Journal of Mechanical Ventilation

Ventilator circuits mechanics and ventilator compensation

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DOI: https://doi.org/10.53097/JMV10113

Cite: Shokry M, Daoud EG. Ventilator circuits mechanics and ventilator compensation. J Mech Vent 2024; 5(4):134-137.

Abstract

Introduction
Invasive mechanical ventilation usually uses a double limb circuit. However, those circuits are not standardized and usually come from different manufacturers with different lengths, diameters, compliances and resistances. Those differences can affect the delivered tidal volumes and pressures delivered to the patient.
We aimed to test three different circuits to measure their compliance and resistance and measure their effects on delivered tidal volume and airway pressures after being calibrated by the ventilator.

Methods
Descriptive study, three different double limb circuits: separate inspiratory and expiratory limb (Vyaire 72 inch length, 22 mm diameter), separate inspiratory with heated wire and expiratory limb (Fisher and Paykel 71 inch, 22 mm diameter), and separate inspiratory and expiratory limb in one tube (Vyaire length 75 inch and 22 mm diameter). Bellavista 1000e ventilator (Zoll, MA, USA) was used to conduct the experiment with the volume controlled mode, tidal volume 500 ml, inspiratory flow of 30 L/min, PEEP of 5 cmH_2O, respiratory rate of 20 bpm. Leak, resistance and compliance obtained from the ventilator display during circuit calibration.
A passive single lung model with compliance of 80 ml/cmH_2O and resistance of 10 cmH_2O/L/s constructed using lung simulator (ASL 5000) used to measure the delivered the tidal volume, flow, airway pressures (Peak, plateau, PEEP) delivered to calculate the total compliance and resistance and the effect of the circuits.

Results
The three circuits had different compliances and resistances. Separate limbs: compliance of 0.84 ml/cmH_2O, Inspiratory resistance 3.37 cmH_2O/L/s, expiratory resistance 5.54 cmH_2O/L/s resulting in total compliance 84.06 ml/cmH_2O, inspiratory resistance 4.8 cmH_2O/L/s. Separate limbs with heated wire in inspiratory limb: compliance 1.88 ml/cmH_2O, Inspiratory resistance 3.22 and expiratory resistance 4.67 cmH_2O/L/s, resulting in total compliance 82.74 ml/cmH_2O, inspiratory resistance 4.81 cmH_2O/L/s. Double limb in one circuit: compliance 2.25 ml/cmH_2O, Inspiratory resistance 4.07 cmH_2O/L/s, expiratory resistance 4.38 cmH_2O/L/s, resulting in total compliance 82.91 ml/cmH_2O, inspiratory resistance 4.81 cmH_2O/L/s.

Conclusion
The measured compliances and resistances of the circuits differed slightly, however the ventilator compensated well for the differences with minimal difference in the combined total compliances and resistances. Further investigation across a broader range of circuit designs and ventilator models could help establish more standardized guidelines and recommendations for circuit selection in clinical practice.

Keywords: Ventilator circuits, circuit compliance and resistance, ventilator compensation

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Conflict of interest/Disclosures: Non

Introduction

Invasive mechanical ventilation typically utilizes a double-limb circuit, with no leak designed to deliver and return airflow to and from the patient's lungs from the ventilator. However, these circuits are not standardized across manufacturers, leading to variability in characteristics such as length, diameter, compliance, and resistance, which can potentially influence ventilation efficiency, and potentially patient outcomes. [1,2] Variations in circuit compliance and resistance may impact delivered tidal volumes and airway pressures. There are published ISO standards (ISO 5367:2014) [3] that specifies basic requirements for breathing sets and breathing tubes intended to be used with anesthetic breathing systems, ventilator breathing systems.

Ideally the circuit should have low compliance to avoid large volumes of wasted air in the circuit (compressive volume) and low resistance to avoid high pressures to be applied to the patient. [1]

The ventilator circuit is connected to the respiratory system in series, i.e., the final resistance and compliance is the sum of both the circuit and the respiratory system. [4]

Variations in circuit compliance and resistance may impact delivered tidal volumes and airway pressures. New generation ventilators test the circuit tubes before initiation of ventilation and calibrate to compensate for the different compliances, resistances, and leaks. [5]

This descriptive study aims to evaluate the compliance and resistance of three distinct double-limb circuits used in invasive mechanical ventilation and examine their impact on tidal volume delivery and airway pressures using a volume-controlled mode with calibrated settings.

