Electromagnetic Inductance Plethysmography to Measure Tidal Breathing in Preterm and Term Infants

N. Pickerd, MD,1 E.M. Williams, PhD,2 and S. Kotecha, FRCPCH PhD1*

Summary. Tidal breathing measurements which provide a non-invasive measure of lung function in preterm and term infants are particularly useful to guide respiratory support. We used a new technique of electromagnetic inductance plethysmography (EIP) to measure tidal breathing in infants between 32 and 42 weeks postconceptional age (PCA). Tidal breathing was measured in 49 healthy spontaneously breathing infants between 32 and 42 weeks PCA. The weight-corrected tidal volume (VT) and minute volume (MV) decreased with advancing PCA (VT 6.5 ± 1.5 ml/kg and MV 0.44 ± 0.04 L/kg/min at 32–33 weeks, respectively; 6.3 ± 0.9 ml/kg and 0.38 ± 0.02 L/kg/min at 34–36 weeks; and 5.1 ± 1.1 ml/kg and 0.28 ± 0.02 L/kg/min at term, VT P < 0.001 and MV P < 0.01 for 32–33 weeks PCA vs. term; VT P = 0.016 and MV P = 0.015 for 34–36 weeks PCA vs. term). Respiratory frequency and the phase angle decreased significantly with advancing PCA but the flow parameter tPTEF/tE did not change significantly. Using a new technique to measure tidal breathing parameters in newborn infants, our data confirms its usability in clinical practice and establishes normative data which can guide future respiratory management of newborn infants. Pediatr Pulmonol. 2013; 48:160–167.

Key words: tidal volume; breathing pattern; minute volume; electromagnetic inductance plethysmography.

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INTRODUCTION

Tidal breathing measurements in infants are a non-invasive measure of lung function which can provide information about respiratory control and pulmonary mechanical function. Normal values for tidal breathing parameters of healthy newborn infants are useful especially to guide mechanical ventilation. However, tidal breathing data on healthy preterm infants without respiratory support are limited. Although a few studies have measured tidal breathing in infants without respiratory support from around 31–33 weeks postconceptional age (PCA),2–5 most were performed before publication of international standards for tidal breathing measurements in infants in 2000.1,6,7

Furthermore, most studies performing tidal breathing measurements in preterm infants have used a pneumotachograph (PNT) attached to a facemask or respiratory inductive plethysmography (RIP). It is well known that placing the PNT mask onto the infant’s face alters the breathing pattern8,9 and the added instrumental deadspace increases tidal volume and respiratory frequency.10–12 RIP avoids interfering with the airflow, as it records the movements of the chest and abdomen during the respiratory cycle as a change in the inductance of two coils, one placed around the chest and one around the abdomen. The volume change in each compartment is proportional to the change in inductance. RIP however does require the use of a PNT for calibration to obtain absolute volume values and the use of the PNT affects the infants’ breathing patterns. The calibration of RIP has been noted to lack accuracy in

Additional supporting information may be found in the online version of this article.

1Department of Child Health, Cardiff University, Cardiff, UK.
2Faculty of Health, Sport and Science, University of Glamorgan, Glamorgan, UK.

Conflict of interest: The study was partially funded by VoluSense and technical support was also provided by VoluSense the makers of FloRight but the study was designed and executed independently of the company.

*Correspondence to: S. Kotecha, FRCPCH PhD, Department of Child Health, Cardiff University School of Medicine, Heath Park, Cardiff CF14 4XN, UK. E-mail: kotechas@cardiff.ac.uk

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infants with a high degree of thoraco-abdominal asynchrony and changing breathing patterns.13

A newer method using electromagnetic inductance plethysmography (EIP), measures the volume changes in chest and abdomen during respiration via changes in the electromagnetic field generated by a weakly electrified vest worn by the infant.12,14 EIP by a new instrument, FloRight (VoluSense, Oslo, Norway) has been shown to be accurate for tidal breathing measurements in term and preterm infants12,14 and does not interfere with the infant’s airway nor requires subject-dependent calibration. It therefore allows measurement of truly undisturbed tidal breathing.

