

Measurement of the specific airway resistance by plethysmography in young children accompanied by an adult

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Measurement of the specific airway resistance by plethysmography in young children accompanied by an adult. B. Klug, H. Bisgaard. ©ERS Journals Ltd 1997.

ABSTRACT: The purpose of this study was to evaluate a procedure for measurement of specific airway resistance (sR_{aw}) by whole body plethysmography in young awake children accompanied by an adult.

sR_{aw} was measured by a single-step procedure, omitting the measurement of the thoracic gas volume. The frequency dependency of sR_{aw} was investigated and the accuracy of simulating body temperature, atmospheric pressure and saturation with water vapour (BTPS) conditions by electronic compensation was assessed.

One hundred and thirty one children with asthma were studied. In 57 children (mean (SD) age 5.6 (1.8) yrs) who performed measurements with and without an accompanying adult, the mean value of sR_{aw} was 1.45 (0.36) and 1.44 (0.38) kPa·s, respectively, with a mean difference of 0.008 (0.152) kPa·s, and mean within-subject coefficients of variations (CV) of 8% and 10%, respectively. In 52 children (mean age 3.3 (0.8) yrs), for whom measurements made only in the presence of an accompanying adult, the CV was 8.5%. No measurements could be obtained in 22 children (17%) (mean age 2.8 (0.5) yrs). Measurements exhibited a significant frequency dependency, and electronic BTPS compensation substantially overestimated sR_{aw} .

In conclusion, the use of electronic compensation for simulating body temperature, atmospheric pressure and saturation with water vapour introduces a bias that affects the accuracy of the estimate of specific airway resistance. Nevertheless, plethysmographic measurements with and without an accompanying adult yielded comparable and equally repeatable estimates of specific airway resistance. The single-step plethysmographic procedure with an accompanying adult is a clinically useful method for evaluating airway function in children too young to perform plethysmographic measurements alone.

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Measurements of respiratory function cannot usually be achieved in preschool children using standard lung function tests [1]. Whole body plethysmography is an established reference method for measurement of airway resistance (R_{aw}) in adults and older children, and has also been adapted for measurements in sedated infants [2]. Plethysmographic measurements can be carried out during normal tidal breathing, which seemingly would favour the use of this technique in young awake children. However, the practical procedures applied to perform the measurements have hindered the use of the technique in young children. Firstly, the child has to sit alone inside the closed plethysmograph for several minutes during the measurements. Secondly, the child must wear a nose-clip and keep his or her lips closely fitted around a mouthpiece. Thirdly, the classical procedure for measuring R_{aw} requires breathing manoeuvres against a closed shutter for measuring alveolar pressure and thoracic gas volume (TGV) [3]. All together, these procedures are too demanding for most young children, and have precluded the measurement of R_{aw} in preschool children.

The likelihood of young children accepting the plethysmographic procedures would be considerably improved if an adult person could accompany the child during measurements. Such a procedure has been applied in school children [4, 5], but its applicability and repeatability have not been studied in young children, probably due to the fact that young children either are unable or unwilling to perform breathing manoeuvres against a closed shutter. This problem can be avoided by measuring the specific airway resistance (sR_{aw}) using a single-step procedure omitting the measurement of alveolar pressure and TGV, which obviates the need to perform breathing manoeuvres against a closed shutter [6, 7].

Measurement of sR_{aw} by single-step procedure, combined with the advantage of having an adult accompanying the child, could allow this method to be used to measure sR_{aw} even in very young children. The present study was conducted to investigate the repeatability of the modified plethysmographic procedure by comparing measurements of sR_{aw} with and without an accompanying adult in young children who were capable of performing measurements unaccompanied, and to evaluate

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applicability and repeatability of the procedure in very young children accompanied by an adult. The use of electronic compensation for simulating body temperature, atmospheric pressure and saturated with water vapour (BTPS) conditions, which has become standard in most commercially available equipment, may introduce a bias affecting the accuracy of the measurements [8]. A secondary aim of the study was to assess the influence of electronic BTPS compensation on the estimate of sR_{aw} .

Patients and methods

Patients

Asthmatic children aged 2–8 yrs were eligible for the study. Asthma was diagnosed if the child had had three or more episodes of cough with wheezy and laboured breathing, after the age of 1 yr. Asymptomatic asthmatics as well as children with signs of mild acute asthma (cough, with wheeze audible by stethoscopy only, and no apparent breathing difficulty) were included, whereas children with breathing difficulty due to acute severe asthma were excluded. The children were recruited from the paediatric asthma out-patient clinic. Only a few older children had performed plethysmographic measurements previously. The study was approved by the local Ethics Committee and written informed consent was obtained from the parents of all children.

