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Evaluation of Intensive Care Mechanical Ventilator Response Time During Varying Levels of Inspiratory Effort

Honors Thesis

Presented to The Honors College of Salisbury University

in Partial Fulfillment of the Requirements for Graduation with University Honors

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Abstract

Objective: Mechanical ventilators must be responsive to a patient's variable inspiratory demand. Responsiveness is one attribute used to compare these expensive, but necessary lifesaving devices. Under varying levels of inspiratory effort, triggering performance was compared between the Maquet Servo-i and Respironics Esprit ventilators.

Methods: The Ingmar ASL 5000 Breathing Simulator was used to provide normal respiratory mechanics (compliance of 50 mL/cm H_2O; resistance, 3 cm H_2O/L/s; spontaneous rate of 15 breaths/min) and inspiratory muscle pressures of 10, 15, and 20 cm H_2O for 5-minutes each. The simulator was connected to each ventilator with the same settings (pressure support (PS) of 10 cm H_2O; positive end-expiratory pressure (PEEP) of 0; and, a trigger flow of 3 L/min). Trigger response time, time from spontaneous effort (SoE) to a minimum pressure (Pmin), and the maximum pressure drop during triggering were collected.

Results: The Esprit ventilator trigger response time and time from SoE to a Pmin decreased under conditions of increased inspiratory effort. The Servo-i trigger response time and time from SoE to Pmin increased with rising inspiratory muscle pressure. Both ventilators demonstrated a greater maximum pressure drop during triggering with each increase in inspiratory muscle pressure. However, for an inspiratory muscle pressure of 15 and 20 cm H_2O, the drop in pressure was much larger for the Servo-i.

Conclusions: Both ventilators are suitable for clinical use, however, the Respironics Esprit ventilator demonstrated a better response to a high ventilatory demand. A potential reason for this is the greater peak inspiratory flow rate (PIFR) capability of the Esprit ventilators. The Esprit's internal flow generator is a turbine and seems to be capable of a faster initial flow than the pneumatic flow design of the Servo-i.

Introduction

The goal of mechanical ventilation is to provide adequate oxygenation and ventilation in order to reduce a patient's work of breathing. Different modes of ventilation can provide either partial or full breathing support for the patient. The timing of breath delivery during mechanical ventilation is dependent upon the set mode and the internal triggering mechanisms of the specific ventilator.

Assist control is a traditional mode of ventilation that provides full ventilatory support by manipulating a volume delivery target or pressure delivery target. These methods are referred to as Assist Control-Volume Control (ACVC) and Assist Control-Pressure Control (ACPC) respectively. Full ventilatory support does not require a patient to have any respiratory effort; however, when a respiratory effort is present, patients often require sedation to maintain synchrony with the ventilator. The common use of sedatives in conjunction with mechanical ventilation could be minimized with proper ventilator settings to match a patient's ventilatory demand. ACVC has a ventilator set tidal volume which guarantees that the patient receives that volume of gas with each delivered breath. This mode of ventilation is used when a minimum minute ventilation needs to be maintained through a guaranteed respiratory rate (breaths delivered/min) and tidal volume. In ACPC, a prescribed pressure (cm H_2O) above positive end-expiratory pressure (PEEP) is set in addition to a respiratory rate. Each breath results from the application of the prescribed pressure, which effects tidal volume delivery. Although the same pressure is applied during each breath, the volume of gas entering the lungs will vary depending on the patient's lung compliance, resistance, and inspiratory effort. As a result, minute ventilation will vary in this mode.

Respiratory mechanics are dictated by compliance and resistance. Lung compliance is a determination of how readily the lungs accept the volume of gas being delivered. Emphysema is an example of a pathology exhibiting abnormally high compliance. In this disease process, the lungs will easily accept the volume of gas being delivered since they have lost elasticity. Lungs with low compliance resist the volume of gas being delivered since the lungs show characteristics often referred to as "stiff." Acute respiratory distress syndrome (ARDS) is an example of a pathology that exhibits reduced compliance. Pressure-controlled breaths are often used for patients who have decreased lung compliance in order to manage pressures delivered to the lungs, thereby reducing the risk of iatrogenic barotrauma. Iatrogenic barotrauma can occur when a healthcare provider provides ventilator settings that over-distend the alveoli in the lungs, resulting in a pneumothorax or acute lung injury. Lung resistance to airflow increases when bronchospasm or copious secretions are present in the airways.

