MECHANICAL VENTILATORS – COMPARISON OF PROXIMAL AND DISTAL RESPIRATORY MECHANICS MEASUREMENTS

G. C. Motta-Ribeiro*, A. Giannella-Neto*, H. Wrigge**, A. R. S. Carvalho*,*** e A. Beda****

*Programa de Engenharia Biomédica - COPPE/Universidade Federal do Rio de Janeiro, Rio de Janeiro, Brazil
**Universitätsklinikum Leipzig - Leipzig Universität, Leipzig, Germany
***Instituto de Biofísica Carlos Chagas Filho - Universidade Federal do Rio de Janeiro, Rio de Janeiro, Brazil
****Departamento de Engenharia Eletrônica - Universidade Federal de Minas Gerais, Belo Horizonte, Brazil
e-mail: gabrielcasulari@poli.ufrj.br

Abstract: Respiratory system (RS) mechanical properties can be calculated using digital data output available from most mechanical ventilators. However, the presence of the breathing circuit (BC) may lead to differences between distal and proximal measurements. In this work inspiratory tidal volume and RS mechanical properties (resistance and elastance) obtained from distal sensors of two commercial ventilators were compared with a reference proximal measurement system. Resistance was better estimated by the proximal system, with distal estimates exhibiting errors up to 48 % and varying with ventilatory settings. Regarding elastance, proximal and distal systems had a better agreement and its estimates varied less than 3 % between positive end-expiratory pressures (PEEP) ranging from 0 to 20 cmH_2O. This suggests that distal sensors in the tested machines could be used for PEEP titration based on the minimization of linear elastance.
Keywords: *Data acquisition, Respiratory Mechanics, Mechanical ventilation.*

Introduction

Most of medical devices currently used in hospitals are equipped with a digital port for communication with other instruments, such as of therapeutic use or computers and printers. Despite this trend started in the 90's, mainly with mechanical ventilators [1], its use is still limited. The real time acquisition of physiological signals enables the follow up of the clinical history, quality parameters estimation [2], or the use of therapy advisory systems. For research, this tool reduces the need of external devices, increases safety, and allows for a long time continuous monitoring.

Mechanical ventilators flow and pressure transducers are usually located distal to the patient and its signals differ from those collected close to the mouth because of the impedance of the BC [3]. However, some advantages exist in comparison with proximal measurement such as reduction of dead space and lower nosocomial risk without additional connectors and instruments.

The objective of this work is to compare distal and proximal measurements of pressure, airflow, volume and the mechanical properties (resistance and elastance) estimated with them. Distal signals were obtained from two commercial ventilators, Evita XL (Dräger, Germany) and Servo-i (Maquet, Germany), and proximal signals from proximal differential pressure sensors.

Materials and Methods

The experiments of this study were carried out at the Leipzig University Hospital, Germany. The two ventilators were in good conditions of use and passed on the respective self-test protocol. To standardize the comparison, the same coaxial adult BC (model U0120-06, King Systems, USA) was used in all tests.

Measurement systems – Both ventilators measure the pressure with internal sensors located at the end of the BC arm with zero flow at each ventilator phase, but differ on flow rate measurement. On Evita XL the inspiratory flow is determined indirectly at the gas mixer using the outlet diameter and the supply pressure. The expiratory flow is measured by a hot-wire pneumotacograph [4]. On the Servo-i the inspiratory flow is measured by a Lily pneumotacograph provided with a differential pressure transducer, while the expiratory is measured by an ultrasonic transducer [5].

The proximal reference system was constituted by a variable orifice pneumotacograph (Hamilton-Medical, Switzerland) connected to a differential pressure transducer 176PC07HD2 (Honeywell, USA) and a pressure transducer 143PC01D (Honeywell) to measure the airways pressure. Signal from both pressure transducers were amplified and low-pass filtered (33 Hz) with a built purpose device (Motramere n° 5 COPPE/UFRJ, Brazil). The transducers were positioned close to the entrance of a physical lung model.

Data acquisition – Distal measurements were directly acquired from the ventilators using manufacturer's serial communication protocol, while proximal signals were acquired with an A/D NI-6009 (National Instruments, USA). Before the experiments all transducers were calibrated with appropriate procedures [6].

