Effect of median sternotomy on respiratory system compliance in humans: evaluation without sophisticated instrumentation

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Abstract

To evaluate the effect of median sternotomy on the static compliance of the respiratory system ($C_{rs}$) in humans, we used a new technique for pressure–volume (PV) curve tracing without sophisticated instrumentation. The accuracy and the reproducibility of the new technique were tested in a lung simulator, while its agreement with multiple-occlusion (MO) technique (the technique most often used in the ICU for $C_{rs}$ measurement) was evaluated in 12 mechanically ventilated patients. Finally, the NCI technique was used in 13 cardiosurgical patients to measure $C_{rs}$ before and after median sternotomy. Measurements provided by the NCI technique were at least as accurate as standard measurements in the bench study. In ICU patients, we observed a good agreement of $C_{rs}$ measurements provided by the two techniques (bias 0.8, 95% limits of agreement -5.6 to 7.2 ml/cm H2O) and a similar reproducibility. In cardiosurgical patients we observed a significant ($P=0.037$) increase in $C_{rs}$ with an upward and leftward shift of the PV-curve after median sternotomy. No adverse effect was observed during PV-curve tracing maneuvers. The simplicity of NCI technique allowed for the first time, to our knowledge, PV-curve tracing in humans during cardiosurgery and revealed 5% increase in $C_{rs}$ immediately after median sternotomy.

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1. Introduction

The supersyringe technique has been extensively used to trace pressure–volume (PV) curves and to measure the total compliance of the respiratory system ($C_{rs}$) in ventilated patients [1]. However, its application requires specific instrumentation and changes in temperature and humidity, or continuing gas exchange during the maneuver must be taken into consideration to avoid errors [1–5]. To minimize these errors, we have proposed to trace PV-curves using a series of non-cumulative inflations performed with the supersyringe [4, 5]. In a similar approach, Levy et al. [6] traced PV-curves using a series of occluded mechanical breaths of varying size (multiple occlusion or MO technique). The MO technique can be applied using only modern ventilators allowing manual control of inspiratory and expiratory valve and disposing an accurate display and measurement of pressure and volume changes [7, 8]. The need to use sophisticated instruments carefully calibrated or modern ventilators has limited the use of PV-curves in clinical practice, especially outside the ICU environment [1, 8].

Our purpose was to evaluate a new technique suitable for $C_{rs}$ measurement without sophisticated instrumentation. A supersyringe was used to perform a series of non-cumulative inflations (NCI technique), while the induced pressure changes were measured with a standard single-use pressure transducer connected to the patient’s monitor. Once the accuracy and the reproducibility of $C_{rs}$ measurements provided by the NCI technique were confirmed, the new technique was used in the operating room to measure for the first time, to our knowledge, PV-curve tracing in humans during cardiosurgery and revealed 5% increase in $C_{rs}$ immediately after median sternotomy.

2. Methods

2.1. Description of the NCI technique and evaluation of its accuracy in the lung simulator

Inflations were performed using a supersyringe of 3 l (model 5530, Hans Rudolph, Kansas City, USA). Inflated volume was simply defined by appropriate positioning of the syringe’s piston before inflation. Airway pressure at the proximal end of the endotracheal tube (Paw) was monitored using a single-use pressure transducer connected to the patient’s monitor. End-inspiratory airway pressure (Pplat) was measured after an inspiratory pause of 3 s.

To evaluate the accuracy and the reproducibility of pressure, volume and $C_{rs}$ measurements provided by the NCI technique we used a lung simulator (Drägerwerk AG Lübeck LS 800, Dräger, Germany) with nominal values 10, 20 30, 50 or 100 ml/cm H2O for compliance and 4 or 16 cm
All patients had at least a continuous monitoring of SaO₂, ECG and arterial blood pressure to detect adverse effects. Exclusion criteria included evidence of hemodynamic instability, cardiogenic edema, myocardial ischemia, cardiac arrhythmias, severe hypoxemia (PaO₂/FIO₂ < 200 mmHg) or hypercarbia (PaCO₂ > 45 mmHg). The only modification of patient’s treatment for the purposes of the study was that tracheobronchial secretions were carefully aspirated and FIO₂ was increased by 20% for safety reasons 30 min before PV-curve tracing. In ICU patients, the NCI and the MO technique were used consecutively in a randomized order. A steady Paw during the inspiratory pause confirmed absence of air leaks in patient’s circuitry. After each inflation or occluded mechanical breath, all patients were allowed to receive at least 2 min of mechanical ventilation. The study was approved by the Ethics Committee of our institution and informed consent was obtained from patients or next of kin.

