Chest wall motion in preterm infants using respiratory inductive plethysmography

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ABSTRACT: Preterm infant tidal breathing may be different from that of healthy full-term infants because of various features of the premature thorax. The purpose of this project was to describe chest wall motion in the preterm infant (gestational age <37 weeks) and compare it with chest wall motion data in a group of healthy, full-term infants. We wanted to use an objective bedside method for assessment with minimal disruption to the infant.

The study population consisted of 61 preterm human infants whose mean($\pm$ SD) postconceptional age at time of study was 35.3 $\pm$ 2.1 weeks. During the study, the infants were quietly awake in a prone position. Preterm infants had initially been admitted to a level III neonatal intensive care unit for acute management and had been transferred to a step-down area, where they were in stable condition for study. Data were collected with a semiquantitatively calibrated, noninvasive respiratory inductive plethysmograph.

Mean($\pm$ SD) phase angle was significantly greater in preterm infants than in full-term infants (60.6 $\pm$ 39.8° versus 12.5 $\pm$ 5.0°, respectively, $p\leq 0.0001$). The laboured breathing index was significantly greater in preterm infants than in full-term infants (1.35 $\pm$ 0.35 versus 1.01 $\pm$ 0.01, respectively, $p=0.001$). The ribcage contribution to breathing did not differ significantly between preterm and full-term infants (25.5 $\pm$ 17.7% versus 36.3 $\pm$ 14.4%, respectively, $p=0.11$).

These results indicate a significant increase in the degree of ribcage and abdomen asynchrony in the preterm subjects compared to the full-term infants. Plethysmography provided a time-efficient and objective method of assessing chest wall motion in this fragile population.

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Respiratory inductive plethysmography (RIP) is the most widely used technique of surface measurement of chest wall motion [1]. Quantification of the degree of asynchrony of the breathing pattern has promise as a noninvasive approach to evaluate chest wall movement and the role of chest wall stability in overall respiratory pump function in the preterm human infant [2]. Preterm infant tidal breathing components that identify asynchrony and paradoxical motion between the ribcage and abdominal compartments may be different from those of the healthy full-term infant because of the shape, deformability and high compliance of the premature thorax [3, 4].

The purpose of this project was to describe chest wall motion in the preterm infant, using an objective bedside method for assessment. RIP can provide such an assessment without requiring airway connections. Any extensive handling of a preterm infant may cause agitation, altering the chest wall motion variables being measured, and may even result in clinical deterioration [5]. Our intention was to study this population in a non-invasive manner and with minimal physical stimulation. We hypothesized that chest wall motion measurements obtained with RIP in preterm infants may have mea-

surable differences among subgroups with various clinical pathologies as well as with chest wall motion measurements of term infants.

Materials and methods

Sixty one preterm infants were enrolled in this study, which was approved by the Institutional Review Board of the University of Arkansas for Medical Sciences. Informed consent was obtained from the parents prior to study. Studies were conducted in the Neonatal Step-down Unit of Arkansas Children's Hospital.

Subjects

Infants were included in the study if they were delivered before 37 weeks gestational age (preterm). We studied stable, preterm infants, who were growing and feeding without acute illness. Diagnoses in the study group, made during acute management, included bronchopulmonary dysplasia, apnoea, and gastro-oesophageal reflux. Forty nine required mechanical ventilatory support during the acute management period. Eighteen infants were receiving supplemental oxygen at the time of study.

Of the preterm infants, 35 were male and 26 were female. Thirty seven infants were Caucasian, 23 African-American, and one Hispanic. Birth weights ranged 560–2,700 g (mean $\pm$ SD 1,360 $\pm$ 493). Gestational age ranged 23–36 weeks (30.0 $\pm$ 3.7). At the time of the study, weight ranged 1,212–3,600 g (1,938 $\pm$ 377). Postconceptional age (gestational age plus age from birth) ranged 29–40 weeks (35 $\pm$ 2).

Seven full-term infants with gestational ages of 37 weeks or greater were studied. Three were male and four were female. Six were African-American and one was Caucasian. Birth weights ranged 2,400–3,600 g (3,100 $\pm$ 404) and gestational age ranged 37–42 weeks (39.3 $\pm$ 1.6). Subjects were studied 12–36 h after birth.

