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Respiratory inductance plethysmography in healthy infants: a comparison of three calibration methods

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Respiratory inductance plethysmography in healthy infants: a comparison of three calibration methods. K.A. Poole, J.R. Thompson, H.M. Hallinan, C.S. Beardsmore. ©ERS Journals Ltd 2000.

ABSTRACT: Respiratory inductance plethysmography (RIP) measures respiration from body surface movements. Various techniques have been proposed for calibration in order that RIP may be used quantitatively. These include calculation of the proportionality constant of ribcage to abdominal volume change (*K*). The aims of this study were to 1) establish whether a fixed value of *K* could be used for calibration, and 2) compare this technique with multiple linear regression (MLR) and qualitative diagnostic calibration (QDC) in normal healthy infants.

Recordings of pneumotachograph (PNT) flow and RIP were made during quiet (QS) and active sleep (AS) in 12 infants. The first 5 min in a sleep state were used to calculate calibration factors, which were applied to subsequent validation data. The absolute percentage error between RIP and PNT tidal volumes was calculated.

The percentage error was similar over a wide range of *K* during QS. However, *K* became more critical when breathing was out of phase. A standard for *K* of 0.5 was chosen. There was good agreement between calibration methods during QS and AS. In the first minute following calibration during QS, the mean absolute errors were 3.5, 4.1 and 5.3% for MLR, QDC and fixed *K* respectively. The equivalent errors in AS were 11.5, 13.1 and 13.7% respectively.

The simple fixed ratio method can be used to measure tidal volume with similar accuracy to multiple linear regression and qualitative diagnostic calibration in healthy unsedated sleeping infants, although it remains to be validated in other groups of infants, such as those with respiratory disease.
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Respiratory inductance plethysmography (RIP) is a technique that can be used to measure both the timing and volume of respiration. It is noninvasive and, once calibrated, does not require the use of a face mask or mouthpiece, which can change the breathing pattern [1, 2] and lead to arousal in infants. This technique involves the subject wearing two inductance bands, one around the ribcage and the other around the abdomen. As the subject breathes, the volume of the ribcage and abdominal compartments change, and these changes are reflected in alterations in the inductance of the coils. It is assumed that the ribcage and abdomen move independently, and that the sum of these compartmental changes is equivalent to the tidal volume (V_T) at the airway opening [3], such that:

$$V_T = \alpha \mathrm{RC} + \beta \mathrm{Abd}, \qquad (1)$$

where RC and Abd are the changes in ribcage and abdominal movements measured using RIP and α and β are the volume/motion coefficients for the RC and Abd respectively. Therefore, in order to quantify V_T, α and β must be calculated. One technique that can be used for this calculation is multiple linear regression (MLR), which has been used in both adults and infants [4–6]. It assumes that V_T measurements are linearly related to RC and Abd. The correlation of the RC and Abd signals to V_T (measured using a pneumotachograph (PNT) or spirometer) are calculated and greater weight is given to the signal that correlates best with the measured V_T. However, this technique requires the use of a "gold-standard" measurement of volume such as that derived from a PNT.

All calibration techniques available for RIP require direct measurements using a face mask to be made for fully quantitative calibration. If only semiquantitative calibration is required, this can be achieved without direct measurements by calculating the proportionality constant of RC to Abd (*K*). Equation 1 can thus be rewritten as follows:

$$V_T = MK\mathrm{RC} + \mathrm{Abd}, \qquad (2)$$

where *K* is equal to α/β and *M* is the scaling factor to absolute volume when a PNT or spirometer is used.

Qualitative diagnostic calibration (QDC) [7] can be used to calculate *K* without the need for direct measurements of volume. This method depends upon variation between breaths in the relative contributions of the ribcage and abdomen during natural breathing to derive *K*. Concerns have been raised about the validity of the QDC technique for RIP calibration [8], although it appears to give good accuracy in infants [7, 9, 10] and adults [7].

