

TECHNICAL NOTE

Pressure sensor plethysmography: a method for assessment of respiratory motion in children

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Pressure sensor plethysmography: a method for respiratory motion in children. P. Banovcin, J. Seidenberg, H. von der Hardt. ©ERS Journals Ltd 1995.

ABSTRACT: Noncalibrated respiratory inductance plethysmography has been used to measure respiratory function by calculation of the phase angle and, more recently, by determination of the ratio of each time to reach peak tidal expiratory flow to total expiratory time (T_{PEF}/T_E). Since T_{PEF}/T_E is known to be decreased in airway obstruction when derived from flow signals obtained by a pneumotachograph, we wanted to develop an alternative method to measure rib cage and abdominal respiratory movements.

For this purpose, we used two pressure sensors attached to the skin above the umbilicus and in the right medioclavicular line at the fourth intercostal space: "pressure sensor plethysmography". We tested the ability of this method to assess thoracoabdominal asynchrony and T_{PEF}/T_E by comparison with respiratory inductance plethysmographic and pneumotachographic measurements in 30 children, aged 1–12 yrs, with airway obstruction.

The mean difference (95% confidence interval (95% CI)) between phase angles obtained by respiratory inductance plethysmography and pressure sensor plethysmography was only -5.8° (range -18.0 to $+6.4^\circ$). Similarly, all methods used to measure T_{PEF}/T_E agreed well: mean differences (95% CI) between pneumotachographic and respiratory inductance plethysmographic, pneumotachographic and pressure sensor plethysmographic, and respiratory inductance plethysmographic and pressure sensor plethysmographic measurements of T_{PEF}/T_E were $+0.01$ (range -0.05 to $+0.06$), -0.03 (-0.09 to $+0.03$) and -0.03 (-0.10 to $+0.04$), respectively.

We conclude that pressure sensor plethysmography is a simple and noninvasive method, and suitable to measure thoracoabdominal asynchrony and T_{PEF}/T_E ratios as well as respiratory inductance plethysmography and pneumotachography.

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In the last decade, new methods for assessing pulmonary function in infants have been developed. Considerable attention has focused on noninvasive measurements of tidal breathing. The shape of the flow curve over time may give some indirect information about the airway calibre [1]. In patients with airway obstruction, a rapid rise to peak tidal expiratory flow was observed [2]. The time necessary to reach peak flow expressed as a ratio of total expiratory time (T_{PEF}/T_E) was proposed as an index for airway obstruction [2–4].

Parameters derived from surface measurements (non-calibrated respiratory inductive plethysmography (RIP), strain gauges, magnetometry) have been subject to controversy in the recent literature [5, 6]. It is thought that these measurements reflect changes in the neuromuscular tone of the upper airways and the compliance of the rib cage rather than actual airway calibre, which would be better evaluated by standard lung function testing. However, surface measurements do not require the use

of a facemask or sedation, which might be necessary when testing 2–5 year old children. ALLEN *et al.* [7] and SIVAN *et al.* [8] used RIP (using the RespiTrace®) to evaluate airway obstruction by measurement of thoracoabdominal asynchrony. More recently, this technique has been validated to assess T_{PEF}/T_E in newborns and in infants [9–11]. The elastic bands (RespiTrace®) may move during the measurement, resulting in artefacts which may be difficult to detect. Additional fixation covers more body surface and possibly interferes with body movements and proper observation of the infants. We therefore developed an alternative technique, measuring rib cage and abdominal motions by small, cheap and widely-used pressure sensors (*i.e.* capsules): "pressure sensor plethysmography" (PSP).

It was the aim of this study to validate the measurements of thoracoabdominal asynchrony and T_{PEF}/T_E by PSP in comparison with conventional techniques, such as RIP and pneumotachography (PTG).

Methods

We examined 30 patients (19 males and 11 females), 1–12 yrs of age (mean 6 yrs) who visited our clinic for lung function testing (body plethysmograph, spirometry, etc.). All patients suffered from clinically diagnosed obstructive airway diseases, such as recurrent wheezy bronchitis or asthma. Parental consent was given in all cases.

