ASL 5000 lung model fails to simulate preset mechanical parameters during HFJV and volume control ventilation with a decelerating flow waveform in some ventilators

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Abstract

ASL 5000 (IngMar Medical, Pittsburgh, PA, USA) is a widely used computer-controlled active lung model. The model precisely simulates preset mechanical parameters of the respiratory system for a wide range of conventional modes of mechanical ventilation. ASL 5000 lung model fails to simulate the preset mechanical parameters properly for High Frequency Jet Ventilation and for volume control ventilation with a decelerating flow pattern in some ventilators. The unexpected behavior is strongly dependent on the shape of the flow curve, i.e., on the ventilator setting and the ventilator used. The improper behavior occurs for low preset resistances and larger preset compliances of the respiratory system. Even in the case that the ASL 5000 does not simulate the preset mechanical parameters correctly, the delivered tidal volume measured by ASL 5000 is determined very precisely.

1 Introduction

ASL 5000 (IngMar Medical, Pittsburgh, PA, USA) is a computer-controlled active lung simulator popular for many applications including design and testing of ventilators and ventilatory monitors, testing of ventilatory modes and interaction of a ventilator with the patient's lungs, education, training of medical staff and other purposes [1, 2]. ASL 5000 is known as very reliable lung model with a very accurate measurement of delivered tidal volume over a wide range of tidal volumes [3].

Figure 1 Experimental setup when ASL 5000 did not performed well. High frequency jet ventilation of a patient simulator ESC (CAE Healthcare, Montreal, CA) with Paravent P ventilator equipped with a facial mask. ASL 5000 replaced the internal lung model of the ESC.

An unexpected behavior of ASL 5000 lung model was observed during our research of a possible combination of high frequency jet ventilation (HFJV) with a facial mask for non-invasive ventilation during cardiopulmonary resuscitation in the field. The experimental setup (Fig. 1) consisted of a Paravent P (Paravent P, Elmet, CZ) HFJV ventilator connected to a facial mask placed on a patient simulator ESC (CAE Healthcare, Montreal, CA). The original lungs of the ESC simulator were replaced with an ASL 5000 lung model so that various combinations of airway resistance and lung compliance could be used during the performed tests. We observed that the delivered tidal volume (V_T) into the ASL 5000 lung model decreased with increasing preset compliance of the model (Fig. 2).

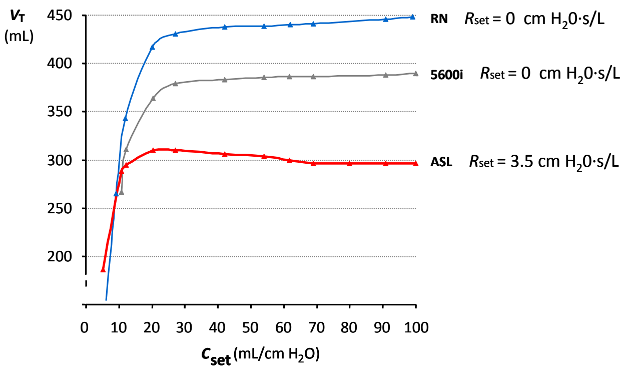

Figure 2 Unexpected decrease in the delivered tidal volume with increasing lung compliance in ASL 5000 lung model compared to other lung models (5600i and a set of rigid lung models RN) during non-invasive HFJV with RR=2 Hz. R_{set}—preset resistance, C_{set}—preset compliance, V_T —delivered tidal volume.

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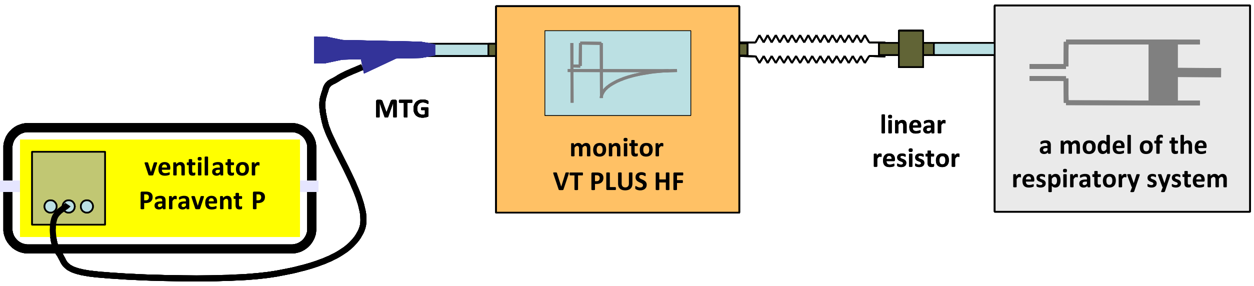

Figure 3 The experimental setup for comparison of behavior of various lung models during mechanical ventilation. MTG—multiple jet generator is a part of the Paravent P ventilator.

