Studies in cow's milk allergy: results from the Dutch EuroPrevall birth cohort

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Publication date
2016

Document Version
Final published version

Citation for published version (APA):

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Accuracy of tidal breathing measurement of FloRight compared to an ultrasonic flowmeter in infants

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Cindy Thamrin
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Urs Frey

Abstract

Introduction
Monitoring breathing pattern is especially relevant in infants with lung disease. Recently, a vest-based inductive plethysmograph system (FloRight®) has been developed for tidal breathing measurement in infants.

We investigated the accuracy of tidal breathing flow volume loop (TBFVL) measurements in healthy term-born infants and infants with lung disease by the vest-based system in comparison to an ultrasonic flowmeter (USFM) with a face mask. We also investigated whether the system discriminates between healthy infants and those with lung disease.

Methods
FloRight® measures changes in thoracoabdominal volume during tidal breathing through magnetic field changes generated by current-carrying conductor coils in an elastic vest. Simultaneous TBFVL measurements by the vest-based system and the USFM were performed at 44 weeks corrected postmenstrual age during quiet unsedated sleep. TBFVL parameters derived by both techniques and within both groups were compared.

Results
We included 19 healthy infants and 18 infants with lung disease. Tidal volume per body weight derived by the vest-based system was significantly lower with a mean difference (95%CI) of -1.33 ml/kg (-1.73; -0.92), p<0.001. Respiratory rate and ratio of time to peak tidal expiratory flow over total expiratory time (tPTEF/tE) did not differ between the two techniques. Both systems were able to discriminate between healthy infants and those with lung disease using tPTEF/tE.

Conclusion
FloRight® accurately measures time indices and may discriminate between healthy infants and those with lung disease, but demonstrates differences in tidal volume measurements. It may be better suited to monitor breathing pattern than for TBFVL measurements.
Introduction

Tidal breathing measurements and monitoring of breathing pattern and apnea in infants have their clinical role, especially in preterm infants. Indices describing the shape of the tidal breathing flow volume loop (TBFVL) such as the ratio of time to peak tidal expiratory flow over total expiratory time (tPTEF/tE), have been shown to correlate with the severity of bronchopulmonary dysplasia in infants, with airway obstruction and with respiratory morbidity in both infants and young children.\(^1\)\(^2\) Current methods for TBFVL measurements, such as pneumotachometers and ultrasonic flowmeters, require the use of a facemask. Besides adding additional dead space, a facemask may alter the breathing pattern and interfere with sleep state.\(^3\) Furthermore, measurements may be uncomfortable for infants over a longer time period and can be technically difficult. To date however, they still represent the most accurate way of TBFVL measurements and are recommended by latest standards of the European Respiratory Society (ERS) and the American Thoracic Society (ATS) for infant lung function testing.\(^4\)

A technique independent of a facemask is respiratory inductance plethysmography (RIP), which is frequently used for long-term monitoring of breathing pattern. It is a non-invasive method using two bands of coiled wire, one placed around the thorax and one around the abdomen. During breathing, the inductance of the coils proportionally changes with differences in the cross-sectional volume enclosed by them. Despite the fact that RIP has long been commercially available, difficulties related to calibration have limited its application in infants. So far, it has often been used without prior calibration in order to obtain relative volume changes.\(^5\)\(^-\)\(^10\) In addition to calibration issues, thoraco-abdominal asynchrony may additionally confound results.\(^5\)\(^-\)\(^10\)\(^11\)

Recently, a new system for TBFVL measurements has been developed (FloRight®, Volusense AS, Oslo, Norway). It is based on similar principles as RIP but allows simpler calibration in addition to being independent of facemask use. In comparison to RIP, FloRight® differs in that the thoracic and abdominal conductor coils, instead of consisting of two narrow elastic bands, are woven into an elastic vest worn by the infant, adding to its practicability. Comparison of the system with a mask-based system has been made, where tidal volumes were systematically underestimated by the vest-based system.\(^12\) Williams et al. also investigated the vest-based system and found this to be within reasonable agreement.\(^13\) In a follow-up study, Pickerd et al. was able to show differences in thoracoabdominal synchrony as well as establish normative values in term and preterm infants using the vest-based system.\(^14\) However the influence of measurement conditions has not been systematically investigated. This is important to determine whether the
origin of the discrepancy is physiological or technical, before clinical utility can be established.