Pressure Support Ventilation (PSV) is an adjunct of ventilatory assistance that provides partial support since it requires the patient to breathe spontaneously. The patient may receive a positive end-expiratory pressure (PEEP), which improves oxygenation by creating an increased surface area for gas diffusion. When a patient spontaneously inhales, a triggering mechanism activates the pressure support, sending pressure and resulting flow to the patient's lungs. When the inspiratory flow meets a preset minimal flow, the ventilator will stop delivering the inspiratory pressure and flow, thereby allowing the patient to exhale passively. It is important to consider that an increased level of pressure support will help the patient inspire a larger tidal volume. This could be essential for maintaining proper minute ventilation, or detrimental by causing barotrauma. Pressure supported breaths also serve the purpose of overcoming the airway resistance of breathing through an endotracheal tube with a small internal diameter.

Patients in the ICU often have a variable inspiratory demand. This can mean that there are vast changes in the volume of gas being inhaled with each breath or that they are "air hungry" and want a breath as quickly as possible. This introduces the component of a peak inspiratory flow rate (PIFR), which is the maximum flow delivered by the ventilator during a breath. An air hungry patient will require a higher PIFR in order to be more comfortable on the ventilator. This is because a high PIFR will deliver a faster initial flow resulting in the majority of gas delivery during the beginning of each breath, thereby satisfying air hunger. PIFR in pressure support ventilation (PSV) is dynamic and determined by patient demand. Appropriate PSV settings will provide a more normal respiratory pattern, which improves patient comfort if the pathophysiology for which they are intubated allows them to achieve adequate minute ventilation during partial breathing support (McGee, Frechette, & Dailey, 2011). Monitoring the average PIFR a patient is generating guides the clinician in determining proper ventilator settings should the patient need full ventilatory support.

Variable inspiratory demand can be the result of pain, acid-base imbalance, abnormalities to the respiratory system, or from injury to the brain. This raises the question of how ventilators perform against a patient with variable inspiratory demand. A previous study done by Olivieri, Costa, Conti and Navalesi (2012) indicated that inspiratory demand can affect ventilator breath delivery in terms of trigger response time, sensitivity, and pressurization. In order to determine the effect of variable ventilatory demand on ventilator responsiveness, triggering performance between two ICU ventilators, the Maquet Servo-I and Respironics Espirit were evaluated under varying levels of inspiratory effort in pressure support ventilation.

Significance

Patient-ventilator synchrony is important in maintaining the life support necessary for a ventilated patient. Synchrony is impacted by the ventilator's ability to efficiently detect a spontaneous breath from a patient and provide the proper pressure and flow so the patient can have a breath that satisfies their inspiratory demand. If a patient's inspiratory demand is not being met, they will become asynchronous from the ventilator.

According to Thille, Rodriguez, Cabello, Lellouche and Brochard (2006), patient-ventilator asynchrony is "defined as a mismatch between the patient and ventilator inspiratory and expiratory times" (p. 1515). It is inevitable that there will be a time delay in recognizing patient effort as technology has not progressed to the point where breath delivery will occur as soon as a patient begins to inhale. There are several patterns of asynchrony that a patient may develop while on a ventilator. Ineffective triggering can occur if a patient has a weak inspiratory effort or intrinsic PEEP due to lung hyperinflation. With this, breath delivery fails to activate, imposing a higher muscle workload on the patient as they attempt to trigger a breath. In cases of high ventilatory demand, a patient may double trigger the ventilator since inspiratory time and PIRF are inadequate. Another pattern of asynchrony is auto-triggering. This occurs when the ventilator falsely interprets leaks in the ventilators circuit or cardiogenic oscillations as an inspiratory effort and delivers a breath (Thille et al., 2006).

Patient-ventilator asynchrony causes obvious discomfort to the patient, leading to respiratory distress. Although changes in ventilator settings may reduce discomfort, this usually introduces the use of sedatives. However, sedation should be avoided if possible, as a study by Kress, Pohlman, O'Connor and Hall (2000) found that daily spontaneous awakening trials, which is when sedation is turned off and a neurological examination is performed, decreased the duration of mechanical ventilation and the length of stay in the intensive care unit. Minimizing ICU length of stay and duration of mechanical ventilation is important in improving patient outcomes. This emphasizes the importance of effective triggering mechanisms in mechanical ventilators in order to maximize patient comfort.

