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Estimating the true respiratory mechanics during asynchronous pressure controlled ventilation

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ABSTRACT

Mechanical ventilation (MV) therapy partially or fully replaces the work of breathing in patients with respiratory failure. Respiratory mechanics during pressure controlled (PC) or pressure support (PS) are often not estimated due to variability induced by patient's spontaneous breathing effort (SB) or asynchronous events (AEs). Thus for non-invasive model-based MV with PC/PS, there is a need for improved estimation of respiratory mechanics. An algorithm is proposed that allows for the improvement of respiratory system mechanics estimation during pressure controlled ventilation, while providing a means of quantifying AE magnitude as one indicator of patient-ventilator interaction, which may be valuable to clinicians to monitor patient response to care. For testing, 10 retrospective airway pressure and flow data samples were obtained from 6 MV patients, with each data sample containing 450–500 breaths. All data samples with AE present experienced a decrease in 5th to 95th range (Range90) and mean absolute deviation (MAD) for the estimated respiratory system elastance after reconstruction. These results suggested improved in respiratory mechanics estimation during pressure controlled ventilation. The median [maximum (max), minimum (min)] decrease in MAD was 29.4% (51%, 18.6%), and the median (max, min) decrease in Range90 divided by median respiratory system elastance was 30.7% (48.8%, 6.4%). The algorithm is robust to many different spontaneous breathing efforts, asynchrony shapes and types. The proposed algorithm demonstrates the potential to effectively improve respiratory mechanics and quantify the magnitude of AEs.

1. Introduction

Patients with respiratory failure require mechanical ventilation (MV) for breathing support [1–3]. To aid the patient's recovery from the underlying disease, his/her work of breathing is partially or fully replaced by the mechanical ventilator [3]. Common MV modes can be divided into volume controlled (VC) or pressure controlled (PC). While VC is able to provide a fixed tidal volume delivery, some clinicians prefer PC mode. This mode can limit the maximum driving pressure delivery during MV. Limiting the maximum pressure can prevent patients from incurring pressure induced lung injury, also known as barotrauma [4,5]. PC ventilation is often extended to pressure support (PS) ventilation, allowing the patient to breathe spontaneously to potentially aid recovery [6].

During PC/PS ventilation, a predefined driving pressure and a corresponding tidal volume are delivered to the patient. Thus, the delivered tidal volume can be variable, depending on the patient's condition. This variability may be beneficial to patients but it affects model-based breath-to-breath respiratory mechanics estimation, causing inconsistency. This inconsistency in respiratory mechanics estimation is further aggravated during PS mode where patients exhibit spontaneous breathing efforts (SB) or an asynchrony event (AE) occurs. An example of the flow and pressure waveforms exhibited in normal and asynchronous breaths is shown in Fig. 1. In pressure control MV, the pressure waveform is the controlled variable and therefore is relatively unaffected.

Asynchrony events are problematic as they obscure the process of identifying the underlying patient-specific respiratory mechanics [7], and have also been linked to poor clinical outcomes

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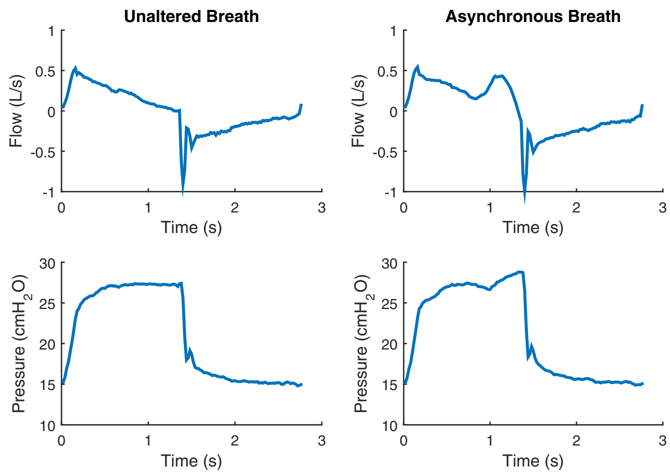

Fig. 1. Example airway flow and pressure plot for a normal and asynchronous breath.

including increased mortality [8–10]. A specific problem of consistent asynchronous breaths occurring during PS ventilation, termed 'reverse triggering', was first documented by Akoumianaki et al. in 2013 [7]. It was noted that this form of neuromechanically coupling has been largely undocumented by clinicians and can prevent accurate determination of the underlying respiratory mechanics [7]. In fact, much of the breathing data utilized in this study exhibits the characteristics of reverse-triggering. To the knowledge of the authors, there are no current extensively tested methods for identifying patient respiratory mechanics during asynchronous pressure controlled MV without the use of invasive protocols or equipment [11,12]. Because of this, during PC/PS ventilation mode, relatively little model-based respiratory mechanics estimation is performed and it is not used to guide mechanical ventilation. A successful method to allow real-time monitoring of respiratory mechanics in pressure-controlled MV patients must be able to separate the asynchronous breathing or patient's own spontaneous breathing efforts from the support by the ventilator.