Methods

Measurements were carried out using a constant volume (830 L) whole body plethysmograph (Master Screen Body 4.2; E. Jaeger GmbH, Würzburg, Germany). Flow and volume were measured with a heated differential pressure screen-type pneumotachograph with a resistance of $0.036 \text{ kPa}\cdot\text{L}^{-1}\cdot\text{s}$, and a dead space of the 160 mL. Measurement of the pressure inside the plethysmograph was performed with a pressure transducer (Nr.660.99007; Hube Control AG, Wuerenlos, Switzerland) with an in-put range of $\pm 100 \text{ Pa}$, a resolution of 0.05 Pa and a linear frequency response up to 10 Hz . The equipment was calibrated daily. The pneumotachograph was volume calibrated with a 2 L syringe and the pressure transducer of the plethysmograph was calibrated using a 50 mL motor-driven piston-pump to generate sinusoidal variations of plethysmographic pressure. Electronic BTPS compensation was applied [9], using a time shift of 60 ms in the compensation, recognizing the fact that changes of gas temperature do not occur instantaneously [10]. Drift of box pressure occurring during the measurement period was corrected separately by the data processing software. The sR_{aw} was measured by a single-step procedure from the relationship between simultaneously recorded measurements of changes of respiratory flow and changes of plethysmographic volume, omitting the measurement of TGV [6]. The ability to measure sR_{aw} without simultaneous measurement of TGV can be derived from relationship between the plethysmographic parameters:

$$sR_{aw} = R_{aw} \times \text{TGV} \quad (1)$$

TGV is determined as:

$$\text{TGV} = \Delta V_{\text{box}}/\Delta P_{\text{mo}} \times (P_{\text{amb}} - P_{\text{H}_2\text{O}}) \quad (2)$$

where ΔV_{box} is the change of plethysmographic volume, ΔP_{mo} is the change of pressure at the mouth during respiratory efforts against a closed shutter, assuming that P_{mo} equals alveolar pressure, P_{amb} is the ambient pressure and $P_{\text{H}_2\text{O}}$ is the pressure of water vapour at 37°C .

R_{aw} is determined by the relationship between changes in alveolar pressure, measured as ΔP_{mo} , and changes of respiratory airflow ($\Delta V'$) ($R_{aw} = \Delta P_{\text{mo}}/\Delta V'$). Measurements of ΔP_{mo} and $\Delta V'$ cannot be obtained simultaneously and, consequently, the measurement of R_{aw} requires a two-step procedure: one step simultaneously measures $\Delta V_{\text{box}}/\Delta V'$, and one serves to relate changes in plethysmographic volume to changes in alveolar pressure by simultaneously measuring $\Delta V_{\text{box}}/\Delta P_{\text{mo}}$. From the ratio between the two measurements, R_{aw} is calculated as follows:

$$R_{aw} = \frac{\Delta V_{\text{box}}/\Delta V'}{\Delta V_{\text{box}}/\Delta P_{\text{mo}}} \quad (3)$$

By substituting TGV in equation (1) with the expression shown in (2), sR_{aw} can be calculated as follows:

$$sR_{aw} = \frac{\Delta V_{\text{box}}/\Delta V'}{\Delta V_{\text{box}}/\Delta P_{\text{mo}}} \cdot \Delta V_{\text{box}}/\Delta P_{\text{mo}} \times (P_{\text{amb}} - P_{\text{H}_2\text{O}}) \quad (4)$$

giving:

$$sR_{aw} = \Delta V_{\text{box}}/\Delta V' \times (P_{\text{amb}} - P_{\text{H}_2\text{O}}) \quad (5)$$

It can be seen that sR_{aw} can be obtained by measuring the changes of respiratory flow relative to the changes of plethysmographic volume (in the following referred to as the specific resistance loop), without simultaneous measurement of TGV. Hence, sR_{aw} can be determined by measuring the slope of the specific resistance loop, of which five typical examples are shown in figure 1a. During measurements the loops were displayed, breath by breath, on a monitor together with the simultaneously recorded spirometry curve (volume *versus* time; fig. 1). sR_{aw} was calculated from the slope of the line connecting the point of maximum ΔV_{box} during inspiration and expiration [7], and the median value from five consecutive breaths was retained. The measured value of sR_{aw} was corrected for the influence of resistance of the screen of the pneumotachograph (R_{screen}), which requires an estimate of TGV:

$$sR_{aw} = \text{measured } sR_{aw} - R_{\text{screen}} (\text{TGV} + V_t/2) \quad (6)$$

where V_t is the measured tidal volume of the subject. Since TGV was not measured, the predicted values of TGV according to body height were used for the above correction. In children aged ≥ 4 yrs, the predicted values of TGV were calculated according to ZAPLETAL *et al.* [11], and in children aged < 4 yrs, TGV was calculated according to STOCKS and GODFREY [12].