It has been shown, in adults, that the error in estimation of V_T by RIP is similar over a wide range of K [11]. Thus a fixed standard K could be used instead of generating calibration factors for each study, thereby simplifying studies and saving time. The first aim of the present study was to determine whether this approach could be applied to infants. The second was to compare the accuracy of this method of calibration to MLR and QDC during quiet sleep, and to compare the accuracy of the three methods in conditions under which the relative contributions of the ribcage and abdomen to V_T may change, such as during active sleep (AS).

Materials and methods

Study subjects

Twenty-one infants were studied at a median (range) age of 5.8 (2.3–12) months. The age, weight and length of those infants with successful recordings were 5.4 (3.0–12) months, 7.2 (5.6–9.5) kg and 63.6 (58.3–74.2) cm respectively. Twenty infants were recruited into a programme of research into respiratory control in healthy infants. The remaining infant was volunteered by its mother on hearing about the present work. Two of the infants were born at 35 weeks of gestation but had not required any respiratory support. Although all of the infants were healthy on recruitment, a detailed questionnaire administered at the time of the study revealed that one infant was reported to have narrowed nasal passages and suspected gastro-oesophageal reflux, treated with sodium cromoglycate nasal spray and Gaviscon-thickened feeds. Another infant had been diagnosed as asthmatic and was being treated with salbutamol (300 µg twice daily, inhaled). All of the infants were brought to the laboratory, where they were studied during a daytime nap. All were well at the time of study.

All parents gave written informed consent and the study was approved by Leicestershire Health Authority Ethics Committee.

Study design

It was planned to collect information on sleep state, and to calibrate and validate the RIP for as long as the infants remained asleep. The first 5 min of the recording in a sleep state were used for calculating calibration factors using MLR, QDC and fixed-*K* method. The subsequent data in the same sleep state were used for validation and were split into 1-min segments.

Methods

Upon arrival in the laboratory, a brief questionnaire was administered and the infant was weighed and measured. RIP bands were positioned snugly, but not tightly, around the abdomen at the level of the umbilicus and around the chest, as close to the axilla as possible, and were observed during the measurements for signs of movement. The infant was offered a feed and allowed to fall asleep naturally, without sedation. When asleep, a face mask and PNT were sealed around the nose and mouth using sterile putty. Each infant was studied lying supine with their head in the mid position. However, if the head moved during the measurements, no attempt was made to reposition it as this would risk arousing the infant. Respiratory movements were monitored using RIP (Model 150; Studley Data Systems, Oxford, UK) with both channels set to a gain of 1.0. Respiratory flow was measured using an infant screen PNT with a linear range of >±1 $L \cdot s^{-1}$ (Erich Jaeger, Market Harborough, UK) attached to a face mask (Rusch size 3; Rendell Baker). The flow was integrated by computer to provide a volume signal.

The infant's sleep state was classified behaviourally as quiet sleep (QS) or AS for each minute of recording [12]. Simultaneous recordings of RC and Abd and tidal flow and volume were made using an International Business Machines (IBM)-compatible computer (Powerpaq pentium; City Business Systems, Leicester, UK) and Respiratory Analysis Programming (RASP) software (PhysioLogic Ltd, Newbury, UK) at a sampling rate of 50 Hz. The choice of sampling rate was a compromise between accuracy and the need for an extended recording time. A rate of 50 Hz has been used previously in tidal breathing analysis of newborn [13] and anaesthetized infants [10].

Data analysis

Changes in the PNT-measured volumes, RC and Abd, were calculated for each breath for all data collected. End-expiratory and end-inspiratory points on the RC and Abd signals were taken at times corresponding to the maxima and minima on the PNT volume signal. Inspiratory and expiratory volumes were calculated separately, and the change in the three signals with each breath was computed as the mean of the inspiratory and expiratory changes.

