume in 1 s (FEV_1)%FVC, FEV_1%IVC and residual volume (RV) were transformed into natural log units (nlog) and described as functions of height (H), age (A) and weight (W) terms where the pool of variables included also other terms (e.g. $A \cdot H$, H/W, $A\sqrt{W}$, IND = $H/\sqrt[3]{W}$ = index of body mass). In the stepwise analysis with forward and/or backward selection, terms were added to or removed from the equation using common statistical criteria. Details on the procedures are reported in [13] and [29].

Covariance analysis

Analyses of covariance [6, 10] with covariates age and height were performed to compare the adjusted means of the spirometric (body plethysmographic) variables obtained from 213 (211) males and 187 (186) female subjects.

Robust regression and outlier detection

The assessment of RV, RV%TLC, FIV_1 and R_{eff} may be inaccurate and high leverage points may have an adverse effect on the regression slope. To eliminate such outliers a robust regression method (Least Trimmed Squares) was applied to RV (females), RV%TLC (females and males), FIV_1 (females) and R_{eff} (females and males) using the reweighted least squares method [27]. At least 5% of these data were weighted to zero and so excluded from the analysis.

Results

Dynamic lung volumes and flows

Tables 2 and 3 contain the prediction equations for dynamic lung volumes and flows derived from 187 girls and 213 boys, respectively, aged 6 to 16 years. Most prediction equations are functions of height and age. No weight terms are included because they contributed less than 0.01 to R^2, when added to height and age terms. We experimented with models suggested by Kristufek et al. [12], Neuberger et al. [20], Schoenberg et al. [28] and Quanjer et al. [25] and compared them with equations based on our own pool of variables. In girls we settled for the choice height and nlog (age) leading to explained variances from 65–93%. In boys, the simplest model with height delivered a good fit without systematic errors having explained variances from 61–93% (Table 3).

In girls and boys most of the ventilatory flow parameters were well described by height; only nlog peak expiratory flow (PEF) and nlog (MEF_{75}) called for the additional variable nlog (age). The explained variances were of the same order for both genders (from 47% to 86%). As expected, FEV_1%FVC and FEV_1%IVC were not (girls) or rather weakly (boys) related to age and height terms.

Analyses of covariance revealed statistically significant differences of the volumes and flow reference values for girls and boys. We found some differences relating to body size, namely significantly higher means of FEV_1 and IVC and significantly lower means of FEV_1%FVC, FEV_1%IVC, MMEF, MEF_{75}, MEF_{50}, MEF_{25} and FEF_{75-85} in boys than girls. Only the prediction curves of PEF were of the same characteristic for both genders.

Static lung volumes and airway resistance

The prediction equations of TLC, FRC, ERV and RV for girls and boys are listed in Table 4, based on observations of 186 female and 211 male children and adolescents. RV was assessed as the difference TLC – IVC. Its residual standard deviation (RSD) was

Table 2 Prediction equations for lung volumes (l) and ventilatory flows (l/s) measured by pneumotachograph spirometry in 187 female children aged 6 to 16 years

Prediction equations	Coefficient of determination (explained variance) (r^2)	RSD	Proportion of subjects (%) below the 5th normal percentile
$\text{nlog}(FVC) = -1.8701 + 1.4246H + 0.3130\ \text{nlog}(A)$	0.91	0.11	6.4
$\text{nlog}(FEV_1) = -1.8605 + 1.3829H + 0.2976\ \text{nlog}(A)$	0.93	0.09	4.8
$\text{nlog}(FIV_1)^a = -1.8054 + 1.6779H$	0.65	0.22	8.4
$\text{nlog}(IVC) = -1.8843 + 1.3947H + 0.3230\ \text{nlog}(A)$	0.92	0.10	4.3
$FEV_1\%FVC = 91.91 \pm 5.25$ (mean ± 1 SD)			
$FEV_1\%IVC = 95.23 \pm 6.75$			
$\text{nlog}(PEF) = -1.2010 + 1.4072H + 0.3164\ \text{nlog}(A)$	0.84	0.15	3.7
$\text{nlog}(MEF_{75}) = -1.1343 + 1.3838H + 0.2598\ \text{nlog}(A)$	0.82	0.15	4.2
$\text{nlog}(MEF_{50}) = -1.2828 + 1.6639H$	0.73	0.18	4.2
$\text{nlog}(MEF_{25}) = -1.8245 + 1.5880H$	0.61	0.23	5.3
$\text{nlog}(MMEF) = -1.4583 + 1.7097H$	0.75	0.17	5.3
$\text{nlog}(FEF_{75-85}) = -2.1733 + 1.6455H$	0.54	0.27	6.4