Methods

Three different double limb circuits: separate inspiratory and expiratory limb (Vyaire 72 inch length, 22 mm diameter), separate inspiratory with heated wire and expiratory limb (Fisher and Paykel 71 inch, 22 mm diameter), and separate inspiratory and expiratory limb in one tube (Vyaire length 75 inch and 22 mm diameter). Bellavista 1000e ventilator (Zoll) was used to conduct the experiment with the volume controlled mode, tidal volume 500 ml, inspiratory flow of 30 L/min, PEEP of 5 cmH_2O, respiratory rate of 20 bpm. leak, resistance and compliance obtained from the ventilator display during circuit calibration.

A passive single lung model with compliance of 80 ml/cmH_2O and resistance of 10 cmH_2O/L/s constructed using lung simulator (ASL 5000) used to measure the delivered the tidal volume, airway pressures delivered to calculate the compliance and resistance and the effect of the circuits.

Results

Results are summarized in figure 1.

The three circuits had different compliances and resistances. Separate limbs: compliance of 0.84 ml/cmH_2O, Inspiratory resistance 3.37 cmH_2O/L/s, expiratory resistance 5.54 cmH_2O/L/s resulting in total compliance 84.06 ml/cmH_2O, inspiratory resistance 4.8 cmH_2O/L/s. Separate limbs with heated wire in inspiratory limb: compliance 1.88 ml/cmH_2O, Inspiratory resistance 3.22 and expiratory resistance 4.67 cmH_2O/L/s, resulting in total compliance 82.74 ml/cmH_2O, inspiratory resistance 4.81 cmH_2O/L/s. Double limb in one circuit: compliance 2.25 ml/cmH_2O, Inspiratory resistance 4.07 cmH_2O/L/s, expiratory resistance 4.38 cmH_2O/L/s, resulting in total compliance 82.91 ml/cmH_2O, inspiratory resistance 4.81 cmH_2O/L/s.

Discussion

This descriptive study highlights subtle differences in compliance and resistance across three double limb circuits and demonstrates the ventilator's ability to adjust for these variations, resulting in consistent tidal volume, airway pressures and thus final respiratory mechanics close to the simulated ones. Despite each circuit presenting unique resistance and compliance characteristics, the ventilator's calibration minimized the impact on delivered volumes and pressures. This finding reinforces the reliability of current ventilator calibration functions in compensating for circuit-specific differences.

However, different ventilators do compensate for circuit compliance and resistance in varied ways. Each ventilator has its own calibration method, algorithms, feedback mechanism for circuit calibration and compensation, which can lead to differences in how accurately they deliver set parameters like tidal volume and airway pressures. [6,7] Furthermore, not all home ventilators have a calibration system. [8]

Circuit	2 Separate Limbs	2 Separate limbs with heated wire	Double limb in one circuit
Compliance ml/cmH2O	84.06	82.74	82.91
Resistance cmH2O/L/s	4.8	4.81	4.81

Figure 1: Top: pictures of the ventilator circuits tested. Middle: circuit compliances and resistances as tested by the ventilator. Bottom: table of the final compliances and resistances as tested by the lung simulator. A: Separate limbs, B: Separate limbs with heated wire, C: Double limb in one circuit.

A bench study showed that pressure controlled ventilation allows a more reliable compensation of breathing circuit compressible volume compared to the volume controlled ventilation. [5] We conducted our study with the volume control only to be able to measure the static compliance and resistance using the end inspiratory and end expiratory pause maneuvers. [9] Another bench study [10] examined the effect of inspiratory effort on the circuit compensation in volume targeted modes and found that the ventilator corrected the delivered tidal volume for volume lost due to compression in the patient circuit as expected but the compensation volume decreased as airway pressure drops due to patient effort. Additionally, the delivered tidal volumes, airway pressures and hence the measured respiratory mechanics might differ according to the ventilator used. A bench study showed that the types and location of the sensors used by the ventilator might make a difference in the delivered tidal volumes and pressures. [11]

Limitations: we only tested three circuits and one ventilator which limits our observation and can't be generalized to all circuits and ventilators. We did not add any filters or HME or use heated water during the experiment to be able to measure the effects of the circuits alone, however this might affect the results in real life situations where all those additional equipment are added to the circuit. This is a descriptive study with no statistical methods or power to make any conclusion about the superiority of one circuit over the others.

Conclusion

Despite the good compensation by the ventilator in our study, clinicians should still be aware of the potential for minor compliance and resistance variability across circuit types, and different ventilators as these could become relevant in more complex situations. Further investigation across a broader range of circuit designs and ventilator models could help establish more standardized guidelines and recommendations for circuit selection in clinical practice.

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