We investigated the accuracy of TBFVL measurements comparing the new vest-based system (FloRight®) with an ultrasonic flowmeter (USFM) requiring a facemask (Spiroson®, Ecomedics, Dürnten, Switzerland) according to latest ERS/ATS standards of lung function testing. We also investigated whether TBFVL indices derived by the new vest-based system are able to discriminate between healthy infants and infants with lung disease. Furthermore, we focused on the influence of measurement conditions, such as duration of the measurement, facemask, vest, respiratory rate and surface underneath the infant on TBFVL measurements.

Methods

Study Population
The study included 19 healthy, term born infants and a group of 18 infants with lung disease (nine preterm infants with chronic lung disease (CLD), five preterm infants without CLD, two term infants with diaphragmatic hernia, one term infant with a diaphragmatic paresis after heart surgery and one term infant with congenital cystic adenomatoid malformation (CCAM)). All infants were of white Middle-European ethnicity. Healthy infants were recruited as part of the ongoing Bern Infant Lung Development (BILD) Birth Cohort, which has previously been described in detail. Lung function in all 18 infants with lung disease was studied as part of the routine clinical work-up. All lung function measurements were performed at 44 weeks of corrected postmenstrual age.

The study has been approved by the ethics committees of the canton of Bern and the University Children’s Hospital Bern. Written informed consent was obtained from all parents.

Equipment and data analysis
Vest-based system (FloRight®)
For measurements using the FloRight® system, the infant wears a vest with two separate woven-in flexible coils (Figure 1). Thus, the coils are wrapped five times helically around the infant’s chest or abdomen when the vests are closed. Depending on the vest-size, the spacing between the coils ranges from 1.2 to 2 cm. During the measurement, an alternating current of about 200 mA with a sine-wave frequency of 38.4 kHz is fed through the coils. A magnetic dipole moment is generated which is proportional to
the summed area of the loops regardless of their cross-sectional shape. An antenna placed above the infant detects the magnetic field generated by the vest. The signal measured with the antenna is translated into volume by calculating the summed area and multiplying this by the spacing between turns of the coils in the vest.\textsuperscript{18-20} Different vest-sizes were available and chosen according to the largest thoracoabdominal circumference of the infant.

**Figure 1: Schematic of the measurement principle**

During breathing a magnetic field is generated by the elastic vest with coils woven in, worn by the infant. The magnetic field is measured by the antennas placed above the infant. This signal is then analysed and converted into volumes through the computer.\textsuperscript{27}

During the course of the study, vests (n=27) were fitted with adjustable Velcro- straps to ensure a snug fit. The vests covered the thorax from the level of the axilla, the full abdomen and, depending on the infant’s length, also a portion of the legs. The vests were worn on top of a diaper and either with (nine infants) or without further clothing (28 infants). The vests we used were designed for single use only. Data was sampled at 100 Hz. For this study, all volume data were low-pass filtered at a cut-off frequency of 10 Hz, all flow data at cut-off of 8 Hz, however the raw data was stored unfiltered. Data analysis was performed using the FloRight\textsuperscript{®} software available with the system. The breaths were segmented, and all variables were calculated for each successive breath. Onset of a breathing cycle was defined as the transition from inspiration (inward airway flow) to expiration (outward airway flow). Discrimination between inspiratory and expiratory
intervals was done by using the instantaneous sign (positive or negative) of the flow signal. All time intervals were measured by counting of waveform samples. Tidal volume was calculated directly from the volume curve as the arithmetic mean of inspiratory and expiratory volume for each breath, using the definition of breathing cycles described above. The instrument measures volume by principle. Instantaneous flow is found by numerical differentiation of the recorded volume trace. This is in contrast to flow-based spirometers, in which volume is found by integration of the flow waveform. Due to the sensitivity of the differentiation process to noise, a digital low-pass filter was used and the filter delay compensated for using a matched digital delay in the volume signal before constructing the flow-volume loop. The software also performs drift correction by resetting the volume baseline every 20 seconds.

**Calibration of the vest-based system**

Calibration was done by connecting a coil with a known volume and recording the magnetic field generated by this coil. The coil area was of similar magnitude to the cross-sectional area of an infant’s torso, and a calibration constant was calculated which related the measured magnetic field to the area of the coil. This calibration can be performed without involving the infant, since the volume measurements are based on absolute physical laws. Areas, and thus volumes, were estimated in a way that did not depend on the cross-sectional shape of the infant’s torso.