Study design

All infants were studied in a prone position in their cot, in a quietly awake state and breathing spontaneously. At the time of this study, the Neonatal Stepdown Unit protocol for preterm infant positioning was prone and reverse Trendelenburg at a 10–15° angle. The prone position afforded improved synchrony between ribcage and abdominal compartments by allowing gravitational stabilization of the anterior chest wall and increasing abdominal pressure [6]. The quietly awake state was determined by clinical criteria described by PRECHTL [7]. Sedation was neither indicated nor utilized. Each subject was closely observed for a clinically stable respiratory pattern, essential for the 5 min calibration period. If, by our observation, the infant was determined to be unstable, the calibration was terminated and restarted when the infant was stable in terms of behaviour state, gross body movement, and respiratory pattern. All infants were at least 30 min postprandial. Calibration and data collection was accomplished over a 25–30 min period.

Methods

Descriptions of RIP have been published [8, 9]. The device consisted of two transducers which were lightweight, elastic, polyester bands, 2.5 cm in width, with sinusoid coils of teflon-insulated wire embedded within them. The transducer bands were placed around the ribcage at the level of the nipple line and around the abdomen 0.5 cm above the umbilicus [10]. Changes in the cross-sectional areas of the ribcage and abdominal compartments altered the self-inductance of the coils and the frequency of their oscillations [11, 12]. The transducers were connected to a computer (Resptrace PT, Non-Invasive Monitoring Systems, Miami Beach, FL, USA) that recorded original breaths and events on a removable hard drive incorporated within the monitor chassis (fig. 1).

Data were downloaded from the removable hard drive directly onto the hard drive of a personal computer (PC). An event data processing (EDP) software program enabled the PC to receive digital information from the RIP monitor and to display real-time uncompressed waveforms on the computer screen in the display mode (fig. 2).

Qualitative Diagnostic Calibration (QDC)

The QDC method used equations that were analogous to those in the isovolume manoeuvre calibration. In the

Fig. 1. – Schematic diagram of the Resptrace PT setup. The ribcage and abdominal resptrands (transducers) are connected by wire to the portable Resptrace monitoring device. A removable hard drive within the device records original breath, electrocardiogram, oximetric waveforms and events. The hard drive is removed and brought to the base station personal computer for downloading of data. An event data processing program allows extensive analysis.

Fig. 2. – Real-time, uncompressed waveforms for volume of: a) ribcage (V_{rc}); b) abdomen (V_{ab}); and c) tidal volume (V_T ; sum of ribcage and abdominal signals) in a representative preterm infant subject. Values are expressed as percentages of baseline V_T .

QDC method of semiquantitative calibration, a single breath isovolume manoeuvre was replaced by a collection of many breaths with the exclusion of breaths with large deviations from the mean [13]. This provided an approximation for a constant tidal volume, for solution of an equation requiring two major assumptions: 1) the respiratory system moved with only two degrees of freedom; and 2) statistical selection of breaths from a calibration period of natural breathing provided a constant or near-constant volume [14]. At the completion of the QDC, subsequent respiration allowed tidal volume to be evaluated in relative terms as the percentage change from baseline.

Analysis

A segment of data from the 20 min collection period was analysed from each subject. Segments were selected on the basis of waveforms from consecutive breaths that presented a consistent pattern, free of twitching or gross body movements. We attempted to analyse at least 1 min of data, representing 30–40 consecutive breaths, on each subject, and tried to extend this to three or four consecutive 1 min segments of consecutive breaths. Short periods of consistent and consecutive breaths were used to provide good quality data, rather than longer periods that included deviation from steady state due to gross motor movement and behaviour state changes.