[a] Reweighted least squares ($n = 177$)

Table 3 Prediction equations for lung volumes (l) and ventilatory flows (l/s) measured by pneumotachograph spirometry in 213 male children aged 6 to 16 years

Prediction equations	Coefficient of determination (explained variance) (r^2)	RSD	Proportion of subjects (%) below the 5th normal percentile
$\text{nlog}(FVC) = -1.9339 + 1.9941H$	0.92	0.11	4.2
$\text{nlog}(FEV_1) = -1.8240 + 1.8456H$	0.93	0.09	3.3
$\text{nlog}(FIV_1) = -1.8394 + 1.6893H$	0.61	0.24	6.5
$\text{nlog}(IVC) = -1.9975 + 2.0115H$	0.91	0.11	4.7
$FEV_1\%FVC = 83.058 + 70.987/A$	0.16	5.31	6.5
$FEV_1\%IVC = 84.537 + 91.726/A$	0.15	7.03	2.0
$\text{nlog}(PEF) = -1.0578 + 1.3521H + 0.2922\ \text{nlog}(A)$	0.86	0.13	4.7
$\text{nlog}(MEF_{75}) = -0.9288 + 1.4008H + 0.1495\ \text{nlog}(A)$	0.85	0.12	4.7
$\text{nlog}(MEF_{50}) = -1.1200 + 1.5134H$	0.76	0.15	5.6
$\text{nlog}(MEF_{25}) = -1.7033 + 1.4668H$	0.55	0.24	3.7
$\text{nlog}(MMEF) = -1.2669 + 1.5429H$	0.74	0.16	4.2
$\text{nlog}(FEF_{75-85}) = -1.9209 + 1.4365H$	0.46	0.27	3.7

Table 4 Prediction equations for lung volumes (l) measured by body plethysmography for female and male children aged 6 to 16 years

Sex	*N*	Prediction equations	Coefficient of determination (explained variance) (r^2)	RSD	Proportion of subjects (%) below the 5th normal percentile
Female	186	nlog(TLC) = −1.2940 + 1.7021H	0.89	0.11	6.9
Male	211	nlog(TLC) = −1.3191 + 1.7383H	0.92	0.10	6.2
Female	186	nlog(FRC) = −2.0159 + 1.7942H	0.87	0.12	4.8
Male	211	nlog(FRC) = −1.8195 + 1.6779H	0.87	0.12	5.2
Female	186	nlog(ERV + 1) = −1.1162 + 0.8410H + 0.2555 nlog(A)	0.72	0.14	6.5
Male	211	nlog(ERV + 1) = −1.1386 + 1.2962H	0.68	0.16	5.6
Female	185	RV = −0.2189 + 0.2042 H^3 + 3.6015/A	0.24	0.25	3.3
Male	211	RV = 0.0046 + 0.1473 H^3 + 2.8681/A	0.12	0.28	4.3
Female	186	FRC%TLC = 55.88 ± 6.26 (mean ± 1 SD)			
Male	211	FRC%TLC = 56.07 ± 6.67			
Female	180	nlog(RV%TLC) = 2.6911 + 4.7997/A	0.19	0.31	6.6
Male	197	nlog(RV%TLC) = 2.4628 + 6.5376/A	0.34	0.31	8.0

relatively high (0.25 and 0.28, respectively) and the explained variance relatively low (24% and 12%, respectively), although robust regression analysis was carried out. However, for the other lung volumes the values of r^2 were satisfactory (from 0.68 to 0.92). Moreover, FRC%TLC does not change during childhood and adolescence, whereas RV%TLC shows a slight decrease. As expected, analyses of covariance yielded significant lower lung volumes for girls than for boys of the same height.