All patients were studied in the supine position. Sedation was only used in infants (chloral hydrate 50–80 mg·kg⁻¹ body weight). Simultaneous measurements were made with PTG, RIP, and PSP.

Flow signals were measured using a Fleisch No. 0, linear up to 440 ml·sec⁻¹, or a Fleisch No. 2, linear up to 3.32 l·sec⁻¹, attached to a facemask or mouthpiece depending on the patient's age.

Rib cage (RC) and abdominal (AB) motions were depicted from a noncalibrated respiratory inductance plethysmograph (Respirace® Corp., Ardsley, NY, USA), of which the RC band was placed at the level of the nipples and the AB band at the level of the upper abdomen [8, 12]. Although noncalibrated, the gains of both the RC and the AB bands were set at equal, in order to reflect the relative portion of both compartments in the sum signal during actual registration of the thoracic and abdominal motions.

For PSP we used two pressure sensor capsules (Star Sync. Sensor®, Hoyer Medizintechn., Germany), which are otherwise used to guide synchronization of artificial and spontaneous ventilation, and are well-known from infant apnoea monitors (Graseby®). The rib cage pressure sensor was placed in the right medioclavicular line in the fourth intercostal space, and the abdominal pressure sensor in the midline 2 cm above the umbilicus. Both sensors were attached to the skin with adhesive tape of standardized size (3×6 cm) and connected to pressure transducers of equal sensitivity (fig. 1). Frequency response of the total system was tested by a sinus wave generator and was reliable up to 200 cycles·min⁻¹. Signals from 20–40 breaths were digitized at a sampling rate of 100 Hz and stored on a personal

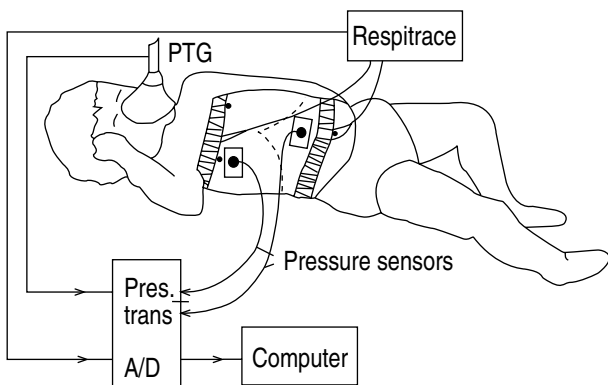


Fig. 1. – Application of pneumotachography (PTG), respiratory inductance plethysmography (RIP, Respirace®) and pressure sensor plethysmography (PSP). Pres. trans: pressure transducer; A/D: analysis-to-digital converter.

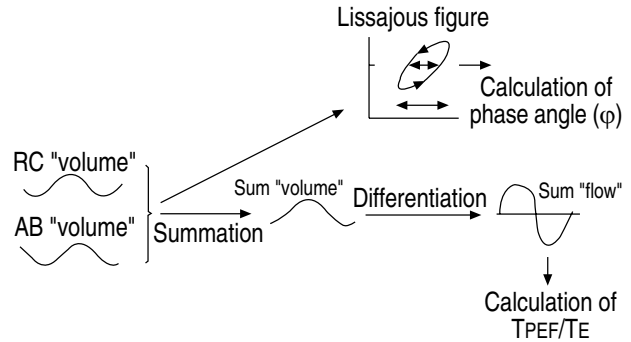


Fig. 2. – Schematic representation of calculation of phase angle (ϕ) and TPEF/TE both from RIP and PSP. RC: ribcage; AB: abdomen; TPEF/TE: ratio of time peak tidal expiratory flow to total expiratory time.

computer. Using a specially developed software, the following parameters were calculated: both from RIP and PSP, the RC and AB signals were summed to obtain sum signals which correspond to noncalibrated volume signals. These volumes were electronically differentiated to obtain flow signals. All derived flow signals (PTG, RIP and PSP) were plotted against time (phase lag <0.001 s) and the ratio TPEF/TE was manually calculated (fig. 2).

