Evaluation of Respiratory Inductive Plethysmography: Accuracy for Analysis of Respiratory Waveforms

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Evaluation of Respiratory Inductive Plethysmography*

Accuracy for Analysis of Respiratory Waveforms

Pierre-Yves Carry, MD, PhD; Pierre Bacconnier, PhD; Andre Eberhard, PhD; Pierre Cotte; and Gila Benchetrit, MD, PhD

Objective: To assess the accuracy of respiratory inductive plethysmography (RIP) waveforms to those obtained with whole body plethysmograph (BP) as this device gives a plethysmographic signal and a pneumotachograph (PNT).

Design: Randomized controlled trial.

Setting: Physiologic laboratory in a university hospital.

Participants: Eleven subjects from the laboratory staff.

Interventions: This study was achieved during four consecutive periods in subjects breathing spontaneously and through different added resistive loads. Using the least square method calibration, two RIP waveforms, VRIP.BP(t) and VRIP.PNT(t), were simultaneously calculated with coefficients obtained from BP and from PNT volume waveforms, respectively VBP(t) and VPNT(t).

For each recording, to compare volume waveforms, we calculated their differences in term of distances, Drip-BP and Drip-PNT, between the normalized RIP volume signal (respectively, VRIP.BP(t) and VRIP.PNT(t)) and its normalized reference (respectively, VBP(t) and VPNT(t)). We also calculated the distance Dpnt-BP between the two normalized references VBP(t) and VPNT(t).

Results: No significant effect of load or time on the distance occurred. Including all the recordings, the mean distance Drip-BP (3.4±1.1%) appears significantly lower than both the mean distance Drip-PNT (4.5±1.3%; p<0.04) and the mean distance Dpnt-BP (4.6±0.9%; p<0.005). For each period or load level, Drip-BP appears to be lower than Drip-PNT and Dpnt-BP.

Conclusion: The RIP seems reasonably accurate for analysis of respiratory waveform while subjects subsequently breathe against resistive loads. (CHEST 1997; 111:910-15)

Key words: body plethysmography; respiratory inductive plethysmography; volume waveform

Abbreviations: ABD=abdomen; ANOVA=analysis of variance; BP=body plethysmograph; DPNT-BP=distance between PNT waveform and body plethysmograph waveform; Drip-BP=distance between RIP waveform calibrated with body plethysmograph and body plethysmograph waveform; Drip-PNT=distance between RIP waveform calibrated with pneumotachograph and pneumotachograph waveform; FETCO2=fractional end-tidal CO2; Pbody=pressure measured by a pressure transducer; PNT=pneumotachograph; RC=rib cage; RIP=respiratory inductive plethysmograph; R4.7=resistive ventilatory load of 4.7 cm H2O/L/s; R7.5=resistive ventilatory load of 7.5 cm H2O/L/s; V=flow at mouth; VBP(t)=waveform from body plethysmographic signal; VPNT(t)=normalized waveform from body plethysmographic signal; VRIP.BP(t)=waveform from pneumotachograph signal; VRIP.PNT(t)=normalized waveform from pneumotachograph signal; VPNT(t)=normalized waveform from pneumotachograph signal; VRIP.BP(t)=waveform from RIP signal calibrated with body plethysmograph; VRIP.BP(t)=normalized waveform from RIP signal calibrated with body plethysmograph; VRIP.PNT(t)=waveform from RIP signal calibrated with pneumotachograph; VPNT(t)=normalized waveform from RIP signal calibrated with pneumotachograph; VT=tidal volume

Different circumstances in anesthesia and intensive care can modify respiratory drive.1 Recently, Benchetrit et al.2 using a quantitative analysis of respiratory waveforms, demonstrated that primary variables (frequency, mean inspiratory flow rate, and fractional inspiratory time) commonly used for monitoring of breathing pattern are not sensitive enough to detect respiratory personality differences. One might expect that the monitoring of respiratory pattern via such a waveform analysis could help in detecting respiratory drive changes in anesthesia and intensive care.