Impact of range of proportionality constants of ribcage to abdominal volume change on accuracy of respiratory inductance plethysmography: choosing a standard value. The impact of K on the accuracy of RIP calibration was investigated by applying a range of K (0.1–2) to the changes in RC and Abd signals with each breath in both QS and AS. The M was calculated (see below) and applied to the data. The absolute percentage error using each K was calculated for the first 5 min of data, and for each minute of validation data. Based on inspection of these data, and the knowledge that infants of this age group breathe predominantly with their abdomens [14], suggesting that a K giving a lower weighting to the RC would be appropriate, a standard K of 0.5 was chosen for the subsequent comparison of the three calibration methods.

Comparison of the accuracy of the three calibration methods. Calculation of calibration factors. The first 5 min of data collected in either sleep state were used for the calculation of the calibration factors by the three methods. These factors were then applied to each subsequent minute of validation data in the same sleep state. Therefore, only recordings of ≥6 min duration were analysed.

MLR was performed using the V_T obtained from the PNT ($V_{T,PNT}$) as the dependent variable and RC and Abd changes with each breath to obtain the regression equation containing α and β (Equation 1). In Equation l, α/β is equivalent to K and $\beta=M$ (Equation 2).

The QDC method uses Equation 2 and proposes that under conditions in which V_T is constant, K can be calculated as the ratio of SD's of the Abd and RC signals. In order to achieve a constant V_T it was suggested that a 5-min calibration period should be used and breaths which lay outside ±1.0 SD of the mean sum RC+Abd excluded [7]. Using this strategy, the SD's of RC and Abd signals were derived to calculate K. This K was then reapplied to the first 5 min of the RIP data to give a term proportional to volume (Equation 2). Regression analysis was then performed to predict $V_{T,PNT}$ (in millilitres) from the semicalibrated RIP V_T ($V_{T,RIP}$) (in arbitrary units). The slope of the regression line obtained is M.

A fixed K of 0.5 was applied to the RC and Abd signals to give a term proportional to volume (Equation 2). Regression analysis was then performed to calculate M in the same manner as described for QDC.

Validation of calibration factors. The K and M calculated from the first 5 min of data for each calibration method were applied to each following minute of data in the same sleep period. For each breath, the difference between $V_{T,PNT}$ and $V_{T,RIP}$ was calculated and the sign ignored. The absolute errors (differences in millilitres) were then expressed as a percentage of $V_{T,PNT}$ for each breath. The mean absolute percentage error was then calculated for each minute of validation data.

Calculation of phase lag between ribcage and abdominal movements. Thoracoabdominal asynchrony was assessed by calculating the percentage of the time during inspiration that the RC and Abd signals were not moving in the same direction, and is referred to hereafter as % paradox. A value of 0% indicates that the ribcage and abdomen are moving synchronously throughout inspiration, whereas a value of 100% indicates asynchronous movement throughout inspiration.

Calculation of the ribcage movement contribution to tidal volume. The percentage RC contribution was calculated from the calibrated RIP signals. The K calculated using each of the calibration methods was applied to the RC signal to give the correctly proportioned RC (Equation 2). The Abd signal was then added to give the total $V_{T,RIP}$ in arbitrary units (Equation 2). The percentage RC contribution was calculated by expressing the correctly proportioned RC as a percentage of the total $V_{T,RIP}$.

Statistical analysis. The percentage error data were analysed using the residual maximum likelihood algorithm in GENSTAT. In order to account for the repeated measures structure of the data, random components were included for subject and for time period within subject. Residual plots indicated that, when analysing the absolute percentage error, there were a number of extreme residuals and marked non-normality. Transformation to $\log_e$ percentage error produced unremarkable residual plots, and this transformation has been used for the calculation of p-values. Fixed effects were assessed using Wald tests.

Differences in the percentage RC contribution calculated with each calibration method were analysed using the Wilcoxon signed-rank sum test for paired nonparametric data. Differences in percentage RC contribution and paradox across sleep states were analysed using the Mann-Whitney U-test for independent nonparametric data.