Methods

Lung Model and Ventilators

The Ingmar Active Servo Lung 5000 lung simulator is capable of mimicking many encountered types of pulmonary physiology through the manipulation of its respiratory mechanics. The ASL 5000 was set to normal respiratory mechanics (compliance of 50 mL/cm H_2O; resistance, 3 cm H_2O/L/s; spontaneous rate, 15 breaths/min; inspiratory rise time of 30%; and, an inspiratory release time of 10%). For both ventilators, data were collected from a 5-minute evaluation period under each varying level of inspiratory muscle pressure of 10, 15, and 20 cm H_2O.

Two intensive care mechanical ventilators were evaluated; the Maquet Servo-i and the Respironics Esprit. Both ventilators were connected to the lung simulator with a standard patient circuit under the same settings (pressure support of 10 cm H_2O; positive end-expiratory pressure (PEEP) of 0; a trigger flow of 3 L/min; and, an inspiratory cycle off of 30%).

Ten breaths were then taken from the last minute of the evaluation period. This was to allow the lung model to stabilize in each test condition, which takes approximately

2-3 minutes (Dexter, McNinch, Kaznoch, & Volsko, 2018). Trigger response time, time from spontaneous effort (SoE) to a minimum pressure (Pmin), and the maximum pressure drop during triggering were analyzed to assess ventilator responsiveness. Triggering performance was evaluated utilizing the ASL software algorithms and the data from the ten selected breaths from each testing condition were imported into excel and calculated for the mean values.

Measured Variables

Trigger response time (TRT) is defined as the time in milliseconds for the pressure to fall and rise back to baseline during an inspiratory effort. This parameter is important because it is an indicator of the ventilators ability to detect a patient's effort to breathe and apply sufficient inspiratory flow to meet their demand (Ferreira, Chipman, & Kacmarek, 2008). It also is a measure of the "inspiratory work required to trigger the ventilator; therefore, the lower its value, the smaller the work required of inspiratory muscles" (Battisti et al., 2005, p. 1785). Time from SoE to Pmin is defined as the time in milliseconds from the start of an inspiratory effort (SoE) to the lowest airway pressure (Pmin) needed to trigger the ventilator. This is a measure of the ventilators ability "to sense inspiratory effort and open the inspiratory flow valve" (Ferreira et al., 2008, p. 1673). The maximum pressure drop during triggering, measured in cm H_2O, is another parameter measuring the inspiratory muscle workload required to trigger ventilator breath delivery. This is important to measure since the magnitude of pressure drop is proportional to inspiratory effort.

Results

Trigger response time for the Maquet Servo-i and the Respironics Esprit trended in opposite directions of each other. The Esprit TRT decreased with each subsequent increase in inspiratory muscle pressure, whereas TRT for the Servo-I increased (see figure 1). Similarly, with time from SoE to a Pmin, the Respironics Esprit demonstrated a decrease in time with an increase in inspiratory muscle pressure, whereas the time in the Maquet Servo-i increased (see figure 2).

Both ventilators demonstrated a greater maximum drop in pressure during triggering with each increase in inspiratory muscle pressure. For an inspiratory muscle pressure of 10 cm H_2O, both ventilators had a similar average of -0.30 cm H_2O in the Esprit and -0.33 cm H_2O in the Servo-i. However, for inspiratory muscle pressures of 15 cm H_2O and 20 cm H_2O, the maximum drop in pressure was much larger for the Servo-I (see figure 3). Tables 1-3 provide the mean values for each measured variable under their respectable level of inspiratory muscle pressure.