All information were collected and saved simultaneously with a data acquisition program developed by the authors in Labview 2011 (National Instruments). This system allows for simultaneous acquisition of different digital sources, respecting the corresponding sampling frequencies and channels numbers. The signals of each source can be independently visualized, and saved with identification, calibration, frequency and physical unit dimension. In the present study pressure, flow and volume were recorded in: mbar, L/min and mL at 125 Hz for Evita XL; and cmH_2O, mL/s and mL at 100 Hz for Servo-i. On the Motramere system only pressure and flow were recorded, respectively, in cmH_2O and L/s at 200 Hz.

RS physical model - The measurements were done ventilating a physical model corresponding to a linear unicompartimental respiratory system [7]. The resistance consisted of a multiple perforated fabric plate element. The elastance was a 20 L glass bottle stuffed with metallic wool to minimize the thermal effects of gas compression. The model was characterized with a resistance of 6.4 ± 1 cmH_2O.s/L and an elastance of 53 cmH_2O/L ± 5%.The model was connected to the ventilators with an endotracheal tube (TOT) # 8.

Ventilatory settings - The physical model was ventilated in two modes: volume controlled ventilation (VCV[1]) and pressure regulated volume control (PRVC[2]). On each mode, a positive end-expiratory pressure (PEEP) titration maneuver was carried out with two tidal volumes, 300 and 500 mL. The maneuver consisted of sequential change in PEEP from 20 to 0 cmH_2O in steps of 2 cmH_2O with 3 min each. In all tests the ventilatory settings were: breath frequency of 14 cycles/min, 21 % of O_2 fraction, inspiration/expiration time ratio of 0.5 and null flow rise time. On VCV an inspiratory pause of about 0.5 s was set. On both ventilators compensation of compressed BC volume was turned on. On the Evita XL the BTPS[3] flow and volume corrections were turned off.

Data processing – Data were processed in Matlab (Mathworks, USA) using dedicated code and the program for biological signals processing, *Mecânica* [8]. All units were converted to the standards of cmH_2O, L/s and L. The comparison between proximal and distal acquisition systems were performed using the calculated inspiratory tidal volume and the mechanical estimates at the "carina" (after the TOT) during the last 2 min of each PEEP step. For each data set, ventilator phases were identified with a zero-crossing flow or the ventilator identifier, and all analyses taken on a cycle-by-cycle basis. To get an estimate of the carina's pressure, the TOT pressure drop was calculated using the Rohrer's equation [7] with $K_1 = 0.148$ cmH_2O.s/L and $K_2 = 6.59$ $cmH_2O.(s/L)^2$ [9].

[1] Denomination used on Servo-i. For Evita XL it's IPPV.
[2] Denomination used on Servo-i. For Evita XL it's IPPV + *auto-flow*.
[3] Body Temperature, Pressure, Saturated volume measurements.

For the distal measurements two different volume waveforms were considered: one directly read from the ventilator (V_V) and one calculated by the numerical integration of its flow signal (V_I). Both were reset to zero at the onset of each breath cycle. The BC compensation algorithm of Evita XL gives both, flow and volume, corresponding ideally to a proximal measurement. The same does not apply for Servo-i, which corrects only the volume. In order to adequate volume and flow, a flow waveform (F_Y) correspondent to the compensated volume was calculated offline in accordance to Equation 1:

$$F_Y = \frac{V_T}{V_T + C_{cir}\,\Delta P} F, \quad (1)$$

where Fy is the corrected flow, F is the measured flow, V_T is the preset tidal volume, C_{cir} is the BC compliance as reported by the ventilator and ΔP the median of the difference between inspiratory end-tidal pressure (PIP) and PEEP (ΔP = median(PIP – PEEP)).

Results

The inspired tidal volume errors, relative to the proximal (V_P), for all 4 ventilatory settings and PEEPs, are shown in Figure 1 and 2 for Evita XL and Servo-I respectively. Values are plotted as median and 90 % interval (between 5 and 95 percentile) of the cycles corresponding to the last 2 min of each PEEP step. It can be noted that the Evita XL errors were lower than Servo-i and the highest difference between V_P and distal volumes occurred in PRVC mode (Figure 2).