Measurements were corrected by a factor compensating for the effect of the volume displacement caused by the subject:

$$\frac{V_{\text{pleth}} - V_{\text{subject}}}{V_{\text{pleth}}} \quad (7)$$

where V_{pleth} is the volume of the plethysmograph and V_{subject} is the volume of the child or the child and accompanying adult. The volume of the subjects was approximated by: 1 kg of body weight = 1 L. All measurements

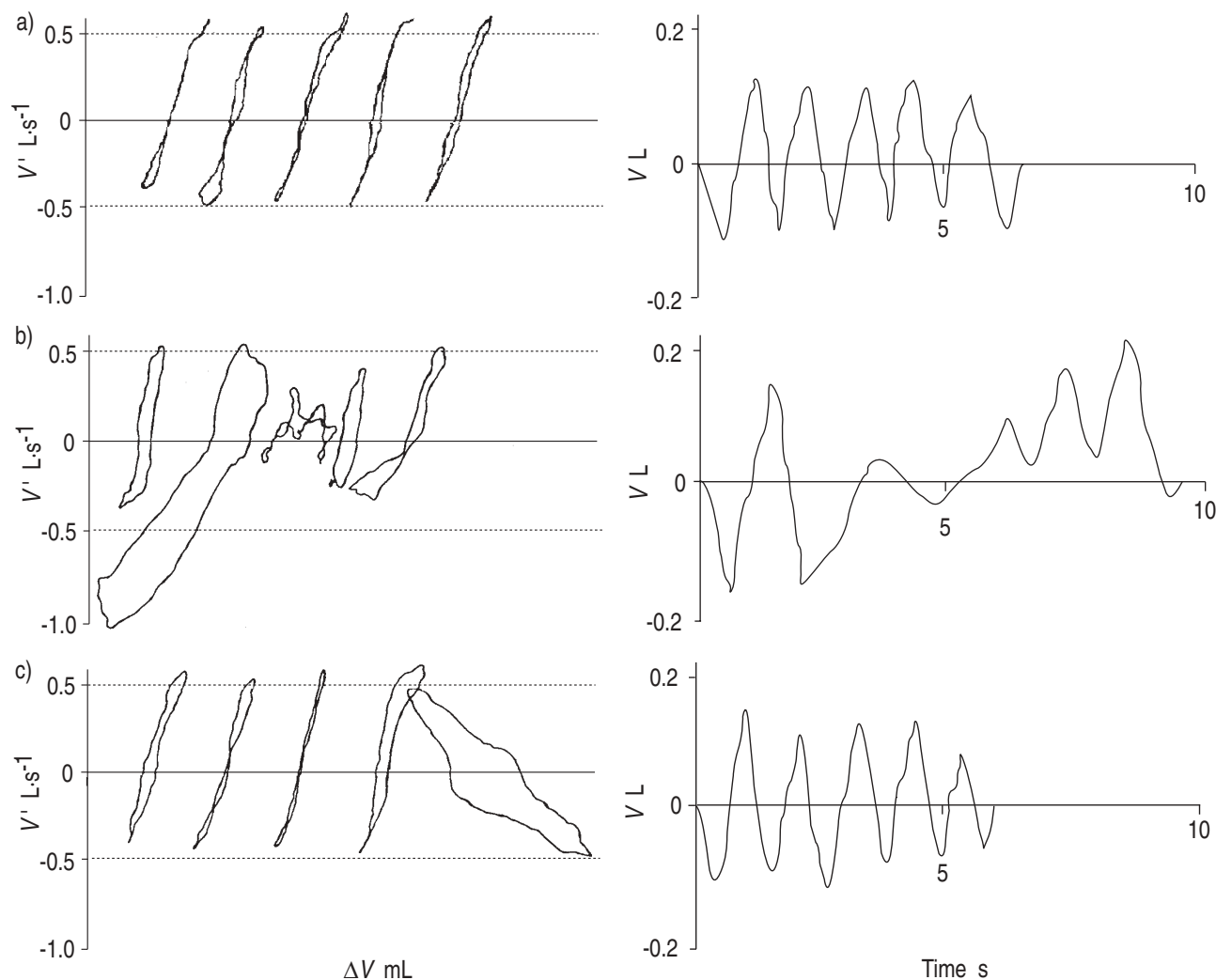


Fig. 1. — Measurements of specific airway resistance (sR_{aw}) by whole body plethysmography in a child aged 4 yrs accompanied by an adult. Recordings of respiratory flow (V') versus change of plethysmographic volume (ΔV) represent specific resistance loops, and curves of the respired volume versus time show the simultaneous recording of the breathing pattern: a) specific loops obtained while the child is breathing regularly and the adult performs a constant slow expiratory manoeuvre; b) severely disturbed specific resistance loops caused by a child breathing irregularly; and c) the last two specific resistance loops show increasing disturbance due to the adult interrupting the slow expiratory manoeuvre, while the child is demonstrating a stable breathing pattern.

reported are corrected for R_{screen} and the volume of the subject.

Measurements were carried out using a face mask (Astratech No 2; Astra, Denmark) fitted with a flexible, noncompressible mouthpiece (internal cross-sectional area of 2 cm²) that prevented nose breathing and provided stable opening of the airway [13, 14].

In a subgroup of older children, measurements of sR_{aw} were also performed, using a heated rebreathing system with a 25 L bag containing humidified air at 37.5°C, to achieve BTPS conditions.

Procedures

Before entering the plethysmograph the procedures were explained and the use of face mask was demonstrated to the child, to ensure both that the child would accept the face mask and that it was used correctly. Measurements with an accompanying adult (investigator or guardian) were performed with the child sitting on the adult's lap. During measurements, the children

were sitting with the neck slightly extended. Children who were not spontaneously breathing at a respiratory rate ≥ 30 breaths·min⁻¹ were coached to do so, though without aiming at any fixed respiratory rate. In older children, measurements were performed using two procedures; 1) the child alone in the plethysmograph; and 2) the child with an accompanying adult. Measurements alternated between the two procedures, and the procedure to be performed first was determined according to a randomized schedule. Two measurements of sR_{aw} were carried with each procedure. In young children, measurements with the child alone in the plethysmograph were not attempted if the child was considered too young or if the child hesitated to enter the plethysmograph alone. In these cases, two measurements of sR_{aw} were performed with an accompanying adult only. Measurements were not initiated until the subjects had been seated in the plethysmograph for at least 1 min. Thereafter, the child started to breathe through the face mask and when a stable breathing pattern was seen on the monitor continuously displaying the spirometry curve,