The aim of this study was to establish baseline values for tidal breathing parameters in healthy infants between 32 and 42 weeks PCA using the FloRight, that is, without interfering with the infant’s breathing pattern.

METHODS

Study Population

Infants between 32 and 42 weeks PCA were studied. They were eligible for the study if they had not received any supplemental oxygen or respiratory support for at least 7 days prior to the study. The infants were divided into three groups according to their PCA (32–33, 34–36, and 37–42 weeks, Table 1). Infants were excluded if they had congenital anomalies, neuromuscular disease or surgical conditions, lack of parental consent or if the attending team deemed the baby unsuitable for study due to clinical or social reasons. The study was approved by the South East Wales Research Ethics Committee. Informed written consent was obtained from the parents.

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>32–33 weeks (N = 15)</th>
<th>34–36 weeks (N = 15)</th>
<th>37–42 weeks (N = 19)</th>
<th>Total (N = 49)</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Males</td>
<td>10</td>
<td>8</td>
<td>8</td>
<td>26</td>
<td>ns</td>
</tr>
<tr>
<td>Gestation (weeks)</td>
<td>31 ± 1 (28–33)</td>
<td>33 ± 1 (29–35)</td>
<td>39 ± 2 (34–42)</td>
<td>35 ± 4 (28–42)</td>
<td>ns</td>
</tr>
<tr>
<td>Birth weight (kg)</td>
<td>1.64 ± 0.30 (1.10–2.10)</td>
<td>1.93 ± 0.34 (1.40–2.62)</td>
<td>3.22 ± 0.67 (2.00–4.25)</td>
<td>2.35 ± 0.87 (1.10–4.25)</td>
<td>ns</td>
</tr>
<tr>
<td>Postnatal age at study (days)</td>
<td>15 ± 9 (4–28)</td>
<td>14 ± 9 (3–40)</td>
<td>4 ± 4 (1–17)</td>
<td>10 ± 9 (1–40)</td>
<td>2,3</td>
</tr>
<tr>
<td>PCA at study (weeks)</td>
<td>33 ± 1 (32–33)</td>
<td>35 ± 1 (34–36)</td>
<td>40 ± 2 (37–42)</td>
<td>36 ± 3 (32–42)</td>
<td>2,3</td>
</tr>
<tr>
<td>Weight at study (kg) range</td>
<td>1.72 ± 0.20 (1.30–2.10)</td>
<td>2.00 ± 0.28 (1.53–2.60)</td>
<td>3.22 ± 0.69 (1.99–4.25)</td>
<td>2.39 ± 0.82 (1.30–4.25)</td>
<td>2,3</td>
</tr>
<tr>
<td>Length at study (cm) range</td>
<td>43.1 ± 2.0 (39.5–47.5)</td>
<td>45.8 ± 3.7 (40–54.5)</td>
<td>51.7 ± 4.6 (43–58.8)</td>
<td>47.2 ± 5.2 (39.5–58.8)</td>
<td>2,3</td>
</tr>
<tr>
<td>Heart rate (beats/min) range</td>
<td>148 ± 10 (130–165)</td>
<td>157 ± 11 (135–174)</td>
<td>129 ± 17 (104–173)</td>
<td>144 ± 18 (104–174)</td>
<td>2,3</td>
</tr>
<tr>
<td>Receiving caffeine</td>
<td>4/15 (27%)</td>
<td>2/15 (13%)</td>
<td>0/19 (0%)</td>
<td>6/49 (12%)</td>
<td>1,2</td>
</tr>
<tr>
<td>Previously intubated and ventilated</td>
<td>9/15 (60%)</td>
<td>3/15 (20%)</td>
<td>1/19 (5%)</td>
<td>13/49 (27%)</td>
<td>1,2</td>
</tr>
<tr>
<td>Previously received surfactant</td>
<td>9/15 (60%)</td>
<td>3/15 (20%)</td>
<td>0/19 (0%)</td>
<td>12/49 (24%)</td>
<td>1,2,3</td>
</tr>
</tbody>
</table>

ns, not significant.

