Informatics in Medicine Unlocked 12 (2018) 44–55

Contents lists available at ScienceDirect

Informatics in Medicine Unlocked

journal homepage: www.elsevier.com/locate/imu

Patient-specific optimization of mechanical ventilation for patients with acute respiratory distress syndrome using quasi-static pulmonary P-V data

Mohsen Nabian[a,*], Uichiro Narusawa[a,b]

[a] Department of Mechanical and Industrial Engineering, Northeastern University, Boston, MA, USA
[b] Department of Bio-engineering, Northeastern University, Boston, MA, USA

ARTICLE INFO

Keywords:
P-V curve
P-V model equation
Mechanical ventilation
Recruited volume
Respiratory system model
Positive end-expiratory pressure (PEEP)
Acute respiratory distress syndrome (ARDS)
Ventilator-induced lung injury (VILI)

ABSTRACT

Quasi-static, pulmonary pressure-volume (P-V) curves were combined with a respiratory system model to analyze tidal pressure cycles, simulating mechanical ventilation of patients with acute respiratory distress syndrome (ARDS). Two important quantities including 1) tidal recruited volume and 2) tidal hyperinflated volume were analytically computed by integrating the distribution of alveolar elements over the affected pop-open pressure range. We analytically predicted the tidal recruited volume of four canine subjects and compared our results with similar experimental measurements on canine models for the validation. We then applied our mathematical model to the P-V data of ARDS populations in four stages of Early ARDS, Deep Knee, Advanced ARDS and Baby Lung to quantify the tidal recruited volume and tidal hyperinflated volume as an indicator of ventilator-induced lung injury (VILI). These quantitative predictions based on patient-specific P-V data suggest that the optimum parameters of mechanical ventilation including PEEP and Tidal Pressure (Volume) are largely varying among ARDS population and are primarily influenced by the degree in the severity of ARDS.

1. Introduction

Since the early definition of acute respiratory distress syndrome (ARDS), a multitude of clinical studies have been published on such subjects as the use of pressure-volume (P-V) curves for mechanical ventilation of patients with ARDS [22,23,35,36,46,58,66], PEEP (positive end-expiratory pressure) vs. ZEEP (zero end-expiratory pressure) and a degree of PEEP for effective ventilation [4,10,15,19–21,27,29,31,37–39,45,47,49,50,60]. Also large-scale ARDS ventilation trials [14,34,43] were conducted to investigate effective mechanical ventilation strategies to prevent hyperinflation and ventilator-induced-lung injury (VILI) [13,17,24,48,51,56,57,61,69] while maintaining sufficient oxygenation. Although these experimental studies have significantly contributed to the optimization of mechanical ventilation and thus the decrease in the mortality rate of ARDS patients, majority of these studies investigated for ”one-size-fits-all” values of PEEP and tidal volume for the entire ARDS population [8,11]. This generalization is criticized by many studies [10,19,24,38,39,45,50,60] that suggest patient-specific PEEP and tidal volume values for the optimization of mechanical ventilation.

Analytical modelings of respiratory system were investigated in Refs. [59] and [9] by developing a statistical model of the inflation process with a power-law distribution of the airway openings. Since then, the modeling studies of the respiratory system and/or the mechanical ventilation include a non-linear circuit model for the mechanical ventilation [47], an application of a sigmoidal P-V equation [65] to optimize the mechanical ventilation [41,60], an examination of lung compliance during the mechanical ventilation [27], and a development of a recruitment function from the P-V curve [32]. Many previous investigations [10,18,19,24,38,39,45,50,54,60] also pointed out needs for balancing alveolar recruitment and hyperinflation as well as for information on ventilation strategy more applicable to individuals than to population.

In Refs. [40,42], quasi-static pulmonary P-V curves along with a respiratory system model developed in Refs. [5–7] were analyzed for the patients with ARDS, canine models and healthy humans to propose four stages of ARDS.

In this paper we aimed to contribute to the researches in the optimization of mechanical ventilation by combining the quasi-static pulmonary P-V curves of individuals with the respiratory system model developed in Refs. [5–7] to further analyze mechanical ventilation of ARDS patients under the hypothesis that our respiratory system model yields quantitative prediction of tidal recruited volume and tidal hyperinflated volume.

We first analytically predicted the tidal recruited volume of four canine subjects as function of PEEP and compared our results with a

* Corresponding author.
E-mail address: monabiyan@gmail.com (M. Nabian).

https://doi.org/10.1016/j.imu.2018.06.003
Received 28 April 2018; Received in revised form 5 June 2018; Accepted 6 June 2018
Available online 19 June 2018

similar experimental measurements on canine models. We then applied our mathematical model to four stages of ARDS (Early ARDS, Deep Knee, Advanced ARDS and Baby Lung) defined in Ref. [42] to quantify the tidal recruited volume and tidal hyperinflated volume. Our quantitative predictions of these two parameters in various ARDS patients suggest that the optimum parameters of mechanical ventilation including PEEP and Tidal Pressure (or Tidal Volume) are largely varying among ARDS population and are primarily influenced by the degree in the severity of ARDS.