The quantitative analysis of respiratory waveforms developed by Benchetrit et al.2 (harmonic or Fourier analysis) relies on the precise measurement of airflow profile. In the intubated patient, this analysis of breathing pattern is easy to perform by attaching a spirometer or a pneumotachograph (PNT) to the patient’s endotracheal tube. During recovery from anesthesia or during weaning from mechanical ven-
tilation, problems arise because these devices, requiring a direct connection to the patient's airway, demonstrate a low tolerance.\(^3\) In addition, the use of mouthpiece produces spurious alterations in the breathing pattern, causing tidal volume (\(V_t\)) to increase and respiratory frequency to decrease.\(^4\) Other devices, such as body plethysmograph (BP), allowing the measurement of expiratory volumes, are not convenient for clinical monitoring, particularly during a prolonged period or during sleep. Consequently, devices have been developed to measure ventilation directly.

Respiratory inductive plethysmography (RIP) is the most widely accepted method for quantitative and qualitative noninvasive respiratory measurements.\(^8\)\(^-\)\(^10\) When correctly calibrated, the RIP allows the measurement of volume and time components of the breathing cycle as well as the relative participation of thorax and abdomen to this cycle.

To our knowledge, the study of Strömberg et al.\(^11\) is the only one that investigates the reliability of the time course profile of RIP as compared to that of the PNT. While studying the influence of RIP accuracy on the respiratory phase chosen for the calibration, these authors observed that RIP underestimated lung volume at the start of inspiration and overestimated lung volume at the end of inspiration. They observed a similar tendency during expiration.

As RIP is supposed to give a plethysmographic waveform,\(^12\) we undertook the present work to assess the accuracy of RIP waveform by comparing it with the volume waveform obtained from the whole BP. We also carried out the same comparison with the PNT as this device is commonly used for breathing pattern analysis.\(^2\) The waveforms of the RIP volume calibrated, respectively, with a BP and a PNT were compared with the waveforms of the volume obtained, respectively, with BP and with PNT. This study was achieved in subjects breathing spontaneously and through added resistive loads to simulate respiratory diseases.

**MATERIALS AND METHODS**

**Subjects**

Eleven healthy subjects (eight male, three female) without history of respiratory disease, recruited from the laboratory staff, volunteered for RIP validation against BP and PNT. The protocol was approved by the local ethics committee and all subjects gave informed consent. The characteristics of these subjects are presented in Table 1.

**Apparatus**

Measurements were made with the subjects seated in a 690-L barometric whole BP. This device (Pulmostat SMB; Geneva, Switzerland), with high-frequency response, allowed the measurements of rapid volume changes.\(^13\) A pressure transducer measured the pressure (Pbody) of gas compressed in BP by pulmonary volume changes, giving after calibration (see below) a first volume waveform \(\text{VP}(t)\). During protocol, absence of gas leaks in the BP was checked by measuring the stability of Pbody during a voluntary apnea. Stability of BP temperature during each recording was checked by the average stability of Pbody signal (no drift). A heated PNT (Fleisch; Lausanne, Switzerland) inserted in the front wall of the BP measured the flow at mouth (V). The zero flow of this channel was carefully set at the beginning of each protocol but was not readjusted afterward. The volume waveform from PNT, \(\text{VPNT}(t)\), was obtained by numerical integration of flow. After zero setting, BP and PNT were calibrated with a 1-L syringe before each procedure.\(^14\) The coefficient of calibration for each signal was determined from five syringe maneuvers.

The rib cage (RC) and abdominal (ABD) displacements were measured using a direct current-coupled RIP. This device consists of two belts, to which wavy coated wires are attached, that encircle the RC and the ABD. A garment incorporating the two coils was developed in our laboratory. It consists of a sleeveless jacket, made of a special fabric with texture allowing horizontal writing only.\(^12\)

During each experiment, the subject had his or her back applied to a wall inside the BP and was instructed to avoid any changes in position to prevent interference of changes in spinal attitude with RIP calibration. This calibration is based on the assumption that the respiratory system behaves with two degrees of freedom motion\(^16\) such that the change in lung volume (\(\text{VRIP}\)) is the sum of the volume changes of the rib cage (\(\text{VRC}\)) and abdominal (\(\text{VABD}\)) compartments. \(\text{VRC}\) and \(\text{VABD}\) are expressed in terms of RC and ABD signals by the volume-motion coefficients a and b: \(\text{VRIP} = a \cdot \text{RC} + b \cdot \text{ABD}\).