The MO technique was used as previously described [6]. To perform NCI patients were disconnected from the ventilator and allowed to expire for 10 s. The supersyringe was then connected to the endotracheal tube and the predefined amount of volume was inflated in 1–3 s. Static Pplat was measured after 3 s of end-inspiratory pause and the patient was reconnected to his ventilator. The maximum inflated volume leading to an increase of Pplat around 35 cm H₂O (Vmax) was calculated by dividing patient’s tidal volume with the corresponding Pplat during mechanical ventilation. The volume of sequential inflations increased progressively by either 100 or 200 ml when Vmax was lower or higher than 1500 ml, respectively. Using this approach, we were able to trace PV-curves using 10–15 points in all patients, without prolonging the time required for each maneuver or inducing overinflation (Pplat ≤ 35 cm H₂O). The same sequence of inflations was used for PV-curve tracing using NCI and MO technique.

3. Statistical analysis

A statistical program (STATISTICA, StatSoft®, Tulsa, OK, USA) was used to provide a linear regression correlation of pressure–volume points included in the linear part of the PV-curve, allowing calculation of the slope of this linear part (=Crs) and of its intercept with the pressure axis (Fig. 1). Agreement and reproducibility of measurements were evaluated using Bland and Altman analysis [9] and calculation of concordance correlation coefficient [10], while Crs measurements before and after median sternotomy were compared using paired t-test. A P < 0.05 was considered significant.

Values of Pplat obtained with single-use pressure transducers correlated very well with ‘standard’ spirometric pressure measurements (r = 0.999, bias = 0.05 cm H₂O and 95% limits of agreement – 1.29 to 1.19 cm H₂O).

After appropriate calibration, volume measurements by the pneumotachograph were in excellent agreement with volumes delivered with the supersyringe, but when the supersyringe was connected to the lung simulator, this agreement was no more satisfactory (bias 190 ml, 95% limits of agreement 106–274 ml, r = 0.467). Therefore, the total volume of the supersyringe (3000 ml) was used as ‘gold standard’ to evaluate agreement with pneumotachographic volume measurements at 16 different settings of respiratory mechanics (20, 30, 50 or 100 ml/cm H₂O of compliance and 4, 8, 16 or 32 mbart/l/s of resistance). To correct errors due to gas compression, the inflated volume was corrected (Vcor) using the formula:

\[ V_{cor} = 3000 \text{ ml} \times P_{bar}/(P_{bar} + \text{Paw}) \]  

(1)

where \( P_{bar} \) = barometric pressure, \( \text{Paw} \) = airway pressure and 3000 ml = the volume of the supersyringe.

Comparative measurements revealed a systematic underestimation of inflated volume by the pneumotachograph, even after correction for gas compression due to the increased Paw. Volume underestimation was around 5% and increased when respiratory resistance increased (Fig. 2). Our results indicate that, in mechanically ventilated patients, changes in respiratory resistance could induce errors in volume measurements provided by pneumotachographs.

During the bench study, \( C_{rs} \) calculated from standard spirometric measurements were in good agreement with \( C_{rs} \) values obtained using the NCI technique (bias = –3.92 ml/cm H₂O and S.D. = ± 5.16 ml/cm H₂O). The two techniques had also a similar and acceptable for clinical purposes...
Comparative measurements of CRS resistance selected in the artificial lung. C30, C50, C100 and R4, R8, R16, R32: the nominal values of compliance and inflated volume with the supersyringe (compression due to the increased plateau airway pressure). An r value of 1.0000 indicates a perfect concordance.

**CCC, concordance correlation coefficient**

reproducibility. Bland and Altman analysis results and concordance correlation coefficients for all comparative CRS measurements are summarized in Table 1.

4.2. Measurements of CRS in patients

Comparative measurements of CRS using the NCI and the MO technique were performed in 12 mechanically ventilated patients admitted to the ICU for several reasons (Table 2). Once again, CRS measurements provided by the two techniques were in good agreement and had a similar reproducibility (Table 1). Total duration of PV-curve maneuvers in our study was 25–40 min for both techniques. The mean number of inflations performed to trace a PV-curve was 11 ± 2 in ICU patients and 13 ± 2 in cardiosurgical patients. No adverse effect was observed during CRS measurements with the MO technique (24 maneuvers) or the NCI technique (50 maneuvers).

