Evaluation of Respiratory Inductive Plethysmography in the Measurement of Breathing Pattern and PEEP-Induced Changes in Lung Volume*

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**Study Objective:** To assess the accuracy of the respiratory inductive plethysmography in the measurement of PEEP-induced changes in end-expiratory lung volume during mechanical ventilation and its accuracy and stability in the measurement of ventilation during controlled mechanical ventilation and spontaneous breathing.

**Design:** An open comparison between two methods using a criterion standard. Either a pneumotachometer (mechanically ventilated patients) or a spirometer (spontaneously breathing subjects) was used as the reference method.

**Setting:** Tertiary care center; a multidisciplinary intensive care unit and a metabolic research unit.

**Patients:** Six mechanically ventilated, paralyzed postoperative open heart surgery patients, six spontaneously breathing COPD patients, and eight healthy volunteers.

**Interventions:** Stepwise increases and reductions of PEEP from zero to 12 cm H₂O during controlled mechanical ventilation; repeated validation of the calibration of the respiratory inductive plethysmography (RIP) in both mechanically ventilated and spontaneously breathing subjects.

**Measurements and Results:** The baseline drift of the RIP in vitro was 10 ml/150 min in an unventilated model and was 20 ml/150 min. In mechanically ventilated patients, the mean error of the calibration after 150 min was within ±5 percent. Change in end-expiratory lung volume (EELV) during the stepwise increase of PEEP from 0 to 12 cm H₂O was 849 ± 136 ml with the RIP and 809 ± 125 ml with the pneumotachometer (PT), and during the stepwise reduction of PEEP it was 845 ± 124 ml and 922 ± 122, respectively (not significant [NS]). The mean difference between methods in the measurement of change in EELV was −6.8 ± 3.5 percent during increasing and 6.6 ± 6.7 percent during decreasing PEEP (NS). Both in mechanically ventilated and spontaneously breathing subjects, the difference between methods was significant for VT and VT/TI. The difference in VT was −2.2 ± 0.2 percent during mechanical ventilation, −1.1 ± 0.5 percent in spontaneously breathing COPD patients, and 2.9 ± 0.4 percent in healthy volunteers (NS between groups).

**Conclusions:** The RIP is sufficiently accurate for the measurement of PEEP-induced changes in EELV during controlled mechanical ventilation. The accuracy of tidal volume measurement is similar during mechanical ventilation and spontaneous breathing. The calibration of the RIP is stable enough for bedside monitoring of changes in lung volumes.

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**Abbreviations:** PEEP = positive end-expiratory pressure; RIP = respiratory inductive plethysmography; VT = tidal volume; EELV = end-expiratory lung volume; AEELViup = change in end-expiratory lung volume measured with RIP; AEELVp = change in end-expiratory lung volume measured with PT; Ψ = minute ventilation; VT/TI or VT/TVTOT = inspiratory duty cycle; TVTOT = total duration of the breath; VT/TI = mean inspiratory flow rate; VT/TVTOT = tidal volume measured with RIP; VT/TVTOT = tidal volume measured with RIP; VT/TI = mean inspiratory flow rate

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Respiratory inductive plethysmography (RIP) has facilitated continuous measurement of the components of breathing pattern (eg, VT, VT/TI, Ti/TvTOT). It has mostly been used as a noninvasive spirometer in spontaneously breathing normal subjects and patients with chronic lung diseases. In addition to monitoring the breathing pattern, the continuous measurement of changes in lung volume by RIP has potential applications in intensive care. It has been used to assess the effects of PEEP on the breathing pattern, changes in lung volume during adjustment of PEEP and inverse ratio ventilation, in the determination of auto-PEEP, and most recently, to measure the effect of PEEP on changes in end-expiratory lung volume (EELV). Signal stability, accuracy, and need for recalibration have been studied during spontaneous breathing. In contrast, only two studies briefly address the validity of the RIP in the measurement of changes in lung volume during mechanical ventilation. The measurement of changes in EELV is relatively inaccurate during spontaneous breathing and CPAP; the accuracy of the RIP in the measurement of individual changes in EELV has been criticized recently and its use for this purpose has been questioned.

Since major changes in EELV during ventilator adjustments may interfere with the calibration of the...
RIP and thus limit its clinical applications, we studied the stability and accuracy of the RIP in the measurement of tidal volume and stepwise changes in end-expiratory thoracic volume during mechanical ventilation. In addition, the measurement of the breathing pattern was validated in detail in a group of spontaneously breathing normal subjects and patients with COPD.