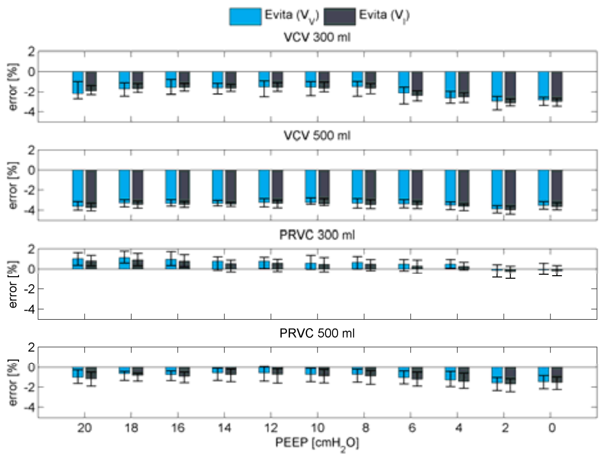

Figure 1–Evita XL inspired tidal volume errors, relative to V_P, for all ventilatory settings. For each PEEP the error was calculated for V_V or V_I and shown as median (bars) and 90 % data intervals (black lines).

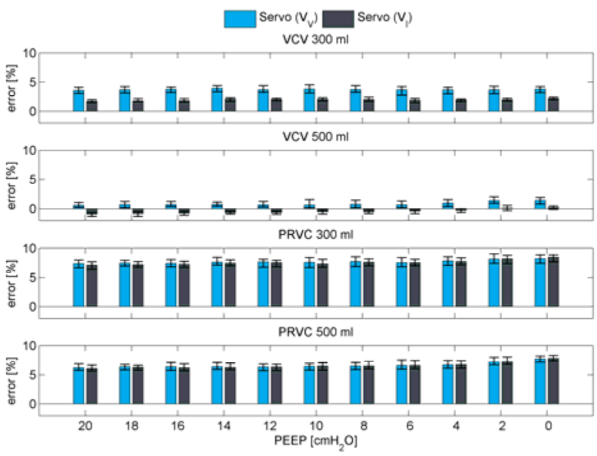

Figure 2– Servo-I inspired tidal volume errors. For details see the legend of Figure 1.

Boxplots of elastance estimates at each PEEP step are shown in Figure 3 for Evita XL and Figure 4 for Servo-i. The RS mechanics were estimated with proximal and distal signals, in this case considering volume as V_V or V_I.

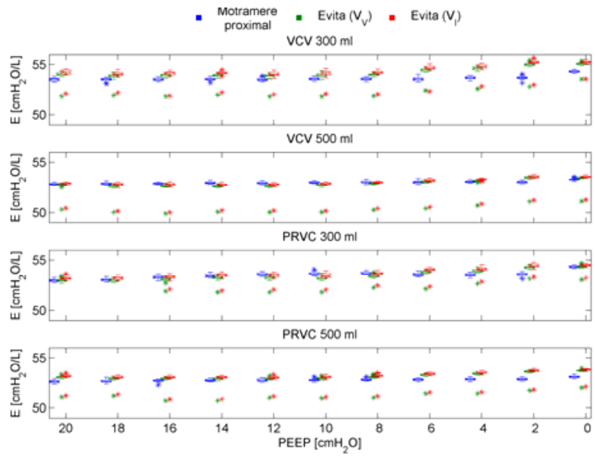

Figure 3 – Boxplots of the estimated elastance during ventilation with Evita XL at each ventilatory setting.

The outliers of elastance distal estimates in Figure 3 are an effect of pressure sensor auto zeroing procedure, which is carried out every 3 min by Evita XL. It also worth noting that difference between distal and proximal elastance estimates was higher in Servo-i.

The resistance estimates are shown in Figure 5 for Evita XL and Figure 6 for Servo-i. Note that the Motramere estimates was consistent among different ventilatory modes and machines and close to the theoretical value of 6.4 ± 1 cmH_2O.s/L. Figure 5 has outliers matching the ones in Figure 3. Opposed to elastance, errors are higher for Evita XL.

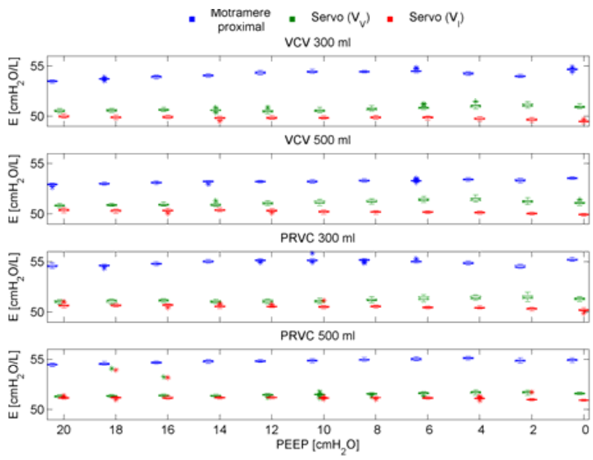

Figure 4 – Boxplots of the estimated elastance during ventilation with Servo-I at each ventilator setting.

