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# MODEL-BASED VENTILATOR SETTINGS IN PRESSURE CONTROLLED VENTILATION

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***Abstract:*** *Mathematical models of respiratory mechanics can be used to optimize ventilatory settings. This paper presents an approach to calculate patient-specific ventilator settings during pressure controlled ventilation. The proposed algorithm identifies the 1st Order Model of respiratory mechanics and calculates ventilator settings that provide a defined alveolar minute ventilation with minimal inspiration pressure and allow sufficient expiration time to avoid the build-up of intrinisic PEEP. The results can also be used to visualize the nonlinear relation of ventilation parameters. Retrospective comparison of calculated ventilator settings in clinical data indicated high concordance to clinically optimized ventilator settings. The proposed algorithm and visualization uncovers the nonlinear interaction of ventilation parameters and supports the determination of individualized ventilator settings. The algorithm minimzes inspiration pressure necessary to achieve a predefined minute ventilation, which may be a useful approach in optimizing lung-protective ventilation.*

***Keywords:*** *Model-based Therapy, Optimized Ventilator Setting, Respiratory Mechanics*

## Introduction

Mechanical ventilation carries the risk of ventilator-induced lung injury (VILI), caused by excessive stress and strain to the lung tissue [1]. To minimize the risk of VILI, ventilator settings should be adapted to the individual breathing mechanics of the patient. Currently there is no general consensus about the "ideal" ventilation strategy for preventing VILI. However, there is evidence that considering individual lung properties might be beneficial [2]. Thus, mathematical models of respiratory mechanics can be used to quantify the characteristics of the respiratory system leading to personalized optimized ventilator settings [2]. This paper presents an approach to calculate and illustrate the influence of patient-specific ventilator settings during pressure controlled ventilation (PCV) to maintain a preset minute ventilation. Finally, ventilator settings with minimal inspiration pressure and sufficient inspiration and expiration time can be selected to minimize alveolar stress and to avoid the build-up of intrinsic PEEP.

## Methods

The alveolar ventilation is the effective part of the applied minute ventilation (MV) penetrating the regions of the lung where gas-exchange occurs. Alveolar ventilation depends on the dead-space volume $V_D$, the tidal volume $V_T$ and the respiratory rate ($RR$):

$$\dot{V}_A = (V_T - V_D) \cdot RR \tag{1}$$

$V_D$ can be approximated using the estimated patient's ideal body weight ($iBW$).

$$V_D = 2\frac{mL}{kg\ iBW} \tag{2}$$

To calculate the required tidal volume to maintain the desired alveolar ventilation, Eq. 1 is rearranged using the inspiration and expiration time ($t_I$ and $t_E$) to represent $RR$:

$$V_T = \frac{\dot{V}_A}{RR} + V_D = \dot{V}_A(t_I + t_E) + V_D \tag{3}$$

The tidal volume in Eq. 1 can be simulated by using a patient-specific model of respiratory mechanics and the applied airway pressure as the defined input signal.

**Respiratory mechanics model:** The 1st Order Model (FOM) of respiratory mechanics is a serial arrangement of a resistive element ($R$) and a compliant compartment ($C$). The FOM is given as a transfer function:

$$H(s) = \frac{V(s)}{p_{aw}(s)} = \frac{C}{1 + sRC} \tag{4}$$

**Model simulation:** During PCV a pressure signal according to Figure 1 is applied by the ventilator. The initial phase for $t < t_R$ and can be described as follows:

$$p_{aw,Ramp}(t) = \frac{p_I - PEEP}{t_R} \cdot t \tag{5}$$

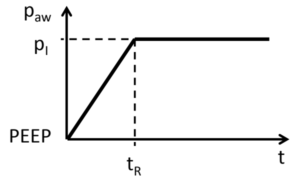


Figure 1: $p_{aw}$ during inspiration phase in PCV

The entire pressure signal during inspiration is constructed by using a step-function $\sigma(t)$:

$$p_{aw}(t) = p_{aw,Ramp}(t) + \sigma(t - t_R)[-p_{aw,Ramp}(t) + p_I - PEEP] \tag{5}$$

The resulting volume as output signal can be derived in Laplace-Domain by multiplying the transfer function and the Laplace-transferred input signal:

$$V(s) = L\{p_{aw}(t)\} \cdot H(s) \tag{6}$$

By an inverse Laplace-Transformation the resulting tidal volume can be derived in the time-domain for $t > t_R$.

Table 1: Patient characteristics with applied ventilator settings ($t_R = 0.2$ s) together with identified model parameters and calculated ventilator settings ($t_R = 0.2$ s).

| Pat. | Height | Diagnosis | *alv.Vent* *(L/min)* | $p_{I,Set}$ *(cmH₂O)* | *PEEP* *(cmH₂O)* | $t_{I,Set}$ *(s)* | $t_{E,Set}$ *(s)* | *R* *(cmH₂O·s/L)* | *C* *(mL/cmH₂O)* | $\tau_E$ *(s)* | $p_{I,Calc}$ *(cmH₂O)* | $t_{I,Calc}$ *(s)* | $t_{E,Calc}$ *(s)* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 170 | Trauma, mod. ARDS | 7.0 | 30.0 | 15.0 | 2.0 | 3.0 | 14.5 | 51.2 | 0.92 | 29.1 | 1.5 | 2.8 |
| 2 | 163 | Gold IV Sepsis | 5.9 | 25.0 | 7.0 | 0.8 | 1.8 | 15.6 | 25.9 | 0.45 | 20.7 | 0.9 | 1.4 |

$$V_T = V(t = t_I) = \frac{C}{t_R} e^{-\frac{t_I}{RC}} (PEEP - p_I) \left[ RC \left( e^{-\frac{t_R}{RC}} - 1 \right) - t_R e^{\frac{t_I}{RC}} \right] \qquad (7)$$