Within the group of 61 preterm infants, this descriptive study had 80% power to detect differences of 0.75 SD units in mean RIP measurements between groups defined by the presence or absence of characteristics affecting 50% of the infants. The study had 70% power to detect a difference of one standard deviation unit in means of RIP parameters between preterm and term infants. The RIP measurements of phase angle, respiratory frequency (f_R), ribcage contribution to breathing, and laboured breathing index (LBI) were compared between preterm and full-term infants. In addition, the same four RIP measurements were compared between preterm infants with and without the following four conditions: bronchopulmonary dysplasia; apnoea; gastroesophageal reflux; and mechanical ventilatory support. Finally, within the group of preterm infants, the four RIP parameters listed above were compared between those 18 infants receiving oxygen at the time of study and the remaining 43 preterm infants. Because of concerns that some of the variables analysed might not be normally distributed and because the group sizes within which to evaluate normality were small, comparisons were conducted with both the two-sample t-test and the Wilcoxon rank sum test. The conclusions were consistent between the two procedures and the reported p-values are from the Wilcoxon procedure. A p-value of less than 0.05 was considered significant.

Breathing pattern component data in an individual subject were recorded as median values, since this summary measure reduces the impact of outliers while retaining all the observations from an individual. Group data were summarized as the mean and SD of the individual medians in addition to medians and ranges.

Phase angle. The ribcage movements were plotted as the ordinate and the abdominal movements were plotted as the abscissa, as described by KONNO and MEAD

[15]. Phase angle (θ) was calculated by the principles employed by AGOSTONI and MOGNONI [16] and the analysis of phase shifts of sinusoid electrical waves according to the following equation: $\sin \theta = m/s$, where θ was the phase angle, m was a line parallel to the abscissa of the ribcage-abdominal plot set one half the distance between the maximal ribcage perpendicular intercept and the origin, and s was the length of a line obtained from the maximal abdominal perpendicular intercept minus the origin. The figures that were formed are commonly called Konno-Mead loops. Synchronous ribcage/abdominal motion has a phase angle of 0° ; paradoxical motion has a phase angle of 180° (fig. 3).

Laboured breathing index. LBI was a global assessment of chest wall motion that reflected of both the phasic relationships of ribcage and abdomen movement and the volume displacement due to that movement. LBI was computed as the ratio of the sum of the integrals of the absolute values of the derivatives of the inspiratory limbs of ribcage and abdomen divided by the corresponding integral of the derivative of the inspiratory limb of tidal volume (fig. 4). Perfect thoracoabdominal co-ordination

Fig. 3. – The degrees of synchrony, asynchrony and paradox of chest wall motion are described by the calculation of phase angle (θ) of a Konno-Mead loop. S: the maximal abdominal excursion distance; M: distance derived from measurement halfway between maximal and minimal ribcage excursion denoting distance between ribcage-abdomen loop intercepts. Counterclockwise loops are produced when ribcage-abdomen asynchrony measurements result in $\sin \theta = 180$ degrees, indicating paradoxical movement.

Fig. 4. – Phase relationships between ribcage and abdominal excursions. When trough-to-peak amplitudes (A to B and C to D) are in phase (synchrony), the laboured breathing index (LBI) approximates unity. When trough-to-peak amplitudes are out of phase (asynchrony) as with P to Q and R to S¹, then LBI exceeds 1.00. V_T : tidal volume.