When the ASL 5000 was replaced with either 5600i (Michigan Instruments, Grand Rapids, MI, USA) purely mechanical lung model or a set of rigid (glass) lung models covering a range of lung compliances from 5 to 100 mL/cm H_2O, the delivered tidal volume increased with increasing lung compliance as was expected.
The aim of the study is to investigate why ASL 5000 lung model does not deliver the expected tidal volumes during HFJV compared to other lung models.

2 Methods

First, the aim was to determine the ventilatory modes when the ASL 5000 lung model does not simulate preset mechanical parameters properly. Then, the cause of the improper simulation was searched.
AVEA (CareFusion, San Diego, CA, USA) and EVITA XL (Drĕger Medical, Lübeck, DE) ventilators in pressure and volume control modes with constant and decelerating flow waveforms were used. Paravent HFJV ventilator was also used but this ventilator is unable to evaluate mechanical parameters of the connected lung model. The delivered tidal volume was measured using VT Plus HF (Fluke Biomedical, Everett, WA, USA) flow analyzer. The experimental setup for a certain combination of a ventilator and a lung model is depicted in Fig. 3.
In order to eliminate possible imprecision of mechanical parameters measurement by ventilators, we compared behavior of ASL 5000 with other lung models: solely mechanical model 5600i (Michigan Instruments, Grand Rapids, MI, USA) and a set of rigid lung models covering a range of compliances from 10 to 100 mL/cm H_2O. This range of compliances was also set on ASL 5000 and 5600i models. A linear resistor 5 or 20 cm $H_2O{\cdot}s/L$ (Hans Rudolph, Shawnee, KS, USA) was connected to 5600i and the rigid models during testing. The airflow resistance of 3.5, 5 and 20 cm $H_2O{\cdot}s/L$ was preset on ASL 5000.
The following modes of ventilation were used in all the three lung models with various combinations of an airway resistance and a lung compliance for comparison of the models' performance: HFJV, pressure control ventilation and volume control ventilation both with a constant and a decelerating flow waveform. Respiratory rate was set from 5 to 180 min^{-1}. Mechanical parameters of the tested models evaluated by ventilators were recorded when the used ventilatory mode allowed their evaluation.

3 Results

Increased respiratory rate did not cased any difference in behavior of ASL 5000 from the other tested lung models during pressure control ventilation both with constant and decelerating flow patterns and during volume control ventilation with a constant flow in inspirium. The delivered tidal volume (Fig. 4) and the measured compliance of the models (Fig. 5) did not differ between the models.

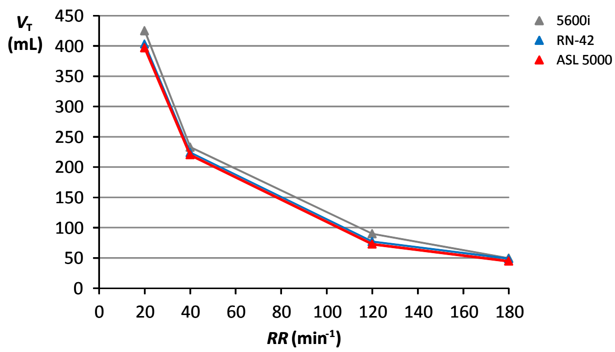

Figure 4 Comparison of delivered tidal volume (V_T) into the models in dependence on respiratory rate (RR). In all models, a compliance of 42 mL/cm H_2O was set. Airway resistance of 5 cm $H_2O{\cdot}s/L$ was set on ASL 5000 or linear resistors of the same value were connected to 5600i and RN-42 lung models.

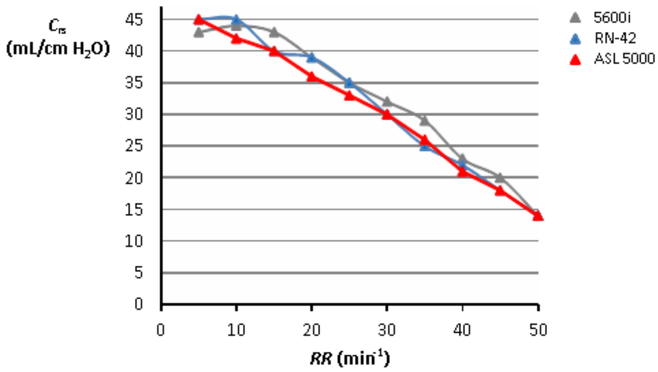

Figure 5 Comparison of compliance evaluated by AVEA ventilator in all three models. The preset parameters were identical as in Fig. 4.