The a and b coefficients are obtained by the least squares calibration procedure.\(^17\) Two RIP waveforms \(\text{VRIP.BP}(t)\) and \(\text{VRIP.PNT}(t)\) are simultaneously calculated with coefficients obtained respectively from BP volume waveform \(\text{VP}(t)\) and from PNT volume waveform \(\text{VPNT}(t)\). These coefficients were calculated from the data recordings from each situation, thus allowing comparisons based on the same source data. All signals (Pbody, V, ABD, and RC) were recorded on a computer (Macintosh Iic) equipped with a 12-bit analogue-to-digital converter (MacAdios; G.W. Instruments; Boston) and each signal sampled at 32 Hz (softwares are written in Think Pascal; Symantec SARL, Suresnes, France).

### Table 1—Subject Characteristics*

<table>
<thead>
<tr>
<th>Subject/Sex/Age, yr</th>
<th>Weight, kg</th>
<th>(\dot{V}_{E}, \text{L/min})</th>
<th>(F, \text{min}^{-1})</th>
<th>(\text{FetCO}_{2}), %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/M/27</td>
<td>68</td>
<td>11.7</td>
<td>10</td>
<td>5.0</td>
</tr>
<tr>
<td>2/M/46</td>
<td>80</td>
<td>12.2</td>
<td>14</td>
<td>4.5</td>
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<td>3/M/23</td>
<td>77</td>
<td>12.5</td>
<td>14</td>
<td>4.4</td>
</tr>
<tr>
<td>4/M/38</td>
<td>92</td>
<td>12.7</td>
<td>18</td>
<td>4.5</td>
</tr>
<tr>
<td>5/M/28</td>
<td>65</td>
<td>8.7</td>
<td>10</td>
<td>5.1</td>
</tr>
<tr>
<td>6/F/24</td>
<td>54</td>
<td>12.0</td>
<td>19</td>
<td>4.6</td>
</tr>
<tr>
<td>7/F/25</td>
<td>55</td>
<td>9.1</td>
<td>11</td>
<td>3.9</td>
</tr>
<tr>
<td>8/F/33</td>
<td>57</td>
<td>7.9</td>
<td>11</td>
<td>5.5</td>
</tr>
<tr>
<td>9/M/37</td>
<td>68</td>
<td>7.1</td>
<td>8</td>
<td>4.6</td>
</tr>
<tr>
<td>10/M/45</td>
<td>75</td>
<td>9.0</td>
<td>8</td>
<td>5.5</td>
</tr>
<tr>
<td>11/M/47</td>
<td>72</td>
<td>12.1</td>
<td>13</td>
<td>4.0</td>
</tr>
</tbody>
</table>

\(^*\dot{V}_{E} = \text{minute ventilation}; F = \text{respiratory frequency.}\)
Experimental Protocol

The study was conducted while the subjects, seated in the BP with the RIP body jacket, wore noseclips and breathed through the mouthpiece connected to the PNT (palms on the cheeks) (Fig 1).

To analyze the effects of load level on RIP volume waveforms, the subjects breathed successively through different load levels. The resistance of the BP-mouthpiece-PNT system was 2.0 cm H2O/L/s; the first and last measurements were obtained when subjects breathed through this equipment (control load level, R2.0). The addition of two different resistive ventilatory loads, respectively, 2.7 and 5.5 cm H2O/L/s, to the outer part of PNT provided two other levels of measurements (R4.7 and R7.5). Linearity of these different resistances was checked by plotting pressure at mouth vs V during tidal breathing. Additional deadspace induced by added resistances was negligible.