**METHODS**

**Subjects**

The stability and the accuracy of the RIP in the measurement of VT, VT/TI, and stepwise changes in EELV were studied in six mechanically ventilated postoperative open heart surgery patients (age 55 ± 9 years) in the immediate postoperative period in the intensive care unit (ICU), when still anesthetized and paralyzed. In addition, the accuracy of measurement of the breathing pattern was studied in spontaneously breathing healthy subjects (n = 8, age 22 ± 1 years) and six patients with COPD (age 66 ± 2 years, FEV1/FVC less than 60 percent predicted).

The drift of the RIP sum signal was evaluated for 2.5 h both in vitro and in vivo. In vitro the baseline drift was measured while the two RIP coils were wrapped around a plastic cylinder and then by using a mechanically ventilated two-compartment torso model. The measurements of drift in vivo were carried out separately in two mechanically ventilated postoperative open heart surgery patients.

The ICU patients were ventilated with a ventilator (Servo 900C, Siemens-Elema, Solna, Sweden). The ventilator settings during the measurements were determined on clinical grounds and were kept unchanged (VT, 9 to 11 ml/kg, frequency of 12/min, FIO2 of 0.40). All measurements were carried out in the supine posture. The RIP with two coils (Respirigraph, NIMS, Miami Beach) was used in the DC-coupled mode, so that changes in the EELV would not be filtered out. The thoracic coil was placed at the level of the nipples and the abdominal coil was placed at the umbilical level. The RIP was calibrated against the integrated flow signal of a heated pneumotachometer (Rudolph pneumotachometer, model 3700; Hans Rudolph Inc, Kansas City, Mo, Validyne flow integrator FV 156-871, Validyne Co, Northridge, Calif) using the semiquantitative single-position calibration method. This calibration procedure consists of three steps. First, the rib cage (RC) and abdominal (AB) electrical gains are correctly proportioned and then the sum signal (RC + AB) is adjusted to be equivalent to the integrated volume signal of the pneumotachometer. In the third step the calibration of the RIP is validated by comparing the VT of several breaths determined by the RIP against those determined by the PT. The validation was accepted only if the error was within 2 percent. The volume signals from the RIP and the PT were recorded on a pen recorder (Mingograph; Siemens, Solna, Sweden) at a paper speed of 10 mm/s.

PEEP was changed during expiration in steps of 2 cm H2O from zero to 12 cm H2O and similarly back to zero with each step lasting 2 to 3 min. A stable end-expiratory volume, as indicated by the RIP sum signal, was confirmed before altering the PEEP. The stability of the calibration was assessed by recording the RIP sum signal at the PEEP level prescribed by the attending physician (5 or 6 cm H2O) for up to 150 min without recalibration. During this period, the stability of the calibration was evaluated by repeating the validation procedure at 30-min intervals using 6 to 10 consecutive breaths.

The spontaneously breathing normal subjects and the patients with COPD were studied in a metabolic research unit, supine, with simultaneous use of the RIP and a canopy-spirometer-gas analyzer system, described in detail previously.11 The canopy was ventilated by a continuous 40 l/min airflow, the inflow and outflow balanced by a computerized controller so that a stable spirometer (SP) baseline was achieved. The RIP (Respiratrace 300, Respitrace, Ardsley, NY) was calibrated against the SP using the single-position loop-area calibration method. A validation procedure was then performed and a maximum difference in VT of 10 percent between the SP and the RIP sum signal was accepted; the difference was −3.1 ± 4.0 percent for normal subjects and −5.7 ± 5.7 percent for patients with COPD (in one patient with COPD, an error of 13 percent was the smallest possible in repeated attempts). After a 15- to 20-min adaptation period, the analog volume signals of the RIP and the SP were recorded for 10 to 15 min by a computer for measurement of VT, VT/TI, Ti/Ttot, and Vr. The signals of the RIP and the SP were recorded using an analog to digital converter with a sampling rate of 30 Hz. After the data collection, the calibration of the RIP was validated once again.

The protocol was approved by the institutional ethics committee and an informed consent was obtained from each patient.

**Data Analysis and Statistics**

The drift of the RIP sum signal was analyzed minute by minute by measuring the change (positive or negative) from the baseline of the previous minute.

