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Circuit compliance compensation in lung protective ventilation

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Abstract—**Lung protective ventilation utilizes low tidal volumes to ventilate patients with severe lung pathologies. The compensation of breathing circuit effects, i.e. those induced by compressible volume of the circuit, results particularly critical in the calculation of the actual tidal volume delivered to patient's respiratory system which in turns is responsible of the level of permissive hypercapnia. The present work analyzes the applicability of the equation for circuit compressible volume compensation in the case of pressure and volume controlled lung protective ventilation. Experimental tests conducted *in-vitro* show that the actual tidal volume can be reliably estimated if the compliance of the breathing circuit is measured with the same parameters and ventilation technique that will be utilized in lung protective ventilation. Differences between volume and pressure controlled ventilation are also quantitatively assessed showing that pressure controlled ventilation allows a more reliable compensation of breathing circuit compressible volume.**

I. Introduction

LUNG protective ventilation is a relatively new ventilation strategy which utilizes small tidal volumes ($\cong$ 6 ml/kg of predicted body mass instead of $\cong$ 12 ml/kg used in conventional ventilation technique) to ventilate critically ill patients with severe lung pathologies, such as respiratory distress syndrome and acute lung injury. The previously indicated technique has been proven to reduce multiple organ dysfunction syndrome, to avoid the risk of barotraumas and to increase the survival of patients [1], [2]. However, when performing a low tidal volume ventilation the physician accepts an increase in the arterial partial pressure of carbon dioxide [3]. Thus, a critical factor for the beneficial effects of protective ventilation appears to be the volume of air that actually reaches the airways of the patient, being this quantity responsible of the level of permissive hypercapnia that can be reached without dangerous situations for the patient. In fact, severe hypercapnia can have serious adverse effects [4].

Due to the fact that most ventilators measure the tidal volume at ventilator level, and not at airway opening, during mechanical ventilation the volume of air that actually enters in the lungs is not exactly known, although it can be estimated by applying the following compensation equation:

$$V_{Tp} = V_{TV} - C_{bc} \cdot \left(PIP - PEEP\right) \tag{1}$$

where V_{Tp} is the tidal volume that actually reaches the airways of the patient, V_{TV} is the tidal volume delivered by the ventilator, C_{bc} is the compliance of the breathing circuit, PIP and PEEP are the Peak Inspiratory Pressure and the Positive End Expiratory Pressure, respectively.

However, accordingly to some researches [5], [6], [7], the application of Eq.(1) in infant ventilation does not appear to be a reliable method in order to estimate the actual tidal volume. This observation, if extended to the case of lung protective ventilation, may be particularly critical due to the uncertainty on the actual value of tidal volume involves in turn an uncertainty on the estimation of hypercapnia level making dangerous the application of this ventilation strategy.

In a previous paper [8] it has been assessed the dependence of the C_{bc} measured value on the flow rate at which the measurement is performed. For this reason it has been outlined the necessity, in order to have an effective compensation of the breathing circuit effects, and consequently a reliable estimation of V_{Tp} based on Eq.(1), that the measurement of the C_{bc} should be performed with the same insufflation law utilized during mechanical ventilation.

In this work we apply the circuit compensation method described in [8] to the case of lung protective ventilation, whether it be performed in volume or pressure controlled mode, in order to experimentally validate the applicability of Eq.(1).

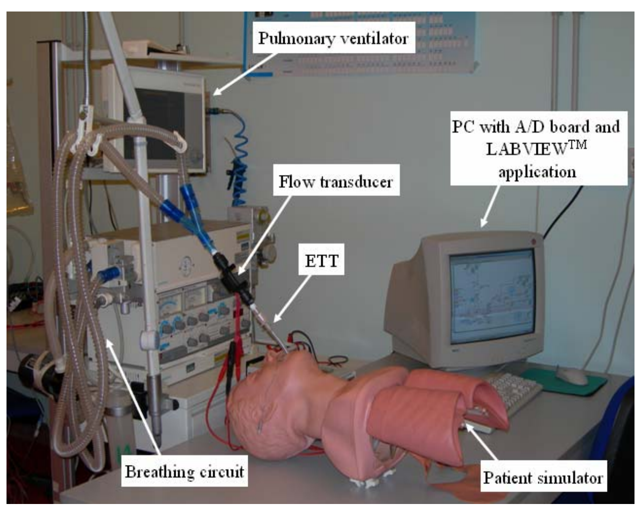

Figure 1 - Picture of the experimental set-up.