Contrary to the lung volumes and flows, the airway resistance variables R_{tot} and R_{eff}, measured during quiet breathing (no panting) did not differ significantly between girls and boys so that the same prediction equation could be used for both genders. For nlog (R_{tot}) and nlog (R_{eff}) (based on robust regression including 164 female and 187 male children) we have

$$\mathrm{nlog}(R_{tot}) = 2.0807 - 1.8812\ \mathrm{H},\ r^2 = 0.80,\ \mathrm{RSD} = 0.17$$

$$\mathrm{nlog}(R_{eff}) = 1.4150 - 1.8420\ \mathrm{H},\ r^2 = 0.67,\ \mathrm{RSD} = 0.24.$$

The specific total airway resistance ($SR_{tot} = R_{tot} \cdot FRC_{box}$) and the specific effective airway resistance ($SR_{eff} = R_{eff} \cdot (FRC_{box} + VT/2)$), however, do not change during childhood and adolescence. For both parameters, the small differences between girls and boys were statistically significant due to the significant higher FRC in boys.

$$SR_{tot} = 0.941 \pm 0.176\ \mathrm{kPa \cdot s},$$
$$SR_{eff} = 0.609 \pm 0.153\ \mathrm{kPa \cdot s\ (female)}$$
$$SR_{tot} = 1.005 \pm 0.177\ \mathrm{kPa \cdot s},$$
$$SR_{eff} = 0.630 \pm 0.150\ \mathrm{kPa \cdot s\ (male)}.$$

Discussion

Body plethysmography cannot be performed with mobile equipment [19]. Hence we analysed the combined lung function data of hospital normals [30]. The subjects came from various regions of Germany and may be considered as lung healthy children and adolescents. The statistical evaluation of our data was similar to the procedure described by Crapo et al. [3] and Gore et al. [6]. By stepwise analysis we were able to identify regression models that describe the data adequately. Robust regression analyses were applied to some lung function variables (FIV_1, RV, RV%TLC, R_{eff}) with extreme outliers to eliminate leverage points. Therefore, the corresponding equations are based on a reduced number of subjects. Using analyses of covariance we were able to compare the adjusted means of the spirometric (body plethysmographic) measurements derived from 213 (211) male and 187 (186) female subjects.

As expected [2, 4, 5, 12, 19, 22, 32, 33] we found higher static lung volumes (IVC, FRC, TLC, ERV, RV, FVC) in boys than in girls relating to height. After correcting for body size we also detected significantly higher dynamic lung volumes (FVC, FEV_1) in boys than girls. However, the flows (FEV_1%IVC, MMEF, FEF_{75-85}, MEF_{75}, MEF_{50}, MEF_{25}) were significantly lower in the male than in the female subjects of the same age justifying separate prediction equations. The same applies to all flow variables. In clinical practice separate prediction equations for male and female children (Tables 3 and 4) may be used. Our results support the hypothesis that girls have higher expiratory flows than boys [2, 30] and, in particular, our findings confirm the measurements of Merkus et al. [18] and Hibbert et al. [7]. On the other hand, boys have higher dynamic lung volumes [8, 14, 18, 26].

