Evaluation of a Model based Optimization Algorithm for Pressure Controlled Ventilation

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Abstract: Mechanical ventilation as a life-saving therapy on intensive care units may lead to severe side effects such as ventilator induced lung injury, when settings are not adapted to the patient. A recently developed algorithm provides model-based individualized ventilator settings for pressure controlled ventilation to meet pre-defined minute ventilation values. This algorithm that delivers exact results given perfect data is now tested in an experimental setup consisting of two glass bottles representing a respiratory mechanics test-lung that is connected to a mechanical ventilator. Various target minute ventilation values are defined and corresponding settings were calculated. A mean compliance of C of 80.8 mL/mbar (SD = 1.8) and resistance of 6.8 mbar·s/L (SD = 0.94) were estimated. Based on these estimates appropriate settings were calculated and the predefined MV values could be reached with a mean deviation of -2.1% (SD = 3.6%). The calculated ventilator settings consider the given physiology and can be immediately applied at the ventilator to provide predefined minute ventilation values.

Keywords: pressure controlled ventilation, evaluation, optimization.

Introduction

Mechanical ventilation is a life-saving therapy on intensive care units (ICU), but has the risk of severe side effects leading to ventilator induced lung injury (VILI) [1, 2]. To minimize the risk of VILI, the ventilator settings should be adapted to the patient’s lung condition. Therefore, mathematical models of respiratory mechanics can be used to capture the physiology of an individual patient. The basic 1st Order Model (FOM) of respiratory mechanics relates airway pressure and flow rate by considering respiratory mechanics as a serial arrangement of resistive element (R) and compliant compartment (C). Furthermore, airway pressure and flow rate during expiration can be described by an exponential function using an expiratory time constant $\tau_E$. These parameters are patient-specific and can be determined by parameter identification methods. Using patient-specific values of $R$, $C$ and $\tau_E$ allows calculating individualized ventilator settings for pressure controlled ventilation (PCV). Such an algorithm was recently proposed and calculates ventilator settings of inspiratory pressure ($p_I$), inspiration and expiration time ($t_I$, $t_E$) to meet a desired minute volume (MV) [3]. The calculated settings consider a sufficient expiration time being $3\cdot\tau_E$ to avoid the build-up of intrinsic positive end-expiratory pressure (PEEP) and a minimal inspiration pressure $p_I$ to reduce alveolar stress.

Until now, the algorithm was evaluated in simulations and retrospectively tested on clinical data and indicated high concordance between the calculated settings and settings applied by experienced ICU physicians [3]. The aim of this study is to prospectively test the algorithm in a controllable environment using a test-lung setup to verify if the desired MV can be obtained with the calculated settings.

Methods

Experimental Setup

The experimental setup builds on a test lung consisting of two glass bottles (25 L and 54 L) filled with copper wool to counteract thermodynamic effects. The bottles were connected as a parallel system to achieve a physiological plausible compliance in the range of 80 mL/mbar (Fig. 1). The lung model was ventilated in BiPAP – mode using an Evita XL ventilator (Draeger medical, Luebeck, Germany).

Algorithm deriving optimized ventilation settings

A LabView based application of [3] was developed to record pressure-, flow- and volume data provided by the ventilator to determine patient-specific parameters $R$ and $C$ by parameter identification of the FOM. $\tau_E$ was estimated by fitting an exponential function to the expiration part of measured volume. Incorporating $R$, $C$ and $\tau_E$ lead to a nonlinear relation between $p_I$ and $t_I$ to reach a preset MV during PCV [3]:

$$p_I = \frac{MV \cdot (t_I + 3\tau_E)}{C \cdot (1 - e^{-t_I/R \cdot C})} + PEEP$$

Figure 1: Experimental setup consists of a mechanical ventilator, a test lung and a PC providing a user interface

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The function \( p_t = f(t) \) has one unique minimum where a defined MV can be reached with minimal inspiration pressure and a fixed expiration time. To provide a sufficient expiration, \( t_E \) is set to \( 3 \cdot t_E \) allowing an expiration of 95% of inhaled volume.

**Experimental protocol and analysis**

Certain values for target MV in the range from 6 to 12 L/Min with a step width of 1 L/Min were defined. The sequence of MV values was 9 – 6 – 10 – 7 – 11 – 8 – 12 L/Min. Note, that the obtained \( R \) and \( C \) values in the given inhomogeneous test-lung setup are frequency dependent and might not be in accordance of \( R \) and \( C \) at the calculated ventilation frequency. Thus, \( R \) and \( C \) were determined at the current ventilation frequency and the calculated settings were applied as initial approach. Afterwards, the optimization including a new parameter identification was repeated as a refinement to adjust the settings at the initially calculated frequency. Measurements were done at PEEP – levels of 0, 5 and 10 mbar. In total, three iterations for each PEEP-level were done with 6 repetitions of the experiment to improve statistical significance leading to 18 measurements for each defined MV.

Five breaths were analyzed to estimate \( R \), \( C \) and \( t_E \) to derive the desired ventilator settings. The settings were entered by rounding to the nearest possible adjustable value. The calculation of the actual \( MV^* \) was done by numerical integration of the measured flow (\( \dot{V} \)).

**Results**

Mean FOM-parameters of \( C = 80.8 \text{mL/mbar (SD = 1.8)} \) and \( R = 6.8 \text{mbar·s/L (SD = 0.9)} \) were identified. An example of measured flow rate and simulated model response is shown in Fig. 3a. The fitted exponential function lead to a mean time constant of \( t_E = 0.58 \text{s (SD = 0.07)} \). An example of a corresponding curve fit to the expiratory volume is presented in Fig 3b.

The reached MV values of the initial approach and the subsequent refinement are presented in Fig. 4. The mean deviation of the refined MV to the intended MV is -2.1 % (SD = 5.6). The maximum deviation is -18.5 % and the minimum deviation is 0.3 %. Target MVs in the range of 6-9 L/Min can be reached with high accuracy, whereas higher MV show a larger deviation. Obviously, the refinement further improves accuracy compared to the initial approaches.

**Discussion**

In general, the calculated settings lead to the desired MV. However, in some cases the resulting MV showed larger differences that can be partly explained by rounding the calculated values to be entered at the ventilator. For example the highest deviation occurred at a desired MV = 11 L/Min that could not be reached by -2.04 L/Min with recommended settings of a \( RR = 24.95 \text{min}^{-1} \), \( p_I = 11.41 \text{mbar} \) and a \( t_I = 0.82 \text{s} \). Resulting inputs were \( RR = 25 \text{min}^{-1} \), \( p_I = 11 \text{mbar} \) and \( t_I = 0.8 \text{s} \). Using a \( p_I = 12 \text{mbar} \) instead would decrease the error to -1.62 L/Min in fact a MV-change of 0.41 L/Min. Additionally the given test-lung system might not be accurately represented by the FOM. It is likely that the connectors of the bottles represent flow dependent nonlinear resistances that could cause a quasi-linear pressure drop of the flow rate above 15 L/Min (Fig. 3). These nonlinear effects are pronounced at higher flow rates due to higher pressures which mainly occur in MV in the range of 10 - 12 L/Min.

Generally, this algorithm can help physicians to derive patient-specific settings for pressure controlled ventilations that can be immediately applied at the ventilator. This first experimental prospective trial shows that the calculated settings lead to the desired MV. Further clinical trials are required to evaluate the benefits of the calculated settings.

**Bibliography**