132–33 weeks significantly different from 34 to 36 weeks.

232–33 weeks significantly different from 37 to 42 weeks.

334–36 weeks significantly different from 37 to 42 weeks.
angle between the two compartments to be calculated. Figure 3 shows representative traces obtained with the FloRight of synchronous and asynchronous breathing in the same infant. The phase angle calculation uses Fourier analysis and is expressed as values between $-180^\circ$ and $180^\circ$ (see online supplement for further details). A positive phase angle indicates delayed expansion of the rib cage relative to the abdomen.

### Tidal Breathing Measurements

All measurements were performed at the infant’s cotside. A fresh new appropriately sized vest was used for each infant chosen according to their chest circumference. Each vest was fitted on the infant without any clothing underneath and the nappy was rolled down to fit below the vest. The vest was tightened to fit snugly without compromising the infant’s breathing. After feeding, the infant was placed supine. Before the measurement, the FloRight system was calibrated by placing a cylinder of known volume next to the infant. Any equipment which caused magnetic field interference was moved away before measurements commenced. Infants were not sedated and continuous measurements were made for at least 5–20 min dependent on how settled and quiet the infant was. The infant’s heart rate and oxygen saturations were monitored continuously throughout the study with a pulse oximeter (Oximax N550, Nellcor, Colorado). Episodes during which the infant was agitated were noted so that they could be excluded from the data analysis. The following parameters were measured: tidal volume ($V_T$, ml), respiratory rate ($f_R$, breaths/min), minute volume ($MV$, L/min), $t_{PTEF}/t_E$ (%), and phase angle ($^\circ$). The $V_T$ and $MV$ were corrected for weight (ml/kg and L/kg/min). Only periods of quiet breathing were included and periods with sighs or apnoeas were excluded. The mean values were derived from three different episodes, each of 10 consecutive breaths.

### Statistical Analysis

The results are presented as mean ± SD or SEM. ANOVA with posthoc comparisons was used to compare the different groups and linear regression to assess the relationships between the tidal breathing parameters and PCA of the infants (SPSS V16, IBM). A $P$-value of $<0.05$ was considered significant.
RESULTS

Forty-nine infants were studied (Table 1). The term infants, as expected, were heavier and longer than the preterm infants and were studied at a significantly younger postnatal age (P < 0.001 32–33 and 34–36 weeks vs. term for all parameters). None of the term infants had previously received surfactant and one required intubation and ventilation compared to 9/15 in the 32–33 weeks group and 3/15 in the 34–36 weeks group who had received both surfactant and were intubated. Out of the 13 infants who were previously ventilated, 10 were ventilated for less than 24 hr, one for 4 days and two for 6 days. Four infants (27%) were receiving caffeine in the 32–33-week group and two (13%) in the 34–36-week group. However, the tidal volumes were similar between two groups: mean VT/kg of 6.8 ± 0.7 and 6.4 ± 0.5 ml/kg in the caffeine and no caffeine groups, respectively, at 32–33 weeks PCA and 6.7 ± 0.1 and 6.3 ± 0.3 ml/kg, respectively, at 34–36 weeks PCA.

The results for the tidal breathing parameters are shown in Table 2 and Figures 4–6. The term infants had significantly lower VT (P = 0.005) and MV (P < 0.001) adjusted for bodyweight (VT 5.1 ± 0.3 ml/kg, MV 0.28 ± 0.02 L/kg/min) than the preterm infants whose tidal and MVs were similar between the two preterm groups (32–33 weeks PCA VT 6.5 ± 0.4 ml/kg, and MV 0.44 ± 0.04 L/kg/min, 34–36 weeks PCA VT 6.3 ± 0.2 ml/kg, and MV 0.38 ± 0.02 L/kg/min) (Fig. 4A and C). The weight adjusted VT and MV decreased with advancing gestation (R = 0.46, P < 0.001 and R = 0.53, P < 0.001, respectively). Also a clear trend of a decrease in fR with advancing PCA was shown (R = 0.32, P = 0.02). The infants studied at term had a significantly lower fR (56 ± 3 breaths/min) than the preterm infants studied between 32 and 33 weeks PCA (67 ± 4 breaths/min, P = 0.041), but not the infants studied between 34 and 36 weeks PCA (62 ± 2 breaths/min, Fig. 4B). The difference in fR between the infants studied at 32–33 weeks PCA and 34–36 weeks PCA was also not significant.