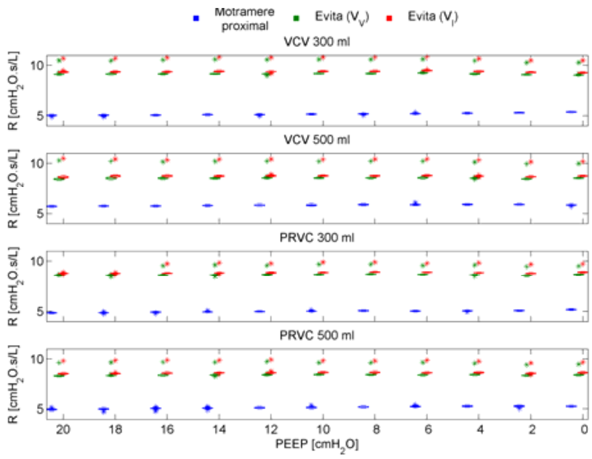

Figure 5 - Boxplots of the estimated resistance during ventilation with Evita XL at each ventilatory setting.

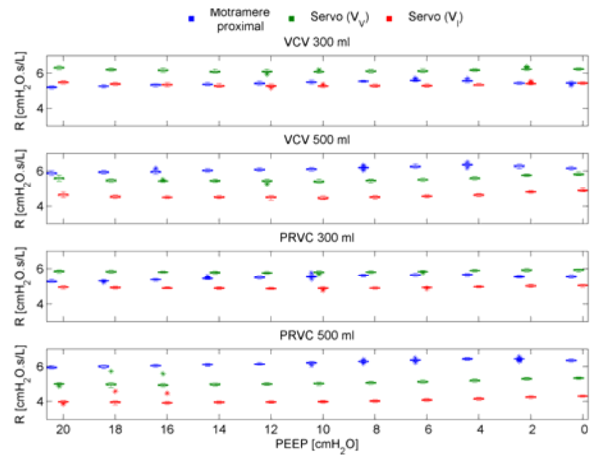

Figure 6 - Boxplots of the estimated resistance during ventilation with Servo-I at each ventilatory setting.

Discussion

Regarding the accuracy, it is expected and known that there is a difference in performance between different machines and ventilators models [10]. Errors obtained between the delivered V_P and distal measurements are lower than reported in previous studies using the same ventilators models during VCV with BC compensation [11], [12], and within the error range declared by the manufacturers. This confirms that the machines were in good condition during the tests. It is also important to note that both V_V have a zero lower limit.

The equivalent deviation of V_V and V_I from V_P, in Figure 1, confirms that flow and volume of Evita XL corresponds, and in Figure 2 shows that the use of Equation 1succeeds in the correction of flow. In this way, Equation 1 is an alternative to make flow and volume waveform compatible for estimating respiratory mechanics with Servo-i. However, an online correction solution is still necessary.

The deviations of volumes and pressures measured by the different instruments can explain the differences of the elastance estimates. But, as can be noted in Figure 3 and 4 its changes between PEEP steps were limited to less than 3 %. This suggests that the elastances obtained by these distal sensors can be employed during a PEEP titration protocol.

Regarding other respiratory mechanics' parameters, the PEEP values were accurately estimated (error < 1 cmH_2O) for all measurement systems and ventilatory modes. On the other hand, the resistance was better estimated with the Motramere signals, being PEEP and mode dependent on distal systems (Figures 5 and 6).

Limitations

The main limitation of this work was that the tests were limited to a constant linear physical lung model. It is known that RS impedance affects the BC compensation performance [11], [12], which can influence the mechanical properties estimates. The elastance estimates were practically independent of PEEP; however, this result cannot be simply generalized to more complex/nonlinear RS [7] with recruitment/overdistension occurring during a PEEP titration. Specific tests should be done in this case.

Conclusion

Monitoring the RS mechanical properties with the digital data output available on mechanical ventilators has advantages over external measurement systems, with potential lower costs and dead space, less instrumentation, increased simplicity and long term stability. However, the BC influence could lead to wrong estimates. Considering Evita XL and Servo-i, the present results indicate that the distal measurement system of both ventilators with BC volume compensation could be used for estimating linear elastance during a PEEP titration maneuver.

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