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Assessing Respiratory Mechanics of Reverse-Triggered Breathing Cycles – Case Study of Two Mechanically Ventilated Patients

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Abstract: Mechanical ventilation patients may breathe spontaneously during ventilator supported breaths, altering airway pressure waveforms and hindering identification of true, underlying respiratory mechanics. This study aims to assess and identify respiratory mechanics for breathing cycles masked by spontaneous breathing (SB) effort using a pressure reconstruction method. The performance of the method is compared to parameters identified using a single-compartment model. Data from two patients (N=6305 breaths) experiencing SB and subsequent periods of muscle paralysis without SB were used for analysis. Patients are their own control and are assessed by breath-to-breath variation using coefficient of variation (CV) of respiratory elastance. Pressure reconstruction successfully estimates more consistent respiratory mechanics during SB by reducing CV up to 78% compared to conventional identification ($p<0.05$). Pressure reconstruction is comparable ($p>0.05$) to conventional identification during paralysis, and generally performs better as paralysis weakens ($p<0.05$). Pressure reconstruction provides less-affected pressure waveforms, ameliorating the effect of SB, resulting in more accurate respiratory mechanics identification.

Keywords: respiratory mechanics, decision support, mechanical ventilation, spontaneous breathing.

1. INTRODUCTION

Model-based methods to monitor respiratory mechanics for mechanical ventilation (MV) patients can assist clinicians to guide MV treatment (Chiew et al., 2011; Rees et al., 2006; Sundaresan & Chase, 2011; van Drunen et al., 2014). However, true respiratory mechanics can be masked by spontaneous breathing (SB) efforts and cannot be estimated in these cases without the use of invasive measuring equipment or clinical protocols (Akoumianaki et al., 2014; Brochard et al., 2012; Talmor et al., 2008). Since SB efforts can be common, the application of respiratory mechanics to guide MV remains very limited (Brochard et al., 2012).

Akoumianaki et al. (2013) described a phenomena where SB during volume controlled ventilation masks the true, measurable, respiratory system mechanics. This phenomenon is referred to as ventilator-induced reverse-triggering of patient muscular breathing efforts. An example of the pressure waveform from a reverse-triggered breath is shown in Fig. 1. The reverse-triggering (or patient effort) creates anomalies in the patient airway pressure waveform, resulting in potential mis-identification of underlying respiratory mechanics if using simple models (Brochard et al., 2012; Lucangelo et al., 2007) or models that do not capture this unique dynamic. Specifically, patient effort reduces the net airway pressure for a given volume and leads to a lower calculated elastance due to the effective negative elastance component resulting from the patient's inspiratory effort (Chiew et al., 2015). Hence, the identified parameters do not represent the underlying mechanics, as the patient-specific, variable inspiratory effort input was not accounted for in the model.

In addition, the level of SB effort is highly variable. While none may occur in any given breath, other subsequent breaths may be heavily affected, as shown in Fig. 1, or only lightly affected. Thus, modelling this input for real-time, breath-to-breath application is not possible, and direct measurements for later use, as with NAVA (Sinderby et al., 1999) for example, are additionally invasive and costly. Hence, there is a need to mitigate these effects with a cost effective method without inducing further stress to patients.

This study presents a simple model-based method capable of improving the consistency of identified respiratory mechanics in real-time. A pressure waveform reconstruction method was used to generate surrogates of SB unaffected breathing cycles, to identify the 'true' underlying respiratory mechanics. In essence, this method seeks to recreate the pressure waveform obscured by SB. These 'unaffected' pressure waveforms can be used to estimate the patient-specific underlying respiratory mechanics in real-time, which can be used to guide MV therapy (Chiew et al., 2015; Pintado et al., 2013; Szlavecz et al., 2014).

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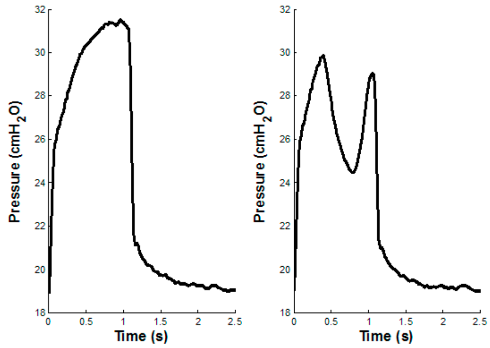

Fig. 1. Comparison of a typical airway pressure waveform during volume control mode (left) to an airway pressure waveform with reverse-triggering effect (right) from the same patient at equal ventilator settings. The reduced airway pressure is evident.