Results

Eighteen continuous recordings of ≥6 min in duration were collected from 12 infants. Data were obtained during 12 periods of QS (median (range) duration of 11 (9–18) min) and six periods of AS (7 (6–13) min). The reasons for not obtaining adequate data in the remaining infants were that the infants only slept for a short time (eight infants), or technical problems (one infant). The group in whom data were collected included one of the preterm infants and both of those receiving treatment. In one subject, large negative K were calculated using MLR during AS. This led to negative $V_{T,RIP}$ (in arbitrary units) and, therefore, only the data obtained during QS were used for this subject.

The mean±SD number of breaths used for the 5-min calibration was 132±33 in 16 of the 18 sleep periods recorded. Since the computer program could analyse a maximum of 175 breaths, the two remaining calibration periods from a rapidly breathing subject were reduced to 3.9 and 4.5 min (173 and 174 breaths respectively). Validation data (91 min) were collected, of which 18 min were during AS. The number of breaths in the 1-min validation periods was 29±8 during QS and 27±8 during AS.

Impact of range of proportionality constant of ribcage to abdominal volume change on accuracy of respiratory inductance plethysmography: choosing a standard value

When a range of K were applied to the data collected during QS, the absolute percentage error was not highly dependent upon K in the majority of subjects (fig. 1a). With one exception, for all data obtained during the first minute of validation during QS, any K would yield an absolute error of ≤6%.

In subject 5, applying K of <0.5 led to marked increases in error. However, over a wide range of K (0.5–2.0), the error changed very little. In this subject, respiration was out of phase (56.7% paradox) and the RC contribution to V_T was high (88.7%).

During AS, the errors seen with any K were generally higher than those seen during QS (fig. 1b). In three subjects, the error was fairly constant over the range of K applied. In the remaining three subjects, the error was more dependent upon K. Subject 5 showed a similar pattern during AS to that seen during QS. In two other subjects (11 and 12), the error was observed to increase steadily with increasing K. In all three of these subjects, breathing was out of phase (paradox ranged 57.6–78.5%), and two of the subjects (11 and 12) had low RC contributions to V_T (15.1 and 7.0% respectively). In contrast, subject 5 had the highest RC contribution to V_T during AS (~80%). Based on these curves obtained during QS and AS, a K of 0.5 was arbitrarily chosen as the standard ratio for comparisons with the MLR and QDC calibration techniques.

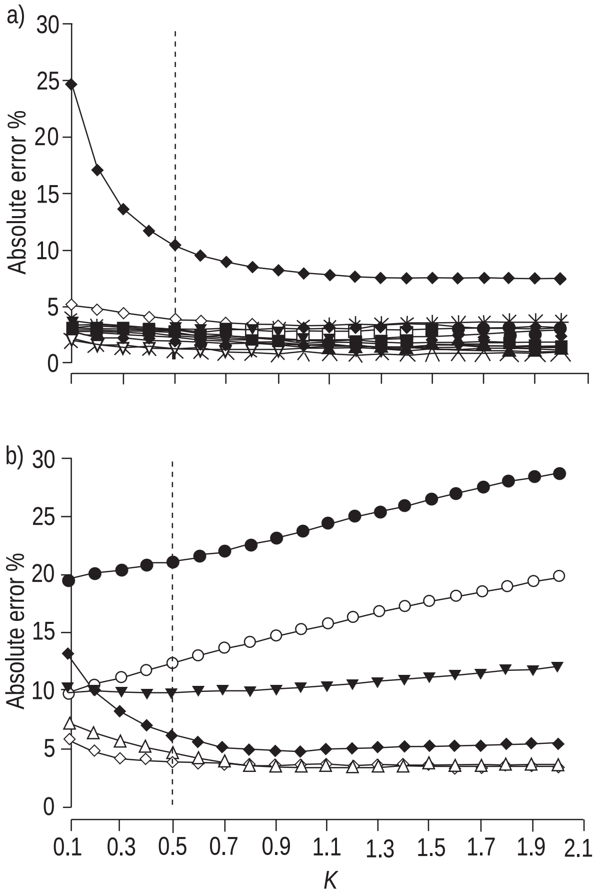

Fig. 1. – Relationship between the proportionality constant of ribcage to abdominal volume change (*K*) and absolute percentage error using minute 1 validation data during: a) quiet sleep; and b) active sleep. ((■): 1; *: 2; (▼): 3; (△): 4; (◆): 5; ×: 6; (□): 7; (▲): 8; (▽): 9; (◇): 10; (○): 11; (●): 12).