**USFM system using a facemask**

In the validated mask-based system, an USFM (Spiroson®, EcoMedics AG, Dürnten, Switzerland) with an infant face mask (size 1, 7.5 ml deadspace; Homedica, Cham, Switzerland) was used. This was set as the reference method for the study and has been described previously in detail. Measurements were performed according to the ERS/ATS standards of infant lung function testing. FloRight® custom-written software was used to match the signals from the two systems to enable analysis from in parallel derived data from the same breaths, using a cross-correlation method.

**Model Experiments**

The two systems were first compared by a simple physical model, consisting of a plastic tube with a circumference of 36.2 cm with a surrounding Teflon membrane, which encloses an inflatable volume around the tube. Simulating changes in thoracoabdominal volume during breathing, this volume can be changed via a connecting 10-ml plastic syringe (Becton Dickinson AG, Allschwil, Switzerland). Measurements were made with
the vest attached around the model. Five sets with 15 slow tidal manoeuvres each were delivered, using the 10ml syringe, simultaneously to the mask-based and the vest-based systems, and the volumes measured by both systems compared.

In a second experiment, we used a standard infant ventilator (Fabian, Acutronics medical systems AG, Switzerland) to perform tidal manoeuvres. Here, a tidal volume (Vt) of 23 ml, comparable to 5-7 ml/kg for infants at the age of 44 weeks postmenstrual age, was delivered simultaneously to both systems. During this experiment, we also assessed the effect of different respiratory rates (RR) ranging from 20-80 breaths per minute. Measurements were performed twice for every frequency, with a minimum of 100 breaths per measurement.

**Tidal breathing measurements**

Measurements in all infants were performed during quiet, unsedated natural sleep, usually after feeding. Infants were studied in a supine position with the head in a midline position.\(^{22}\) Measurements were performed according to ERS/ATS standards.\(^{4,15,23}\) First, a 10 minute measurement with only the mask-based system was made. Second, a simultaneous measurement with the two systems was made for 10 minutes whenever possible.

The first 100 available regular, consecutive breaths were analysed according to ATS/ERS standards.\(^{4,15,23}\) Sighs were excluded from analysis, including the 10 breaths before and after a sigh, and the first 20-30 breaths after mask placement were excluded.\(^{22}\) Data from all infants were included regardless of health or lung disease status.

**Comparison of tidal breathing parameters**

In all infants studied, we compared all volumes measured over 100 breaths by the two systems. Secondly, we compared mean Vt and minute ventilation (Vt multiplied by RR) over 100 breaths between the two systems. In order to investigate the influence of the measurement length, the comparisons above were made not only over 100 breaths but also over 10 breaths. From the same measurements, mean RR, peak tidal expiratory flow (PTEF) and the ratio time to peak tidal expiratory flow over total expiratory time (tPTEF/tE) over 100 and 10 breaths were also compared between the two systems. We also investigated the effect of using software from the vest-based system to analyse data obtained by the USFM, by exporting raw flow data from the USFM software (EcoMedics AG, Duernten, Switzerland). Using custom-written software (VoluSense AS, Oslo, Norway) the raw flow data was integrated to give volume, de-trended to remove drift and then data was resampled to 100 Hz and reformatted to enable import by the FloRight analysis software. Since the FloRight software requires two volume traces (from
The volume values were split in equal halves between the two locations.

**Possible influencing factors on tidal breathing**

One factor known to influence tidal breathing measurements is the facemask. We investigated this by measuring tidal breathing with the vest-based system for 20 breaths without the mask placed on the infants face and 20 breaths with the facemask placed. For this analysis, only ten breaths before removal and ten breaths after placement of the mask were excluded from analysis due to the limited time of quiet natural sleep in infants.

In order to rule out a possible influence of the vest on tidal breathing, 10 minutes of tidal breathing were measured with the mask-based system only and 10 minutes with the vest- and mask-based system simultaneously. We analyzed 100 breaths from both measurements and compared Vt and RR with and without the vest.

The respiratory rate has the potential to influence any differences between volumes obtained at the mouth by the mask-based system and at the chest by the vest-based system. This was investigated in a model experiment as well as in the infants.

Measurements were performed with the infant sleeping on one of the three possible surfaces (cot, stroller or arms of mother or nurse). The mean differences between the two systems were compared.