In addition, RC and AB signals were set to equal amplitudes to obtain Lissajous figures by plotting the RC versus AB signals for RIP and PSP [13] (figs 2 and 3). From the Lissajous figures phase angles (ϕ) were calculated as an index of thoracoabdominal asynchrony (TAA), according to the equation:

$$\sin \phi = m/s \text{ or } \phi = 180^\circ - u \text{ (} u = m/s \text{)}$$

The width m is the distance between the intercepts of the RC-AB loop on a line drawn parallel to the x-axis placed half the distance between maximal and minimal RC-AB excursion. The width s is the total AB displacement [7, 14, 15] (fig. 3).

The phase angle as well as the ratio TPEF/TE were calculated for at least 10 representative and consecutive breaths selected from the RIP sum volume trace during

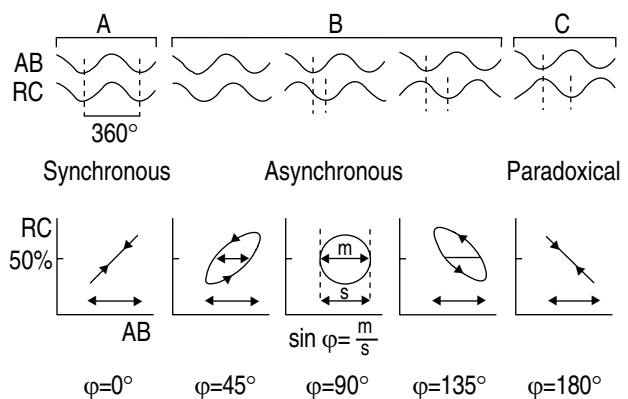


Fig. 3. – Calculation of the phase angle (ϕ) under various degrees of thoracoabdominal asynchrony (synchronous, asynchronous and paradoxical respiratory motions). m : distance between the intercepts of the ribcage-abdomen (RC-AB) loop on a line drawn parallel to the x-axis placed half the distance between maximal and minimal RC-AB excursion; s : width, i.e. total AB displacement.

quiet and undisturbed breathing. The mean values and coefficients of variation were calculated.

The agreement between PTG, RIP and PSP was assessed using the methods described by BLAND and ALTMAN [16]. The differences between two measurements of the phase angle were tested by using Student's paired t-test.

Results

The similarity of RIP and PSP measurements is demonstrated in figure 4. A substantial contribution of the abdominal movement to the total respiratory movement could be observed in all children: 71–91% of the total respiratory motion was contributed by the abdominal compartment.

T_{PEF}/T_E was 0.25 (range 0.11–0.43) for all patients when measured by PTG. The corresponding T_{PEF}/T_E values were 0.25 (range 0.12–0.38) for RIP, and 0.28 (range 0.12–0.48) for PSP. The mean difference (95% confidence interval (95% CI)) between the T_{PEF}/T_E ratios obtained by PTG and RIP was +0.01 (-0.05 to +0.06), -0.03 (-0.09 to +0.03) for the PTG and PSP

technique, and -0.03 (-0.10 to +0.04) for the RIP and PSP technique (fig. 5). No differences were statistically significant ($p > 0.05$).

This concordance of T_{PEF}/T_E values measured by different techniques could also be observed in severe airway obstruction, when T_{PEF}/T_E values (PTG) are very low. There might be a trend for overestimation of T_{PEF}/T_E obtained by PSP *versus* PTG in less severe airway obstruction with higher T_{PEF}/T_E values (fig. 5b).

The reproducibility of the T_{PEF}/T_E measurements from 10 to 15 consecutive breaths was 9.3% (range 5.4–16.1%) for PTG; 10.7% (range 4.1–17.3%) for RIP, and 8.7% (range 4.1–18.0%) for PSP.

In all children we observed thoracoabdominal asynchrony. Lissajous figures showed a counterclockwise direction, which means that outward motion of the abdomen preceded outward motion of the rib cage. Although the Lissajous figures were not always elliptical, they were similar within each individual subject. The coefficient of variation of the phase angle was 8.5% (range 1.4–14.6%) for RIP and 9.7% (range 1.7–15.1%) for PSP.

