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Tidal volume measurement error in pressure control modes of mechanical ventilation: A model study☆

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ABSTRACT

Tidal volume (V_T) measurement during pressure control (PC) ventilation with preset inspiratory time may produce errors due to patient inspiratory effort. We evaluated V_T error in 3 common ICU ventilators.
Methods: Simulated patient: 60 kg adult with ARDS using IngMar Medical ASL 5000 having moderate inspiratory effort. Ventilators evaluated: Covidien PB 840, Maquet Servo-i, and Dräger Evita XL, PC breaths at preset inspiratory time (T_I) 0.6–1.4 s. V_T error was defined as ventilator displayed V_T minus the simulator displayed V_T (mL/kg or % of true).
Results: Relaxation of inspiratory effort caused flow reversal (exhalation) during T_I, which led to V_T error. For the PB 840, V_T error was proportional to T_I (maximum −2.0 mL/kg, −19%). For the Servo-i, V_T error was not related to T_I (maximum error −0.2 mL/kg or −1.2%). Volume error for Evita XL was not related to T_I (maximum error was −0.7 mL/kg or −6%).
Conclusions: Calculation of V_T as the integral of flow over the preset inspiratory time rather than the period between zero crossings of flow may result in underestimation of both inhaled and exhaled volumes. The size of V_T error can be large enough to potentially affect patient outcomes on some ventilators.

1. Introduction

Modern intensive care ventilators are often designed with what is called an “active exhalation valve” [1]. This means that during pressure control ventilation, the patient is free to inhale and exhale during the preset inspiratory time. This feature may increase patient comfort as the preset inspiratory time becomes long relative to the patient's neural inspiratory time (i.e., duration of inspiratory effort), an extreme case being the mode called Airway Pressure Release Ventilation.

Inspiratory tidal volume is defined as the integral of flow over the inspiratory time, i.e., the period from the start of positive (inspiratory) flow to the start or negative (expiratory) flow [2]. Expiratory tidal volume is defined in a similar way but using the period of negative flow. In other words, the time periods for calculating tidal volume are defined by zero crossing of flow (or flow reversals). However, some ventilators calculate tidal volume (V_T) as the integral of flow over the inspiratory time *preset* on the ventilator, independent of actual flow reversals. For a passive patient during pressure control ventilation, these time intervals coincide. However, if the patient makes an inspiratory effort during the preset inspiratory time, and the duration of effort is less than the preset inspiratory time, then as the effort decreases (i.e. muscles relax and muscle pressure, Pmus, decreases) flow reverses (from positive to negative) and volume is exhaled due to the active exhalation valve feature. Thus, if the ventilator uses the preset inspiratory and expiratory times for calculating volume, the displayed V_T will be underestimated, because the true inspired tidal volume is the maximum value of the change in lung volume relative to the end expiratory value.

This situation of “flow reversal” during pressure control ventilation was described by Crooke et al. in 1998 [3]. In the presence of flow reversal, the true tidal volume is the integral of flow between points of zero flow (i.e., the period representing the patient's “neural inspiratory time”). In contrast, integration over the preset inspiratory time leads to underestimation of the tidal volume because it subtracts the volume that escapes through the active exhalation valve (during inspiration) or never recognizes it in the first place (during expiration). If a ventilator does this, it will display a lower “measured” volume than delivered resulting in a *volume error*. This volume error is, in effect, an inadvertent overdose of tidal volume. Clinically, the consequence of overdosing with tidal volume may be ventilator-induced lung injury [4]. Unfortunately, the effect of overdosing is difficult to discern from the “expected” injury from receiving mechanical ventilation in

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vulnerable patients. Therefore, the potential magnitude of volume error is an important ventilator performance characteristic.

The purpose of this paper was to describe the performance of two common algorithms for calculating tidal volume, one using inspiratory/expiratory times based on flow reversal and one using preset inspiratory/expiratory times (independent of flow reversal), as implemented on three different ventilators.

2. Methods

2.1. Simulation parameters

This study was conducted using an IngMar Medical ASL 5000 breathing simulator (sw 3.4). The simulation model used by the simulator can be represented by a simplified form of the equation of motion for the respiratory system:

$$P_{vent}(t) + P_{mus}(t) = \frac{1}{C}V(t) + R\dot{V}(t)$$

In this equation, the variable functions of time (t) are symbolized as: P_{vent} = transrespiratory pressure difference (i.e. pressure at the airway opening minus pressure on the body surface), displayed as airway pressure on a ventilator, V = volume, $\dot{V}$ = flow. P_{mus} is the effective transrespiratory pressure generated by the simulated muscles that a patient would use for inspiration. These variables are measured relative to their end expiratory values (eg, PEEP, FRC, and zero respectively). The constants in the equation are compliance ($C = \Delta V/\Delta P$) and resistance ($R = \Delta P/\Delta \dot{V}$). The simulator allows separation of inspiratory from expiratory resistance (R_{in} vs R_{out}, respectively) because expiratory resistance is generally larger than inspiratory resistance.

The simulator was programmed with a *lung model* (parameters R and C) to represent the respiratory system mechanics of a 60 kg (ideal body weight) adult patient with Acute Respiratory Distress Syndrome based on previously published data [5,6]. Lung model parameters used for the study were: R_{in} = 11 cm H_2O/L/s, R_{out} = 16 cm H_2O/L/s, C = 29 mL/cm H_2O.