a measurement consisting of five consecutive specific resistance loops was obtained. Similarly, measurements with an accompanying adult awaited stabilization of the child's respiration while the adult was breathing normally. When the child had established a stable respiration, the adult performed a deep inspiration and then exhaled slowly, generating a constant low expiratory flow during a 15–20 s period. After an initial disturbance by the adult's breathing manoeuvre, the specific resistance loops gained a normal shape once the child had completed 5–7 breathing cycles whilst the adult continued the slow expiratory manoeuvre.

sR_{aw} was calculated as the median value of five consecutive technically satisfactory loops, and accepted or rejected according to the appearance of the five loops and the simultaneously recorded spirometry trace. The criteria for acceptance were that the traces showed five loops of similar shape (fig. 1a). Disturbance of the measurements could be caused by the child breathing irregularly (fig. 1b) or the adult performing the slow expiratory manoeuvre incorrectly (fig. 1c). If one or more loops were disturbed, a new sequence of five loops was obtained, and if a technically satisfactory measurement had not been obtained after a maximum of 10 attempts, no further attempts were made, and the cause of the failure to obtain measurements was noted.

In 13 older children, duplicate measurements were performed using a heated humidified rebreathing system and electronic BTPS compensation. In 11 older children, duplicate measurements were performed at respiratory rates of 20, 35, 50 and 75 breaths·min⁻¹, to investigate the frequency dependence of the estimate of sR_{aw} when using electronic BTPS compensation.

Statistical analysis

Repeatability was estimated from two measurements carried out with each procedure, and was assessed by the within-subject SD (the SD of the difference between measurements divided by the square root of two), and the within-subject coefficient of variation (the SD of the difference between measurements expressed as a percentage of their mean, divided by the square root of two) [15]. Measurements with and without an accompanying adult were compared using the mean value of paired measurements obtained with each procedure. The mean of the difference between sR_{aw} measurements obtained with and without an accompanying adult was calculated to estimate the mean bias (d) and limits of agreement ($d \pm t_{0.025} (df) \times SD_{dif}$), where $t_{0.025} (df)$ is t at the 2.5% level for a given number of degrees of freedom (df) in the t -distribution, and SD_{dif} is the SD of the difference between sR_{aw} with the two methods [16]. To evaluate the interaction between the repeatability and the magnitude of sR_{aw} , the difference between paired measurements was plotted against their mean. Comparisons of coefficients of variation and measurements of sR_{aw} in children with and without symptoms were performed using the Mann-Whitney ranked sign test for unmatched pairs. Measurements using a heated rebreathing system *versus* electronic BTPS were compared using the Mann-Whitney ranked sign test for matched pairs. The frequency dependence of sR_{aw} measurements were evaluated

by Pages test for trend. A p -value of less than 0.05 was considered statistically significant.