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II. EXPERIMENTAL SETUP

In order to validate the viability of the method we utilized a ventilation system composed by a Siemens Servo 900C pulmonary ventilator, an adult breathing circuit with an 8.0 mm ID endotracheal tube and a patient simulator (Laerdal - AirMan). Moreover, an air flow transducer (range -20/+20 l/min and accuracy ± 0.2 % of the measured value) was positioned between the Y-piece of the breathing circuit and the endotracheal tube in order to measure the actual tidal volume V_{Tp}. A picture of the experimental set-up is shown in Fig.1.

All the tests were conducted by setting the respiratory frequency equal to 15 bpm, the inspiratory time to 25 % of the breathing period, the pause duration to 10 % and null PEEP. Hence, the breathing period duration was set to 4 s, whereas the inspiratory and pause time to 1 s and to 0.4 s, respectively. Tidal volumes utilized ranged from 25 ml to 125 ml in steps of 25 ml.

The compliance of the breathing circuit, C_{bc}, was experimentally measured by insufflating the same tidal volumes with the same parameter settings afterwards utilized for the ventilation of the patient simulator, both in pressure and volume controlled modes.

A Labview™ application was implemented in order to gather the pressure and flow signals from the ventilator and from the flow transducer; flow signals were numerically integrated to obtain the tidal volumes. All signals were sampled at 1 kHz by an A/D 16-bit PC board and each measurement were repeated five times in order to allow the statistical post processing of collected data. All the results are reported as the mean ± standard error calculated with a Student reference distribution (4 degrees of freedom and confidence 95 %).

A first set of experiments aimed to measure the compliance of the breathing circuit (C_{bc}), both in volume and pressure controlled ventilation, for each tidal volume delivered. Compliance were measured using the ventilator along with the breathing circuit and the flow transducer with outlet occluded. C_{bc} values were calculated as follows:

$$C_{bc} = \frac{V_{TV}}{\Delta P} \qquad (2)$$

where ΔP is the pressure increment in the breathing circuit due to the insufflation of V_{TV}.

The measurement of C_{bc} allowed, by the application of Eq.(1), to obtain an estimation of V_{Tp}, indicated as $\overline{V}_{Tp}$. Thus, another set of experiments were carried out on the entire system, composed by the breathing circuit and the patient simulator, in order to measure the actually delivered tidal volume (V_{Tp}) and compare its value with the calculated $\overline{V}_{Tp}$, for both ventilation modes above cited.

III. RESULTS AND DISCUSSION

As far as it concerns the first set of experiments carried out, the breathing circuit compliance C_{bc} is reported in Fig.2 as a function of the tidal volume delivered by the ventilator in the case of volume controlled ventilation. By an examination of Figure 2 it emerges that the breathing circuit compliance decreases from 18.0 ± 1.1 ml/kPa to 16.8 ± 0.1 ml/kPa as the tidal volume supplied by the ventilator increases from 31.0 ± 0.9 ml to 123.4 ± 0.7 ml. The progressive decrease of C_{bc} as the tidal volume increases confirms the results reported in [8] showing a relationship of inverse proportionality between the measured compliance and the flow rate at which the insufflation is actuated. However, the diminution of C_{bc} in the flow range utilized for lung protective ventilation is fair less than the decrease observed in the flow range utilized for infant ventilation [8]. The present experimental outcome indicates that the application of Eq.(1) in lung protective ventilation may not lead to the high estimation errors encountered for infant applications [5].

