

Estimation of Inspiratory Respiratory Elastance Using Expiratory Data

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Abstract: Models of respiratory mechanics can be used to titrate patient-specific mechanical ventilation (MV) settings in critical care, but often perform poorly in the presence of patient breathing effort. Respiratory mechanics are conventionally calculated using only inspiratory data. Muscle activity is normally assumed relatively minimal or absent during passive expiration regardless of the presence of inspiratory spontaneous breathing (SB) efforts. Hence, this study assesses whether expiratory lung elastance can be used to estimate inspiratory lung elastance for spontaneously breathing, reverse triggered patients. Clinical data from recruitment manoeuvres in fully sedated patients were used to determine a relationship between inspiratory and expiratory modeled lung elastance. The validity of this relationship was assessed using data recorded pre- and post- sedation from different patients.

A strong, linear relationship was found between inspiratory and expiratory elastance in fully sedated patients, with gradient 1.04 [95% CI: 1.03-1.07] and intercept 1.66 [1.06-2.08] with $R^2 = 0.94$. After adjustment according to the linear relationship, expiratory elastance produced stable estimations post sedation, with similar median and variance as inspiratory elastance. However, variation in estimates pre-sedation, although significantly improved, may be larger than clinically acceptable in some cases. The results of this study show that the typically ignored expiratory data may be able to provide insight into patient condition when conventional methods fail. Clinically, these methods could have an impact in guiding MV therapy by providing clinicians with information about lung mechanics under the effect of patient SB effort.

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1. INTRODUCTION

Respiratory failure patients are mechanically ventilated for breathing support. Mechanical ventilation (MV) relies on finding an optimal level of positive end expiratory pressure (PEEP) to maintain recruitment of previously collapsed alveoli and aid gas exchange (Amato et al. (1998); McCann et al. (2001)). However, high PEEP risks damaging healthy and mildly injured alveoli, negating any positive effects and further complicating patient care (Richard et al. (2001)).

Model-based methods to monitor respiratory mechanics in critical care provide clinicians with useful information to optimise PEEP and guide individualised MV therapy (Bates (2009); Sundaresan et al. (2009)). However, many models are too complex for monitoring respiratory mechanics in real-time or are unsuitable for spontaneously breathing patients (Baoshun and Bates (2010); Tawhai et al. (2004); Tawhai and Bates (2011); Reddy

et al. (2011); Kitaoka et al. (2007); de Ryk et al. (2007); Schirrmann et al. (2010)). Patient spontaneous breathing (SB) efforts modify measured pressure and flow waveforms, and cannot be captured by simple lung models without additional invasive manoeuvres or measures (Khirani et al. (2010); Brochard et al. (2012); Chiew et al. (2015)). To provide individualised MV, it is essential to have a method of estimating respiratory lung mechanics of both fully and partially sedated SB patients in real-time at the bedside.

Respiratory mechanics are conventionally calculated using only inspiratory data, neglecting the entire expiratory portion. During passive expiration, muscle activity is assumed to be relatively minimal or absent regardless of the presence of inspiratory SB efforts (Al-Rawas et al. (2013); Grinnan and Truwit (2005)). Hence, this paper proposes a method of analysing expiratory respiratory mechanics to estimate inspiratory respiratory mechanics of SB patients.

The ability to accurately estimate inspiratory respiratory mechanics for SB patients would allow for titration of PEEP at lower levels of sedation, potentially reducing the time MV is required.

2. METHODOLOGY

2.1 Linear single compartment lung model

Patient-specific model-based lung mechanics can be identified from clinical data using a clinically accepted linear single compartment lung model defined (Chiew et al. (2015); Bates (2009); Chiew et al. (2011)):

$$P_{aw}(t) = R_{rs}Q(t) + E_{rs}V(t) + P_0 \quad (1)$$

where P_{aw} is the airway pressure, t is time, E_{rs} is the respiratory system elastance, R_{rs} is the combined resistance of the conducting airway and endotracheal tube, V is volume, Q is flow, and P_0 is the offset or positive end expiratory pressure, PEEP (Bates (2009)). This model assumes no patient effort is present during the breath. Any anomalous airway pressures caused by SB efforts cause the misestimation of elastance (Grinnan and Truwit (2005); Brochard et al. (2012); Newberry et al. (2015); Kannangara et al. (2016)).

The expected flow measured for a sudden drop in airway pressure, as seen in expiration, can be derived from (1), yielding:

$$Q = \frac{-(P_i - PEEP)}{R_{rs}} e^{-\frac{tE_{rs}}{R_{rs}}} \quad (2)$$

The expiratory pressure and flow waveforms measured during MV closely match the expected response of the model, as shown in Figure 1. Previous work suggests that measured expiratory pressure in MV contains no additional, useful physiological information (van Drunen (2013); Mller et al. (2009); G. L. Chelucci et al. (1991)). However, this paper proposes that data measured during expiration is physiologically accurate and may contain clinically useful information, since it contains the same respiratory mechanics properties as inspiration.

