CHAPTER 9

Indicator for lung status in a mechanically ventilated COPD patient using lung-ventilation modeling and assessment

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Abstract

We have developed a lung-ventilatory index (*LVI*), based on a lung model represented by a first-order differential equation in lung-volume dynamics to assess lung function and efficiency in the case of chronic-obstructive-pulmonary-disease (COPD) patients requiring mechanical ventilation because of acute respiratory failure. Herein, we have attempted to evaluate the efficacy of the *LVI* in identifying improving or deteriorating lung condition in such mechanically ventilated chronic-obstructive-pulmonary-disease (COPD) patients, and whether it could provide valuable information regarding their lung status and consequently if *LVI* can be used as a potential indicator to predict ventilator discontinuation. For this purpose, we undertook a bioengineering study of 13 COPD patients who were mechanically ventilated because of acute respiratory failure. When their *LVI* was evaluated, it provided a clear separation between patients with improving and deteriorating lung condition. Finally, we formulated a nondimensional lung-improvement index (*LII*) representative of the overall lung response to treatment and medication and κ that corresponds to the rate of lung improvement and reflects the stability of lung status with time.

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1 Introduction

In mechanically ventilated patients with chronic-obstructive-pulmonary-disease (COPD), elevated airway resistance and decreased lung compliance (i.e. stiffer lung) are observed with rapid breathing. Many indices have been developed based on indicators of lung-status improvement to predict the successful discontinuation of mechanical ventilation. The existing indices include breathing pattern, arterial blood gas, frequency of breathing, tidal volume, and rapid shallow-breathing index, all of which are related to respiratory-system output. The need for accurate predictive indicators of lung-status improvement is essential for ventilator discontinuation through stepwise reduction in mechanical support, as and when patients are increasingly able to support their own breathing, followed by trials of unassisted breathing preceding extubation, and ending with extubation.

For determining if a patient is ready to be discontinued from mechanical ventilation after the clinician has chosen an appropriate indicator to assess lung status s/he will incorporate this indicator into three general approaches for ventilator discontinuation that are (i) synchronized intermittent mandatory ventilation (SIMV) wherein the number of breaths is supplied by the ventilator and lowering the ventilator breaths will initiate more spontaneous breaths in the patient, (ii) pressure-support ventilation (PSV) that provides inspiratory pressure assistance based on spontaneous efforts, and (iii) spontaneous breathing trial (SBT). The intent of the ventilatory discontinuation process is to decrease the level of support provided by the ventilator, requiring the patient to assume a greater proportion of the ventilatory workload.

For stepwise reduction in mechanical ventilatory support, the most useful clinically employed indicators have been the rapid shallow-breathing index (RSBI) < 65 breaths/min/L (measured using ventilatory settings) and respiratory rate or frequency (RF) < 38 breaths/min. However, these are extrinsic empirical indices, currently there is no known easy-to-use, reliable indicator that incorporates the intrinsic parameters governing the respiratory-system mechanics for indicating lung-status improvement or deterioration, and eventual ventilator discontinuation. For this reason, we have developed an easy-to-employ lung-ventilatory index (LVI), involving the intrinsic parameters of a lung-ventilatory model, represented by a first-order differential equation in lung-volume response to ventilator driving pressure. The LVI is then employed for evaluating the lung status of chronic-obstructive-pulmonary-disease (COPD) patients requiring mechanical ventilation because of acute respiratory failure. Herein, we have also tested the efficacy of LVI for assessing the lung status in mechanically ventilated COPD patients in acute respiratory failure.

In general, the ventilator discontinuation process can be outlined in three stages. In the first stage, the clinician progressively reduces (in a stepwise fashion) the level of support. In the second stage, the patient undergoes a trial of unassisted breathing. In the final stage, the clinician extubates the patient. Any successful indicator for lung-status improvement will help validate the extubation process in the first stage itself. All COPD patients recruited in our study were discontinued from SIMV (synchronized intermittent mandatory ventilation) mode to a combination of SIMV and PSV (pressure support ventilation), and to a breathing trial.

2 Methodology

We recruited 13 mechanically ventilated patients with chronic-obstructive-pulmonary-disease (COPD) in acute respiratory failure. All patients met the diagnostic criterion of COPD. The first attempt of discontinuation for every patient was made within a short duration (not exceeding 88 hours). The patients in the study were between the ages of 54–83 years. All the patients were on SIMV mode with mandatory ventilation at initial intubation. Based on the physician's judgment, the modes were changed for eventual discontinuation of mechanical ventilation. The time period for recording observations was one hour. The indices developed were not involved in any of the decision making during the stages of ventilator discontinuation. For all purposes in this study a successful ventilator discontinuation is defined as the toleration to extubation for 24 hours or longer and a failed ventilator discontinuation is defined as either a distress when ventilator support is withdrawn or the need for reintubation. From hereon, we will be using the term discontinuation for "ventilator discontinuation".