Proportionality constants of ribcage to abdominal volume change calculated using multiple linear regression and qualitative diagnostic calibration and effects upon error

The *K* calculated using MLR and QDC were similar in the majority of subjects during QS (fig. 2a). In two subjects, the values calculated using the two methods were very different, but this did not affect the error markedly (fig. 2b). During AS, QDC yielded slightly higher *K* than did MLR in the majority of subjects (fig. 2a). However, the percentage error was unaffected (fig. 2b).

Comparison of the accuracy of the three calibration methods

Quiet sleep. When applying calibration to the validation data, the mean absolute percentage errors for the group were significantly greater when the fixed-*K* method was used compared to MLR (p=0.01); (table 1). However, the mean difference in percentage error between these two techniques was only 2.1%. QDC gave higher mean absolute percentage errors than MLR but the differences were not statistically significant.

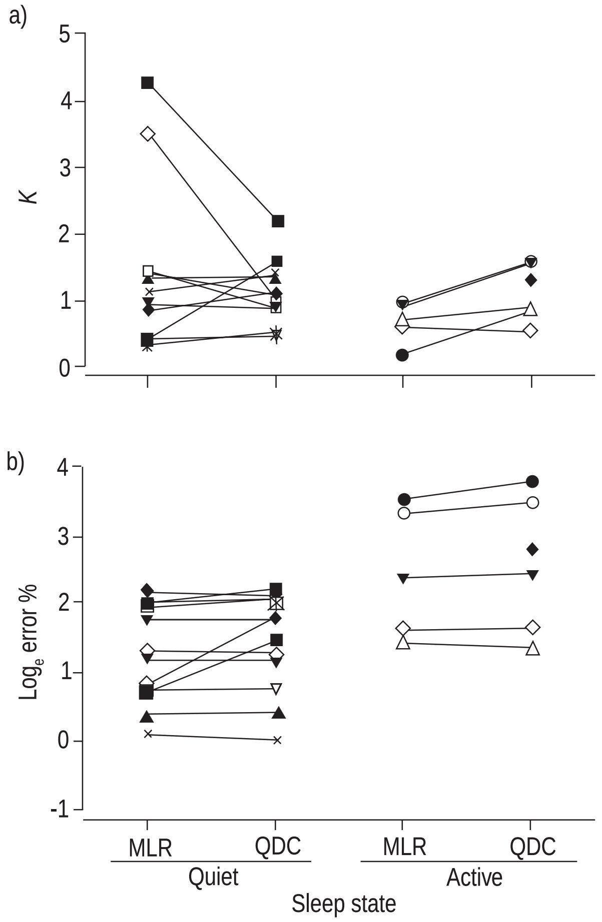

Fig. 2. – a) Proportionality constant of ribcage to abdominal volume change (*K*); and b) $\log_e$ percentage error calculated using the multiple linear regression (MLR) and qualitative diagnostic calibration (QDC) techniques during quiet and active sleep. ((■): 1; *: 2; (▼): 3; (△): 4; (◆): 5; ×: 6; (□): 7; (▲): 8; (▽): 9; (◇): 10; (○): 11; (●): 12).

The agreement between the three methods was also investigated within individual subjects. The narrowest 95% limits of agreement were seen when comparing MLR and QDC (mean difference $\log_e$(MLR-QDC)=-0.19%; 95% limit of agreement 0.91–0.53%), and the widest when MLR and the fixed-*K* method were compared (mean difference $\log_e$(MLR-*K*)=-0.43%; 95% limit of agreement -1.67–0.81%). In the majority of subjects, the discrepancies in accuracy of the methods were trivial.