Table 1. Mean Values for an Inspiratory Muscle Pressure of 10 cm H_2O

Ventilator	Trigger Response Time (ms)	Time from Soe to Pmin (ms)	Maximum Pressure Drop (cm H_2O)
Servo-i	73	59	-0.33
Esprit	62	54	-0.30

Table 2. Mean Values for an Inspiratory Muscle Pressure of 15 cm H_2O

Ventilator	Trigger Response Time (ms)	Time from Soe to Pmin (ms)	Maximum Pressure Drop (cm H_2O)
Servo-i	76	61	-0.60
Esprit	56	51	-0.43

Table 3. Mean Values for an Inspiratory Muscle Pressure of 20 cm H_2O

Ventilator	Trigger Response Time (ms)	Time from Soe to Pmin (ms)	Maximum Pressure Drop (cm H_2O)
Servo-i	79	63	-0.86
Esprit	54	46	-0.55

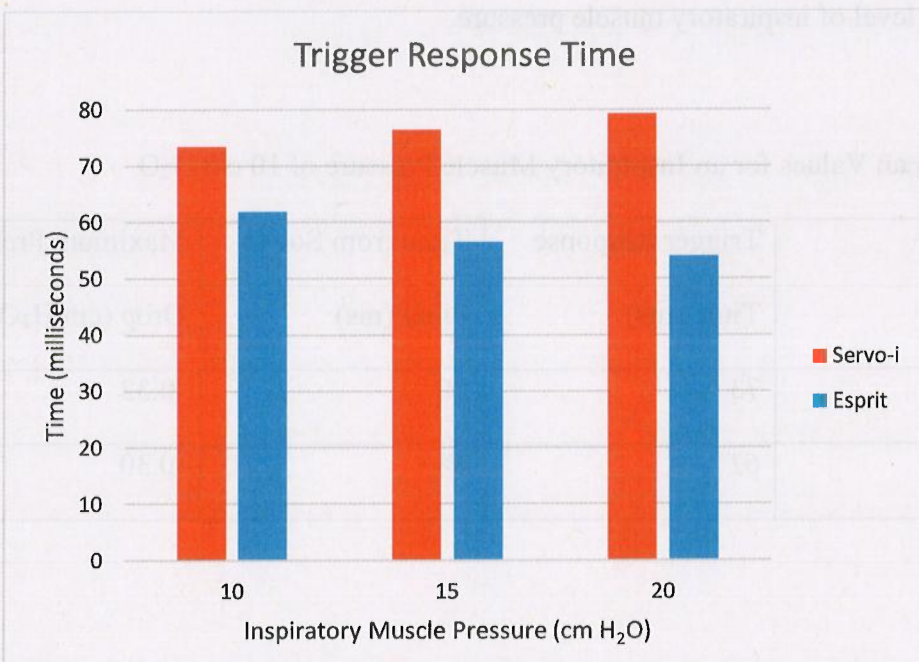

Figure 1. Mean Trigger Response Time

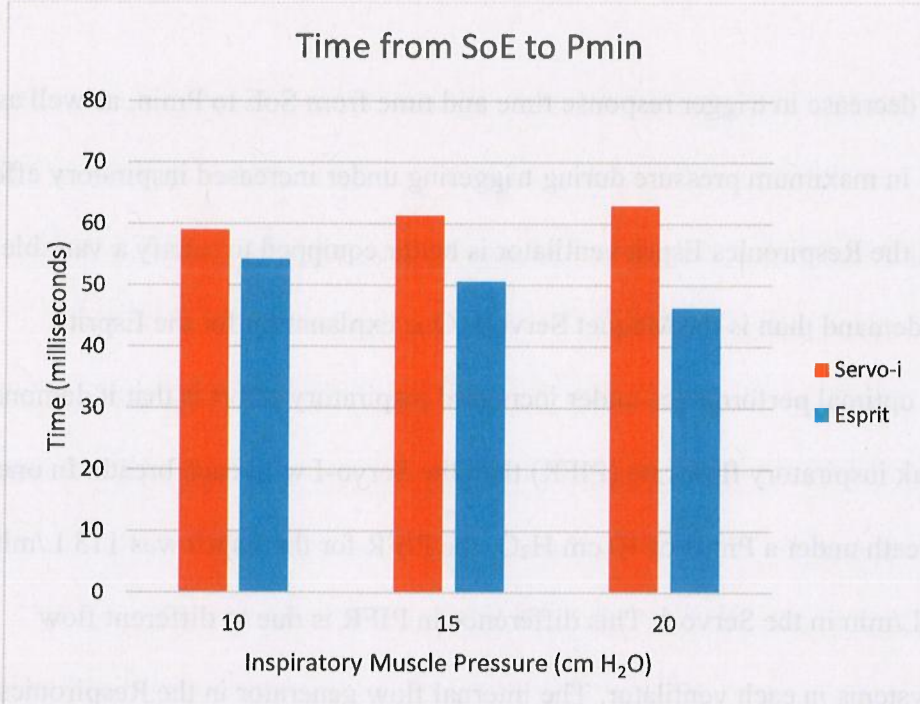

Figure 2. Mean from SoE to Pmin

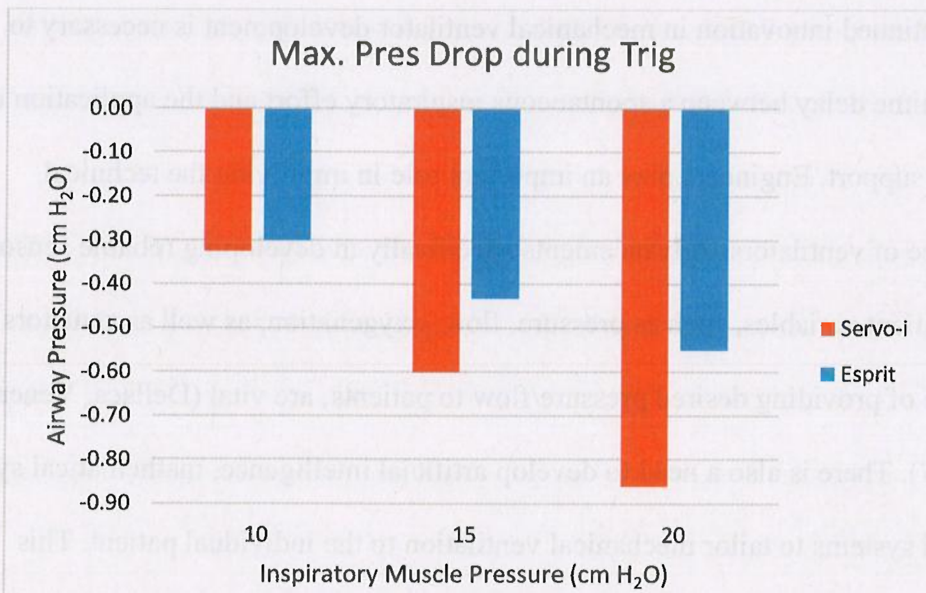

Figure 3. Mean Maximum Pressure Drop during Triggering

Discussion

The decrease in trigger response time and time from SoE to Pmin, as well as lower drops in maximum pressure during triggering under increased inspiratory effort, suggest that the Respironics Esprit ventilator is better equipped to satisfy a variable ventilatory demand than is the Maquet Servo-i. One explanation for the Esprit ventilator's optimal performance under increased inspiratory effort is that it demonstrated a higher peak inspiratory flow rate (PIFR) than the Servo-I with each breath. In one analyzed breath under a Pmus of 10 cm H_2O, the PIFR for the Esprit was 113 L/min versus 105 L/min in the Servo-i. This difference in PIFR is due to different flow generator systems in each ventilator. The internal flow generator in the Respironics Esprit is a turbine, which is capable of delivering a higher initial flow over the pneumatic gas system in the Maquet Servo-i.

Continued innovation in mechanical ventilator development is necessary to reduce the time delay between a spontaneous inspiratory effort and the application of ventilatory support. Engineers play an important role in improving the technical performance of ventilators. Advancements specifically in developing reliable sensors to measure patient variables, such as pressure, flow, oxygenation, as well as actuators which are capable of providing desired pressure/flow to patients, are vital (Dellaca, Veneroni, & Farre, 2017). There is also a need to develop artificial intelligence, mathematical systems, and control systems to tailor mechanical ventilation to the individual patient. This requires a multidisciplinary approach since engineers may not know the intricacies of respiratory pathophysiology.

Conclusions

All mechanical ventilators must undergo bench studies to determine if they meet the safe minimum human usage threshold as determined by the FDA. Many bench studies have indicated that a trigger response time <100 ms is deemed clinically satisfactory, as it is below the conscious threshold of inspiratory effort (Battisti et al., 2005). Although both the Maquet Servo-i and the Respironics Esprit mechanical ventilators are suitable for clinical use, this study suggests that the Esprit is better equipped to support patients with high ventilatory demand in the context of the studied variables.

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