**Comparison between health and lung disease**

For all tidal breathing parameters we investigated if the two systems were able to discriminate between healthy infants and infants with lung disease.

**Statistical analysis**

Graphs were created and statistical analysis performed using SigmaPlot 11 (Systat Software Inc., Richmond, CA). With regards to comparisons of tidal breathing parameters between the two systems, correlation between the two methods was first examined, reported as the correlation coefficient r over 10 and 100 breath traces. The equivalence of both methods was then determined using Bland and Altman method by plotting differences of paired measurement against means of paired measurements. Comparisons between the two systems and between measurements with and without a mask or vest were made using paired t-tests (Wilcoxon signed rank tests if data was not normally distributed). With regards to influence of various factors on the difference between the two systems: The relationship between the difference in tidal volume
assessed by the two systems (vest-based minus mask-based) and respiratory rate was evaluated using linear regression for both model and infant experiments. The influence of the measurement surface was evaluated by unpaired comparisons of the difference in tidal volume assessed by the two systems measured between the different surfaces. Comparisons between health and disease were made using t-tests (Mann-Whitney rank sum tests where data was not normally distributed). A p-value < 0.05 was considered statistically significant.

**Results**

**Study Population**

The healthy and lung disease groups were similar in postmenstrual age, but significantly different with respect to gestational age (p<0.001), body weight (p=0.01), body length (p=0.04) and body circumference (p=0.005). Characteristics of the two groups are displayed in Table 1.

<table>
<thead>
<tr>
<th>TABLE 1: Anthropometric characteristics of study population</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td>Healthy infants (n=19)</td>
</tr>
<tr>
<td>Mean (SD)</td>
</tr>
<tr>
<td>Mean (SD)</td>
</tr>
<tr>
<td>Gestational Age (weeks)</td>
</tr>
<tr>
<td>Postconceptional age at lung function (weeks)</td>
</tr>
<tr>
<td>Body weight (kg)</td>
</tr>
<tr>
<td>Body length (cm)</td>
</tr>
<tr>
<td>Body circumference (cm)*</td>
</tr>
<tr>
<td>Sex (male/female)</td>
</tr>
</tbody>
</table>

a: body circumference is the largest measured circumference around chest or abdomen out of 3 measurements

**Model Experiments**

The model experiment using a syringe displayed good agreement between the two systems. Tidal volumes were not significantly different between the two systems with a mean difference (95%CI) of -0.14 ml (-0.51; 0.23), p=0.351. The influence of RR on this difference was minimal but significant (p=0.002), see also figure 2.
FIGURE 2: Vt measured by both the vest- and mask-based system while the volume was delivered by an infant ventilator with increasing frequency.

- ● Vt obtained by mask-based system; ■ Vt obtained by vest-based system ▲ Difference between Vt-mask and Vt-vest.

**Comparison of tidal breathing parameters**

Results of simultaneously measured tidal breathing indices are found in Table 2. Correlation between the two systems was higher for 10 breaths with a mean r (95% CI) of 0.98 (0.96; 0.98) than for 100 breaths with a mean r (95% CI) of 0.79 (0.73; 0.84).

**TABLE 2: Tidal breathing parameters measured simultaneously by mask- and vest-based system in all infants**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mask-based system Mean (SD)</th>
<th>Vest-based system Mean (SD)</th>
<th>Mean difference (95% CI), p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tidal volume per body weight (ml/kg)</td>
<td>7.43 (1.27)</td>
<td>6.10 (1.40)</td>
<td>-1.33 (-1.73; -0.92), p &lt; 0.001</td>
</tr>
<tr>
<td>Minute ventilation per body weight (ml/kg/min)</td>
<td>361 (63.8)</td>
<td>300 (76.8)</td>
<td>-60.5 (-78.5; -42.6), p &lt; 0.001</td>
</tr>
<tr>
<td>Respiratory rate (/min)</td>
<td>50.1 (11.9)</td>
<td>50.8 (11.9)</td>
<td>0.71 (0.24; 1.17), p = 0.031</td>
</tr>
<tr>
<td>Peak tidal expiratory flow (ml/s)</td>
<td>67.1 (13.4)</td>
<td>67.7 (19.3)</td>
<td>0.63 (-3.57; 4.83), p = 0.76</td>
</tr>
<tr>
<td>tPTEF/TE</td>
<td>33.9 (12.4)</td>
<td>36.6 (13.1)</td>
<td>2.71 (-0.47; 5.90), p = 0.14</td>
</tr>
</tbody>
</table>
The Bland-Altman plots showed a systematic underestimation of Vt (mean difference (± 2SD) -1.327 (2.446) ml/kg (Figure 3) and minute ventilation (mean difference (± 2SD) -60.535 (107.667) ml/kg/min by the vest-based system. This was the case for both health and lung disease groups.