Results

One hundred and thirty one children were enrolled in the study, and in 22 children no measurements were obtained: in 16 of the 22 children (mean (SD) age 2.8 (0.5) yrs) the child did not accept the face mask; in four children, measurements failed because the child was breathing irregularly; and in two cases the adult was unable to perform the slow expiratory manoeuvre correctly.

Technically satisfactory measurements were obtained in 109 children. In 57 children (age 5.6 (1.8) yrs) measurements were performed with and without an accompanying adult and in 52 children (age 3.3 (0.8) yrs) measurements were carried out with an accompanying person only. Patient characteristics and data on sR_{aw} measurements are presented in table 1. During measurements with an adult, 98 children were accompanied by the investigator and 11 children by their guardian. The respiratory rate in older children with and without an accompanying adult was 41 (9) and 40 (10) breaths·min⁻¹, respectively. The respiratory rate in young children accompanied by an adult was 37 (8) breaths·min⁻¹. When studied, 24 children had signs suggestive of present airway obstruction and 85 children had no signs of airways obstruction. Seventy two children were treated regularly with topical steroids, and 103 were treated with bronchodilators as required, inhaled from a spacer with a face mask attached (86 children), or from a dry powder inhaler (17 children, aged ≥ 6 yrs). Six children were treated with an oral bronchodilator only.

Data on repeatability are presented in table 2. The within-subject coefficient of variation of sR_{aw} measurements in older children was not significantly different

Table 1. – Characteristics of 109 children who performed measurements of the specific airway resistance (sR_{aw}) by whole body plethysmography

	With and without an accompanying adult	With only an accompanying adult
Children n	57	52
Age months	66 (22)	39 (10)
Sex female/male	25/32	20/32
Height cm	113 (11)	98 (8)
Weight kg	20.8 (4.7)	15.8 (2.6)
sR_{aw} kPa·s		
With an accompanying adult		
Asymptomatic	1.32 (0.26) (n=41)	1.44 (0.27) (n=44)
Symptomatic	1.80 (0.40) ⁺ (n=16)	1.69 (0.29) [*] (n=8)
Total	1.45 (0.36) (n=57)	1.48 (0.30) (n=52)
Without an accompanying adult		
Asymptomatic	1.32 (0.25) (n=41)	-
Symptomatic	1.77 (0.49) [†] (n=16)	-
Total	1.44 (0.38) (n=57)	-

Data are presented as mean (SD). ⁺: $p < 0.001$; ^{*}: $p < 0.05$; [†]: $p < 0.003$, *versus* asymptomatic.

Table 2. – Measures of repeatability of measurements of specific airway resistance (sR_{aw}) in relation to plethysmographic procedure and age

	With or without adult present (n=57)	Only with adult present (n=52)
Mean (SD) age yrs	5.6 (1.8)	3.3 (0.8)
Within-subject SD $kPa \cdot s^{-1}$		
Child alone	0.13	-
Child with adult	0.11	0.12
Within-subject COV %		
Child alone	10	-
Child with adult	8	8.5

COV: coefficient of variation.

for measurements performed with and without an accompanying adult, with mean values of 8% and 10%, respectively. In young children accompanied by an adult, the mean within-subject coefficient of variation was 8.5%, and not significantly different from the values found in older children. The repeatability of sR_{aw} measurements was found to be independent of the magnitude of sR_{aw} . The mean difference (± 1 SD) between duplicate measurements is depicted in figure 2a. The interrelationship between measurements with and without an accompanying adult is presented in figure 2b. The mean value of sR_{aw} measured with and without an accompanying adult was 1.45 (0.36) and 1.44 (0.38) $kPa \cdot s$, respectively, with a mean difference of -0.008 (0.152) $kPa \cdot s$, and lower and upper limit of agreement between the two procedures of -0.31 to 0.30 $kPa \cdot s$, respectively. In children with current signs of airway obstruction, sR_{aw} was significantly higher than in children without signs of airway obstruction (table 1).