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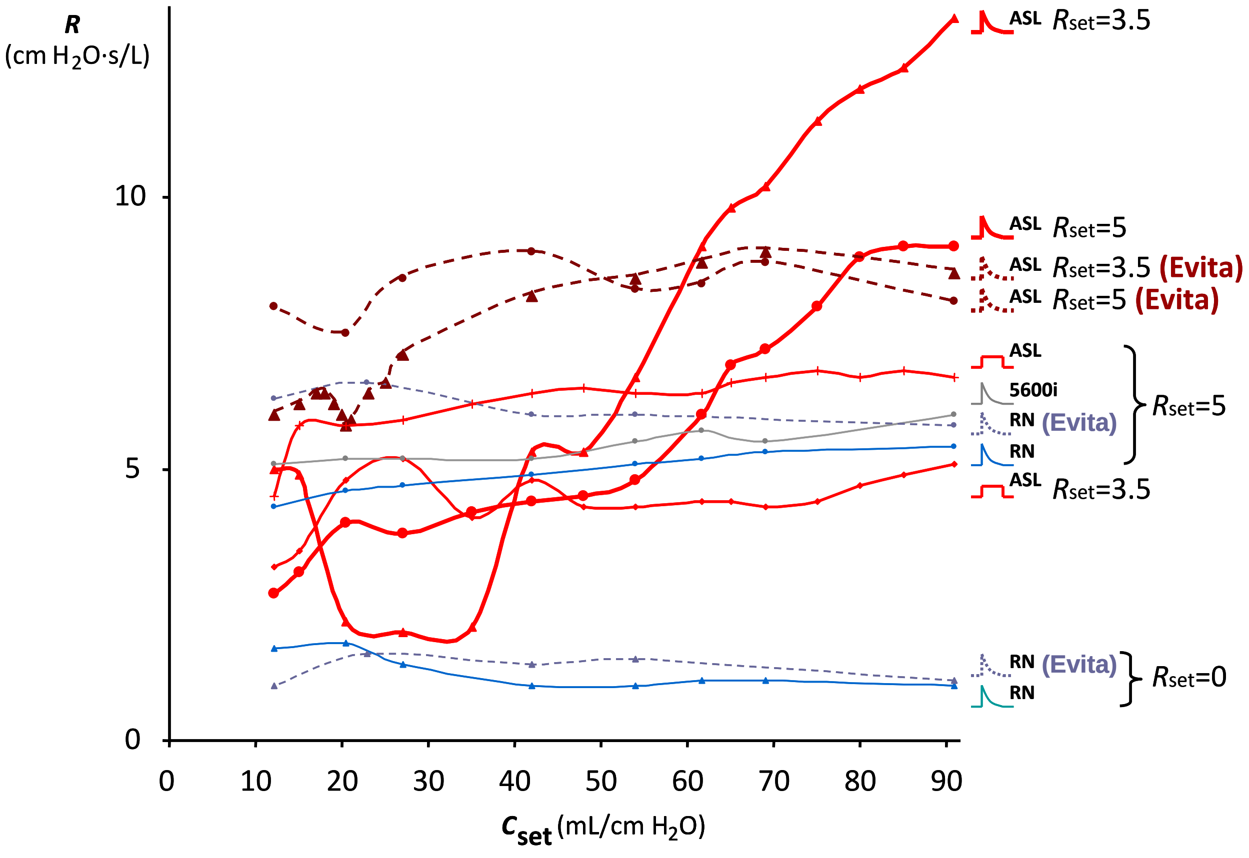

Figure 6 Simulated resistance of the lung models (R) measured by a ventilator in dependence on a preset compliance (C_{set}) whereas the preset resistance of the models (R_{set}) was kept constant. Volume control ventilation with a decelerating ( ) and a constant ( ) flow in inspirium was provided by two ventilators: EVITA (labeled with "Evita") and AVEA (unlabeled). Respiratory rate $RR = 15$ min^{-1}. Lung models tested: ASL 5000, 5600i and a set of rigid lung models (RN).

The unexpected performance of ASL 5000 was recorded during volume control ventilation with a decelerating flow waveform and during HFJV only.