While the specific phenomenon of reverse-triggered breaths during phenomenon has only been brought to attention in the past few years, the problem of determining the patient's underlying respiratory mechanics during spontaneous breathing has been a long-time subject of research. The flow interrupter technique (FIT), a method of determining the respiratory mechanics during spontaneous breathing, was first introduced by Von Neergaard and Wirz in 1927 [13] and has been refined in more recent years [14,15]. However the method involves obstructing the flow of air delivered and is most suitable for non-intubated patients. It is not compatible with continuous monitoring of respiratory mechanics and does not allow for separation of spontaneous breathing efforts from those of the ventilator [16]. Similarly, body plethysmography allows for measurement of airway resistance which can be utilized to calculate elastance [17]. It requires the patient to be situated in a glass container during use and therefore is not appropriate for use in intensive care.

Methods developed for monitoring of respiratory mechanics in intubated, mechanically ventilated patients have also been developed, such as the transient flow reduction technique described by Younes et al. [16]. However, similar to FIT, the technique requires the flow to be obstructed during measurements and is therefore not suitable for real-time continuous monitoring of respiratory mechanics. Dubois et al. developed a forced oscillation technique in which small-amplitude pressure oscillations are superimposed onto a regular breath, allowing for frequency domain analysis of respiratory mechanics [18,19]. Such methods have been demonstrated to allow for titration of PEEP through determining a patient's respiratory mechanics [20]. However, implementation into clinical practice would require modification to current ventilator hardware. Other methods include the measurement of esophageal pressure to account for pressure changes in the pleural cavity due to muscular efforts [21]. Such methods are invasive due to balloon catheterisation of the esophagus and thus have not seen widespread clinical application [22].

Non-invasive model-based methods for determining respiratory mechanics during asynchronous MV have only appeared in recent years. These methods only require acquisition of patient airway pressure and flow data from the ventilator. Redmond et al. developed a method for reconstructing a pressure waveform, however this only applies to volume controlled MV [23]. A different approach is taken by Rigo et al. in which breathing cycles are uniquely selected to estimate respiratory mechanics [24]. While such an approach may be effective for times in which only some breaths are affected by spontaneous breathing efforts, it may not be suitable for periods of continuous entrainment in which every breath is asynchronous, as has been seen in the data utilized in this study. For PC mode, Vicario et al. have recently developed a constrained optimisation method to account for patient diaphragmatic effort [25]. The method demonstrates an ability to improve estimation of respiratory mechanics in mechanically ventilate patients, however the method has yet to be extensively tested on human data.

Thus, there is still a need to improve current capabilities of identifying patient respiratory mechanics during pressure controlled MV, so that model-based methods of guiding treatment may take place. Additionally, there is a need to quantify the size or magnitude of AEs so that clinicians may be provided with valuable information on patient-ventilator interaction during the course of treatment.

This study presents a proof of concept iterative method to improve model-based respiratory mechanics estimation during pressure controlled ventilation. Specifically, an iterative interpolative flow reconstruction method is used. This method operates by identifying whether a pressure controlled or pressure supported breath is distorted by spontaneous breathing effort or an AE. This method then reconstructs the affected airway flow to a single compartment respiratory model airway flow profile. This method yields a pseudo airway flow profile that is unaffected by spontaneous breathing or asynchrony, allowing estimation of the unaffected, underlying patient-specific respiratory mechanics, while quantifying the magnitude of AEs.

2. Method

2.1. Patient data

Airway pressure and flow data from MV patients admitted to the Christchurch Hospital intensive care unit (ICU) were used in this study. The patients were ventilated with Puritan Bennett 840 ventilation using synchronous intermittent mandatory ventilation (SIMV) pressure controlled mode to achieve tidal volume of 6 ~ 8 ml/kg [26]. Ten data samples, each having 450–500 breathing cycles (~30 min) were extracted from 6 patients included in this study. It is assumed that underlying respiratory mechanics and patient condition do not change significantly over a short period of time. Therefore, the respiratory system elastance, E identified from reconstructed flow profiles is expected to be far more constant than far those affected by SB or AE. All data were sampled at 50 Hz and processed using MATLAB (R2014a, The Mathworks, Natick, Massachusetts, USA).