Active sleep. During AS, the RC contributions to volume were lower than those seen during QS, although the differences were not statistically significant (table 2). In addition, a significantly greater percentage of paradoxical breathing during inspiration was seen during AS (p=0.005) (table 2).

The mean absolute percentage errors for the three calibration methods were higher during AS than QS (table 1). As during QS, MLR gave the lowest mean absolute percentage errors for the group, and the fixed-*K* (0.5) method gave the highest (table 1). There were no significant differences between methods. The narrowest 95% limits of agreement were seen between MLR and QDC (mean difference $\log_e$(MLR-QDC)=-0.09%, 95% limit of

Table 1. – Absolute percentage errors using the three calibration techniques during quiet and active sleep*

	Quiet sleep				Active sleep			
Minute	Subjects n	MLR	QDC	Fixed-*K* (0.5)	Subjects n	MLR	QDC	Fixed-*K* (0.5)
1	12	3.5 (2.3–5.3)	4.1 (2.7–6.3)	5.3 (3.5–7.9)	6$^+$	11.5 (4.9–27.1)	13.1 (5.9–29.1)	13.7 (6.6–28.8)
2	11	4.0 (2.2–7.3)	4.7 (2.6–8.3)	6.2 (3.7–10.5)	3$^+$	4.8 (1.9–12.1)	7.9 (2.7–23.1)	9.8 (2.5–38.9)
3	10	4.3 (2.5–7.3)	5.1 (3.4–7.8)	6.9 (4.4–10.7)				
4	11	5.9 (3.4–10.4)	6.6 (3.9–11.1)	8.2 (5.1–13.2)				
5	10	5.2 (3.0–8.9)	6.2 (4.0–9.7)	7.2 (4.7–11.3)				
6	9	6.4 (3.4–11.8)	6.6 (3.8–11.3)	6.6 (3.8–11.6)				

Data are presented as mean (95% confidence interval). *: calibration derived from first 5 min of recording and applied to each subsequent minute of validation data; $^+$: it was not possible to calculate calibration factors for subject 5 using multiple linear regression (MLR); therefore, n=5 and 2 respectively. QDC: qualitative diagnostic calibration; *K*: proportionality constant of ribcage to abdominal volume change.

agreement -0.29–0.11%) and the widest were seen between QDC and the fixed-*K* method (mean difference log$_e$(QDC-fixed-*K*)=0.05%, 95% limit of agreement -0.65–0.75%). There was little overall bias.

Ribcage contributions calculated by the three methods

The RC contributions calculated for minute 1 validation data were variable for each method (table 2). During both QS and AS, the fixed-*K*(0.5 method) gave significantly lower RC contributions to volume when compared to QDC. In addition, during QS, the RC contribution calculated using the fixed-*K* method was also significantly lower than that calculated using MLR. There were no statistically significant differences in percentage RC contribution between MLR and QDC.

Discussion

The primary aim of the present study was to investigate whether or not a simple fixed-*K* could be used to calibrate RIP in infants with similar accuracy to established techniques, such as MLR and QDC. This is the first study of its kind in infants, and recordings were attempted in 21 infants. Measurements were obtained in 12 healthy infants during unsedated natural daytime sleep. It was found that the error in measurement of *V*T,RIP was similar over a wide range of *K* during both QS and AS. A fixed-*K* of 0.5 was chosen and compared to MLR and QDC. Although there were differences in the error between the three methods, these were small and unlikely to be of any practical significance.

Data collection

The present studies were performed in infants at a time of day when they would normally be expected to sleep. In spite of this, eight infants either did not sleep or the duration of sleep was too short to obtain adequate recordings, even though they would often be in the laboratory for several hours. More recordings were obtained during QS than AS, reflecting the difficulty in recording *V*T through a face mask during AS in infants of this age. Therefore, when planning to measure *V*T,RIP in infants, the difficulties associated with obtaining adequate data should be borne in mind. Studies conducted overnight may be more successful.