Measurements obtained in 13 children (mean age 6.9 (0.6) yrs) demonstrated that electronic BTPS compensation yielded significantly higher values of sR_{aw} than measurements obtained with a heated rebreathing system, 1.25 (0.28) and 0.87 (0.3) $kPa \cdot s$, respectively, and when expressing the difference between sR_{aw} measured with a heated rebreathing system the median overestimation of sR_{aw} was 43% (95% confidence interval (95% CI) 30–70%) (fig. 3a). In 11 children aged 7.2 (0.8) yrs sR_{aw} was measured at increasing respiratory rates of 21 (1.1), 36 (1.7), 53 (2.5) and 75 (3) breaths·min⁻¹. A significant positive frequency dependence was found with median values of sR_{aw} of 0.98, 1.19, 1.35, and 1.48 $kPa \cdot s$, respectively. Measurements at 21 breaths·min⁻¹ were 11% (95% CI 8–15%) lower when compared with measurements obtained at a respiratory rate of 36 breaths·min⁻¹, whereas measurements obtained at 53 and 75 breaths·min⁻¹, were 12% (95% CI 9–16%) and 17% (95% CI 10–24%) higher, respectively (fig. 3b).

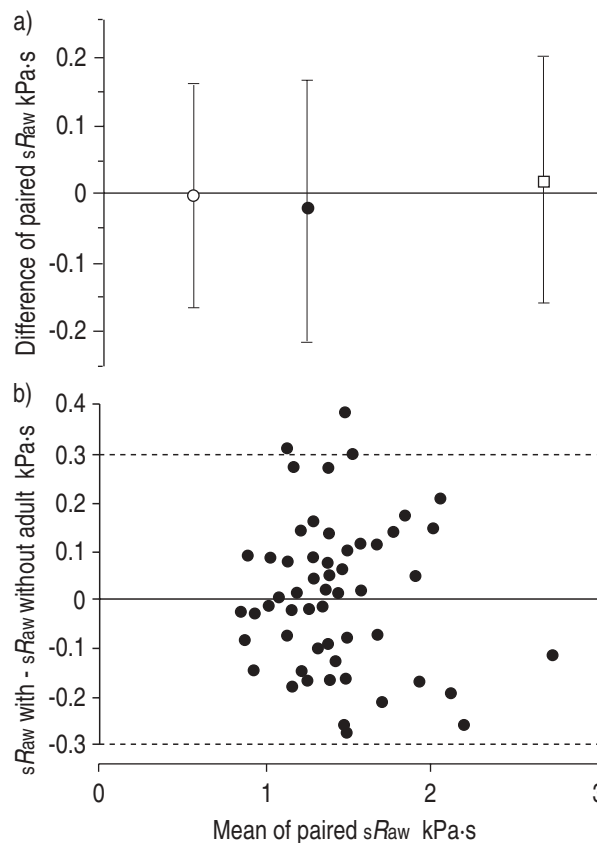


Fig. 2. – Plethysmographic measurements of specific airway resistance (sR_{aw}): a) difference (mean ± 1 SD) between paired measurements of sR_{aw} in 57 children (mean age 5.6 yrs) with (\circ) and without (\bullet) an accompanying adult and in 52 very young children (mean age 3.3 yrs) accompanied by an adult (\square); and b) difference between measurements of sR_{aw} with and without an accompanying adult plotted against their mean value in 57 children. The dotted lines denote the limits of agreement.