After a 15-min temperature stabilization period, the instruments were calibrated. Each subject underwent four consecutive periods of 92-s recordings: control (P1); first added resistive load (P2); second resistive load (P3); control (P4). The subjects were allowed to choose their own breathing pattern. The order of R4.7 and R7.5 were at random. Each subject underwent then one of the following load sequences: (R2.0 - R4.7 - R7.5 - R2.0) or (R2.0 - R7.5 - R4.7 - R2.0). For each period, recordings were undertaken once fractional end-tidal CO2 (PETCO2) was in steady state. PETCO2 was measured by a capnograph (Engström Eliza; Bromma, Sweden) through a side port of the mouthpiece (this side port was closed during recording periods).

Data Analysis

The primary signals V, Pbody, ABD, and RC were simultaneously sampled and recorded on the microprocessor system during periods of 92 s (which corresponds to 2,944 points at 32 Hz sampling frequency for each signal).

The accuracy of the two RIP volume waveforms (VRIP.BP[t] and VRIP.PNT[t]) during the four different periods was estimated in the following way. We compared the closeness of VRIP.BP[t] and VRIP.PNT[t] with the corresponding reference waveform, respectively, VBP(t) and VPNT(t). To compare the waveforms of these four signals, we had to eliminate any discrepancy due to baseline or to amplitude difference. These conditions were realized by normalizing each signal waveform (ie, mean value of each waveform at zero, and SD at 1) (Fig 2).

For each recording, we calculated the mean square difference ∆2 between each normalized RIP waveform (VRIP.BP[t] or VRIP.PNT[t]) and its normalized reference (VBP[t] or VPNT[t]) on the whole recordings (2,944 points): \[ \Delta^2 = \frac{1}{N} \sum_i (VRIP.BP(i) - VBP(i))^2 \] \[ \Delta^2 = \frac{1}{N} \sum_i (VRIP.PNT(i) - VPNT(i))^2 \]

To have a comparison between the reference signals, we also calculated the mean square difference between the normalized signals VBP(t) and VPNT(t):

\[ \Delta^2 = \frac{1}{N} \sum_i (VBP(i) - VPNT(i))^2 \]

As waveforms are normalized, 95% of the values lie between −2 and +2, then a near maximum value for ∆2 is equal to 16 (a situation in which each sample pair is 2 SDs apart). The square root of ∆2 being equivalent of an euclidean distance, we called D this distance between each waveform and its reference, expressed in percentage of this maximum, respectively:

\[ D_{RIP-BP} = 100 \left( \frac{\Delta^2}{16} \right) \]

\[ D_{RIP-PNT} = 100 \left( \frac{\Delta^2}{16} \right) \]

Statistics

The effects of load level and time on distances were analyzed using analysis of variance (ANOVA). The paired t tests were used to compare the global mean values of distances. The level of statistical significance was taken as p<0.05.

RESULTS

ANOVA shows that the load level has no significant effect on the mean distances (Drip-BP, Drip-PNT, or DPNT-BP) (Fig 3). However, mean distances were similar whatever the period: ANOVA did not evidence any statistical difference (Fig 4).

The mean values of the three distances for each subject are gathered in Table 2. Including all the recordings, the statistical analysis exhibits that the mean distance Drip-BP (3.4±1.1%) appears significantly lower than both the mean distance Drip-PNT (4.5±1.3%; p<0.04) and the mean distance DPNT-BP (4.6±0.9%; p<0.008). No statistical difference appears between Drip-PNT and DPNT-BP (p=0.63).

Figure 1. The system used in the present study, showing the following: (1) flow at the mouth from PNT; (2) Pbody from whole BP; (3) RC and ABD signals from RIP.
Figure 2. (A) The four waveforms VBP(t), VPNT(t), VRIP.BP(t), and VRIP.PNT(t) for one breath during a recording period in a representative subject; (B) normalized curves \( \text{VBP}(t) \) and \( \text{VRIP.BP}(t) \) waveforms from this breath showing that they almost overlap each other; (C) part of \( \text{VBP}(t) \) and \( \text{VRIP.BP}(t) \) waveforms has been enlarged and the distance for one sample \( \text{VRIP.BP}[i] - \text{VBP}[i] \) is illustrated (see text for commentary).