Data from the mechanically ventilated patients were analyzed as demonstrated in Figure 1. To allow the signals to stabilize, the first five breaths of each PEEP level were discarded and the subsequent five breaths were used to compare the VT measured by the RIP and the PT. These same breaths and the last five breaths of the previous PEEP level were used to determine the changes in EELV. The total number of analyzed breaths was 420. The inspiratory and expiratory tidal volumes were measured and the mean value for each breath was used as VT. The error between the tidal volume measured by the RIP sum signal (Vtrir) and the pneumotachometer (Vtrr) was calculated as 100 × (Vtrrr − Vtrir)/Vtrr percent and the error in ΔEELV as a ratio 100 × (ΔEELVtrr − ΔEELVtrir)/ΔEELVtrir percent, respectively. The error in VT/TI was calculated similarly.

In the spontaneously breathing subjects, the signals of the RIP and the PT were analyzed breath by breath for the volume, flow, and timing components of the breathing pattern. A total of 1048 breaths were analyzed in the normal subjects and 965 breaths were analyzed in the patients with COPD.

The stability of the calibration of the RIP in the mechanically ventilated patients during 150 min was tested by analysis of variance for repeated measurements (Procedure MANOVA, SPSS/PC+; SPSS Inc, Chicago, III). Furthermore, the stability of the calibration during 30 min of the recording was compared with the two groups of spontaneously breathing subjects. The effect of PEEP on the tidal volumes, VT/TI, and ΔEELV measured by the RIP compared with PT were tested by analysis of variance for repeated measures with three within-subject factors (method, increasing-decreasing PEEP level of PEEP) and the errors between methods in measuring VT, ΔEELV, and VT/TI with two within-subject factors (increasing-decreasing PEEP level of PEEP). In the spontaneously breathing subjects, data were analyzed with repeated measures (Procedure MANOVA, SPSS/PC+; SPSS Inc, Chicago, III).

**Figure 1.** PEEP-induced change in end-expiratory lung volume (EELV). RIP sum = sum signal of the respiratory inductive plethysmography (RIP); PT = pneumotachometer.
I. Introduction

II. Methods

III. Results

RESULTS

Stability

In vitro the baseline drift of the end-expiratory level of the RIP sum signal for 2.5 h was 10 ml/150 min (0.067±0.26 ml/min) and with the torso model it was 30 ml/150 min (0.20±0.38 ml/min). In the two mechanically ventilated patients, the drift was 130 ml and 180 ml/150 min (0.87±1.1 ml/min and 1.2±1.7 ml/min, respectively).

The validation error after 150 min in mechanically ventilated patients was between -5 percent and 0 percent and no significant change occurred in the repeated validations (Fig 2, A). The validity of the calibration of the RIP did not change significantly during the study in any of the groups (mechanically ventilated, COPD, or healthy) and differences between the groups after 30 min were not significant (Fig 2). Within subjects, the calibration remained relatively stable. In the normal subjects, the mean difference between the validation errors at the beginning and the end of the study was 5±1 percent and

in the patients with COPD it was 9±2 percent. A difference of 20 percent between repeated validations was observed in one patient with COPD, whereas in the remaining patients it was between 5 and 9 percent. The maximum difference between repeated validations during mechanical ventilation was 6±1 percent; a maximum difference of 13 percent was observed in one patient, whereas in the remaining patients it was 4 to 6 percent.

Mechanically Ventilated Patients

Tidal Volume: In the mechanically ventilated patients, Vr by the PT was 688±8 ml and by the RIP it was 702±8 ml (p<0.001), with a mean difference of -14.4±1.3 ml and a mean error of -2.2±0.2 percent. Vr/Ti measured with the PT was 472±8 ml/s and with the RIP it was 482±8 ml/s (p<0.001), with a mean difference of -10±1 ml/s and a mean
error of \(-2.4 \pm 0.2\) percent. Application of PEEP had a significant effect on the error both in VT and VT/TI (p<0.001): at higher levels of PEEP, the difference between the PT and the RIP was reduced.