Impact of proportionality constant of ribcage to abdominal volume change range on accuracy of respiratory inductance plethysmography: choosing a standard ratio

In agreement with the findings of Banzett *et al.* [11] in adults, it was found that, when a wide range of *K* were applied, the absolute percentage error changed very little when breathing was in phase, but that *K* became more critical when breathing was out of phase. Having demonstrated this, it was investigated whether it was possible to use a standard ratio for all subjects during both QS and AS. A value of 0.5 was chosen based on the present data and the expectation that infants of this age group would breathe predominantly with their abdomens [14], such that a *K* giving a lower weighting to the RC would be better. However, as *K* is not highly critical, it would be expected that similar results would have been obtained if a different *K* had been chosen.

The present finding that the error was not highly dependent on the *K* calculated during calibration may have

Table 2. – Tidal volume, percentage paradox and percentage ribcage contribution using the three calibration methods*

	*V*T,PNT mL	Paradox %	Ribcage contribution %		
			MLR	QDC	Fixed-*K* (0.5)
Quiet sleep	65.9 (51.0–91.1)	9.7 (2.4–56.7)	50.2 (10.3–88.7)	50.0 (25.2–91.0)	32.1 (7.1–82.2)§,‡
Active sleep	65.4 (56.5–94.8)	44.7 (14.5–78.5)¶	15.1 (7.0–65.8)$^+$	24.4 (15.1–63.4)	16.2 (5.6–61.6)$^{+,\#}$

Data are presented as median (range) (n=12 during quiet sleep (QS) and n=6 during active sleep (AS); *: calculated from minute 1 validation data during QS and AS. *V*T,PNT: tidal volume obtained from pneumotachograph; MLR: multiple linear regression; QDC: qualitative diagnostic calibration; *K*: proportionality constant of ribcage to abdominal volume change. $^{\#}$: p=0.04 *versus* QDC; §: p=0.01 *versus* MLR; ‡: p=0.004 *versus* QDC; ¶:p=0.005 *versus* QS.

important implications for other methods of calibration. Recently, it was suggested that the *K* calculated using QDC, may be arbitrary and depend upon the width of the inclusion interval [8]. It has also been suggested that breaths falling within ±1SD of the mean sum of the uncalibrated RC and Abd can be used for calculation of *K* [7]. However, relaxing or restricting the inclusion interval changes the *K* calculated in an expected way [8]. Nevertheless, QDC has been reported to give good accuracy in infants and adults. One possible reason for QDC appearing to perform satisfactorily may be *K* is not critical to error.

Comparison of the accuracy of the three calibration methods

Quiet sleep. There were statistically significant differences in the percentage error between methods, with the fixed-*K* method giving the greatest errors. However, the differences in percentage error between the methods were small, with an average difference between MLR and the fixed-*K* method of only 2.1%. The errors found in the present study are similar to those found in other studies using QDC [7, 9] BROWN *et al.* [10] found that the 95% limits of agreement between $V_{\mathrm{T,PNT}}$ and $V_{\mathrm{T,RIP}}$, when calibrated using QDC in anaesthetized infants breathing spontaneously, were -2.3–3%.

When the three methods were compared in individual subjects, the widest limits of agreement were seen when MLR and the fixed-*K* method were compared. In general, MLR was more accurate than both QDC and the fixed-*K* method, and QDC was more accurate than the fixed-*K* method. In the majority of subjects, the differences between methods were trivial. However, there were a few subjects in whom the fixed-*K* was less accurate than MLR. The worst case was subject 10 (min 5), when the error with MLR was equivalent to 1.69% and the fixed-*K* method 10.56%. In this case, breathing was in phase (paradox 7.8%), but there was a high RC contribution to V_{T} (85.4%). Therefore, when the fixed-*K* method was applied, the weighting of RC was reduced in relation to Abd; this may explain why the fixed-*K* method was associated with an increased error in comparison, with MLR and QDC. This infant was reported as having narrow nasal passages and reflux, and was being treated with sodium cromoglycate and Gaviscon. In addition, QDC was less accurate than MLR in this subject (error 1.69% for MLR and 5.49% for QDC).