There was a trend of a decrease in phase angle with advancing gestation (R = 0.31 and P = 0.03, 32–33 weeks PCA 23.8 ± 6.7°; 34–36 weeks PCA 11.6 ± 3.1° and term 6.6 ± 1.9°). The difference in the phase angle between the infants of 32–33 weeks PCA and term infants was statistically significant (P = 0.012) (Fig. 5).

Whilst the tPTEF/tE in infants at 34–36 weeks PCA and term infants was very similar (40.3 ± 2.63% and 41.3 ± 3.1%, respectively) the infants studied at 32–33 weeks PCA had lesser values (35.6 ± 2.9%) (Fig. 6). The differences were not, however, significantly different between the groups.

DISCUSSION

In this study, we measured tidal breathing in infants between 32 and 42 weeks PCA using the new technique of EIP. The weight corrected VT decreased with advancing PCA from 6.5 ± 0.4 ml/kg at 32–33 weeks PCA to 5.1 ± 0.3 ml/kg at term, equivalent to a decrease of 0.19 ml/kg per week (Fig. 4) as did the fR and weight corrected MV. The phase angle decreased with advancing gestational age from 23.8° at 32–33 weeks PCA to 6.6° in the term infants. No significant differences were noted for tidal breathing parameters between the two preterm groups (Table 2).

Few studies have previously reported detailed tidal breathing data: Dellaca et al. using optoelectronic plethysmography (OEP) studied 20 infants of between 30 and 44 weeks PCA (mean 36 ± 4 weeks) and noted that VT decreased by 0.26 ml/kg per week (Fig. 7). The decrease in weight corrected VT with advancing gestation is most likely due to a decrease in the ratio of physiological deadspace to alveolar ventilation. The larger VT in the preterm infants may be partly attributed to the use of caffeine which is known to increase tidal volume although only a few infants were receiving this drug at the time of study (32–33 weeks n = 4/15, 34–36 weeks n = 2/15). The values in weight corrected VT at different gestations are important to clinicians who use weight corrected VT to titrate ventilation.

### TABLE 2—Results of Tidal Breathing Parameters at Different Gestations (Mean ± SEM)

<table>
<thead>
<tr>
<th>Tidal breathing parameters</th>
<th>32–33 weeks (N = 15)</th>
<th>34–36 weeks (N = 15)</th>
<th>37–42 weeks (N = 19)</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>VT/kg (ml/kg)</td>
<td>6.5 ± 0.4</td>
<td>6.3 ± 0.2</td>
<td>5.1 ± 0.3</td>
<td>1, 2</td>
</tr>
<tr>
<td>Respiratory rate (breaths per minute)</td>
<td>67 ± 4</td>
<td>62 ± 2</td>
<td>56 ± 3</td>
<td>1</td>
</tr>
<tr>
<td>MV/kg (L/kg/min)</td>
<td>0.44 ± 0.04</td>
<td>0.38 ± 0.02</td>
<td>0.28 ± 0.02</td>
<td>1, 2</td>
</tr>
<tr>
<td>tPTEF/tE (%)</td>
<td>35.6 ± 2.9</td>
<td>40.3 ± 2.63</td>
<td>41.3 ± 3.1</td>
<td>ns</td>
</tr>
<tr>
<td>Phase angle (°)</td>
<td>23.8 ± 6.7</td>
<td>11.6 ± 3.1</td>
<td>6.6 ± 1.9</td>
<td>1</td>
</tr>
</tbody>
</table>

ns, not significant.