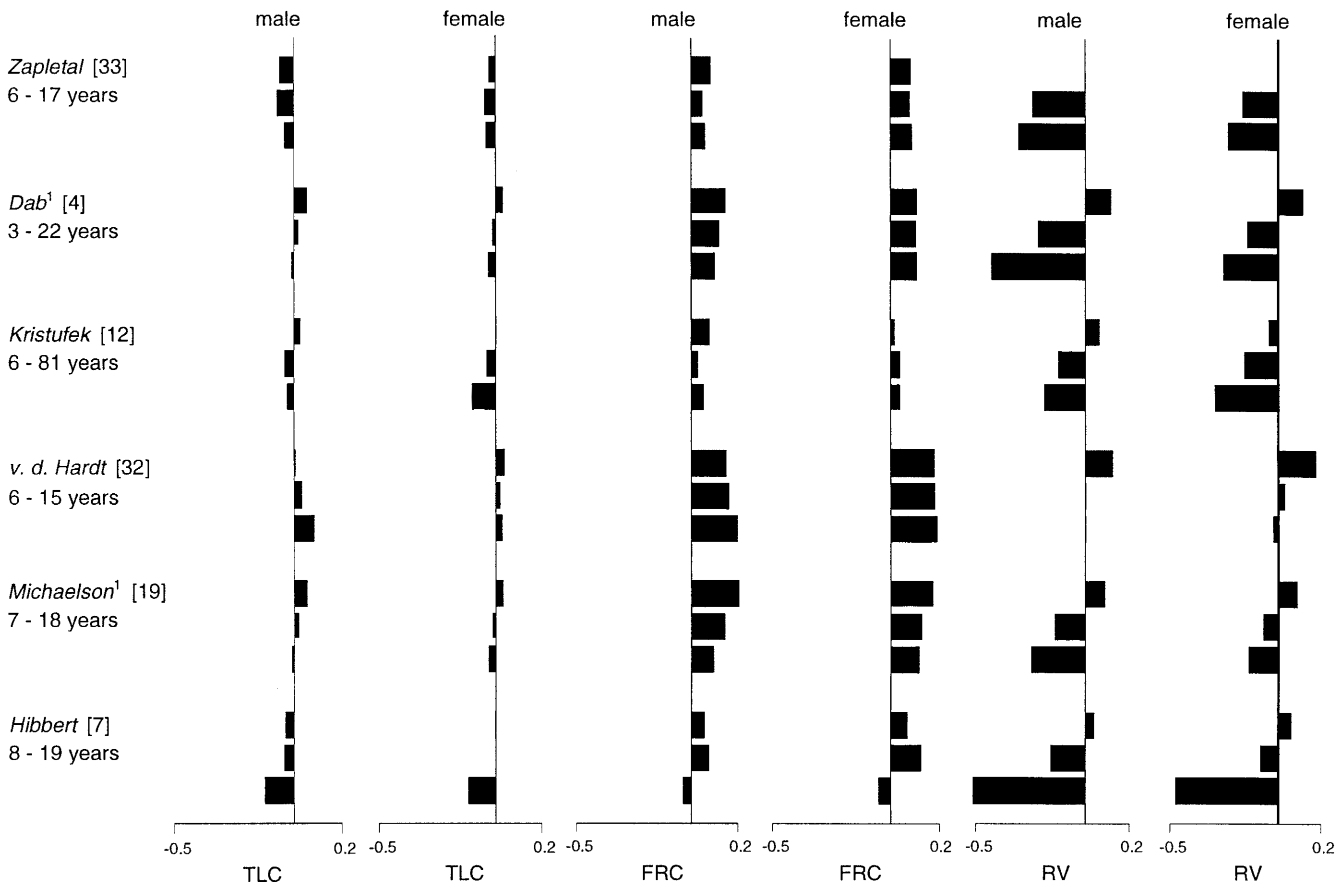
Our FVC and FEV_1 reference values are similar to those from the Austrian spirometric studies by Kummer [14] and Rapatz [26]. Likewise, the FVC and FEV_1 values derived by Polgar and Promadhat [22] from several published studies and those calculated by Quanjer et al. [25] from spirometric data sets collected in six different European centres deviate slightly from our values. On the other hand, the predicted values of PEF, MEF_{75}, MEF_{50}, MEF_{25} vary considerably among the different reference populations. Our values are best comparable with those of the Austrian study of Neuberger et al. [20].

As already mentioned, there are only a few studies on body plethysmographic reference values based on sufficiently large samples. For that reason summarised equations composed of data, compiled from several authors, are being used in the United States [2, 21, 22]. In Europe the prediction equations for TLC, FRC_{box} and RV of Zapletal et al. [33] are mainly recommended for use; however, their reference population comprises a rather small sample of 174 males and females only. A comparison of our reference values with those of Zapletal et al. [33] reveals that, on average, TLC is 5% lower and FRC 8% higher in our studied population. Thus, FRC%TLC is also higher, i.e. 55.97 ± 6.5% versus 49.2 ± 3.5% for males and females combined. Likewise, the reference values of FRC of other authors are lower or even considerably lower than ours (Fig. 1).

The differences in measurements may be explained to some extent by the use of older types of plethysmographs (e.g. Siregnost FD–91 and body test with body temperature pressure saturation unit) [33]; Fenyves-Gut box with a Douglas body temperature pressure saturation bag [11]. Using the completely computerised MasterLab system, FRC was evaluated in close relation to the beginning end-expiratory level (closure volume) which is 2%–4% higher than the real end-expiratory resting level (corrected FRC_{box}) [15]. The measurements of TLC and RV are not influenced by that.