Active sleep. During AS, the median percentage paradox increased and the percentage RC contribution to V_{T} fell when compared to QS. Although MLR and QDC gave slightly lower mean percentage errors than the fixed-*K* technique, the differences were so small as to be of no practical significance. The limits of agreement for the comparisons of the three methods were narrower during AS than QS, although fewer data were available. Therefore, when the breathing pattern changed during AS, the fixed-*K* technique compared favourably with the other two methods.

The errors seen with all of the methods were much greater during AS compared to QS. The infant has a compliant chest wall [15] which is prone to distortion [16], particularly during AS when the intercostal activity that usually helps to stabilize the chest wall is silenced and paradoxical movements occur [17]. Consequently, the chest wall may move with more than two degrees of freedom during AS, leading to greater percentage errors regardless of calibration technique. In spite of this, one other study has investigated the difference in accuracy of RIP during QS and AS when calibrating using QDC in either sleep state, and reported that there were no significant differences between the two sleep states in newborn infants [9].

In the present study, *K* and *M* were calculated during a given sleep state and applied to validation data from the same sleep state. Other investigators have combined data from both sleep states for calibration purposes [18]; however, it was not possible to do this in the present study since recordings during both QS and AS were obtainable in only three subjects.

The percentage errors reported in the present study (table 1) are dependent upon both *K* and *M*. When performing this study, it was felt that assessment of the error associated with the three methods in the way that they would be applied in practice was important. When calibrating RIP for V_{T} measurement, *K* is calculated first using the chosen method of calibration. A face mask and PNT can then be used to calculate *M*. Both *K* and *M* are then used to calculate $V_{\mathrm{T,RIP}}$. This approach was used in the present study to compare the three calibration methods, since it gives a realistic indication of the errors that would be encountered in practice.

Potential limitations of the forced-proportionality constant method

The results of the present study suggest that, in healthy infants, a fixed-*K* technique may be used in place of other calibration methods. It was found that, when breathing was out of phase, *K* became more critical, but that the fixed-*K* method was not associated with increased error in comparison with the other methods during AS. However, the authors would suggest that the fixed-*K* technique be used with some caution in situations in which breathing is out of phase, *e.g.* AS. Airflow obstruction in infants also results in thoracoabdominal asynchrony [19], and, under these circumstances, *K* may become more critical. The present study was limited to healthy infants and consequently the authors recommend that the fixed-*K* technique be validated before application in other groups of infants.

A potential drawback of using a fixed ratio is that it may not give correct proportioning of the RC and Abd signals and thus apnoeas may not be detected reliably [20]. Although the present study was not designed to investigate this, one infant had a spontaneous obstructive apnoea of 3 s during data collection. The use of RIP calibrated using the fixed-*K* technique showed clear attenuation of breathing, but would not have enabled distinction to be made between apnoea and hypopnoea with certainty. Therefore, before advocating the use of this technique for calibration of RIP for the purpose of apnoea detection, further investigation is required. It should also be noted that the accuracy of apnoea detection when QDC method is used for calibration in infants has not yet been fully investigated.

Conclusions

Although minor differences in accuracy were found between the three methods of calibration, they were so small as to be of no practical importance. The fixed-proportionality constant method of calibration is of similar accuracy to multiple linear regression or qualitative diagnosis calibration in healthy unsedated sleeping infants during both quiet and active sleep. However, proportionality constant of ribcage to abdominal volume change may become critical when breathing is out of phase, and, therefore, the present authors would urge caution in using the fixed-proportionality constant technique under these circumstances until it has been fully validated. Further work is also required before this technique can be applied to infants who are born prematurely or have respiratory disease. However, the advantage of making semiquantitative measurements of ventilation without the need for application of a face mask or a 5-min calibration period paves the way for studies of respiratory control in the healthy unsedated infant.

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