As far as it concerns the measurement of C_{bc} in pressure

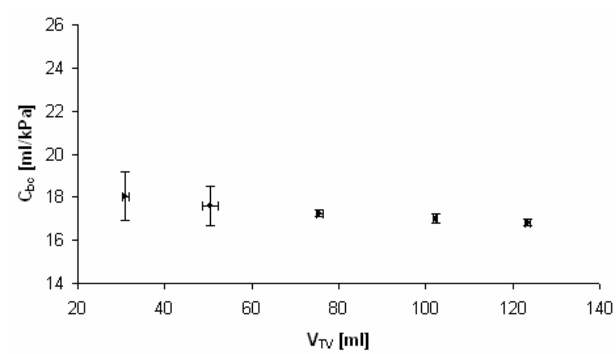

Figure 2 - Breathing circuit compliance as a function of the tidal volume delivered by the ventilator in the case of volume controlled ventilation.

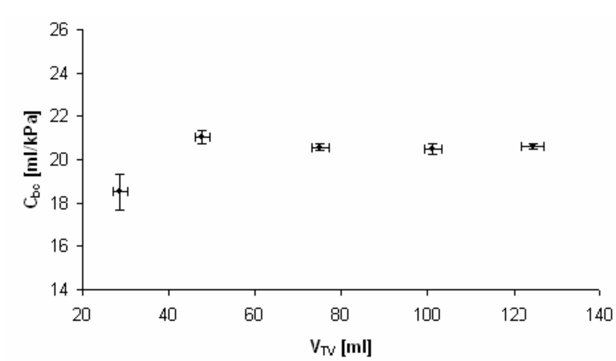

Figure 3 - Breathing circuit compliance as a function of the tidal volume delivered by the ventilator in the case of pressure controlled ventilation.

controlled ventilation, Fig.3 shows the results obtained. In this case C_{bc} slightly increases from 18.5 ± 0.8 ml/kPa to

20.6 ± 0.1 ml/kPa when the V_{TV} increases from 25 ml to 50 ml, then its value remains approximately constant and equal to 20.5 ± 0.8 ml/kPa in the range of tidal volumes from 47.8 ± 1.6 ml to 124.6 ± 2.6 ml.

From a comparison of the results reported in figures 2 and 3 it can be observed that the C_{bc} value is different whether the insufflation is conducted in volume controlled or pressure controlled mode. A percent difference of 10 % on the measured values confirms the hypothesis that also in lung protective ventilation the value of the measured breathing circuit compliance is dependent on the ventilation technique, i.e. on the insufflation law at which the measurement is carried out. Thus, for an effective estimation of the tidal volume actually delivered to the patient it is necessary to utilize Eq.(1) with the value of C_{bc} measured with same insufflation law in which ventilation is performed with.

In order to validate the reliability of Eq.(1) in predicting the correct value of the actual tidal volume delivered to the patient we substituted in Eq.(1) the values of C_{bc} obtained by means of the previous experiments and measured the difference (PIP-PEEP) when ventilating the patient simulator. With such a procedure we obtained a predicted value of actual tidal volume delivered ($\overline{V_{Tp}}$). Thus, we compared the predicted $\overline{V_{Tp}}$ values, indicated with a continuous line in figures 4 and 5, with the V_{Tp} values experimentally measured by the flow transducer placed at Y-piece, and indicated in figures 4 and 5 as dots with the relative associated uncertainties.

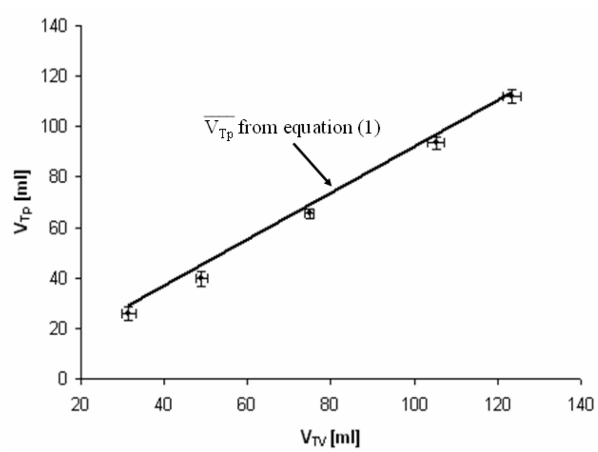

Figure 4 - Actual tidal volume delivered to patient as a function of the tidal volume supplied by the ventilator in volume controlled ventilation, the line represents the tidal volume calculated by Eq.(1).