2. Background

2.1. Respiratory system model (RSM)

A proposed P-V model equation [5–7] in the form of error-function is (See Fig. 1(c)):

$$V = V_U - \frac{\Delta V}{2} + \frac{\Delta V}{2} \cdot erf\left(\frac{\sqrt{\pi}}{4}\Lambda \cdot \left(\frac{P}{P_0} - 1\right)\right) \tag{1}$$

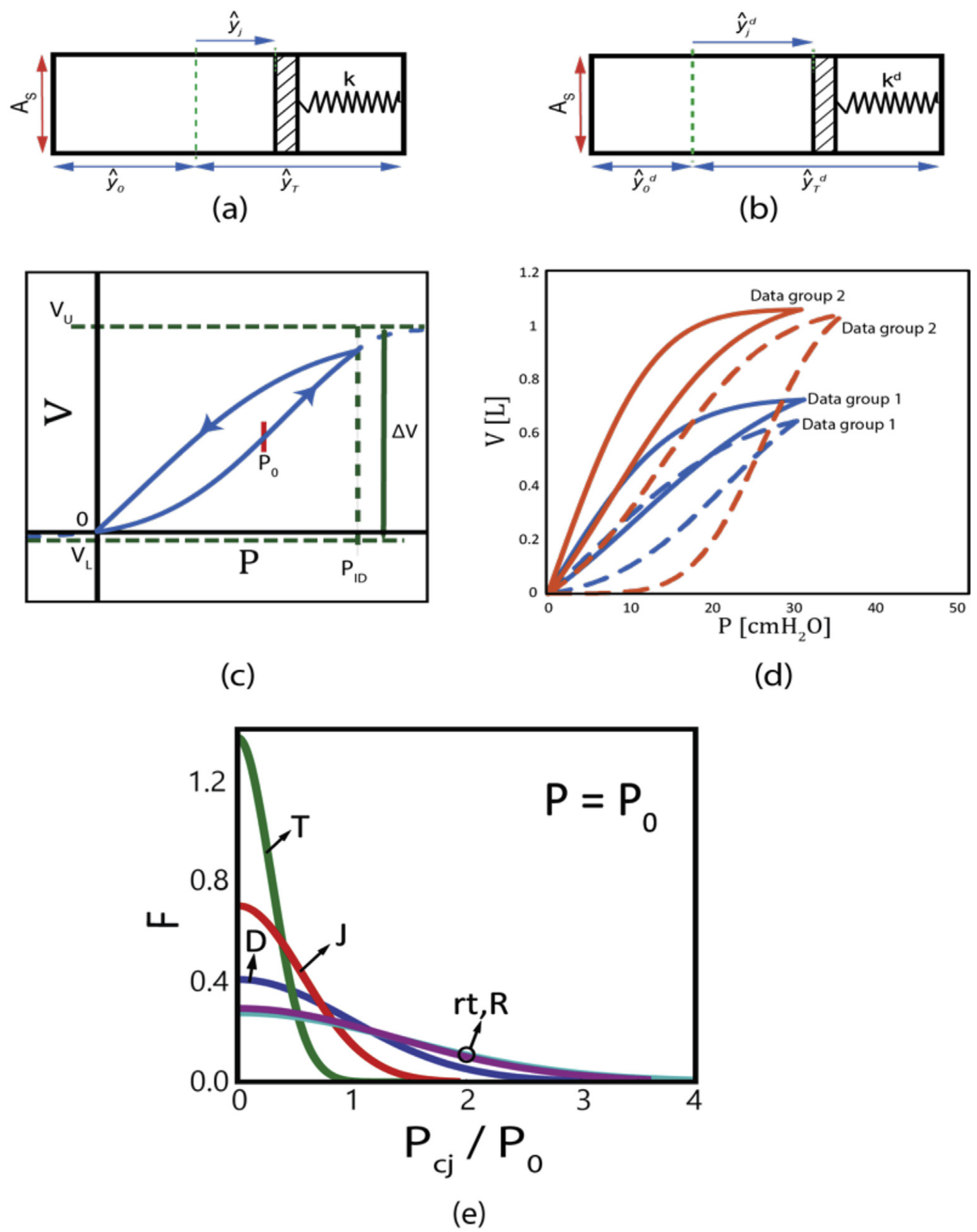

Fig. 1. (a) Alveolar element for inflation: The element pops-open as its pressure exceeds the P_{cj}. $A_s\hat{y}_0 = \hat{V}_0$ (pop-open volume of an element), $A_s\hat{y}_T = \hat{V}_{distension}$ (volume increase due to elastic wall distension). (b) Alveolar element for deflation. Superscript, d, indicates properties of deflation. (c) Quasi-static inflation-deflation P-V curve. V_U = upper volume asymptote (total lung capacity), V_L = lower volume asymptote, ΔV (=$V_U - V_L$) = vital lung capacity, P_0 = pressure at the midpoint of P-V curve, P_{ID} = pressure at the intersection of inflation- and deflation-curve. (d) P-V curves of Data group 1 and Data group 2 (solid = Before Injury, dotted = After Injury). (e) Normalized distribution of alveolar elements at $P = P_0$. Data sets D, J, R, T of Data group 3 (ARDS) and Data set rt of Data group 5 (healthy human).