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Assessing SB effort via a non-invasive model-based method in mechanically ventilated patients in malaysian ICU hospital

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ABSTRACT

Patients with Acute Respiratory Distress Syndrome (ARDS) required mechanical ventilation (MV) for breathing support. However, some MV patients encountered spontaneous breathing (SB) efforts while fully sedated which can obscure the true underlying respiratory mechanics of these patients. Thus, a model-based method is required to reconstruct the missing pressure and calculate the breathing effort that produced by the patients without additional clinical protocols or invasive procedure. In this paper, results of spontaneous breathing effort in Malaysian critically-ill patients adopting the developed pressure reconstruction model are presented. By using the pressure reconstruction model, the SB affected pressure waveform is reconstructed to approximate true respiratory mechanics and quantifies the SB effort. The SB breathing efforts were computed and compared with the results from Christchurch Hospital, New Zealand. The substitute measure of SB effort can be indicated from the difference between the reconstructed and unreconstructed pressure. Results shows that all patients from both cohorts exhibited SB effort with the highest SB effort at 11.48% for Malaysian patient and 21.07% for Christchurch patient. Overall, the well-developed non-invasive pressure reconstruction method is able to measure the SB effort produced by Malaysian MV patients that help the clinicians in selecting the optimal MV setting. This first non-invasive guidance in selecting the optimal setting of MV in Malaysia is potentially reduced the ICU cost and improve the MV management in Malaysian hospital.

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1. INTRODUCTION

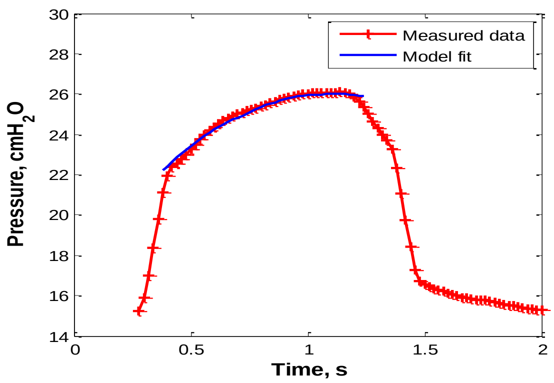
Acute respiratory Distress Syndrome patients require mechanical ventilation (MV) as a breathing support [1, 2]. However, MV can further injured the damaged lungs known as a ventilator-induced lung injury (VILI) if it is not properly managed [3, 4]. The main goal of MV in ARDS patient is to minimize any additional damage while preserving sufficient gas exchange [5].

Characterization of patient-specific state and reaction to treatment can be evaluated from the respiratory mechanics [6, 7]. Respiratory mechanics refers to the declaration of lung function through measures of flow and pressure. However, during ventilator supported breaths, the alteration of airway pressure waveforms can occur in many patients that exhibited spontaneous breathing efforts. Consequently, the model-based identification will be obscured from showing the true, original respiratory mechanics required for a better MV guidance.

Reverse-triggering of patient breathing efforts, induced by ventilator, is referred to as an asynchrony where SB exhibits during a ventilator supported breathing cycle that inaccurately measured the true underlying of the respiratory mechanics [8, 9]. As shown in Figure 1, the reduction in the patient's airway pressure waveform were formed by the patient's own breathing effort. Thus, this lead to a poor model fitting when the existing developed model were applied to calculate the lung elastance.

Particularly, the decrement in airway pressure of a specific volume would also decrease the value of respiratory elastance due to the SB exhibited by the patient. This is because the patient inhalation effort produces negative elastance component [6, 10]. In consequence, the acknowledged parameters are not the true representation of the real underlying mechanics since the input of variable inhalation specifically produced by the patient was not taken into account. On top of that, patients with SB effort may not be ventilated correctly based on their ability to breathe spontaneously. They may need different type of ventilator mode that provides mechanical breaths to a patient such as Synchronized Intermittend Mandatory Ventilation (SIMV) [11].