**Calculating ventilator settings:** To find the relation of inspiration pressure and inspiration time to meet the calculated tidal volume in Eq. 3, Eq. 7 is rearranged in terms of inspiration pressure.

$$p_I = \frac{RC^2 \left( e^{\frac{t_R}{RC}} - 1 \right) PEEP - t_R e^{\frac{t_I}{RC}} (C \cdot PEEP + V_T)}{C \left[ RC \left( e^{\frac{t_R}{RC}} - 1 \right) - t_R e^{\frac{t_I}{RC}} \right]} \qquad (8)$$

Patient-specific ventilator settings with respect to sufficient expiration time require an expiration time being at least three times the time constant during expiration $\tau_E$ [3]. Thus, $p_I$ is calculated for for two different $t_E = 3 \cdot \tau_E$ and $t_E = 4 \cdot \tau_E$ and two different $t_R$, being 0 and 0.2 s for various $t_I$ in the range of 0.1 to 4 s.

**Model identification:** The patient-specific parameters *R* and *C* were determined by fitting the FOM to inspiratory data of measured PCV-cycles using multiple linear regression method. $\tau_E$ is estimated by fitting an exponential function to the expiratory flow data.

**Analysis of clinical data:** Data sets of two ventilated patients in PCV from a previous clinical trial were used for this analysis (Table 1). Written informed consent had been obtained from the patients. The clinical ventilator settings had been optimized by experienced ICU-physicians to provide a clinically acceptable minute ventilation with minimal $p_I$ while avoiding the build-up of intrinsic PEEP. The recorded data were used to identify the model as described and the algorithm calculated ventilator settings that would yield the same alveolar minute ventilation.

## Results

After estimating *R*, *C* and $\tau_E$ of the ventilated patients (Table 1), the nonlinear relation between the ventilator settings of $p_I$ and $t_I$ for $t_E = 3 \cdot \tau_E$ and $4 \cdot \tau_E$, and $t_R = 0.0$ s and 0.4 s were obtained (Fig. 2). Obviously, these relations show a unique minimum for $p_I$. Longer $t_E$ and longer $t_R$ lead to higher $p_I$ to maintain the same alveolar ventilation. Additionally, the effect of $t_R$ on $p_I$ is more dominant in regions of shorter $t_I$ and gets smaller with increasing $t_I$. The clinical settings in Patient 1 (Fig. 2, left) indicate, that the patient was ventilated with $t_E$ being in the region of $3 \cdot \tau_E$. To minimize $p_I$, $t_I$ could be reduced from 2.3 to 1.8 s. Patient 2 (Fig. 2, right) was ventilated with $t_E \approx 4 \cdot \tau_E$. The applied $p_I$ could be decreased from 25 $cmH_2O$ to 21 $cmH_2O$ by shortening $t_E$ to $3 \cdot \tau_E$ and $t_I$ from 1.4 s to 0.9 s.

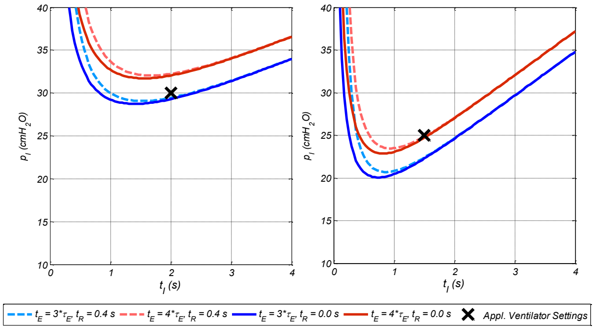


Figure 2: Patient-specific relation of ventilator settings. $p_I$ over $t_I$ to achieve a defined alveolar ventilation, for various $t_E$ and $t_R$ (left: Patient 1, right: Patient 2)

## Discussion

The methodology proposed offers clinically acceptable patient-specific suggestions of ventilator settings that are directly applicable at the ventilator. The settings at minimal $p_I$ could be considered as lung-protective as mechanical stress may be minimized and additionally the risk of intrinsic-PEEP build-up is reduced. The visualization of the nonlinear interaction of ventilator settings can be helpful for the clinician to get an impression on the quality of ventilation and to find a direction for further optimization to following therapeutic goals. The nonlinear relation of ventilation parameters becomes transparent and may support the determination of optimized ventilator settings that consider the individual lung physiology.

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## Bibliography

[1] J. D. Ricard, D. Dreyfuss *et al.*, “Ventilator-induced lung injury,” *Curr Opin Crit Care,* vol. 8, no. 1, pp. 12-20. 2002.

[2] S. E. Rees, C. Allerød *et al.*, “Using physiological models and decision theory for selecting appropriate ventilator settings,” *J Clin Monit Comput,* vol. 20, no. 6, pp. 421-9, Dec. 2006.

[3] M. S. Lourens, B. van den Berg *et al.*, “Expiratory time constants in mechanically ventilated patients with and without COPD,” *Intensive Care Med,* vol. 26, no. 11, pp. 1612-8, Nov. 2000.