In both cases it can be seen that the relationship between the volume actually delivered to the patient simulator and the tidal volume delivered by the ventilator is approximately linear. In fact, the amount of tidal volume delivered to the simulator increases from 26.0 ± 2.7 ml up to 112.0 ± 2.7 ml as the tidal volume at ventilator level increases from 31.4 ± 1.7 ml to 123.4 ± 2.1 ml in the case of volume controlled ventilation (Fig.4). On the other hand, in the case of pressure controlled ventilation the volume delivered to the patient increases from 42.9 ± 0.7 to 118.0 ± 1.5 ml as the tidal volume at ventilator level increases from 48.4 ± 1.9 to 127.8 ± 2.7 ml (Fig.5).

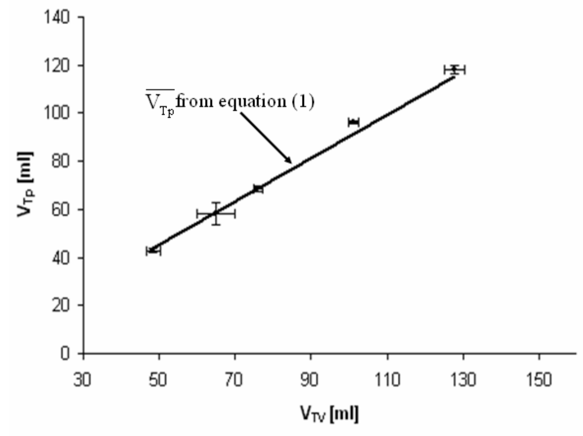

Figure 5 - Actual tidal volume delivered to patient as a function of the tidal volume supplied by the ventilator in pressure controlled ventilation, the line represents the tidal volume calculated by Eq.(1).

Figures 4 and 5 show that the tidal volume actually delivered to the patient is a fixed ratio of the tidal volume supplied by the ventilator. As far as it concerns volume controlled ventilation, the ratio is expressed as follows:

$$\overline{V_{Tp}} = 0.92 \cdot V_{TV} \tag{3}$$

whereas in case of pressure controlled ventilation the ratio is expressed by:

$$\overline{V_{Tp}} = 0.90 \cdot V_{TV} \tag{4}$$

where $\overline{V_{Tp}}$ is the estimated amount of tidal volume delivered to the patient.

Equations (3) and (4) show that in volume controlled ventilation the estimated V_{Tp} is about 92 % of the tidal volume supplied by the ventilator, whereas in the case of controlled pressure ventilation it is about 90 % of V_{TV}. Thus, V_{Tp} in the volume controlled ventilation is greater than the one delivered to the patient in the case of pressure controlled ventilation.

Finally, the calculation of MSE (Mean Standard Error) to evaluate the differences between the estimated values of $\overline{V_{Tp}}$, calculated by means of Eq.(1), and the experimentally measured values of V_{Tp} further confirmed the validity of the estimation procedure.

MSE has been calculated as follows:

$$MSE = \frac{1}{n} \cdot \sum_{i=1}^{i=n} (\overline{V_{Tp_i}} - V_{Tp_i})^2 \tag{5}$$

where V_{Tpi} is the tidal volume delivered to the simulator measured by the flowmeter, $\overline{V}_{Tpi}$ is the estimated value of V_{Tp} calculated by Eq.(1) and, finally, n is the number of experimental tests.

A $MSE = 8.5\ ml^2$ has been obtained in the case of pressure controlled ventilation, whereas a $MSE = 13.4\ ml^2$ in volume controlled one. Thus, the use of Eq.(1) results more reliable in the case of pressure controlled ventilation as it better approximates the experimental results allowing a better compensation of the breathing circuit.

IV. Conclusions

Lung protective ventilation strategies require a reliable procedure for circuit compliance compensation in order to reduce the uncertainty on the level of permissive hypercapnia.

This work shows that the amount of tidal volume actually reaching the respiratory system of the patient is lower than the tidal volume delivered by the ventilator. However, an efficacious compensation of the breathing circuit dead volume can be obtained by measuring circuit compliance with the same insufflation law that will be utilized in mechanical ventilation.

The compensation of the breathing circuit is critical in lung protective ventilation in order to guarantee that arterial partial pressure of carbon dioxide reaches a controlled and safe level.

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