Previously, breathing effort was estimated invasively by inserting the balloon catheter [12, 13]. Thus, SB patients required a non-invasive pressure reconstruction model that is able to reconstruct the missing pressure and calculate the SB effort for a better MV management. Damanhuri et. al has developed a pressure reconstruction model that is able to assses the breathing effort in SB ventilated patients without additional tools and protocol by using the Christchurch Hospital data [14]. Hence, this study aims to assess, evaluate and compare the SB ventilated patients in Malaysian ICU setting, International Islamic University (IIUM) Hospital against Christchurch Hospital, New Zealand. This would be the first non-invasive model development for Malaysian ICU patients that is beneficial in managing the MV setting specifically for SB patients which could guide clinicians in better MV management and reduce the ICU cost at the same time.



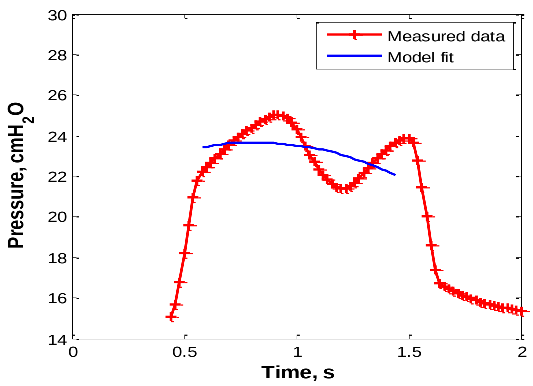


Figure 1. Differentiation of (left) a normal airway pressure waveform with good model fitting to (right) an airway pressure waveform with breathing effort that leads to a poor model fit to the pressure waveform [14]

2. RESEARCH METHOD

2.1. Patient Data and Analysis

The data used in this study was obtained from 883 breathes aggregated from 7 mechanically ventilated patients admitted to the intensive care unit (ICU) between August 2017 and October 2017 at the IIUM Medical Centre, Malaysia with respiratory failure [15]. There were also 635 breathes from 5 MV patients of Christchurch Hospital, New Zealand ICU between April 2014 and November 2014 [16, 17]. The patients involved were ventilated using Puritan Bennett PB980 ventilator (Covidien, Boulder, CO, USA). Data collection was performed by using a CURE soft system [18] where airway pressure and flow were recorded for each patient as shown in Figure 2. The inclusion criteria of the patients enrolled were those aged above 16, requiring invasive MV and with ratio of oxygen partial pressure to fraction of inspired oxygen (P_aO2/F_iO2) less than 300 mmHg. While the elimination conditions comprise of patients who mostly in 24 hours, are to be withdrawn from MV, patients with a great injury of spinal cord with motor function loss, and also patients who are not expected to last for more than 72 hours or in a dying state. The trial number for IIUM patients is IREC66 while for the Christchurch Hospital patients is

ACTRN12613001006730. Table 1 and 2 shows the demographics of the patients enrolled for both cohorts in this study.