The observed minor error in simulation of compliance could not cause the wrong performance of ASL 5000 as there was only a small difference between simulated (measured by a ventilator) compliance and its preset value in ASL 5000. Furthermore, the simulated compliance was even slightly higher than the preset value and not lower which would be expected due to the decreased delivered tidal volumes.

The simulated airflow resistance, measured by ventilators, was significantly higher than its preset value in ASL 5000. The similar effect was not observed in other lung models tested (Fig. 6).

The error of airway resistance simulation in ASL 5000 depends on three conditions as it is apparent from Fig. 6:

(1) Magnitude of the preset compliance of the model: The higher the preset lung compliance, the higher the difference between the measured airway resistance and its preset value.

(2) Magnitude of the preset airway resistance of the model: The lower the preset resistance of the model, the higher the difference between the measured airway resistance and its preset value.

(3) Ventilatory mode and airflow curve: The significant difference between measured and preset airway resistance in ASL 5000 was observed for volume control ventilation with a decelerating flow waveform, whereas the behavior described above were not observed when a constant flow waveform was selected. Furthermore, much stronger difference between preset and measured airway resistance in ASL 5000 was observed in AVEA ventilator, whereas this difference in Evita XL ventilator was weak but still noticeable.

During the ventilation modes, where ASL 5000 exhibited the error in simulation of airway resistance and therefore unexpected values of delivered tidal volume, there were not a significant difference between delivered tidal volumes measured by the VT Plus HF flow analyzer and the corresponding values of delivered tidal volumes evaluated by ASL 5000 lung model itself (Fig. 7).

No significant difference in performance between ASL 5000 lung model and other lung models tested was recorded during volume control ventilation with a constant flow waveform.

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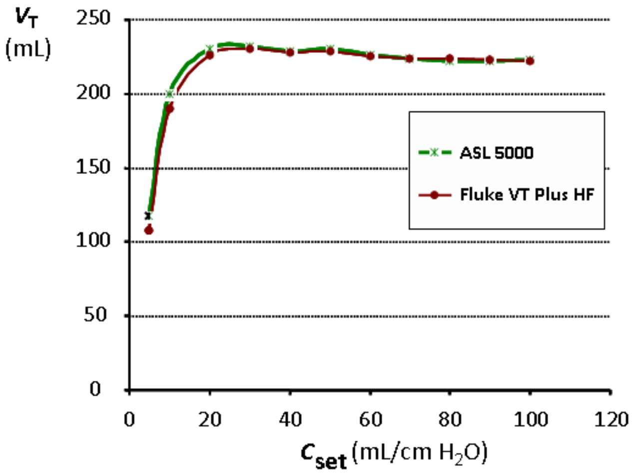

Figure 7 Agreement between delivered tidal volume (V_T) measured by Fluke VT Plus HF flow analyzer and its corresponding value evaluated by ASL 5000 lung model.

4 Discussion

ASL 5000 lung model performs well in a wide range of conventional modes of mechanical ventilation. The unexpected behavior of the model occurs only if sharp peaks of flow rate are present in the airflow signal as it is common for both HFJV and volume control ventilation with a decelerating flow pattern.

The inability to perform well during HFJV may be expected as unconventional HFJV was most likely not considered during the ASL 5000 design.

Even though the simulated mechanical parameters of the respiratory system differ from their preset values in these cases, the delivered tidal volumes evaluated by ASL 5000 correspond with the externally measured values.

The improper simulation of airway resistance and compliance at least partly compensates each other during their joint effect upon the delivered tidal volume. Therefore, the deviations between delivered and expected tidal volumes may not be disturbing. Nevertheless, when a certain or precise simulated value of airway resistance is required, a solely mechanical lung model will serve better than ASL 5000 when a low airway resistance together with a high lung compliance are required.

As a result of a closed-loop control utilized inside the active lung model ASL 5000, the response of the model to any change in airway pressure or airflow is oscillating. The oscillations are typically not apparent on ventilatory monitors as their upper cut-off frequency is often lower than the frequency of the oscillations. Nevertheless, these oscillations present in the airways may interact with the monitoring and control systems of the ventilator and therefore they may affect its close-loop control and contribute to an observed improper performance of the model.

5 Conclusion

Unlike in the majority of ventilatory modes where ASL 5000 performs very well, in some ventilatory modes (HFJV and volume control ventilation with a decelerating waveform) the ASL 5000 lung model does not simulate the preset mechanical parameters of the respiratory system precisely. The inaccurate function of ASL 5000 is caused by its inability to simulate a low preset airway resistance especially when a high compliance of the respiratory system is selected during HFJV and volume control ventilation with a decelerating waveform.

6 Acknowledgment

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