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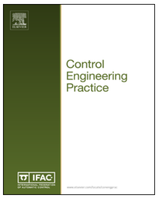

Performance of variations of the dynamic elastance model in lung mechanics

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ABSTRACT

Acute respiratory distress syndrome (ARDS) is associated with high mortality and it is a major clinical problem. A common therapy for ARDS patients is mechanical ventilation (MV). However, poorly applied MV can be potentially fatal and optimal MV settings are patient specific. Thus, choosing a good positive end expiratory pressure (PEEP)-level compromise is a clinical challenge. Physiological modeling of the lung is one way to support the selection of the optimal settings for mechanical ventilation.

This research makes the reasonably well-supported assumption that optimal PEEP is in the region of minimal elastance of the lung-tissue. The first order model of pulmonary mechanics (FOM) was modified in two differing ways in order to determine the patient-specific pressure range that coincides with minimal elastance. The extensions to the FOM (multiplicative elastance correction and additive volume correction parameters) are compared and evaluated.

The addition of the correction parameters ultimately improved the consistency of the modeled elastance across PEEP levels for most patients tested. The results for minimal elastance were in very similar ranges for both approaches. Although this consistency offers a partial validation of the robustness of the approaches, discernment of the optimal approach cannot be determined. Further validation across differing patient states and experimental inputs must be undertaken to determine which method is more representative of true patient physiology.

1. Introduction

Acute respiratory distress syndrome (ARDS) captures a variety of pulmonary dysfunctions. It was first described in the late 1960s by Ashbaugh et al., (1967). Due to the wide range of etiology and pathogenesis, ARDS is noted for its complexity and heterogeneity. The causes of ARDS can include pneumonia, sepsis, trauma, asthma, chronic obstructive pulmonary disease (COPD), pancreatitis, burns, and near drowning. The pathologic syndromes include edema (alveolar and interstitial) and fibroses (Donahoe, 2011; Silversides & Ferguson, 2013). ARDS remains a major clinical problem with ambiguous understanding of the benefits of different treatment approaches, and little consensus within the clinical community regarding the optimal treatment of ARDS patients.

Mechanical ventilation (MV) is an essential therapy for ARDS patients. The current general MV approach is known as lung protective ventilation, which uses low tidal volumes (6 ml/kg) and higher positive end-expiratory pressure (PEEP) levels (Afifi, 2002). Studies have reported that these settings in combination with recruitment maneuvers decrease the mortality and the recovery-time of patients (Halter et al., 2003; Lellouche & Lipes, 2013). However, some studies have claimed that the influence of PEEP (Brower et al., 2004) or recruitment maneuvers (Kacmarek & Villar, 2011) on outcome/final patient mortality is small.

Furthermore, some research has hypothesized that a higher PEEP may be a compromise that balances recruitment and overdistension (Ambrosio et al., 2012). Higher PEEP and recruitment maneuvers induce alveolar recruitment and keep the alveoli open during expiration. This recruitment strategy increases alveolar oxygenation (PaO_2, FiO_2), but will also increase the probability of ventilator induced lung injury (VILI), which can involve lung inflammation due to over-distention (mechanotransduction mechanism (Sutherasan et al., 2014)), circular depression, edema, or other pathophysiologic effects. Hence, the selection of optimal

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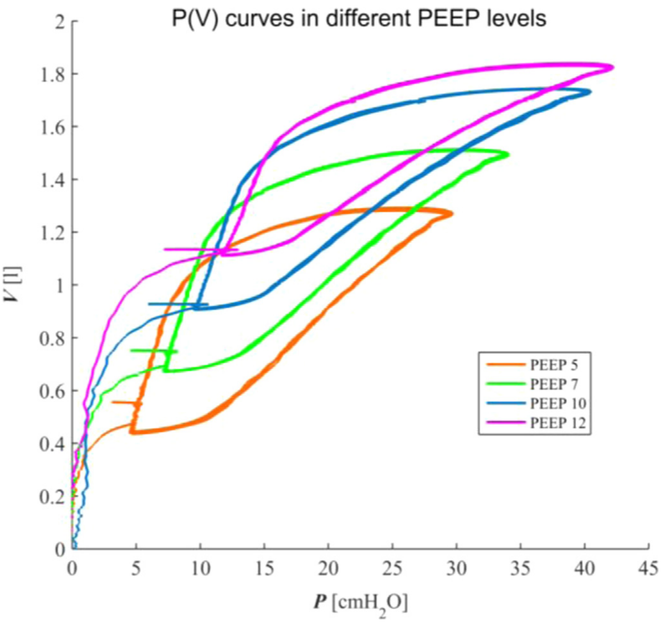

Fig. 1. $P(V)$ curves of different PEEP levels of Patient 10 (Bersten).

PEEP-level remains a challenge.