FIGURE 3: Bland Altman plot of Tidal Volumes measured with mask- (Vt_mask) and vest-system (Vt_vest).

Showing on the x-axis the mean of the two volumes and on the y-axis the difference. ●: healthy infants; ▼: infants with lung disease; Solid line indicating the mean, dotted line the limits of agreement at ± 2SD, dashed line indicating zero

There was also a significant difference when comparing analysis of the same mask-based signal using the vest-based versus mask-based software for both Vt and minute ventilation. Mean difference Vt (95%CI) -0.09ml/kg (-0.12; -0.061), p<0.001, and mean difference minute ventilation (95%CI) -3.32ml/kg/min (-4.50; -2.14), p<0.001.

Bland-Altman plots showed an overestimation of RR by the vest-based system (mean difference 0.71/min, 95%CI 0.24; 1.17, p=0.031), though this was not dependent on the magnitude of the measurement. Comparison of PTEF and tPTEF/E did not reveal a significant difference between the mask- and vest-based systems. Again here was a statistical difference between the values measured with the mask and the values measured with the mask, but analysed with the vest-software (mean difference PTEF -1.01ml/s, 95% CI -1.22; -0.81, p<0.001), (mean difference tPTEF/E 2.20%, 95% CI 1.83; 2.58, p<0.001).
Factors influencing tidal breathing

Application of the facemask showed a significantly higher Vt compared to the breaths when there was no mask placed over the infants nose and mouth (mean difference (95%CI) 1.79 ml/kg (1.50; 2.07), p<0.001). There was no difference found in RR between measurements with or without facemask (mean difference (95%CI) -0.71/min (-3.42; 2.00), p=0.597). This comparison was done in 18 healthy infants and 15 infants with lung disease, due to insufficient length of sleep in the other four infants.

Measurements with or without the vest were not significantly different for Vt (mean difference (95%CI) -0.13 ml/kg (-0.45; 0.18), p=0.39) and RR (mean difference (95%CI) 2.40/min (-0.55; 5.35), p=0.102). This comparison was done in 18 healthy infants and 13 infants with lung disease, due to insufficient length of sleep in the six excluded infants.

Possible influencing factors on differences between the two systems

While the difference in Vt between the two systems was associated with RR for the model, this was not the case in the infants (p=0.091).

The surface underneath the infant had a significant influence on the difference in Vt between the systems, with a smaller difference using a cot compared to stroller or arms (mean difference stroller versus cot (95%CI) -1.66 ml/kg (-2.75; 0.56), p=0.005; mean difference arms versus cot (95%CI) -0.84 ml/kg, (-1.65; -0.03), p=0.041. Between stroller and arms, there was no significant difference (mean difference Vt (95%CI) -0.81ml/kg (-2.30; 0.67), p=0.257).

![Figure 4: Discriminating between health and lung disease using tPTEF/te with both the mask- and the vest-system](image)

Columns indicating the system used and if the infant was healthy (healthy) or having lung disease (disease).
Comparison between health and lung disease

The only parameter able to discriminate between health and disease was tPTEF/tE in both systems (Table 3a). Mean tPTEF/tE (SD) was 40.5% (9.10) vs 27.0% (11.8) in the mask-based system, and 42.5% (8.34) vs 30.4% (14.4) in the vest-based system (figure 4). These results also held when consider only infants with CLD (mean tPTEF/tE (SD) was 21.6% (7.93) in the mask-based system, and 28.0% (16.9) in the vest-based system) i.e. the majority of the disease group (table 3b). Minute ventilation was also able to discriminate between health and disease, but only with the mask-based system and in the total lung disease group.