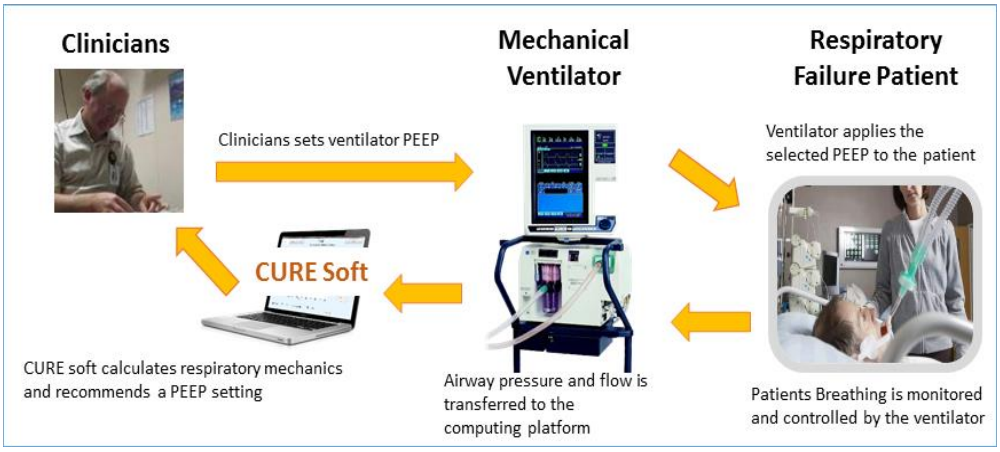


Figure 2. CURE software application for respiratory mechanics monitoring in the ICU [18]

Table 1. Characteristics of Patients in IIUM Hospital, Malaysia

Patient no.	Gender	Age	Clinical Diagnostic
M1	Female	43	Hospital Acquired Pneumonia (HAP)
M2	Male	54	Hospital Acquired Pneumonia (HAP)
M3	Male	52	Lung Cancer
M4	Male	64	Hospital Acquired Pneumonia (HAP)
M5	Female	63	Hospital Acquired Pneumonia (HAP)
M6	Female	73	Septic Shock
M7	Female	64	Community Acquired Pneumonia

Table 2. Characteristics of patients in Christchurch Hospital, New Zealand

Patient No.	Gender	Age	Clinical Diagnostic
C1	Female	53	Faecal peritonitis
C2	Male	71	Hospital Acquired Pneumonia (HAP)
C3	Male	60	Pneumonia
C4	Male	36	Pneumonia
C5	Male	61	Pneumonia

2.2. Time Varying Elastance Model

Respiratory mechanics can be used to represent patient-specific condition and feedback to treatment, and are conservatively estimated using a single-compartment linear lung model [11, 19] as in (1):

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

The airway pressure is labelled as P_{aw}, the respiratory system elastance is defined as E_{rs}, while V is the lung volume, the respiratory system resistance is denoted as R_{rs}. Q means the airway flow, and when the intrinsic positive end expiratory pressure (PEEP) is none, the offset pressure or PEEP is P_o. By applying an integral based-method, the values for E_{rs} and R_{rs} can be easily calculated with flow data and inspiratory P_{aw} [20, 21].

$$\int P_{aw}(t)dt = R_{rs}\int Q(t)dt + E_{rs}(t)\int V(t)\,dt + \int P_0\ dt \quad (2)$$

Next, for every PEEP data level, with reference to the value of R_{rs}, the lung resistance average value (R_{ave}) is calculated. While the identification of the time-varying lung elastance, E_{drs} can be made using [22]:

$$E_{drs}(t) = \frac{P_{aw}(t) - P_0 - (R_{ave}Q(t))}{V(t)} \quad (3)$$

The area under the curve of E_{drs} (AUC E_{drs}) is then identified for every breathing cycle as a substitute of respiratory elastance over the breath.

2.3. Pressure Reconstruction Model

Pressure recontruction model was first developed by Damanhuri et. al [14]. Due the SB effort produced by the MV patients even if sedated, it thus creates a significantly lower identified lung elastance, which inaccurately measure the respiratory mechanics of MV patients. Thus, with pressure reconstruction model, it helps to reconstruct the missing pressure and able to estimate the true underlying respiratory mechanics of SB patients as shown in Figure 3 [14, 23].

The airway pressure's gradient during exhalation cycle can be the determined by referring to points *a* and *b* as seen in Figure 3b. The connecting line of point *a* and *b* is extrapolated further to the point c_1 where it reaches the same value as the highest pressure which is defined as c_2 now. The peak and end inspiratory gradient are connected through a line from point c_1 and c_2.