In agreement with all authors we found RV (TLC–IVC) to be the lung volume with the highest relative variability. This might be due to the combination of three separate measurements, i.e. IC, FRC and IVC. Moreover, boys and girls at ages 6–9 years seem to have by nature a high RV relative to height, as may be derived from our regression equation (Table 4) or that of Zapletal et al. [33]. For children at age 8 years (Fig. 1), all reported similar RV reference values. However, at ages 12 and 16 years, the prediction equations of Zapletal et al. [33], Dab and Alexander [4], and Hibbert et al. [7] lead to considerably higher values than ours (up to 50% at age 16). These discrepancies seem to reflect the high variability of RV which remains the least reliable of all static spirometric variables and "in clinical practice one single abnormal value should be interpreted with due care" [4]. If necessary the measurement should be repeated several times.

Fig. 1 Comparison of the predicted values for TLC, FRC and RV of boys and girls aged 8 years (1.33 m), 12 years (1.56 m) and 16 years (males 1.73 m; females 1.63 m) of our study with those of six other studies. The relative differences are presented as fractions (present model – published model)/(present model). Higher prediction values of our (present) model are indicated by *bars to the right*, lower ones by *bars to the left*



[1] Same model for boys and girls.

Table 5 R_{tot} (kPa l^{-1}s) in boys and girls aged 6, 10 and 14 years. Predicted values of our study (R_{eff} and R_{tot}) and those reported in the literature

Age (years)	Height (m)	Own study		[32] R_{tot}	[4] R_{tot}	[33] R_{tot}
		R_{eff}	R_{tot}			
6	1.20	0.45	0.84	0.71	0.88	0.51
10	1.42	0.30	0.55	0.51	0.64	0.33
14	1.63	0.20	0.37	0.39	0.47	0.23

In general our prediction equations for body plethysmographic variables might be superior to those related only to height and calculated from populations with a small proportion of young children. They are (FVC, FEV_1, TLC, FRC as well as MEF_{25}, MEF_{50}, MEF_{75}, MMEF) not significantly different from those of Hibbert et al. [7], who took into account age and height likewise, but did not examine children below 8 years of age. Obviously, there do not seem to be any adequate reference values concerning the airway resistance related to height in the anglo-american literature [2]. In Europe adequate prediction equations for R_{tot} are proposed by von der Hardt and Leben [32] and Dab and Alexander [4]. Our reference values are lower than those of [4], but higher than and closer to those of [32]. The R_{tot} reference values of Zapletal et al. [33] are considerably lower and correspond well with our R_{eff} values (Table 5). There were no significant differences of the observed measurements between girls and boys in all four studies (Table 5) so that the same prediction equations may be used for both genders. Since flows are lower and more variable in children, the assessment of R_{eff} measured at every sample point of the resistance loop by computerised analysis is more accurate than the assessment of R_{tot} measured at the peak pressure points [15, 17] and may be preferred. It is now more often used also in adults and even in infants [9].