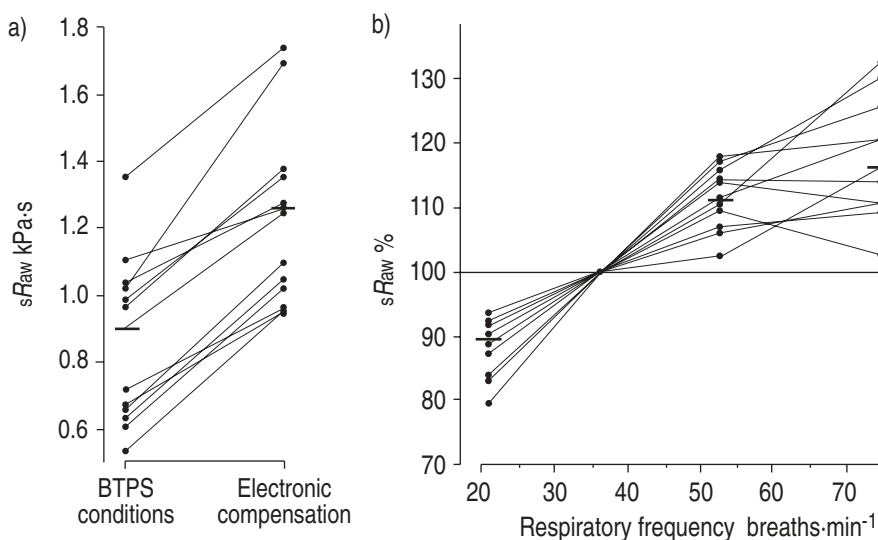


Fig. 3. – a) measurements of specific airway resistance (sR_{aw}) in 13 children using body temperature, atmosphere pressure and saturation with water vapour (BTPS) conditioned air and electronic BTPS compensation, respectively, showing that significantly higher values are obtained by using electronic BTPS compensation. Horizontal bars indicate median values. b) measurements obtained using electronic BTPS compensation for measuring sR_{aw} at different respiratory frequencies (21, 36, 53 and 75 breaths·min⁻¹), showing a significant positive frequency dependence. For each child, the value of sR_{aw} at various respiratory frequencies is expressed as a percentage of the value measured at 35 breaths·min⁻¹.

Discussion

The present study demonstrates that repeatable measurements of sR_{aw} can be obtained by whole body plethysmography in young awake children when accompanied by an adult, and that sR_{aw} measured by this procedure shows good agreement with measurements obtained without an accompanying adult.

When an adult accompanies the child, measurements can be obtained even in very young children, who would otherwise be unwilling or unable to perform measurements reliably. Other investigators have performed plethysmographic measurements in school children accompanied by adults [4, 5], but despite the potential advantages of this procedure, it has not yet been evaluated in preschool children. The classical plethysmographic measurement of airway resistance is a two-step procedure that requires breathing manoeuvres against a closed shutter for measuring alveolar pressure and TGV [3]. In a pilot study we observed that the majority of young children became scared by the closing of the shutter and often refused to continue, or performed the TGV manoeuvre insufficiently, as also noted by other investigators [6, 17]. The single-step procedure, by which sR_{aw} is measured directly from the specific resistance loops without measuring TGV, greatly facilitates the plethysmographic procedure. Measurements of sR_{aw} by the single-step procedure reflect the overall dimensions of the airways, including the influence of TGV on the calibre of the airways at the time of the measurement, though without providing a measure of TGV. Consequently, it is not possible to evaluate TGV separately, or to determine the relative contribution from changes of TGV when measuring changes of airway patency. The nature of respiratory disturbances may be more completely characterized by obtaining measurements of TGV [18]. However, it should be noticed that the accuracy of measurements of TGV in infants and young children is a matter of controversy, and particularly in the case of measurements performed during airway obstruction [19, 20].

From a clinical point of view, it is important to know whether clinically relevant information is lost when using the single-step procedure for measuring sR_{aw} . In a study of children aged 5–8 yrs BUHR *et al.* [17] found that the single-step sR_{aw} measurement more accurately discriminated between healthy and asthmatic children than did the separate measurement of R_{aw} and TGV, and that sR_{aw} measured by the single-step procedure and sR_{aw} calculated from R_{aw} and TGV provided equivalent information [17]. Moreover, the single-step procedure is at least as sensitive as R_{aw} in detecting acute changes of airway calibre during histamine challenge in children [7] and adults [21]. From these observations it would seem that in airway obstruction, the diagnostic yield from the single-step procedure is comparable to that of the combined measurement of R_{aw} and TGV. Yet another advantage of measuring sR_{aw} is that beyond infancy sR_{aw} is largely independent of body size [22–24], facilitating the interpretation of measurements carried out longitudinally in individual children.

If not corrected for the resistance of the pneumotachograph, measurements will slightly overestimate sR_{aw} [25]. The magnitude of the overestimation is approximately 5%, as shown by HALUSZKA *et al.* [26], who have established a formula for correcting sR_{aw} measurements by the single-step procedure. In the present study a cor-

rection was made for the resistance of the pneumotachograph (according to equation (6)), using the predicted value of TGV, since this was not measured. This correction does not allow for the possible influence of an abnormal TGV; however, this will introduce only a negligible error to the corrected estimate of sR_{aw} . Also, to avoid overestimation of sR_{aw} when measured with an accompanying adult, a correction must be made to allow for the volume displacement caused by the adult.

In older children, the repeatability of sR_{aw} measurements was comparable for measurements obtained with and without an accompanying adult, and the presence of an accompanying adult did not introduce any bias to the estimate of sR_{aw} . Measurements with and without an accompanying adult could not be compared in young children, since all measurements were performed with an accompanying person. However, the repeatability of sR_{aw} with an accompanying adult was comparable in young children and in older children.