When the NCI technique was used in the operating room to measure CRS before and immediately after median sternotomy the mean increase of CRS was 5% (P=0.037) and the intercept of the linear part of the PV-curve with the pressure axis (Fig. 1) was significantly decreased (P=0.023).

5. Discussion

The classic supersyringe technique was considered as the reference method for PV-curve tracing under static conditions, but its use in clinical practice remained limited [1, 8]. The NCI technique does not require any special, difficult to calibrate or expensive equipment and allows PV-curve tracing at the bedside in every clinical setting (mainly outside the ICU).

5.1. Comparison of the NCI technique to other similar measurements

Our results in the bench study indicate not only that NCI technique provides accurate pressure and volume measurements, but also that measurements provided by a pneumotachograph could underestimate inflated volume especially in patients with high respiratory resistance. In ICU patients, the NCI and the MO technique showed a good agreement and a similar reproducibility and no adverse effects were observed. Therefore, the two techniques can be used interchangeably in clinical practice. The total duration of PV-curve tracing was similar for both techniques (25–40 min). Rodriguez et al. reported that 30–46 min were required to trace a PV-curve with the MO technique [11].

When compared to the classic supersyringe technique, the NCI technique has a shorter duration of lung inflations, which is expected to decrease the error due to ongoing oxygen consumption during PV-curve tracing [4, 5]. The use of an airway pressure up to 35 cm H2O as an upper limit during the NCI technique, allows PV-curve tracing until the lungs are inflated almost up to the total lung capacity (at least for patients with normal lungs and chest wall). In addition, the NCI technique provides also the intercept the linear part of the PV-curve with the pressure axis.

### Table 1

<table>
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<tr>
<th>Comparative measurements of CRS</th>
<th>Bland and Altman analysis*</th>
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<td>-0.27</td>
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<td>-0.59</td>
<td>-4.5 to 3.3</td>
</tr>
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*Compliance bias and limits of agreement are measured in ml/cm H2O.

**CCC, concordance correlation coefficient (r_c).

An r_c value of 1.0000 indicates a perfect concordance.
There are of course several limitations of the NCI technique as a result of its simplicity: a) only the inspiratory limb of the PV loop is provided and there is no possibility to evaluate the relative effect of the lungs and the thorax; and b) since inflations are performed after disconnection from the ventilator, PEEPi is not taken into consideration. On the other hand, the PV-curve may reflect better the underlying alterations of the lung parenchyma under these circumstances, since there is no confounding effect due to the prescribed ventilatory pattern. Disconnection of the patient from the ventilator several times is another limitation of the NCI technique and may be contraindicated in ICU patients without severe respiratory failure seems not harmful, since no adverse effect was observed during 50 maneuvers in our study. This is in accordance to the observation of Lee et al. that compliance measurements with the supersyringe technique is well tolerated in most ICU patients [12].

5.2. Changes in $C_{rs}$ induced by median sternotomy

Although most clinicians would expect an increase in $C_{rs}$ after median sternotomy (provided that the pleura are not opened), this was never quantified in humans. Only in dogs, Wohl et al. [13] have reported excised lungs to be more distensible than in vivo with the chest closed. The simplicity of the NCI technique allowed us to use it in the operating room and revealed a statistically significant increase of $C_{rs}$ (5%) after median sternotomy, as well as a significant decrease (20%) of the intercept of the linear part of the PV-curve with the pressure axis. From a clinical point of view, a 5% increase of $C_{rs}$ indicates a minor change in respiratory mechanics and does not imply a modification in patient’s ventilatory setting. During pressure control ventilation, however, such an increase in $C_{rs}$ is expected to induce a 5% increase in delivered tidal volume (30–50 ml if we take into consideration between patients variability).

In conclusion, our study describes a new very simple technique for PV-curve tracing in ventilated patients, using only a supersyringe and a pressure transducer connected to the patient’s monitor. Since the new NCI technique and the MO technique showed a similar accuracy and reproducibility for $C_{rs}$ measurement and a good agreement, these two techniques can be used interchangeably in the clinical setting, when modern ventilators or sophisticated instrumentation are not available. Under this perspective, the simplicity of the NCI technique allowed us to trace PV-curves in the operating room and to demonstrate a 5% increase of $C_{rs}$ after median sternotomy in humans.

References


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