The mean value of the phase angle was 46.1° for RIP (range $9\text{--}103^\circ$) and 59.2° for PSP (range $14\text{--}133^\circ$); this difference was significant ($t=4.02$; $p < 0.001$). As shown

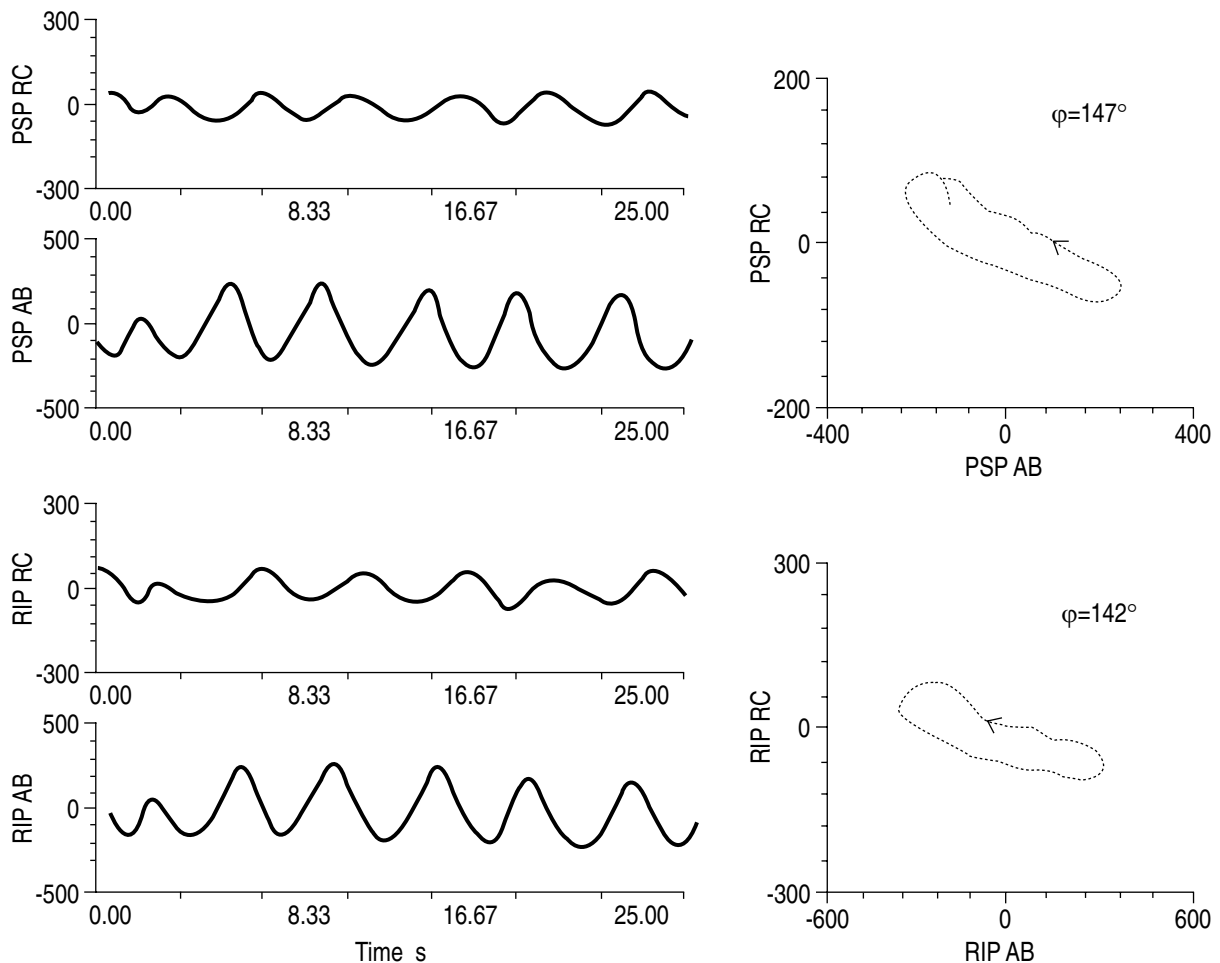


Fig. 4. — Original recording of rib cage (RC) and abdominal (AB) respiratory movements recorded by pressure sensor plethysmography (PSP; upper traces, left) and respiratory inductance plethysmography (RIP; lower traces, left). Graphical evaluation of the phase relationship (Lissajous figures) for both methods (right). Phase angles were calculated after setting RC and AB to equal amplitudes.