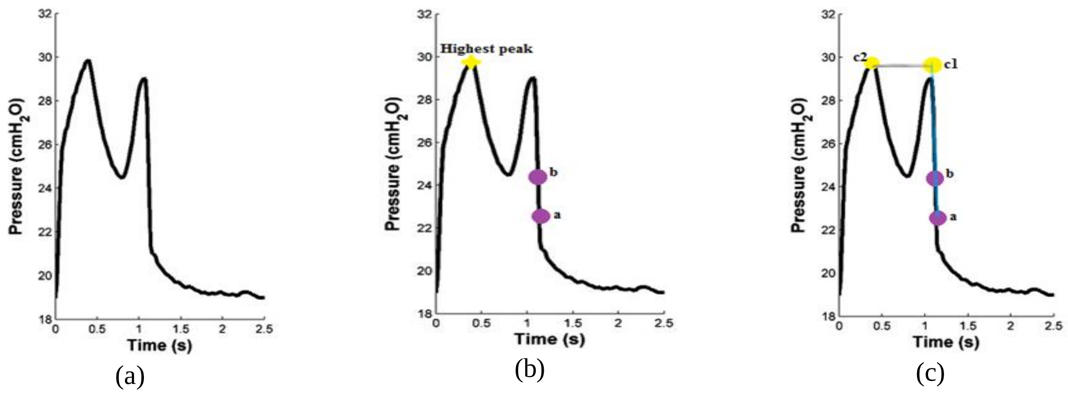


Figure 3. The steps on the reconstruction process (a) The airway pressure in SB patient. (b) The point *a, b* and the highest peak are identified. (c) The slope of point *a* and point *b* is extrapolated until point c_1, which has the same pressure value as the highest peak denoted as c_2.

2.4. Estimation of Spontaneous Breathing Effort

When a mechanically ventilated patient exhibits SB effort during MV, the contraction of diaphragm generates a negative pressure in the pleural space, which generates a drop in the airway pressure. The level of SB effort can be assessed after the pressure has been reconstructed by calculating the difference of AUC E_{drs} between the reconstructed and unreconstructed pressure, which is denoted as the substitute of SB effort.

As shown in Figure 4, A_1 is defined as the area of the entrained pressure waveform which has lower overall time varying elastance (AUC E_{drs}) compared to the reconstructed waveform [14, 23]. The value of elastance could be led higher with an addition of A_2 which is defined as the area of missing pressure. This would reduced the effect of SB effort thus, the identification of SB effort in percentage can be made as [14]:

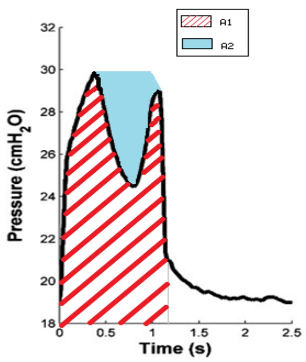


Figure 4.The shaded areas of the entrained pressure waveform, A_1 and the missing pressure waveform, A_2.

$$\text{SB effort} = \frac{A_2}{A_1 + A_2} \times 100\% \quad (4)$$

3. RESULTS AND ANALYSIS

All MV patients who are usually in full volume controlled mode and fully sedated may produce SB efforts that affect the patients' respiratory mechanics as they vary the normal airway pressures [14, 24]. Figure 5 shows the unreconstructed airway pressure waveforms for Patient C1 and Patient M1 at PEEP of 15 and 4 cmH_2O respectively. It can bee seen that both Patient M1 and C1 encountered some pressure reductions or an entrainent in the airway pressure waveform that occurred due to the SB actions.

Thus, pressure reconstruction method is applied and the results are depicted in Figure 6. As shown in Figure 6, the pressure reconstruction method is able to reconstruct the missing pressure and produce an almost perfect airway pressure in Patient C1. In contrast, for Patient M1, the pressure reconstruction method is not perfectly reconstructed the missing pressure. This might be due to the different ventilation mode applied [14, 24].