2. METHODS

2.1 Respiratory System Mechanics Model

Respiratory mechanics can be used to characterise patient-specific condition and response to treatment, and are conventionally estimated using a single-compartment linear lung model (Bates, 2009; Lucangelo et al., 2007).

$$P_{aw} = E_{rs} \cdot V + R_{rs} \cdot Q + P0 \quad (1)$$

P_{aw} is the airway pressure, E_{rs} is the respiratory system elastance, V is the lung volume, R_{rs} is the respiratory system resistance, Q is the airway flow, and $P0$ is the offset pressure or positive end expiratory pressure (PEEP) if there is little or no intrinsic PEEP. Using easily measured inspiratory airway pressure and flow data, E_{rs} and R_{rs} can be estimated using linear regression (Chiew et al., 2011; Lucangelo et al., 2007; van Drunen et al., 2014).

2.2 Pressure Reconstruction Method

This method utilises a simple algorithm that superimposes consecutive breath waveforms. Despite the effect of SB efforts, each breathing cycle contains variable regions unaffected by SB, as illustrated in Fig. 2. Superimposing multiple breathing cycles can thus extend the region of 'unaffected' data. A measurable portion of an unaffected breathing cycle can be reconstructed by overlaying affected pressure curves and extracting the maximum values.

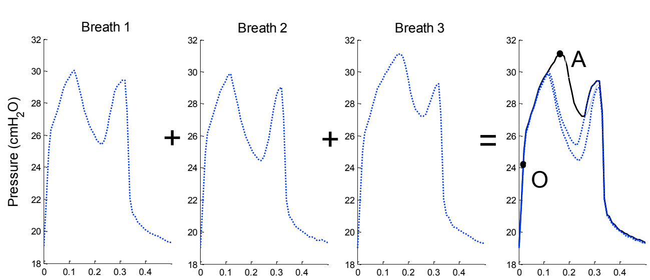

Fig. 2. How pressure waveform reconstruction is used to reconstruct a breathing cycle with more 'correct' data from three pressure waveforms affected by reverse-triggering.

It is important to note that it may not be possible to reconstruct a full, unaffected waveform, as with the example shown in Fig. 2. Incomplete pressure reconstruction is due to the variability of SB magnitude and timing and the number of breaths used. Previous work has reported five breaths to be an optimal balance between efficacy and effort (Redmond et al., 2014). It is thus important to identify the unaffected pressure waveform region. A Hamming windowed low-pass filter allows identification of the point where the pressure gradient first becomes negative (Point A of Fig. 2). After Point A, the pressure waveform data is considered to be compromised by patient induced SB. Point A of Fig. 2 could be extended by adding another SB affected breath with an early and localised drop in pressure. Every breath added improves data quality.

The reconstructed pressure waveform is inspected for gradient sign changes to determine the unaffected portion of each waveform. A typical non-SB pressure waveform (Fig. 1, left) is expected to have zero or one change in gradient sign (positive – negative) during inspiration. If the reconstructed pressure waveform has more than one change in slope (positive – negative – positive [– negative]) as in Fig. 1 (right), the waveform is classified as SB affected and the point at the first sign change (Fig. 2, point A), is identified. Data from 0.1 seconds past the beginning of inspiration (Fig. 2, point O) to this point can then be used to identify respiratory mechanics, as these data points match the model's assumptions.

2.3 Patients and Analysis

In this study, selected data from two MV patients from Christchurch Hospital ICU with respiratory failure were used to test the performance of the proposed pressure reconstruction algorithm. These patients were ventilated using a Puritan Bennett 840 ventilator (Covidien, Boulder CO, USA), using SIMV mode delivering fixed tidal volume (6-8ml/kg) in ramp flow. The airway pressure and flow data were collected using a bedside airway pressure, flow and respiratory mechanics monitoring tool connected to the ventilator (Szlavecz et al., 2014). The collection and use of this data is approved by the New Zealand Southern Region Ethics Committee.

Both patients underwent a stepwise PEEP recruitment manoeuvre (RM) (Szlavecz et al., 2014). Prior to the RM, patients were given muscle relaxants to reduce or eliminate SB effort and allow the patient to adapt to the changes in PEEP settings, per clinical standard (Bennett & Hurford, 2011; Fan et al., 2008; Meade et al., 2008). Airway pressure and flow was collected, starting before muscle paralysis and continued for 3 hours after the RM, as illustrated in Fig. 3.

To test the performance of the proposed pressure reconstruction algorithm, two regions (A and B in Fig. 3) of pressure and flow data were considered. Specifically, Region A was before the recruitment manoeuvre (RM) where patient-specific SB effort was prevalent for these two patients, but diminished with the administration of muscle relaxants per clinical protocol. Region B included 3 hours after the RM, during which time the paralysing agents were metabolised and their effect weakened –patient-specific SB efforts reappeared.

Varying SB efforts causes an increase in breath-to-breath variability of identified respiratory elastance. Conventional