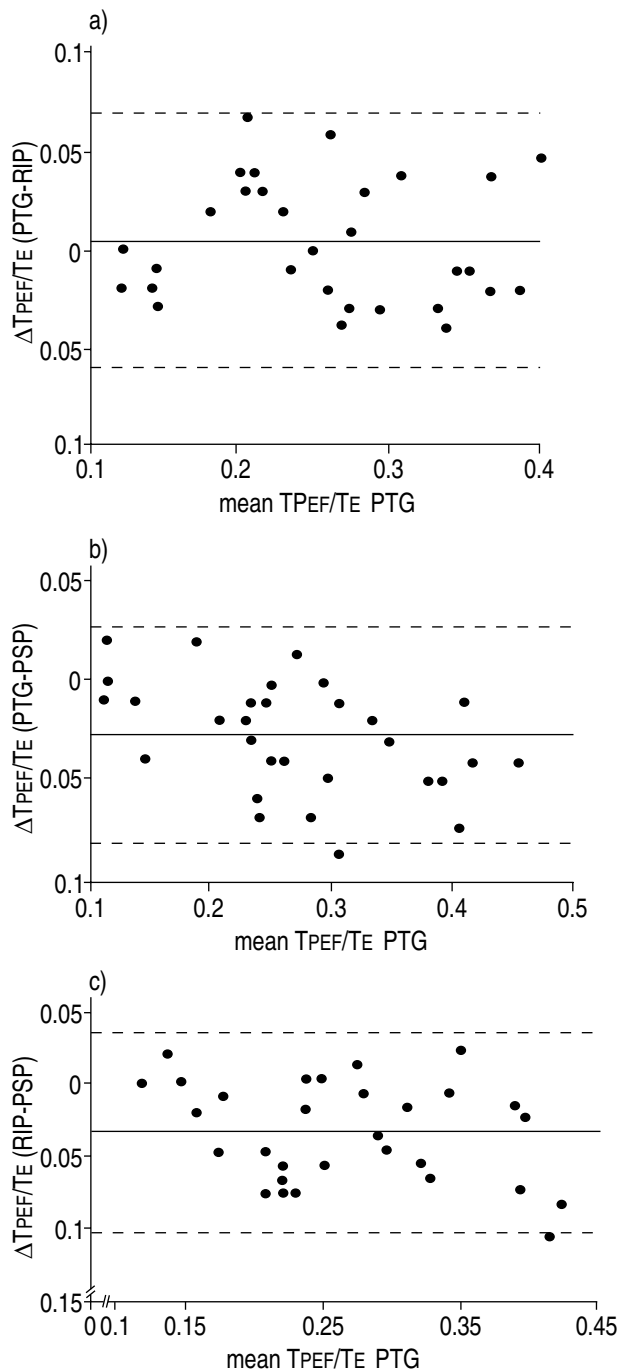


Fig. 5. – Differences between T_{PEF}/T_E ($\Delta T_{PEF}/T_E$) values measured by: a) PTG and RIP; b) PTG and PSP; and c) RIP and PSP, in relation to the mean T_{PEF}/T_E measured by PTG (according to BLAND and ALTMAN [16]). —: mean; - - -: mean+2 SD. For abbreviations see legends to figures 1 and 2.

in figure 6, the overestimation of the phase angle by PSP *versus* RIP tended to be greater with higher values of phase angle.

The maximum difference between phase angles determined by RIP and PSP was -19° . The mean difference intraindividually was -5.8° , and the standard deviation of the differences was 6.1° , indicating that 95% of all values obtained by PSP fell between -18° and $+6.4^\circ$ of the values measured by RIP (fig. 6).