**DISCUSSION**

The purpose of the present study was to test the hypothesis that the RIP volume waveform is as accurate as that obtained from BP and from PNT. To confirm this hypothesis, we analyzed the stability of the different signals during the recording period and demonstrated that the measurements from the RIP, BP, and PNT were comparable.

Following the initial work of Konno and Mead,\textsuperscript{16} several investigators proposed RIP as a method to analyze RC-ABD motions. In clinical situations, the RIP generally is used for continuous noninvasive monitoring.\textsuperscript{18} These different utilizations of RIP...
Table 2—Mean Values of Distance for Each Subject*

<table>
<thead>
<tr>
<th>Subjects</th>
<th>Drip-bp</th>
<th>Drip-pnt</th>
<th>DPNT-bp</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.6 ± 1.0</td>
<td>5.0 ± 1.0</td>
<td>4.0 ± 0.9</td>
</tr>
<tr>
<td>2</td>
<td>2.8 ± 0.6</td>
<td>7.0 ± 0.4</td>
<td>6.8 ± 0.7</td>
</tr>
<tr>
<td>3</td>
<td>2.6 ± 0.2</td>
<td>2.6 ± 0.2</td>
<td>3.4 ± 0.2</td>
</tr>
<tr>
<td>4</td>
<td>4.5 ± 0.7</td>
<td>5.6 ± 2.0</td>
<td>4.3 ± 1.4</td>
</tr>
<tr>
<td>5</td>
<td>4.6 ± 1.6</td>
<td>4.2 ± 1.8</td>
<td>5.3 ± 1.7</td>
</tr>
<tr>
<td>6</td>
<td>3.5 ± 1.5</td>
<td>5.5 ± 2.2</td>
<td>5.3 ± 2.4</td>
</tr>
<tr>
<td>7</td>
<td>2.7 ± 0.3</td>
<td>3.7 ± 1.2</td>
<td>4.4 ± 0.7</td>
</tr>
<tr>
<td>8</td>
<td>2.2 ± 0.1</td>
<td>5.0 ± 1.3</td>
<td>5.1 ± 1.2</td>
</tr>
<tr>
<td>9</td>
<td>4.7 ± 0.8</td>
<td>4.1 ± 1.5</td>
<td>4.6 ± 0.4</td>
</tr>
<tr>
<td>10</td>
<td>1.8 ± 0.1</td>
<td>3.0 ± 0.4</td>
<td>4.4 ± 0.4</td>
</tr>
<tr>
<td>11</td>
<td>2.5 ± 0.3</td>
<td>3.4 ± 0.5</td>
<td>3.5 ± 0.8</td>
</tr>
<tr>
<td>Mean</td>
<td>3.4 ± 1.1</td>
<td>4.5 ± 1.3*</td>
<td>4.6 ± 0.9*</td>
</tr>
</tbody>
</table>

*Data include all the situations and all subjects. Plus sign indicates subjects for whom R7.5 was imposed before R4.7. Drip-bp distance between BP and RIP calibrated with BP; Drip-pnt, distance between PNT with RIP calibrated with PNT; DPNT-bp distance between BP and PNT. Results are expressed in percent ± SD.

p<0.05 vs Drip-bp.
*Not significant vs Drip-pnt.

assume (1) a minimum drift of the RIP signal and (2) the stability of calibration during the time of recording. Such assumptions must also be tested for other comparative methods. Using current RIP technology with transducers placed on different-shaped models, Watson et al.39 confirmed the baseline stability of RIP. Two studies demonstrated that the RIP calibration was well maintained in normal subjects.20,21 Hjulde et al.22 using inductance vest in COPD patients, showed that calibration changed minimally after 240 min.