Table 1. – Chest wall motion data in full-term and preterm infant subgroups

	n	Phase angle °		f_R breaths·min ⁻¹		Ribcage %		LBI	
		Mean (SD)	Median (Range)	Mean (SD)	Median (Range)	Mean (SD)	Median (Range)	Mean (SD)	Median (Range)
Full-term	7	12 (5)	13 (6–18)*	55 (13)	53 (37–75)	36 (14)	38 (16–62)	1.01 (0.01)	1.01 (1.00–1.02)*
Preterm	61	61 (40)	48 (9–148)	62 (18)	65 (30–100)	25 (18)	26 (–16–77)	1.35 (0.35)	1.30 (1.00–2.50)
Preterm subgroups									
Bronchopulmonary dysplasia	31	56 (40)	47 (9–147)	66 (17)	66 (39–100)	29 (21)	27 (–16–77)	1.37 (0.38)	1.30 (1.00–2.50)
Nonbronchopulmonary dysplasia	30	65 (40)	52 (14–148)	58 (17)	62 (30–88)	22 (13)	22 (–3–54)	1.33 (0.27)	1.30 (1.00–2.20)
Apnoea	24	54 (39)	46 (9–131)	72 (16)	72 (39–100)*	25 (19)	26 (–16–62)	1.35 (0.38)	1.20 (1.00–2.50)
Nonapnoea	37	65 (40)	54 (14–148)	57 (16)	57 (30–88)	26 (17)	26 (–3–77)	1.35 (0.29)	1.30 (1.00–2.20)
Gastro-oesophageal	14	44 (23)	46 (12–108)	74 (15)	76 (53–100)*	31 (18)	27 (1–62)	1.22 (0.19)	1.20 (1.00–1.70)
Non-gastro-oesophageal	47	65 (43)	55 (9–148)	59 (17)	62 (30–100)	24 (18)	25 (–16–77)	1.39 (0.35)	1.30 (1.00–2.50)
Ventilatory support	49	58 (39)	48 (9–148)	64 (18)	65 (30–100)	26 (18)	25 (–16–77)	1.33 (0.32)	1.30 (1.00–2.50)
No support	12	71 (44)	62 (14–129)	55 (15)	55 (30–73)	23 (17)	26 (–3–54)	1.42 (0.35)	1.50 (1.00–2.20)
Currently using O ₂	18	53 (40)	42 (12–147)	70 (17)	74 (42–100)#	32 (22)	28 (–16–77)*	1.32 (0.35)	1.20 (1.00–2.20)
No current O ₂	43	64 (40)	54 (9–148)	59 (17)	62 (30–100)	23 (15)	22 (–3–54)	1.37 (0.32)	1.30 (1.00–2.50)

+: $p \leq 0.0001$, full-term versus preterm; †: $p = 0.001$, full-term versus preterm; ‡: $p = 0.001–0.01$, apnoea versus nonapnoea, and gastro-oesophageal reflux versus non-gastro-oesophageal reflux; #: $p = 0.03$, current O₂ versus no current O₂; *: $p = 0.06$, current O₂ versus no current O₂; †: respiratory frequency; Ribcage: ribcage contribution to breathing; LBI: laboured breathing index.

produced an LBI value of 1.0 [17]. LBI can only be utilized when calibration has been accomplished, either by relative (QDC) or absolute volumes (pneumotachograph).

Ribcage contribution to breathing. This was calculated by dividing ribcage amplitude by the algebraic sum of ribcage amplitude and abdomen amplitude. With severe lack of thoracoabdominal co-ordination, values can be >100% or <0% [18].

Results

The tidal volume baseline of 100% was established during the 5 min calibration period. The change of tidal volume from baseline and during the 20 min data collection period ranged 77–115% (mean±SD 96.09±0.09) in 61 subjects. Time segments of consecutive breaths used for data analysis on a subject ranged 0.4–4.0 consecutive minutes (1.7±0.7). We were unable to find a complete minute of consistent waveforms in one subject, although that subject produced 36 consecutive breaths acceptable for analysis.

Subgroups of preterm infants defined by the presence or absence of bronchopulmonary dysplasia, apnoea, gastro-oesophageal reflux, ventilatory support, or current oxygen support were compared with respect to four RIP measurements: phase angle, f_R , ribcage contribution to breathing, and LBI (table 1). Within the preterm group, there were no statistically significant differences in the four RIP parameters between those with bronchopulmonary dysplasia and those without dysplasia or between those who had required mechanical ventilatory support

Fig. 5. – Counterclockwise Konno-Mead loops in a representative subject.

and those who had not. fR differed significantly between preterm infants with or without apnoea, between those with or without gastro-oesophageal reflux, and between those receiving or not receiving oxygen at the time of study. Ribcage contributions to breathing was marginally different between those with and without oxygen use ($p=0.06$). No other parameters differed significantly between any of the groupings considered.

Phase angle, fR , ribcage contribution to breathing, and LBI were compared between the group of 61 preterm infants and seven full-term infants. Both phase angle and LBI were significantly increased in the preterm infants ($p \leq 0.0001$ and $p=0.001$, respectively). Neither fR nor ribcage contribution to breathing differed significantly between the preterm and full-term infants ($p=0.28$ and 0.11 , respectively). In all preterm subjects, the direction of the vast majority of Konno-Mead loops was counterclockwise, indicating outward motion of the abdomen preceded that of the ribcage (fig. 5). Loops tended to be nonelliptical, displaying asynchronous breaths.