Studies have been carried out to determine the optimal lung protective ventilation by finding a minimal elastance range (Amato et al., 1998). Some such studies have implied that optimal ventilator settings would be in the region of minimal elastance (Chiew et al., 2011; Guttmann et al., 1994; Suter et al., 1975). In particular, minimal elastance range would minimize the energy transferred to the lung by mechanical ventilation. Chiew et al. showed that the energy is equal to the weighted sum of patient specific resistive and elastance terms (Chiew et al., 2011). Furthermore, their strategy states that minimizing the energy transferred to the lung by mechanical ventilation could potentially be used to determine the optimal PEEP level. Since energy transfer is proportional to elastance and tidal volume, minimal energy transfer could be achieved for a given tidal pressure by setting the PEEP level such that the pressure range exists in the minimal region of a patient specific elastance/pressure curve.

In this study, the concept introduced by Chiew et al., (2011) is further developed via the introduction of terms that link pressure dependent elastance ($E(P)$) across PEEP levels. In particular, two different approaches are proposed and investigated to determine the minimal $E(P)$ by using different extensions to a single compartment lung model (Fig. 1). It is hypothesized that models that can determine behavior across multiple PEEP levels can capture patient specific information that could eventually help clinicians provide individualized care for ARDS patients (Hahn et al., 2009; Le et al., 2010; Smith et al., 2005).

2. Methods

2.1. Patients and clinical protocol

This comparison study was based on the retrospective clinical data of Bersten (1998), where 12 patients with different levels of lung injury or ARDS were included ventilated in square wave profile volume controlled mode at 3 or 4 different PEEP levels. As described in the study of Sundaresan et al. (2011), which was based on the same dataset, Bersten et al. reported 10 patients in this paper. However, an additional two patients were not reported due to limited PV loops recorded. These data sets include PV loops (Harris, 2005) (see Fig. 1) for each patient at a minimum of three different PEEP values with a measured dynamic functional residual capacity (dFRC). PEEP was applied and held for 30 min before sampling was done. During the final 60 s, the data was then sampled at 100 Hz. After approximately 40 s of tidal ventilation at PEEP, the ventilator is then set to zero end expiratory pressure (ZEEP), allowing the lung to deflate to functional residual capacity FRC. In this study the last 6 breathing cycles before the reduction to ZEEP were analyzed as they provided a steady-state.

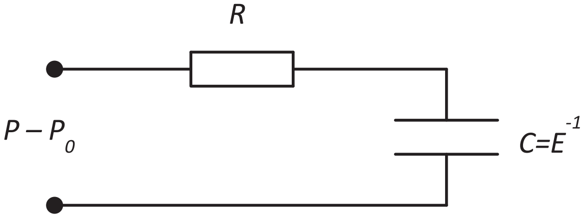

Fig. 2. The first order model (FOM) of pulmonary mechanics.

2.2. Models

Ockham's razor implies that, in the absence of contrary evidence, the simplest model of pulmonary mechanics is best to describe the respiratory behavior of the lung. Hence, the first order model (FOM) was defined. The airway passage is symbolized by a single resistance and the tissue property of the lung and airways is described by a capacitance (or inverse elastance). The FOM equation is shown in Eq. (1) and the electrical analogy is shown in Fig. 2.

$$P=E(V-V_0)+R\dot{V}+P_0 \tag{1}$$

where P is the airway pressure, E is the respiratory system elastance, V is the volume, V_0 is the offset volume, R is the respiratory system resistance,$\dot{V}$ is the flow and P_0 is the offset pressure.

However, the first order model was not intended to fully capture all of the behavior of the breathing process. van Drunen et al. (2014) extended the FOM by introducing a pressure-variant dynamic elastance ($E(P)$), considering R to be constant. $E(P)$ was determined after constant E and R values were determined by linear regression over a single breath. The evaluation of $E(P)$ was determined using

$$E(P)=\frac{P-P_0-R\dot{V}}{V-V_0} \tag{2}$$

But the application of this approach caused a shift between the elastance curves of different PEEP levels and no continuous prediction curve for $E(P)$. Therefore in this study, further enhancements of the first order model employed two different extensions of the dynamic elastance model.

The first method is the α-method, which introduces multiplicative correction terms according to the PEEP levels (Knörzer et al., 2014)

$$E(P)=\frac{P-P_{0,i}-R\dot{V}}{\alpha_i(V-V_0)} \tag{3}$$

where α_i was the correction factor at a given PEEP level ($P_{0,i}$), $i=1\ldots n$ and n is the number of PEEP levels.

Hence, if $\alpha_{i+1}>\alpha_i$, the model indicates alveoli recruitment in at the higher PEEP-level ($i+1$) and $\alpha_i>\alpha_{i+1}$ denotes derecruitment at higher PEEP. The second method tested is the β-method, which introduces a consistent shift to $E(P)$ according to the PEEP level

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