2.2 Model identification

Lung mechanics of expiration were calculated by least squares fitting to the expiratory portion of data. Pressure and volume measurements were shifted to have initial values of zero.

Patient SB effort occurring at the end of inspiration affects the measured end-inspiratory pressure, resulting in incorrect expiratory lung mechanics estimation. To identify breaths likely to have been affected by unmodelled end-inspiratory patient breathing efforts, the simple reconstruction method described by Damanhuri et al. (2016) was used. This method estimates the unaffected pressure by extrapolating the gradient of end-inspiratory pressure back up to peak pressure. The reconstructed pressure creates a proxy for the correct, unaffected pressure waveform. Thus, the change in area after reconstruction gives an indication of the magnitude of SB effort present in the breath. In this study, expiratory elastance was not calculated if the change in area after peak pressure was more than 12.5%.

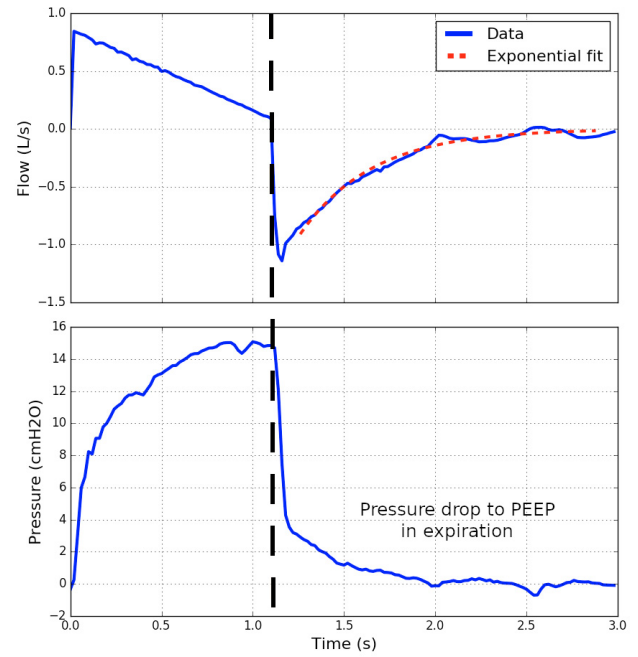


Fig. 1. Top: Flow profile of a breathing cycle with an exponential model fit to expiration. Bottom: Pressure profile of a breathing cycle with pressure measurements relative to PEEP.

SB efforts can last the entire duration of inspiration, effectively reducing measured peak pressure. To identify such a reduction in peak-pressure, the median peak pressure of the breath being analysed and the previous 6 breaths was determined. Expiratory elastance was not calculated if the peak pressure of the breath being analysed was below 90% of this value.

2.3 Data

Retrospective datasets from 8 patients were used in this study. All patients in this study were ventilated using PB-840 ventilators (Covidien-Puritan Bennet, Boulder, CO) on synchronous intermittent mandatory ventilation (SIMV) mode with a volume control ramp flow profile. Table 1 shows ventilation details for each patient.

2.4 Ethics

The NZ Upper South Island Regional Ethics Committee granted approval for this study and the use of the clinical data analysed in this study.

2.5 Analysis

Retrospective clinical data from patients 1A - 1D were used to identify non-patient specific relationships between inspiratory and expiratory elastance. The data contained 12 recruitment manoeuvres (RM) free of SB effort (1013 breaths), with 4, 2, 1, and 5 RMs recorded for patients 1A - 1D respectively. Inspiratory and expiratory elastance were calculated for each breath, and an overall trend line determined. A 95% confidence interval was calculated on this regression line using bootstrapping, with 1000 random subsets of 1013 breaths selected with replacement. The

Table 1. Mechanical ventilation parameters for each patient and primary diagnosis for ICU admission

Patient	Primary diagnosis	Tidal Volume (ml)	Respiratory rate (1/minute)	PEEP (cmH ₂ O)
1A	Peritonitis	320 - 520	20	14 - 27
1B	Pneumonia	465	18	11 - 20
1C	Pneumonia	385	20	12 - 32
1D	Ischaemic gut	420 - 470	18 - 20	20 - 36
2A	Peritonitis	365	18	15
2B	Peritonitis	370	19	17
2C	Cardiac surgery	480	14	11
2D	Pneumonia	540	18	13

95% prediction interval was also calculated to show the range of variation at any given point.