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References

1. American Thoracic Society (1991) Lung function testing: selection of reference values and interpretative strategies. Am Rev Respir Dis 144: 1202–1218
2. Cotes JE (1993) Lung function throughout life: determinants and reference values. In: Cotes JE (ed) Lung function: assessment and application in medicine. 5th (revised) Ed, Blackwell, Oxford, Chap. 15: 445–513
3. Crapo RO, Morris AH, Gardner RM (1981) Reference spirometric values using techniques and equipment that meet ATS recommendations. Am Rev Respir Dis 123: 659–664
4. Dab I, Alexander F (1979) Lung functions measured with a whole body plethysmograph, standard values for children and young adults. Acta Paediatr Belg 32: 259–267
5. Dickman ML, Schmidt CD, Gardner RM (1971) Spirometric standards for normal children and adolescents (ages 5 years through 18 years). Am Rev Respir Dis 104: 680–687
6. Gore CG, Crockett AJ, Pederson DG, Booth ML, Bauman A, Owen N (1995) Spirometric standards for healthy adult lifetime nonsmokers in Australia. Eur Respir J 8: 773–782
7. Hibbert ME, Lannigan A, Landau LI, Phelan PD (1989) Lung function values from a longitudinal study of healthy children and adolescents. Pediatr Pulmonol 7: 101–109
8. Hibbert M, Lannigan A, Raven J, Landau L, Phelan P (1995) Gender differences in lung growth. Pediatr Pulmonol 19: 129–134
9. Jackson AC, Tennhoff W, Kraemer R, Frey U (1999) Airway and tissue resistance in wheezy infants. Am J Respir Crit Care Med 160: 557–563
10. Kleinbaum DG, Kupper LL, Muller KE (1988) Applied regression analysis and other multivariate methods. PWS–Kent, Boston
11. Kraemer R, Zehnder M, Meister B (1986) Intrapulmonary gas distribution in healthy children. Respir Physiol 65: 127–137
12. Kristufek P, Brezina M, Ciutti P, Strmen J, Mayer M (1987) Reference values and modelling of lung functions development as a transcendent function of age, body height and mass. Bull Eur Physiopath Respir 23: 139–147
13. Kühnel K (1995) Referenzmodelle für spirometrische und bodyplethysmographische Meßparameter von Knaben. Diplomarbeit, Institut für Statistik, Technische Universität Graz, Austria
14. Kummer Ch (1995) Spirometrische Bezugswerte für Mädchen und Frauen. Diplomarbeit, Institut für Statistik, Technische Universität Graz, Austria
15. Manual of the Jaeger MasterLab Pro V4.3 (1997) Resistance and FRC_{box}, chapter 17, p 41–45
16. Mathsoft Inc (1997) S-Plus programmer's guide, version 4.0. Data Analysis Products Division, Mathsoft Inc., Seattle, WA
17. Matthys H, Orth U (1975) Comparative measurements of airway resistance. Respiration 32: 121–134
18. Merkus PJFM, Borsboom GJJM, van Pelt W, Schrader PCh, van Houwelingen HC, Kerrebijn KF, Quanjer PhH (1993) Growth of airways and air spaces in teenagers is related to sex but not to symptoms. J Appl Physiol 75: 2045–2053
19. Michaelson ED, Watson H, Silva G, Zapata A, Serafini–Michaelson SM, Sackner MA (1978) Pulmonary function in normal children. Bull Eur Physiopath Respir 14: 525–550
20. Neuberger M, Kundi M, Wiesenberger W, Frank W (1994) Lungenfunktionsreferenzwerte für Schüler von 6–16 Jahren. Pneumologie 48: 175–181
21. Pattishall EN (1990) Pulmonary function testing reference values and interpretations in pediatric training programs. Pediatrics 85: 768–773
22. Polgar G, Promadhat V (1971) Pulmonary function testing in children: techniques and standards. Saunders, Philadelphia
23. Quanjer PhH, Polgar G, Wise M, Karlberg J, Borsboom G (1989) Compilation of reference values for lung function measurement in children. Eur Respir J 2[Suppl 4]: 184–261
24. Quanjer PhH, Tammeling GJ, Cotes JE, Pedersen OF, Peslin R, Vernault JC (1993) Lung volumes and forced ventilatory flows. Report working party standardization of lung function tests. European community for steel and coal. Official statement of the European respiratory society. Eur Respir J 6[Suppl 16]: 5–40
25. Quanjer PhH, Borsboom GJJM, Brunekreef B, Zach M, Forche G, Cotes JE, Sanchis J, Paoletti P (1995) Spirometric reference values for white European children and adolescents: Polgar revisited. Pediatr Pulmonol 19: 135–142
26. Rapatz G (1995) Die Modellierung der Lungenfunktionsentwicklung bei Knaben und Männern. Diplomarbeit, Institut für Statistik, Technische Universität Graz, Austria
27. Rousseeuw PJ, Leroy AM (1987) Robust regression and outlier detection. Wiley, New York
28. Schoenberg JB, Beck GJ, Bouhuys A (1978) Growth and decay of pulmonary function in healthy blacks and whites. Respir Physiol 33: 367–393
29. Seidel M (1995) Spirometrische und bodyplethysmographische Normalwerte von Mädchen. Diplomarbeit, Institut für Statistik, Technische Universität Graz, Austria

30. Stocks J, Quanjer PhH (1995) Reference values for residual volume, functional residual capacity and total lung capacity. ATS workshop on lung volume measurement. Official statement of the European respiratory society. Eur Respir J 8: 492–506
31. Taussig LM, Chernick V, Wood R, Farrell P, Mellins RB (1980) Standardization of lung function testing. Proceedings and recommendations of the GAP conference committee, cystic fibrosis foundation. J Pediatr 97: 668–676
32. Von der Hardt H, Leben M (1976) Bodyplethysmography in healthy children. Measurement of intrathoracic gas volume and airway resistance. Eur J Pediatr 124: 13–21
33. Zapletal A, Samanek M, Paul T (1987) Lung function in children and adolescents. Karger, Basel