**EELV:** The cumulative volume change in the EELV measured during increasing PEEP (from 0 to 12 cm H\(_2\)O) was 849±136 ml (range, 460 to 1,290 ml) by the RIP and 809±125 ml (range, 425 to 1,150 ml) by the PT, and during decreasing PEEP (from 12 to 0 cm, H\(_2\)O) it was 845±124 ml (385 to 1,150 ml) by the RIP and 922±122 ml (455 to 1,285 ml) by the PT (NS) (Fig 3). The changes in EELV measured with the RIP and PT were similar during increasing and decreasing PEEP and at each PEEP level. The mean error of all PEEP levels combined during increasing PEEP was \(-6.6 \pm 3.5\) percent and during decreasing PEEP it was \(6.6 \pm 6.7\) percent (NS).

**Spontaneously Breathing Subjects**

In the spontaneously breathing normal subjects, the error in VT was \(2.9 \pm 0.4\) percent and in patients with COPD it was \(1.1 \pm 0.5\) percent. The signals from the RIP and the SP were in close agreement in most of the recorded variables; in healthy volunteers, the difference between the two signals was less than 5 percent for all variables, except for VT/TI (6.7 percent) and TI/TI\(_{TOT}\) (\(-5.2\) percent). In the patients with COPD, the difference was less than 5 percent for all the variables. Though small, most of these differences were relatively constant and, hence, statistically significant in the paired breath-by-breath comparison of the two signals. The breathing pattern was different in the two groups and between methods: significant differences were observed for VT/TI and TI/TI\(_{TOT}\) (Table 1).

**DISCUSSION**

Noninvasive measurement of changes in EELV during mechanical ventilation would be of interest both for clinical monitoring and research. The validity of the RIP in measurement of \(\Delta\)EELV has been questioned, mainly due to the inaccuracy observed during spontaneous breathing with CPAP.\(^1\) The ability of the RIP to measure PEEP-induced increases in EELV during mechanical ventilation with an error of \(-6.6 \pm 3.5\) percent appeared markedly more accurate than previously reported during spontaneous breathing. During staggered inflations in the supine posture in spontaneously breathing subjects, Sackner et al\(^1\) found an error of 15.9±2.5 percent and in the sitting position the error was even greater.\(^1\) Another study found an error of 12±9 percent (±5D) in the semirecumbent position, when PEEP from zero to 12.5 cm H\(_2\)O was used to induce a change in EELV.\(^6\)

The cumulative changes in EELV during increasing and decreasing PEEP were practically identical by the RIP, whereas a tendency to a larger cumulative volume by the PT during decreasing PEEP was observed. In contrast, when measured after a slow single breath, as in voluntary staggered inflation-deflation trials\(^1\) or using a syringe in paralyzed patients,\(^\text{13}\) the deflation volume measured with the SP or PT has been smaller than by the RIP and attributed to gas exchange.\(^\text{13}\) Since we defined changes in EELV from several consecutive breaths during stepwise changes in PEEP, effects of gas exchange are likely to be excluded but gradual changes in thoracic blood volume may have occurred.

For clinical applications, stability of calibration and lack of drift during prolonged measurements are essential. Previous studies have demonstrated that the calibration of RIP is well maintained after 4 h of measurement during spontaneous breathing.\(^7\) Our results demonstrate that the validity of calibration remains practically unchanged in repeated validations for up to 2.5 h during mechanical ventilation, which is in agreement with previous observations.\(^7\)

The small baseline drift of the RIP sum signal in the present study in *vitro* agrees with a recent study, which found that the drift in 12 h was less than the minimum volume resolution of the RIP.\(^\text{14}\) Measurements with the torso model show that the influence of the ventilation itself on the drift is relatively small. The drift in *vitro* may partially reflect postoperative physiologic changes in EELV due to lung expansion and changes in blood volume. The effect of this slow change in EELV was avoided by using the breaths immediately preceding and those 0.5 to 1 min after the change of PEEP.

The accuracy of the RIP in the measurement of VT in mechanically ventilated patients and spontaneously breathing subjects appeared very similar. The measurement of VT/TI was slightly less accurate in the spontaneously breathing subjects, but the error was always less than 10 percent and in most cases below 5
percent. We found that during controlled mechanical ventilation, the Vr in 93 percent of all measured breaths was within ±10 percent error, which is identical to the observation of Tobin et al in mechanically ventilated, unparalyzed patients.

We conclude that the RIP is accurate for the measurement of instant changes in EELV induced by PEEP during controlled mechanical ventilation in supine paralyzed patients, but in the measurements of longer periods (hours), the drift, even though small, has to be taken into account. The accuracy of tidal volume measurement by the RIP is similar during mechanical ventilation and spontaneous breathing.

REFERENCES