Furthermore, with the pressure reconstruction method, the SB effort for all patients from both cohorts were able to be estimated as tabulated in Table 3 and 4 respectively. These results show the ability of this reconstruction method to estimate the level of SB effort in MV patients non-invasively and does not require any additional clinical protocols. From Table 3, it shows that Patient M1 exhibited the highest level of SB effort as compared to other patients from the same cohort which is 11.48% at PEEP 4 cmH_2O. On the other hand, Patient C1 from Christchurch Hospital exhibited the highest level of SB of 21.07% at PEEP 4 cmH_2O. Patients in IIUM were ventilated at lower PEEP level and thus, not much breathing effort can be seen as compare to the patients from Christchurch Hospital. Thus, from this research, it can be perceived that, regardless of being anesthetized and ventilated in full controlled mode, the SB affected breaths for all patients can still be measured and estimated as tabulated in Tables 3 and 4.

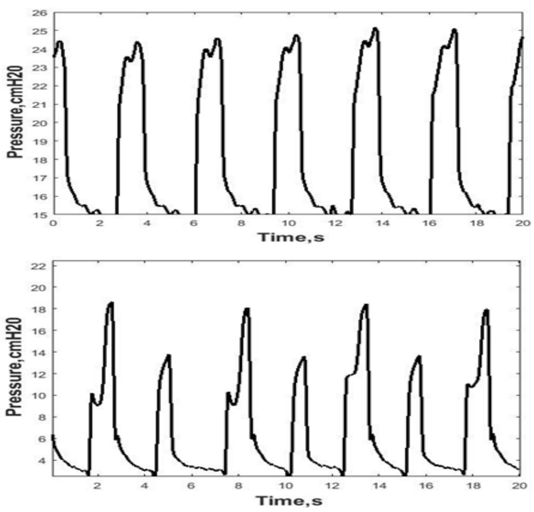


Figure 5. The unreconstructed airway pressure waveforms. *Top*: Patient C1 at PEEP of 15 cmH_2O. *Bottom:* Patient M1 at PEEP of 4 cmH_2O

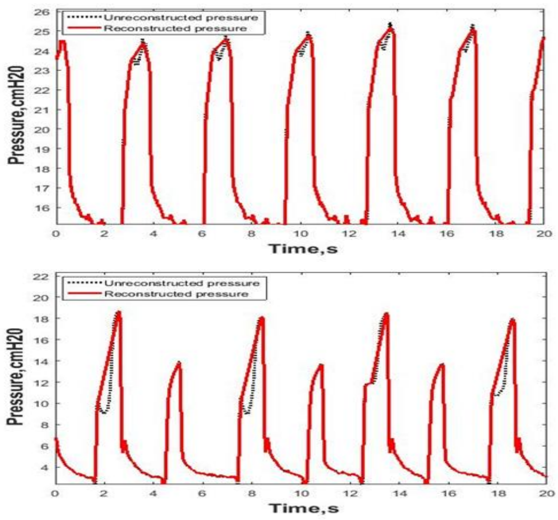


Figure 6. The reconstructed airway pressure waveforms. *Top*: Patient C1 at PEEP of 15 cmH_2O. *Bottom:* Patient M1 at PEEP of 4 cmH_2O.

On the other hand, the analyzation of the variability of E_{drs} through all PEEP in the 7 patients from IIUM Hospital and 5 patients from Christchurch Hospital were done as this project also aims to compute the variability in the respiratory mechanics. Due to the SB effort, it produced a negative elastance in the patient's lung [25]. Thus, this will lead to the variability of the lung elastance in MV patients. The study of the elastance's variability in the patients was done by applying [1] and for each cycle of breath, the AUC E_{drs} was assessed and analysed. As seen in Figure 7, for each patient, the AUC E_{drs} differs at each PEEP level. Precisely, Christchurch patients at PEEP = 15 cmH_2O produced lower variability of elastance with median = 4 and IQR value of [3.29 – 4.58] compared to Malaysian patients that has the highest range of elastance at PEEP = 3 cmH_2O with median of 29.6 and IQR value of [23.19 – 34.38]. From the results of the median and

IQR through all levels of PEEP, it shows that Christchurch patients have higher range of variability of AUC E_{drs}. These results were already predicted as Christchurch patients specifically patient C1 exhibited more SB effort compared to Malaysian patient as shown in previous results above. This concludes that each patient exhibited different levels of SB effort independent from MV setting, indicating the need for non-invasive, real time assessment of SB effort.