Before measurements, the RIP must be calibrated. As noted by Sartene et al.,23 the choice of the calibration method depends on experimental or clinical conditions. Among the different methods,16,17,24 Chadha et al.17 proposed the least squares method as the most accurate during long-term trial when change in body posture and/or VR cannot be controlled. Tobin et al.20 confirmed that the least squares method provides the most reliable measurements during loaded breathings. However, the changes of position after calibration and patient movements could possibly have an adverse effect on satisfactory measurements.11,26 In our study, each subject seated in the BP was instructed to avoid any changes in position and to breathe through the mouthpiece, palms on the cheeks during recording to prevent excessive interference of movements.7

When the waveform signal was obtained from BP, the drift is essentially associated with the variations of temperature and humidity in the box. Between each recording, the subjects breathed without connection with the mouthpiece. In these conditions, no drift of plethysmographic signal was observed during the recording periods. To obtain the correct V offset during steady-state period, we hypothesized that the end-expiratory volume is the same at the beginning and at the end of each level of recording as proposed by Peslin et al.27

The comparison of the waveforms of the different signals needs the stability of the transducers and electronics used. In addition, if one needs to quantify the RC-ABD motion changes with RIP, one has to demonstrate the reliability of the time course of the signal. The frequency responses of measurement devices must also be compatible. The pressure-compensated volume-displacement BP has a frequency response compatible with that of the PNT.28 Boynton et al.29 demonstrated in dogs that the sum of the RC and ABD band signals underestimated determined volume change above 8 Hz. A frequency spectral analysis of the three signals demonstrated that frequency spectra were very similar up to 10 Hz, except for RIP which exhibits higher cardiogenic oscillations (between 1 and 1.5 Hz). This can only be responsible for a parallel increase of Drip-bp and Drip-pnt relative to DPNT-bp and cannot explain the observed difference between Drip-bp and Drip-pnt. We then think that the lower degree of damping of cardiogenic oscillations found in RIP does not influence the results of the present study. In our study, we demonstrated the closeness of RIP waveform VRIP.BP(t) and VRIP.PNT(t) with the corresponding reference waveform, respectively, VBP(t) and Vpnt(t). Our results suggest that the RIP frequency response is comparable to that of the PNT and BP. Finally, paired t tests applied to VR obtained from the four different volume measurement methods exhibit no statistical difference between methods. This confirms the accurate calibrations of the three devices.

Currently, the RC and ABD coefficients were obtained from RIP calibrated with low signal or volume signal.7,23,26 The qualitative comparison of simultaneous volume waveforms from RIP and spirometer, in normal subjects breathing through low levels of resistances, exhibited no difference.31 We calibrated RIP against PNT as currently performed. Simultaneously, RIP was also calibrated against BP as these two measurement methods are based on the same physical property, volume displacement. In our study, the comparison of waveforms exhibits that the RIP signal is closer to the BP signal than to the PNT signal. This confirms that RIP is a good plethysmograph that is possibly suitable for use during pulmonary rehabilitation.14

Comparing the mean distances Drip-bp and Drip-pnt, we demonstrated no difference whatever the periods or added resistances used. Stromberg et al.11 comparing RIP and PNT measurements, showed that the RIP underestimated volume profile at the start of inspiration or expiration and overesti-
mately it at the end of inspiration or expiration. They attributed these phase differences to the fact that the movements of the RC and the ABD are not linearly related to the lung volume. This discrepancy may be interpreted by the physical approach. The phase differences observed between volume displacement (measured by RIP) and air displacement (measured by PNT) may be attributed to gas compression which is similarly observed when volume displacement (measured by BP) and air displacement at mouth are used to assess airway resistances.25,30

The comparison between different signals was carried out in subjects breathing against different resistive loads. These resistive loads were lower than the values inducing respiratory muscle fatigue proposed by Tobin et al.25 However, the resistive levels obtained by added resistances were chosen to be comparable with the values of airway resistances during steady state in some human diseases.9 The values of resistances were calculated with BP using a reference method to measure resistances.31

In conclusion, the results of this study indicate that the RIP seems reasonably accurate for analysis of respiratory waveform while subjects subsequently breathe against resistive loads. This confirms that RIP can be considered as a good plethysmograph. If this were to be also true in clinical situations, one would then get a precise and noninvasive tool of chest wall motion monitoring.

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