1. 32–33 weeks significantly different from 37 to 42 weeks.
2. 34–36 weeks significantly different from 37 to 42 weeks.
The decrease in the phase angle with advancing gestation was not unexpected as preterm infants are known to have a more compliant ribcage due to less ossification and less contractility of the intercostal muscles. The phase angles measured in this study were lower than those reported by Levy et al.\(^{17}\) and Warren et al.\(^{18}\) at similar gestations.

It has previously been shown that the flow parameter \(t_{\text{PTEF}}/t_{\text{E}}\) is dependent on the postnatal age.

Fig. 4. Influence of PCA on tidal breathing parameters (mean ± SEM). (A) Tidal volume, (B) respiratory frequency, and (C) minute ventilation. * 32–33 weeks significantly different from 37 to 42 weeks, # 34–36 weeks significantly different from 37 to 42 weeks. Otherwise no differences were found.

The \(t_{\text{PTEF}}/t_{\text{E}}\) decreases during the first week of life from 45% at birth to 32% at 5 days\(^{19,20}\) and then further during first 2 months of life.\(^{21}\) In the current study, the preterm infants were significantly older chronologically than the term infants at the time of the study (Table 1). The difference in age could possibly explain the higher \(t_{\text{PTEF}}/t_{\text{E}}\) in the term infants (41%) compared to the preterm infants (32–33 weeks PCA 36%) although these differences were not statistically significant. A similar finding was described by Latzin et al.\(^{22}\) who compared preterm and term born infants at a corrected gestational age of 44 weeks. The preterm infants who were on average 85 days old at the study had a significantly lower \(t_{\text{PTEF}}/t_{\text{E}}\) than the term infants (mean ± SD: SD: 31 ± 9% vs. 36 ± 11%, \(P = 0.001\)) who were on average 35 days old at the study date. Both values for preterm and term infants reported by Latzin et al.\(^{22}\) were lower than in our study, but their infants were chronologically much older. Our results were comparable to those from other studies.\(^{19-21}\)

Fig. 5. Influence of PCA on phase angle (mean ± SEM). * 32–33 weeks significantly different from 37 to 42 weeks. Otherwise no differences were found.

Fig. 6. Influence of PCA on \(t_{\text{PTEF}}/t_{\text{E}}\) (mean ± SEM). No significant differences were found.
These baseline values for tidal breathing parameters measured in healthy infants at different PCA without the use of a facemask are useful to clinicians to guide respiratory management, assess the effect of drug treatments (i.e., diuretics) and also as a comparison to results obtained in infants on continuous positive airway pressure (CPAP) support.

**Comparison to the Published Literature**

We have compared our results to the studies published since 2000 which reported weight-corrected $V_T$ in infants at least 1 day old who were not receiving any respiratory support (Fig. 8). Olden et al.\(^{14}\) measured a $V_T$ of $5.4 \pm 1.23$ ml/kg (mean $\pm$ SD) in 10 healthy term infants (gestation 40 weeks) at 1–2 days old using the FloRight as well (Fig. 8). This compares well to the $V_T$ of $5.1 \pm 0.3$ ml/kg we measured in the 19 term infants in this study of a similar age (Fig. 8).

Studies using PNT or ultrasonic flowmeter, however, have reported greater $V_T$ in preterm and term infants than the current study (Fig. 8). It is well recognized that the facemask stimulates the infant and increases the $V_T$.\(^{8,9}\) Furthermore, the deadspace introduced by the instrument increases the $V_T$ due to an increased hypercapnic drive.\(^{10-12}\) Hjalmarson and Sandberg\(^{15}\) reported a weight corrected $V_T$ of $7.1 \pm 1.3$ ml/kg (mean $\pm$ SD) in 53 term infants using a PNT and facemask. Hulskamp et al.\(^{23}\) and Fuchs et al.\(^{24}\) studied term infants at a PCA of about 44 weeks using an ultrasonic flowmeter and reported a weight corrected $V_T$ of $6.8 \pm 1.3$ ml/kg (mean $\pm$ SD) and $7.48 \pm 1.29$ ml/kg (mean $\pm$ SD), respectively. The higher $V_T$ measured in term infants with an airflow sensor as compared to the FloRight was also observed in preterm infants. Brar et al.\(^{25}\) used a PNT and facemask in preterm infants with a mean PCA of 34 weeks and measured a $V_T$ of $7.9 \pm 1.4$ ml/kg which is greater than the $V_T$ we measured in preterm infants with a PCA of 32–33 weeks ($6.5 \pm 0.4$ ml/kg) and 34–36 weeks ($6.3 \pm 0.2$ ml/kg). Leipala et al.\(^{26}\) and Landolfo et al.\(^{27}\) reported a weight corrected $V_T$ of $6.5 \ (3.9-9.5)$ ml/kg (median, range) and $6.4 \pm 1.2$ ml/kg (mean $\pm$ SD), respectively, in infants with a mean PCA of 36 weeks measured with a PNT. These are again larger than the $V_T$ of our cohort ($V_T \ 5.9 \pm 1.4$ ml/kg) which also had a mean PCA of 36 weeks (Fig. 8).