### TABLE 3A: Difference in tidal breathing parameters between healthy infants and infants with lung disease using both the mask- and vest-based system simultaneously

<table>
<thead>
<tr>
<th></th>
<th>Mask-based system</th>
<th>Vest-based system</th>
<th>p-value</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tidal volume per body weight (ml/kg)</td>
<td>-0.074 (-0.93; 0.79)</td>
<td>0.86</td>
<td>0.11 (-0.83; 1.06)</td>
<td>0.81</td>
</tr>
<tr>
<td>Minute ventilation per body weight (ml/kg/min)</td>
<td>-54.6 (-93.5; 15.7)</td>
<td><strong>0.007</strong></td>
<td>-41.6 (-91.6; 8.39)</td>
<td>0.10</td>
</tr>
<tr>
<td>Respiratory rate (/min)</td>
<td>-8.44 (-15.9; -0.95)</td>
<td>0.066</td>
<td>-8.95 (-16.4; -1.46)</td>
<td>0.05</td>
</tr>
<tr>
<td>Peak tidal expiratory flow (ml/s)</td>
<td>-5.50 (-14.4; 3.36)</td>
<td>0.22</td>
<td>-5.35 (-18.3; 7.61)</td>
<td>0.41</td>
</tr>
<tr>
<td>tPTEF/tE</td>
<td>13.5 (6.45; 20.5)</td>
<td><strong>&lt;0.001</strong></td>
<td>12.1 (4.30; 19.9)</td>
<td><strong>0.001</strong></td>
</tr>
</tbody>
</table>

### TABLE 3B: Difference in tidal breathing parameters between healthy infants and infants with CLD (majority of the lung disease group) using both the mask- and vest-based system simultaneously

<table>
<thead>
<tr>
<th></th>
<th>Mask-based system</th>
<th>Vest-based system</th>
<th>p-value</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tidal volume per body weight (ml/kg)</td>
<td>-0.54 (-1.56; 0.48)</td>
<td>0.56</td>
<td>-0.14 (-1.41; 1.12)</td>
<td>0.82</td>
</tr>
<tr>
<td>Minute ventilation per body weight (ml/kg/min)</td>
<td>-40.5 (-87.5; 6.59)</td>
<td>0.062</td>
<td>-24.0 (-85.7; 37.7)</td>
<td>0.43</td>
</tr>
<tr>
<td>Respiratory rate (/min)</td>
<td>-2.70 (-9.96; 4.57)</td>
<td>0.45</td>
<td>-3.81 (-11.3; 3.64)</td>
<td>0.43</td>
</tr>
<tr>
<td>Peak tidal expiratory flow (ml/s)</td>
<td>-7.67 (-18.8; 3.43)</td>
<td>0.26</td>
<td>-8.94 (-25.7; 7.80)</td>
<td>0.28</td>
</tr>
<tr>
<td>tPTEF/tE</td>
<td>18.9 (11.6; 26.2)</td>
<td><strong>&lt;0.001</strong></td>
<td>14.5 (4.79; 24.2)</td>
<td><strong>0.004</strong></td>
</tr>
</tbody>
</table>
Discussion

Summary of findings
The vest-based FloRight® system accurately measures indices like RR, PTEF and tPTEF/tE compared to a mask-based system. However, the volumes measured by this vest-based system showed a tendency to underestimate the volumes measured by the mask-based system. Factors significantly influencing the difference between the tidal volumes measured with the two systems were mainly RR and the surface underneath the infant. Only tPTEF/tE was able to discriminate between healthy infants and infants with lung disease for both systems.

Significance and strengths of technique and study
The major advantage of the vest-based system is the avoidance of a facemask, which was seen to significantly increase tidal volumes, as is also previously known.\textsuperscript{1,25} Also, the vest represents a non-invasive component of the measurement, which does not disturb the infant during long-term monitoring applications. However, the volumes measured by the vest-based system cannot be compared to volumes measured by the mask-based system; despite the small groups, all data showed underestimation of the volumes by the vest-based system, except for two, healthy infants. On the other hand, time-based indices measured by the systems are similar, and thus the vest-based system may be suitable for monitoring and apnoea detection. Another advantage is the easy calibration procedure compared to similar systems such as RIP.

Limitations of the technique and study
The technique also has some practical limitations. First, a good fit of the vest is crucial. Any moving surface area not adequately covered by the vest will mean underestimation of volumes measured. The vest has to be placed as high up into the axilla as possible, there should be no wrinkles in the cranial-caudal direction, and it should cover the whole abdomen. Second, the system samples volume at a frequency of 100Hz. The standards recommend that a sampling rate of 200 Hz be used in order to adequately measure parameters such as tPTEF/tE.\textsuperscript{4,15} However, discriminative ability between health and disease was still apparent in the vest-based system.