Discussion

In the present study, tidal volumes measured during the data collection period and utilized for analysis deviated by an average of -4% from tidal volumes measured during the 5 min calibration period. This information suggests that the present subjects were quiet and displayed a consistent tidal breathing pattern that was similar to the breathing pattern during the calibration period with minimal gross body movements and no change in behavioural state.

The RIP measurements distinguished significant differences between the preterm group ($n=61$) and the full-term infant group in the major determinants of ribcage and abdomen asynchrony: LBI and phase angle. Differences in ribcage contribution to breathing and fR did not reach statistical significance between the two groups. Values obtained in our term infant group for LBI and phase angle were similar to values obtained by other investigators [19]. Analysis of the preterm group identified no significant differences between any of the diagnostic groups and the RIP parameters describing chest wall motion asynchrony.

Anatomical factors distinguishing the preterm from the full-term infant chest wall include: less ribcage ossification resulting in increased flexibility in the preterm infant; less mature contractile activity of the intercostal and accessory muscles of respiration; and reduced efficiency of diaphragmatic contraction due to limited excursion [20, 21]. The negatively sloped Konno-Mead loops demonstrate the asynchrony of ribcage-abdomen movement produced by the inward excursion of the compliant chest wall that occurs with diaphragmatic contraction during inspiration. Subjects displayed their own individual patterns to cope with increased respiratory load.

There are several alternative explanations of the absence of significant differences in the components of chest wall motion among the preterm groups within the study population: 1) the number of subjects may have been insufficient to allow differences to be revealed by the statistical methodology; 2) Respirace PT may not be capable of detecting subtle differences in ribcage and

abdominal motion in the preterm infant at the level of stable, tidal breathing; 3) the influence of pulmonary pathophysiologies and medical interventions may be minimal with regard to ribcage and abdominal compartment movement; and 4) the predominant influence of ribcage and abdomen asynchrony of the preterm infant may have reduced the mechanical efficiency of the diaphragm-ribcage interaction in addition to central nervous system respiratory control mechanisms.

In 1989, SACKNER *et al.* [13] developed a single position calibration procedure for the respiratory inductive plethysmograph that could be applied to natural breathing. BROOKS *et al.* [18] performed the second step of validation of the QDC procedure using integrated pneumotachography in premature infants and showed a significant linear relationship between pneumotachograph volume and the ribcage and abdomen sum signal of the RIP. That relationship was not altered by sleep state, position, ribcage or abdomen asynchrony, fR , or ribcage contribution to the ribcage + abdomen sum signal. In 1993, ADAMS *et al.* [14] concluded, in a study of 21 full-term infants, that the QDC method of calibration of RIP provided clinically acceptable tidal volume measurements.

ALLEN *et al.* [19] applied an uncalibrated RIP on 10 premature infants with bronchopulmonary dysplasia. A mean $\pm$ SEM phase angle of $102 \pm 16^\circ$ was reported. They also reported that six full-term control infants all had phase angles less than 30° . WOLFSON *et al.* [22] reported the use of an uncalibrated RIP device on 24 preterm quietly sleeping infants who were in a recovery stage from respiratory distress [22]. A mean $\pm$ SEM phase angle of $32.0 \pm 3.9^\circ$ was reported. The degree of thoracoabdominal asynchrony demonstrated by their reported phase angle may reflect a change in the natural breathing pattern with an increased tidal volume and a decreased fR due to a facemask-pneumotachograph assembly utilized in their study [23–26].

In conclusion, the respiratory inductive plethysmography device was easily applied to the preterm infant at the bedside with minimal disruption to routine and no discomfort to the subject or watchful parent from invasive equipment. The qualitative diagnostic calibration method allowed semiquantitative measurements of chest wall motion components of the breathing pattern in nonsedated, quietly awake preterm infants. We identified consistent data in form and rate using consecutive breaths on individual subjects. Both laboured breathing index and phase angle were significantly increased in the preterm infant group when compared to the full-term infant subjects.

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