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Visualisation of Time-Variant Respiratory System Elastance in ARDS Models

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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_{drs}) 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_{drs} 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_{drs}. Monitoring breath-to-breath time-variant E_{drs} 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:

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

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

$$E_{drs}(t) = \frac{P_{aw}(t) - P_0 - R_{rs} \times Q(t)}{V(t)} \qquad (2)$$

Patient-specific E_{drs} is only analysed during the inspiration portion of the breathing cycle. Arranging each breathing cycles' E_{drs} curve such that it is bounded by the E_{drs} curve of the preceding breath and the subsequent breath leads to a three-dimensional, time-varying, breath-specific E_{drs} 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 manœuvre* 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_{drs} surface for the lavage ARDS piglets. The top surface shows the E_{drs} 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.

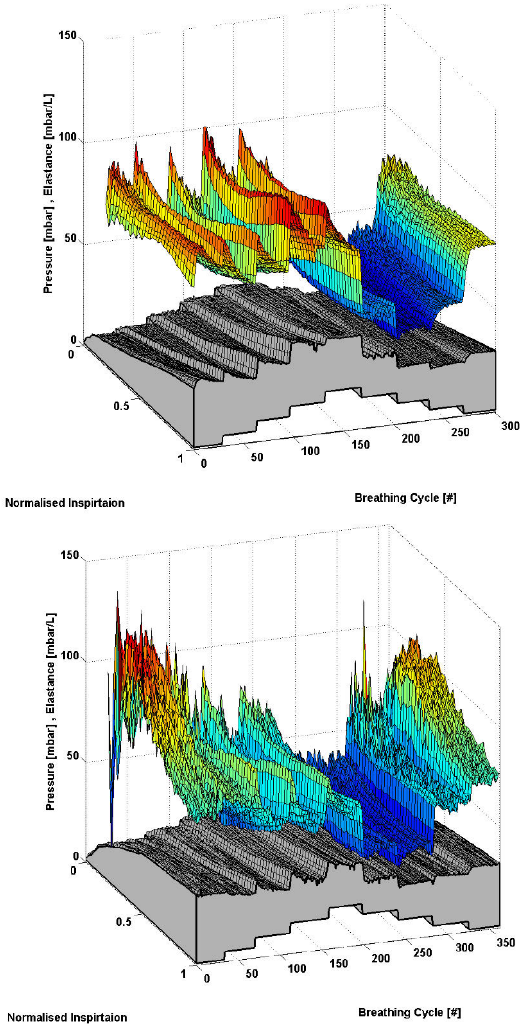

Figure 1: E_{drs} surface across a normalised breath during a RM for two lavage ARDS piglets.

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 minimum 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

[1] A. Sundaresan and JG. Chase, "Positive end expiratory pressure in patients with acute respiratory distress syndrome - The past, present and future," Biomedical Signal Processing and Control, vol. 7, pp. 93-103, 2011.

[2] L. Brochard, G. Martin *et al.*, "Clinical review: Respiratory monitoring in the ICU - a consensus of 16," Crit Care, vol. 16, p. 219, 2012.

[3] A. Carvalho, F. Jandre *et al.*, "Positive end-expiratory pressure at minimal respiratory elastance represents the best compromise between mechanical stress and lung aeration in oleic acid induced lung injury," Crit Care, vol. 11, p. R86, 2007.

[4] F. Suarez-Sipmann, S. H. Bohm *et al.*, "Use of dynamic compliance for open lung positive end-expiratory pressure titration in an experimental study," Crit Care Med, vol. 35, pp. 214 - 221, 2007.

[5] B. Lambermont, A. Ghuysen *et al.*, "Comparison of functional residual capacity and static compliance of the respiratory system during a positive end-expiratory pressure (PEEP) ramp procedure in an experimental model of acute respiratory distress syndrome," Crit Care, vol. 12, p. R91, 2008.

[6] C. A. Stahl, K. Moller *et al.*, "Dynamic versus static respiratory mechanics in acute lung injury and acute respiratory distress syndrome," Crit Care Med, vol. 34, pp. 2090 - 2098, 2006.

[7] Y. S. Chiew, JG. Chase *et al.*, "Model-based PEEP optimisation in mechanical ventilation," BioMedical Engineering OnLine, vol. 10, p. 111, 2011.

[8] S. P. Albert, J. DiRocco *et al.*, "The role of time and pressure on alveolar recruitment," Journal of Applied Physiology, vol. 106, pp. 757-765, March 2009 2009.

[9] Z. Zhao, D. Steinmann *et al.*, "PEEP titration guided by ventilation homogeneity: a feasibility study using electrical impedance tomography," Crit Care, vol. 14, p. R8, 2010.