Finally, during analysis we found a small but significant difference between the analysis of the mask-based parameters using the mask-based software or the vest-based software. Since these differences where very small, we consider them clinically insignificant.
Comparison between the two systems and possible influences

There was good agreement between the systems with regards to timing indices, but not with regards to volume measurements. Previous studies found the difference between the two systems to be significant but small, with a mean difference of 0.096 ml for Vt found by Olden et al.\textsuperscript{12} and 0.4 ml found by Williams et al.\textsuperscript{13} Ours is the first study examining the various factors affecting the difference between the vest-based system and the mask-based system in more detail. Importantly, we found the vest-based system to have good agreement with the mask-based system in measuring timing indices, making the system well suited for long-term monitoring of timing indices. However, the difference in volume measurements compared to mask-based system was much larger than previous work when studied over several minutes, and the cause for the discrepancy could not be ascertained. It is possible that non-stationary conditions due to patient motion and drift, which are not accounted for during calibration, can contribute to this discrepancy, however care has been taken to minimise motion and these factors are likely to have only a minor effect. While the system may be useful for short-term monitoring of tidal volumes, these volumes should not be expected to be a true reflection of tidal volume measured at the airway opening, especially over longer term. To explain the underestimation we investigated possible influencing, methodological factors, i.e. respiratory rate, surface beneath the infant, and disease status. The effect of respiratory rate may provide an explanation as suggested by model experiments, however, this was not found to be significant in the study population. We speculate this may be due to a greater presence of gas compression effects in the real lung.

The surface underneath the infant was found to be a significant contributor to the discrepancy. A possible reason for this could be that the vest-based system measures changes in volume in the cross-sectional direction and not changes in volume in the cranial-caudal direction, which may cause the volumes measured with the vest to underestimate the “true” volumes. By using a different, firmer surface underneath the infant, this effect was minimised. We have seen a larger discrepancy when the infant was placed in a stroller or the arms compared to a cot (with firmer surface) during measurements, however sizeable discrepancies remained when using a cot. Also the need for using a standardised firm surface may limit the clinical application of the system and may not be suitable for general bedside measurements.

The discrepancy between vest- and mask-based Vt measurements were similarly found in both healthy and sick infants, i.e. the disease was not a critical factor for the discrepancy. Thoraco-abdominal asynchrony has been described as confounder in RIP measurements.\textsuperscript{5,10,11} Pickerd et al also showed a difference between term and preterm
born infants. We have not been able to investigate thoraco-abdominal asynchrony in the present study.

**Discriminating between health and disease**

In our study, we found that the measurement tPTEF/tE obtained using either system was able to discriminate between health and lung disease. tPTEF/tE has been described as a sensitive parameter to distinguish between health and disease. Thus, in terms of time-based indices, the two systems are equivalent. However, in terms of volume-based indices, the mask-system was also able to discriminate using minute ventilation, where the vest-system could not. This is consistent with the finding that volumes measured by the two systems were not interchangeable. While the differences in volumes between the two systems could be attributable to physiological, anatomical and software or analysis factors, the effect of these factors on discriminative capacity could not be examined due to the small numbers.

The lung disease group also includes five preterm infants. It is known that preterm infants show significant burden of respiratory disease in the first year of life and more often suffer from wheeze, more often use inhalation therapy and are more often re-hospitalized compared to term born infants. Thus, we have decided to include them in the lung disease group, even though it may be debatable whether these infants have lung disease.

**Future outlook**

For monitoring functions, the system ideally needs to be able to measure breathing parameters over long term. There was a difference in the correlation between volumes measured by the two systems when considering 100 versus 10 breaths. This is most likely attributable to the drift correction algorithm in the FloRight® software. Thus, in terms of long-term monitoring, while the system is ideal for detection apnoeas or calculation of timing-related breathing parameters, it is not suitable for tidal volume measurements (for example weaning of breathing support) or hypopnoea detection. Any calculation of tidal breathing parameters needs to be calculated over a shorter-term and continually updated for long-term monitoring functions.
Conclusion

The currently investigated vest-based system (FloRight®) accurately measures time-indices and discriminates between health and lung disease. However, volume measurements can not be compared with the standard mask-based systems, and can be susceptible to practical limitations. Thus, the new system seems more suited as a monitoring tool for the detection of apnoeas or time-based breathing parameters, while its use as a lung function tool would require overcoming some of its current limitations and more validation.
References


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