Retrospective clinical data from patients 2A - 2D were used to assess whether expiratory elastance could be used to estimate inspiratory elastance during SB. Each dataset contained 30 breaths before and approximately 3 minutes after sedation, totaling 60 breaths. Before sedation, patients exhibited significant asynchronous spontaneous breathing. Patients were then sedated for clinical reasons. No changes were made to ventilation after sedation or immediately before the pre-sedation sample. Within this short period, expiratory elastance pre- and post-sedation are expected to be very similar (Richard et al. (2001)). The median absolute deviation (MAD) and median elastance values were used to assess the efficacy of estimating inspiratory elastance corrupted by SB efforts with expiratory elastance.

3. RESULTS

The correlation between estimated expiratory and inspiratory elastance across patients 1A - 1D is shown in Figure 2. The 95% CI of the gradient ranges from 1.03 to 1.07 and the 95% CI of the offset ranges from 1.04 to 2.05. The median 95% PI containing 95% of the data points is ± 2.38 cmH₂O/L. The best fit line shows a strong, linear, cohort wide relationship between inspiratory and expiratory elastance ($R^2=0.94$).

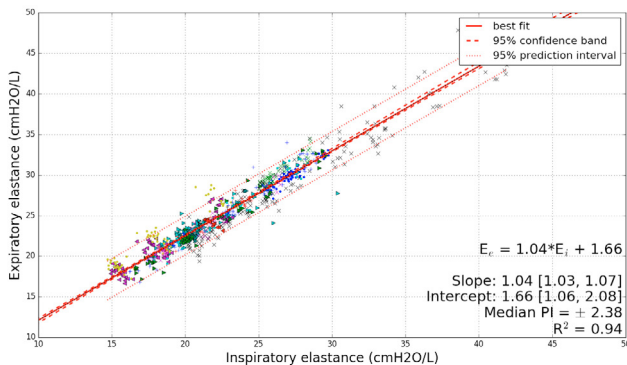


Fig. 2. Linear regression of elastances (cmH₂O/L) for non-SB breathing with best fit, 95% CI and 95% PI. Each of N=12 data sets has a different marker

Figure 3 shows the cumulative distribution of inspiratory and expiratory elastance values for patients 2A - 2D. A less vertical distribution indicates greater variability, where the sedated case represents an ideal minimal level of patient-specific breath-to-breath variability. Expiratory elastance

values were adjusted using the relationship in Figure 2 to estimate inspiratory elastance. Thus, the cumulative distributions of inspiratory elastance post-sedation and expiratory elastance are expected to be very similar. The results are summarised in Table 2.

No expiratory elastance values were calculated for dataset A due to all breaths either being overly affected by end-inspiratory SB effort or showing a significantly reduced peak pressure. In contrast, inspiratory elastance was very accurately predicted in dataset D. Post-sedation MAD was low and similar between expiration and inspiration for all datasets, as expected. Post-sedation, the maximum difference in median elastance between inspiration and adjusted expiration was 2.99 cmH₂O/L (11.6% of inspiratory median elastance) in dataset A.

Table 2. Median [interquartile range] and median absolute distribution (MAD) of E (cmH₂O/L) identified pre- and post-sedation for each patient.

		Inspiration		Expiration (adjusted)	
		Median [IQR]	MAD	Median [IQR]	MAD
A	pre	-20.51 [-27.98:-18.70]	2.91	NA [NA:NA]	NA
	post	25.69 [25.11:26.52]	0.72	28.68 [28.33:29.01]	0.35
B	pre	10.46 [2.25:26.48]	9.74	23.57 [22.49:25.42]	1.29
	post	26.92 [26.76:27.26]	0.24	27.99 [27.88:28.12]	0.12
C	pre	15.66 [12.99:17.65]	2.60	16.91 [16.45:18.55]	0.86
	post	19.38 [18.87:19.83]	0.51	21.59 [21.09:22.49]	0.51
D	pre	16.75 [13.84:17.32]	0.99	18.38 [17.92:19.05]	0.66
	post	18.17 [17.83:18.42]	0.30	19.10 [18.75:19.42]	0.33

4. DISCUSSION

A strong, linear, non-patient specific relationship was found between inspiratory and expiratory elastance in breaths without SB effort. This relationship may allow for real-time lung mechanics estimation for SB patients, without additional invasive equipment. However, the relationship was identified over a small cohort. Therefore, the linear relationship may not be appropriate beyond the range of elastance values analysed, approximately 15-45 cmH₂O/L.

In this study, the measured expiratory elastance was slightly higher than inspiratory elastance, matching previous studies which observed higher dynamic elastance during expiration (Officer et al. (1998); Ulmer and Schfer (2004)). This result provides a further validation of the methods and underlying model.