An *effort model* (P_{mus} function) represented a breathing patient. Inspiratory effort was simulated as the amplitude of inspiratory muscle pressure, Pmus, (set on the simulator as P_{max}, in cm H_2O). A moderate effort was used, sufficient to produce about 50% of an unassisted tidal volume. The duration of effort is defined by the simulator as the "increase percent" setting times the ventilatory period. The increase percent is the percent of ventilatory period (reciprocal of frequency) during which the simulated inspiratory effort is increasing or held constant. For example, at a frequency of 25 breaths/min, the period is 60/25 = 2.4 s and the duration of effort for a preset P_{mus} increase of 30% is 2.4 × 0.3 = 0.72 s. For our simulation, the basic effort model was: unassisted tidal volume = 249 mL, breathing frequency = 25/min, P_{max} = 10 cm H_2O, increase = 30%, hold = 0%, release = 20%. The effort model screen of the ASL 5000 breathing simulator is shown in Fig. 1.

In preliminary testing, we discovered that only one ventilator (Covidien PB 840) demonstrated clinically important volume error due to using a volume calculation algorithm based on preset inspiratory/expiratory times. We expanded the simulation testing for this ventilator to better understand the probability of observing volume error with different effort models. The simulation parameters were modified to include a wider range of inspiratory effort (P_{mus}). We are aware of only one study that actually measured Pmus during mechanical ventilation [6]. From that study we determined that the smallest expected Pmus was 5 cm H_2O ("low

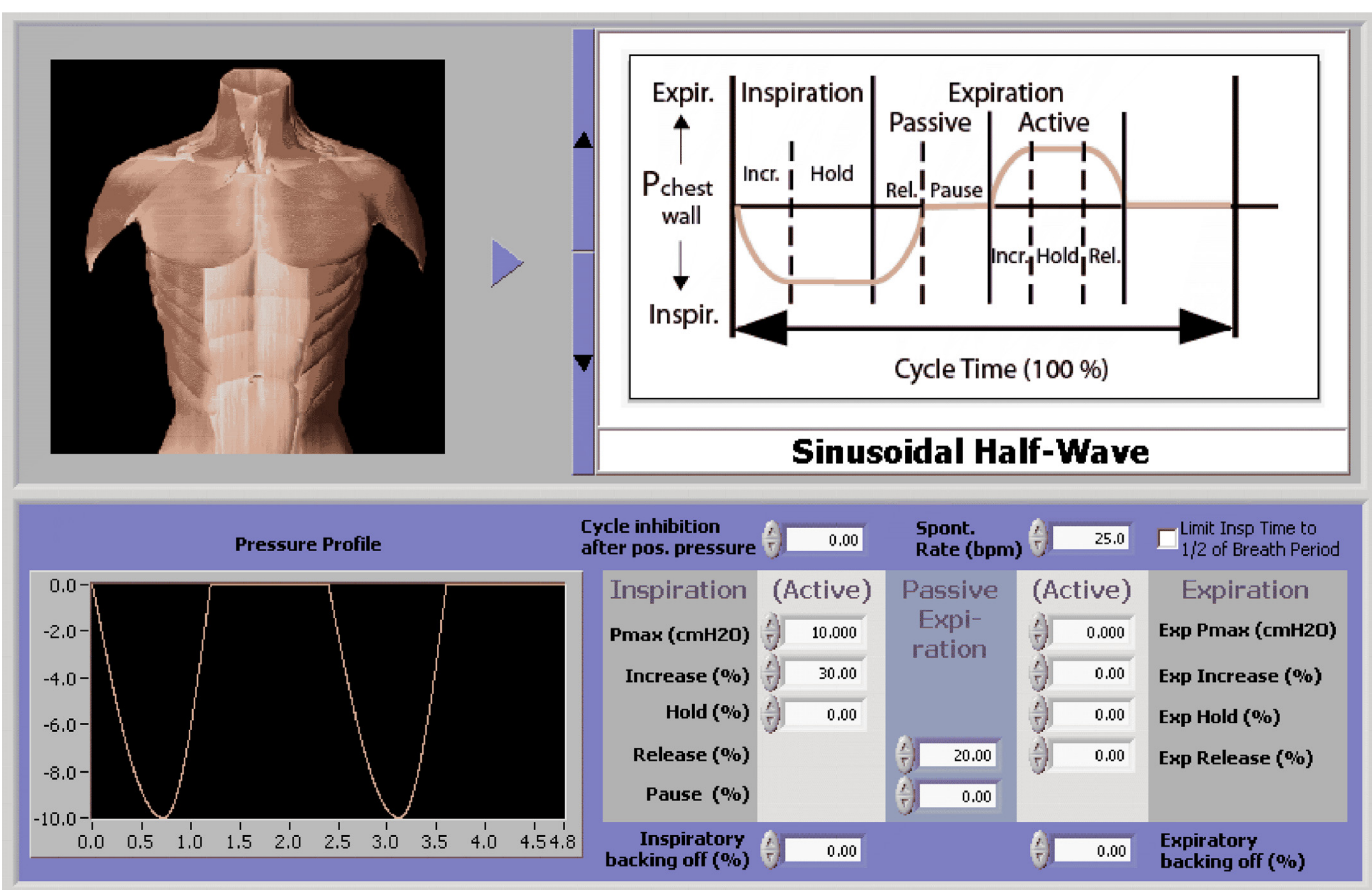

Fig. 1. Screen shot of the ASL 5000 Breathing Simulator effort model.