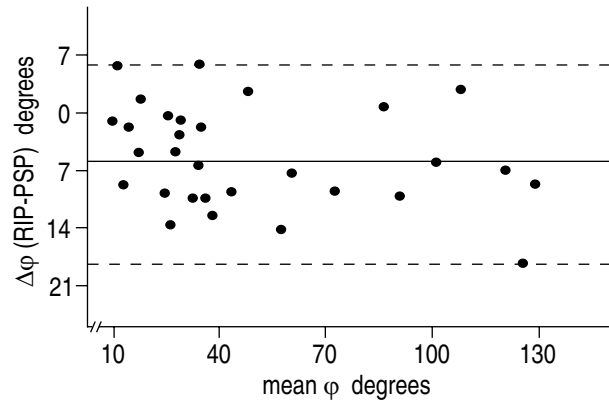


Fig. 6. – Graph showing agreement of phase angle (φ) measurements using RIP and PSP. Difference between φ ($\Delta\varphi$) measured with RIP and PSP (y-axis) in relation to the average value of φ from both measurements (x-axis). —: mean; - - -: mean+2 SD. For abbreviations see legend to figure 1.

There was no significant correlation between the age of the patients and the observed differences between RIP and PSP derived values.

Discussion

A good concordance of the flow traces and derived values (T_{PEF}/T_E , phase angle) between PTG, noncalibrated RIP and the newly developed PSP could be demonstrated in the present study, even in patients with severe airway obstruction (figs 4–6). HUDGEL *et al.* [17] demonstrated a similar agreement of flow traces from PTG and calibrated inductance vest in chronic obstructive pulmonary disease (COPD) patients. MAXWELL *et al.* [18] used calibrated RIP to estimate lung volume changes during histamine-induced bronchoconstriction in recurrently wheezy infants. They demonstrated a close correlation between the volume trace using PTG and those traces derived from the summed RC and AB signal of calibrated RespiTrace®. The accuracy of the different signals remained stable throughout the provocation test, although the phase lag between the RC and the AB compartment changed.

The T_{PEF}/T_E ratios measured by noncalibrated RIP, the most commonly used method, have been carefully tested and accepted as correctly assessing airway function in infants without airway obstruction [1]. However, the influence of spontaneous changing of the upper airway calibre, *i.e.* muscle tone and of the compliance of the thoracic wall on T_{PEF}/T_E ratio derived from tidal breathing manoeuvres, has been the subject of discussion. The ratio might reflect the neuromuscular effects on the total respiratory system more than the true function of the airways. It was not the aim of the present study to enter into this controversy.

At present, the ratio T_{PEF}/T_E derived from PTG signals has been used to examine airway obstruction [2, 3, 4, 19]. Noncalibrated RIP has also been applied when RC and AB motions were synchronous [10, 11].

The question of whether uncalibrated surface measurements can correctly assess T_{PEF}/T_E in patients with

thoracoabdominal asynchrony (TAA) can, in part, be answered positively by our results. We found asynchronous AB and RC motions in all patients, and could still demonstrate good agreement of results for T_{PEF}/T_E obtained from the sum signals of PSP and RIP. Because the contribution of the abdominal motion to the sum signal was more than 70%, we suggest that volume calibration of the signal is not necessary. However, whether this suggestion is true for equal contribution of both signals requires further examination.

In addition to the degree of airway obstruction, age by itself may influence the phase angle and T_{PEF}/T_E [2, 7, 20, 21]. Therefore, we included patients covering a large range of ages with various degrees of airway obstruction, but we could not find an age-dependent difference between PSP and the other methods, even in severe airway obstruction.

Generally, the phase angles measured by PSP were significantly higher when compared to those measured by RIP. AB signals derived from PSP and RIP were in phase with volume signals obtained by PTG. However, a phase lag could be observed between the RC signals derived from PSP and RIP. This difference between PSP and RIP measurements could be explained by the different position of the pressure capsule compared with the elastic bands of RIP. As shown by HILLMAN *et al.* [22], there is also a phase lag in patients with acute asthma between the RC signal derived from lower rib cage position and the RC signal derived from an upper rib cage position. Similar results were reported by RINGEL *et al.* [20] in asthmatics with cold air induced airway obstruction, which means that the rib cage signal is more variable than the abdominal one.

We conclude that uncalibrated PSP is comparable to RIP in assessing RC and AB respiratory movements, even in severe airway obstruction. PSP reliably measures the phase angle for determination of TAA. PSP also reliably measures T_{PEF}/T_E in infants and children. Generally, PSP seems to be a valid technique, since it is noninvasive, well accepted by preschool children, and much cheaper than RIP, especially if pressure transducers from PTG are already available.

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