The clinical data from patients 2A - 2D contained examples of SB efforts ranging from mild to severe. Analysis of expiratory data generally resulted in stable elastance estimates, although the variability of elastance pre-sedation

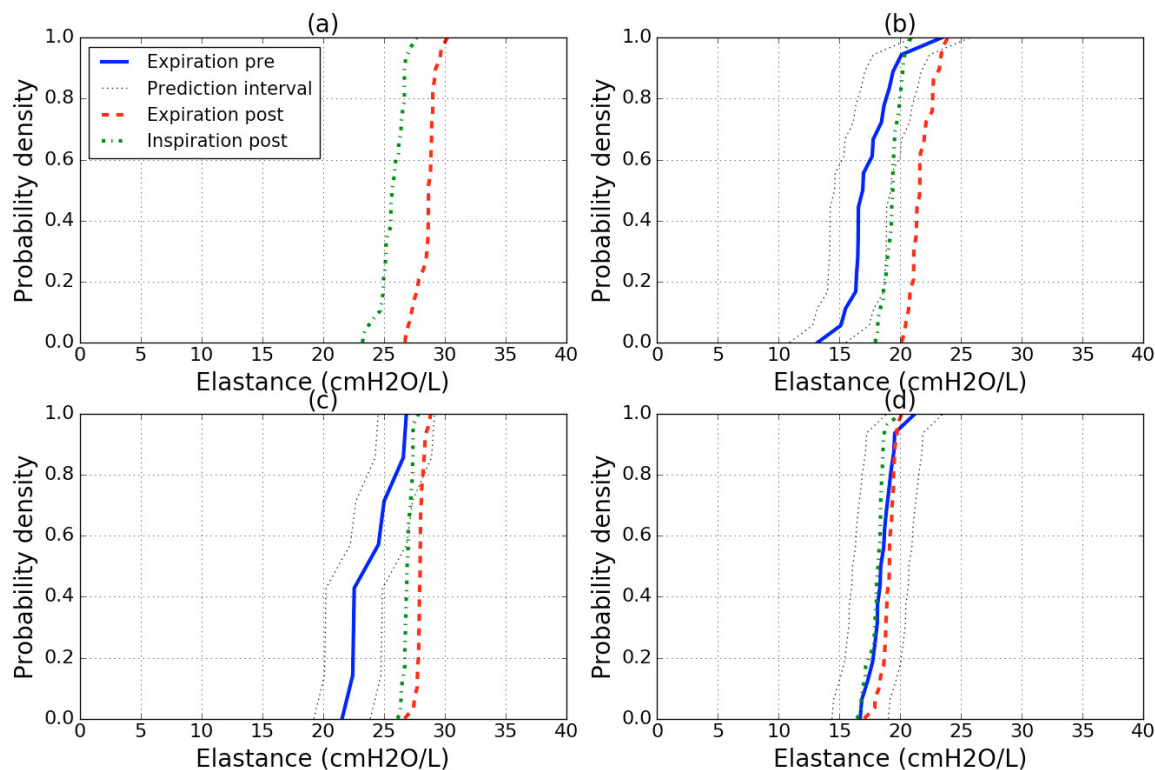


Fig. 3. Cumulative distributions of expiratory elastance (cmH₂O/L) in pre-sedation (solid) with prediction interval (dotted) and post-sedation (dashed), and inspiratory elastance (cmH₂O/L) post-sedation (dash-dot).

may be larger than is clinically acceptable. Moreover, this method was shown to be robust in the absence of SB effort, producing similar variation and median values as inspiratory data post-sedation.

Unlike other methods, the pressure data was not altered in an attempt to remove patient effort from the waveform (Redmond et al. (2016); Vicario et al. (2015); Schranz et al. (2012)). Any alterations to the pressure waveform must assume lung behaviours and can only give a proxy for the correct shape. By using the measured expiratory pressure, the identified lung mechanics were expected to reflect the true underlying lung mechanics. However, the major limitation of this method is the inability to correctly estimate lung mechanics in breaths affected by significant end-inspiratory SB efforts. These breaths were not included in this analysis, resulting in dataset A having no estimates of expiratory elastance.

4.1 Limitations

This study used data solely from patients ventilated in volume control mode. Therefore, the results of this proof of concept study are only applicable to this ventilation control mode. Further, only four datasets were used to evaluate performance. However, these datasets represent a range of SB effort, from mild to very severe, where dataset A represented the most severe case, and is an example of the worst case result for this method. Overall, the results provide a reasonable proof of concept justifying prospective clinical analysis.

5. CONCLUSIONS

This proof of concept study presents methods to assess the magnitude of end-inspiratory SB effort and determine expiratory elastance. When combined, these methods were able to provide reasonably stable estimates of underlying inspiratory respiratory mechanics of SB patients, for breaths without significant end-inspiratory SB effort. These methods are simple enough for real-time lung mechanics estimation and require no additional sedation or equipment. The results of this study show that the typically ignored expiratory data may be able to provide insight into patient condition when conventional methods fail. Clinically, these methods could have an impact in guiding MV therapy by providing clinicians with information about lung mechanics under the effect of patient SB effort.

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