Visualisation of Time-Variant Respiratory System Elastance in ARDS Models
van Drunen EJ\(^1\), Chiew YS\(^1\), Zhao Z\(^2\), Lambermont B\(^3\), Janssen N\(^4\), Pretty C\(^5\), Moeller K\(^2\), Chase JG\(^1\)
\(^1\)Department of Mechanical Engineering, University of Canterbury, New Zealand  
\(^2\)Institute of Technical Medicine, Furtwangen University, Germany  
\(^3\)Medical Intensive Care Unit, University Hospital of Liege, Belgium  
\(^4\)Emergency Department, University Hospital of Liege, Belgium  
\(^5\)GIGA-Cardiovascular Sciences, University of Liege, Belgium

erwin.vandrunen@pg.canterbury.ac.nz

Abstract: Model-based mechanical ventilation (MV) can be used to characterise patient-specific condition and response to MV. This paper presents a novel method to visualise respiratory mechanics during MV of patients suffering from acute respiratory distress syndrome. The single compartment lung model is extended to monitor time-varying respiratory system elastance within each breathing cycle. Monitoring continuous in-breath mechanics allows changes to be observed continuously, providing more insight into lung physiology. Thus, this new monitoring method may potentially aid clinicians to guide MV in a heterogeneous population.

Keywords: Respiratory mechanics, mechanical ventilation, ARDS

Introduction
Modelling the breath-to-breath respiratory mechanics of acute respiratory distress syndrome (ARDS) patients can potentially provide a non-invasive, patient-specific method to obtain clinically useful information in real-time to guide treatment [1, 2]. However, this method of monitoring is limited in clinical application [2-5].

Dynamic respiratory system elastance (\(E_{drsv}\)) is a breath-specific time-varying elastance [6, 7]. This dynamic parameter within a single breath provides unique insight into a patient’s breathing pattern, revealing lung recruitment and overdistension. In addition, identifying minimum \(E_{drsv}\) also reveals the potential to titrate optimal patient-specific positive end-expiratory pressure (PEEP) to maximise recruitment without inducing lung injury [7]. This work presents a novel method in visualising \(E_{drsv}\). Monitoring breath-to-breath time-variant \(E_{drsv}\) can provide a higher resolution metric to guide MV therapy than existing respiratory mechanics monitoring.

Methods
Dynamic Respiratory System Elastance Model
The equation of motion describing the airway pressure as a function of the resistive and elastic components of the respiratory system is defined as:

\[
P_{aw}(t) = R_{rsv} \times Q(t) + E_{rsv} \times V(t) + P_0 \tag{1}
\]

where \(P_{aw}\) is the airway pressure, \(t\) is time, \(R_{rsv}\) is the resistance of the conducting airway, \(Q\) is the air flow, \(E_{rsv}\) is the respiratory system elastance (1/compliance), \(V\) is the lung volume and \(P_0\) is the offset pressure. \(E_{rsv}\) and \(R_{rsv}\) can be determined using multivariate regression or the integral-based method [7]. If \(R_{rsv}\) is assumed constant throughout a breath [3, 4, 7], \(E_{drsv}\) can be re-estimated using Equation (2) after \(R_{rsv}\) is estimated using Equation (1).

\[
E_{drsv}(t) = \frac{P_{aw}(t) - P_0 - R_{rsv} \times Q(t)}{V(t)} \tag{2}
\]

Patient-specific \(E_{drsv}\) is only analysed during the inspiratory portion of the breathing cycle. Arranging each breathing cycles’ \(E_{drsv}\) curve such that it is bounded by the \(E_{drsv}\) curve of the preceding breath and the subsequent breath leads to a three-dimensional, time-varying, breath-specific \(E_{drsv}\) surface. This method of visualisation will give clinicians new insight into how respiratory mechanics change with time over the course of treatment.

Lavage ARDS Animal Models
A study was performed using experimental ARDS piglets. After intubation via tracheotomy, the piglets were ventilated using a Draeger Evita2 ventilator (Draeger, Lubeck, Germany). The ventilator was set to intermittent positive pressure ventilation mode (IPPV) to deliver a tidal volume of 8-10 ml/kg, with a FiO\(_2\) of 0.5, at 20 breaths/min. The subjects underwent repeated lavage to induce ARDS. The arterial blood gases were monitored and once diagnosed with ARDS (PaO\(_2\)/FiO\(_2\) < 200 mmHg), each subject underwent a staircase recruitment manoeuvre (RM) with PEEP settings at 1–5–10–15–20–15–10–5–1 mbar. Each PEEP level was maintained for 10-15 breaths before changing to the next PEEP level. For the duration of the RM, a visage manoeuvre was maintained to ensure an adequate level of seriousness. Airway pressure and flow were measured using a 4700B pneumotachometer (Hans Rudolph Inc., Shawnee, KS).

Results
Figure 1 shows two examples of the \(E_{drsv}\) surface for the lavage ARDS piglets. The top surface shows the \(E_{drsv}\) for every breathing cycle. The change in airway pressure...
from PEEP to peak inspiratory pressure (PIP) is shown in grey at the bottom of each plot.

Figure 1: $E_{drs}$ surface across a normalised breath during a RM for two lavage ARDS piglets.

**Discussion**

Immediately after a PEEP increase, the $E_{drs}$ trajectory descends to a minimum before once again increasing towards the end of inspiration. Rising $E_{drs}$ at the end of inspiration indicates a potential for lung damage due to overstretching which may not be captured by a single value of $E_{rs}$. However, as PEEP is maintained for a few breaths, it was found that each successive breath has a reduced $E_{drs}$ rise, indicating a period of stabilisation and a time-dependency of respiratory elastance and viscoelastic properties, reducing the hysteresis.

The $E_{drs}$ surface for both ARDS piglets shows a significant reduction in respiratory elastance during decreasing PEEP titration. It was found that global minimal elastance PEEP occurs at 10 mbar. During a PEEP increase, $E_{drs}$ decreases as recruitment of new lung volume outweighs lung stretching [7]. It was found that $E_{drs}$ during increasing PEEP is significantly different to $E_{drs}$ during decreasing PEEP ($p<0.005$). Thus, this case shows the typical finding where PEEP should be titrated after the lung has been recruited [3-5, 7]. However, a local minimum $E_{drs}$ was also found at 10 mbar during increasing PEEP titration, suggesting similar optimal PEEP settings.

Selecting PEEP is a trade-off in minimising lung pressure and potential damage, versus maximising recruitment. In addition, recruitment is also a function of PEEP and time [8]. Therefore, true minimal $E_{drs}$ can only be determined after a stabilisation period is provided at each PEEP level. Setting PEEP at minimal elastance theoretically benefits ventilation by maximising recruitment, reducing work of breathing and avoiding overdistension [3-5, 9].

The time-varying $E_{drs}$ is a higher resolution metric of dynamic adaptation to PEEP than a single elastance value, $E_{rs}$, used in existing clinical practice. Thus, real-time monitoring of $E_{drs}$ can potentially guide decision making in the intensive care unit. Changes in ventilator mode to modify the $E_{drs}$ surface could also be used to guide therapy.

**Bibliography**