Table 3. Characteristics of Patients in IIUM Hospital, Malaysia

Patient no.	PEEP (cmH_20)	Breathing Cycle	SB Affected Cycle	SB Effort (%)
M1	4	63	37	11.48
	3	74	40	9.91
M2	9	168	12	1.02
	10	14	4	4.23
M3	16	90	24	0.02
M4	9	65	44	7.19
	10	68	42	7.47
M5	9	155	30	1.02
M6	8	10	4	0.09
	9	90	48	0.21
M7	10	28	16	4.59
	11	58	37	7.77

Table 4. Characteristics of Patients in Christchurch Hospital, New Zealand

Patient no.	PEEP (cmH_20)	Breathing Cycle	SB Affected Cycle	SB Effort (%)
C1	15	106	106	21.07
C2	16	127	93	12.67
C3	13	112	44	0.12
	14	18	11	0.15
C4	22	130	113	0.76
C5	13	34	6	0.05
	14	108	5	0.03

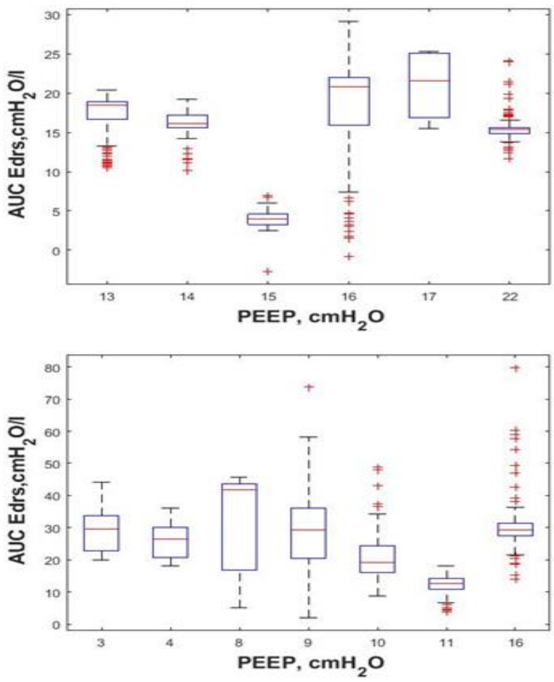


Figure 7. The distribution of AUC E_{drs} at every PEEP level. *Top*: Data from all 5 patients in Christchurch Hospital. *Bottom:* Data from all 7 patients in IIUM Medical Centre

4. CONCLUSION

Patients on ventilator support who are not fully sedated can exhibit SB effort which may cause an alteration in the pressure waveforms recorded during the MV. This will result in an inaccurate estimation of true respiratory mechanics that will eventually lead to further lung damage. Thus, a computationally simple, non-invasive modelling of pressure reconstruction method is proposed based on data IIUM Hospital and compared with the Christchurch Hospital. The results show that the proposed model was able to estimate the SB effort produced by the MV patients although they were fully sedated. Results shows that all patients from both cohorts exhibited SB effort with the highest SB effort at 11.48% for Malaysian patient. Thus, this method allows more accurate estimation of mechanical properties that can be used by clinicians in guiding patient-specific MV care as it takes into account the existence of SB that masked the true concealed respiratory mechanics. It also opens a new venture in monitoring the lung elastance performance especially for SB patients in Malaysian Hospital.

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