Other investigators have used a procedure by which the adult performs a breath-holding manoeuvre [5] or a slow inspiratory manoeuvre [4] in order to reduce the disturbance caused during measurements. During breath-holding there is a risk of thoracic excursions causing disturbance, whereas this is less likely to occur during a continuous inspiratory or expiratory manoeuvre. We chose to use a slow expiratory rather than an inspiratory manoeuvre, since we found it easier to generate a constant flow rate for a period of 15–20 s during expiration. The slow expiratory manoeuvre gives rise to a slight continuous drift of the signal measuring changes of plethysmographic volume. However, the influence of drift seems appropriately corrected by the data processing software of the equipment, supported by the fact that measurements with an accompanying adult were not found to introduce any significant bias to the estimate of sR_{aw} .

If BTPS conditions are not maintained by the use of a heated rebreathing system, variations of temperature and humidity of the inspired and expired air will lead to inaccurate measurements and underestimation of sR_{aw} , particularly at low breathing frequencies [10]. An alternative approach is the use of electronic compensation for simulating BTPS conditions, which has become standard in most commercially available plethysmographs. However, this method does not completely simulate BTPS, as demonstrated by PEGLIN *et al.* [8] who found a significant positive frequency dependence of sR_{aw} when using electronic BTPS compensation. We assessed the accuracy of the electronic BTPS compensation by comparing measurements of sR_{aw} at a fixed respiratory rate using electronic BTPS compensation and a heated rebreathing system. At the respiratory frequency of 36 breaths·min⁻¹, which is approximately the spontaneous frequency observed during measurements in young children, we found that electronic BTPS compensation caused sR_{aw} to be overestimated by 43% when compared with measurements obtained using BTPS conditioned air. Furthermore, measurements obtained using electronic BTPS compensation exhibited a significant positive frequency dependency. Measurements of sR_{aw} at 21 breaths·min⁻¹ were 11% lower than measurements at 36 breaths·min⁻¹, whereas measurements at 53 breaths·min⁻¹ were 12% higher (fig. 3). Apparently, the magnitude of frequency dependence is less in children than in adults [8], which may partly be explained by the fact that the ratio between instrumental dead space and tidal volume

in children is higher and will tend to reduce the thermal artifact. BUHR *et al.* [17] studied the frequency dependence of sR_{aw} in children using a heated rebreathing system and found that by increasing the respiratory rate from 24 to 60 breaths·min⁻¹, sR_{aw} was reduced by 13% and 19% in healthy and asthmatic children, respectively. This suggests that the presence of a negative frequency dependence of sR_{aw} tends to counteract the positive frequency dependence found when using electronic BTPS compensation. In young children it is not feasible to perform measurements at very high respiratory frequencies (panting) or even at some fixed lower frequencies. However, very low respiratory frequencies can be avoided by coaching the relatively few children who spontaneously breathe at <30 breaths·min⁻¹, which also helps reduce the risk of disturbance caused by irregular breathing (fig. 1b).

The acceptability of the procedure is of major importance for its practical application. The children enrolled in the present study were unfamiliar with the procedures and equipment used, though it should be noted that more than half of the children were regularly treated with asthma medications inhaled *via* a spacer with a face mask attached. Measurements of sR_{aw} could be obtained in >80% of the children and the reason for failure was almost exclusively that the face mask was less well accepted by the youngest children, whereas rejection of measurements due to poor quality was the case in only a few children. In a population of untrained young asthmatics a success-rate of 80% is most satisfactory and, from our experience, a short period of training can further improve this figure, since the vast majority of very young children will accept the face mask if they are allowed to spend some time playing with it. This suggests that the described plethysmographic procedure could be applied for routine purposes, though the high costs of the equipment may restrict the method from gaining widespread use. For research purposes, the procedure may be used for evaluating the performance of new techniques for measuring airway function in young children [13, 14].

In conclusion, the use of electronic compensation for simulating body temperature, atmospheric pressure and saturation with water vapour introduces a systematic, as well as a frequency dependent, bias affecting the accuracy of the estimate of specific airway resistance. Nevertheless, plethysmographic measurements with and without an accompanying adult yielded comparable and equally repeatable estimates of specific airway resistance. Measurements could be achieved in the majority of very young children and were as repeatable as measurements in older children. The modified plethysmographic procedure described in the present study is a clinically useful method for evaluating airway function in children too young to perform plethysmographic measurements alone.

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