The weight corrected $V_T$ reported from studies using the flow through technique, which eliminates the instrumental dead space but still uses a facemask, is approximately 70% of that reported by studies using an airflow sensor without flow through technique, but still higher than measurements by the FloRight which does not interfere with the airways. Schmalisch et al.\(^{28,29}\) studied two cohorts of healthy term infants using the flow through technique and measured a weight corrected $V_T$ of $5.58 \pm 1.0$ ml/kg and $5.57 \pm 1.06$ ml/kg (mean $\pm$ SD) (Fig. 8).

A study using calibrated RIP has been published by Levy et al.\(^{17}\) and they reported a $V_T$ of $4.50 \pm 5.71$ ml/kg (mean $\pm$ SD) in preterm infants with a PCA of $33.6 \pm 1.4$ weeks (Fig. 8). This value is about 60% of the tidal volume we measured in the infants at 32–33 weeks PCA ($6.5 \pm 0.4$ ml/kg) and 34–36 weeks PCA ($6.3 \pm 0.2$ ml/kg). However, the accuracy of the calibration of RIP in infants with changing breathing patterns such as preterm infants has been questioned in the past.\(^{13}\)
Dellaca et al.\(^5\) reported the first and so far only study using OEP in a similar cohort of infants to ours (mean PCA 36 ± 4 weeks). OEP also avoids airway interference. They reported \(V_T\) of 8.9 ± 1.6 ml/kg (mean ± SD), which is higher than the \(V_T\) reported in any other study (Fig. 8).

The current study is the first to report tidal breathing parameters over a wide range of gestations measured with the FloRight. We have previously validated the technique in infants with a PCA between 29–42 weeks.\(^{12}\) However, the data of this study are only applicable to infants with a PCA of 32–42 weeks, as with previous studies, we were unable to study the most important group of infants namely those less than 32 weeks gestation as the vast majority needed oxygen as minimum form of respiratory therapy. In addition, it was impossible to study our study population within a few days of birth as even at 32–33 and 34–36 weeks of gestation many infants were requiring respiratory therapy thus we opted to study the infants at a PCA of 32–33 and 34–36 weeks. We used three epochs of ten consecutive breaths obtained during quiet breathing for the analysis which is in line with current recommendations for tidal breathing analysis\(^1\); however, analyzing a larger number of breaths may improve the accuracy of the results obtained.

In summary, the FloRight can be used to measure tidal breathing in infants with a PCA between 32 and 42 weeks; the methodology avoided introduction of a face mask and instrumental deadspace thus provide accurate results to guide respiratory therapy. The weight corrected \(V_T\) decreases with advancing gestational age along with \(fR\), MV, and phase angle. The flow parameter \(t_{PTEF}/t_{E}\) changes were not significantly different between the groups but this observation may be accounted by the differing postnatal ages between the groups. The results obtained in healthy infants can be useful for clinicians when treating infants of these gestations with respiratory disease. Our study highlights that tidal breathing measurements are influenced by the technique used especially resulting in higher values when methods using a face-mask are adopted. Thus, the method used to estimate breathing parameters needs to be borne in mind when interpreting the results obtained.

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