3 Lung-ventilation model

From a ventilatory-mechanics viewpoint, the lungs can be considered analogous to a balloon, which can be inflated and deflated (passively). The gradient between the mouth-pressure (P_{m}) and the alveolar pressure (P_{al}) causes respiration to occur. During inspiration, $P_{\mathrm{m}} > P_{\mathrm{al}}$ that causes air to enter the lungs. During expiration P_{al} increases, and is greater than P_{m}; this causes the air to be expelled out of the lungs passively. These pressure differentials provide a force driving the gas flow. The pressure difference between the alveolar pressure (P_{al}) and pleural pressure (P_{p}) counterbalances the elastic recoil. Thus the assessment of respiratory mechanics involves the measurement of flows, volumes (flow integrated over time) and pressure-gradients. The lung-ventilation model (shown in Fig. 1) is based on the following dynamic-equilibrium differential equation (eqn. (1)), expressing lung-volume response to pressure across the lung.

$$R\mathring{V} + \frac{V}{C} = P_{\mathrm{L}}(t) - P_{\mathrm{e}} = P_{\mathrm{N}}(t), \tag{1}$$

wherein:

(i) the driving pressure, $P_{\mathrm{L}} = P_{\mathrm{m}} - P_{\mathrm{p}}$
(ii) the parameters of the governing equation (1) are lung compliance (C) and airflow resistance (R), with both R and C being instantaneous values
(iii) $V = V(t) - V_{\mathrm{e}}$ (wherein V_{e} is the end-expiratory lung volume)
(iv) P_{e} is the end-expiratory pressure

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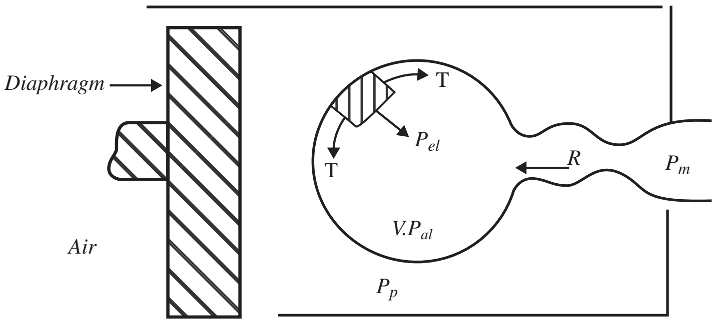

Figure 1: Alveolar model.

Let B be the amplitude of the net pressure wave form applied by the ventilator, C_a be the averaged dynamic lung compliance, R_a the averaged dynamic resistance to airflow, the driving pressure P_L and the net pressure P_N be given as $P_\mathrm{L} = P_\mathrm{e} + B\sin(\omega t)$, $P_\mathrm{N} = B\sin(\omega t)$. The governing equation (1) then becomes:

$$R_\mathrm{a}\mathring{V} + \frac{V}{C_\mathrm{a}} = P_\mathrm{N} = B\sin(\omega t). \tag{2}$$

The volume response to P_N (the solution to eqn. (2)) is given by:

$$V(t) = \frac{BC_\mathrm{a}\{\sin(\omega t) - \omega k_\mathrm{a}\cos(\omega t)\}}{1+\omega^2 k_\mathrm{a}^2} + H\mathrm{e}^{-t/k_\mathrm{a}}, \tag{3}$$

wherein:

(i) $k_\mathrm{a}(=R_\mathrm{a}C_\mathrm{a})$ is the averaged time constant,
(ii) the integration constant H is determined from the initial conditions,
(iii) the model parameters are C_a and k_a (i.e. C_a and R_a), and
(iv) ω is the frequency of the oscillating pressure profile applied by the ventilator.

An essential condition is that the flow rate is zero at the beginning of inspiration and end of expiration. Hence, the flow rate $\mathrm{d}V/\mathrm{d}t = 0$ at $t = 0$. Applying this initial condition to our differential equation (3), the constant H is obtained as:

$$H = \frac{BC_\mathrm{a}\omega k_\mathrm{a}}{1+\omega^2 k_\mathrm{a}^2}. \tag{4}$$

Then, from eqns. (3) and (4), we obtain:

$$V(t) = \frac{BC_\mathrm{a}\{\sin(\omega t) - \omega k_\mathrm{a}\cos(\omega t)\}}{1+\omega^2 k_\mathrm{a}^2} + \frac{BC_\mathrm{a}\omega k_\mathrm{a}}{1+\omega^2 k_\mathrm{a}^2}\mathrm{e}^{-t/k_\mathrm{a}}. \tag{5}$$

Figure 2 illustrates typical data of $V, \mathring{V}$ and P_N. For evaluating the parameter k_a , we will determine the time at which $V(t)$ is maximum and equal to the tidal volume (TV), Hence, putting $\mathrm{d}V/\mathrm{d}t = 0$ in eqn. (5), we obtain:

$$\cos(\omega t) + \omega k_\mathrm{a}\sin(\omega t) = \mathrm{e}^{-t/k_\mathrm{a}}. \tag{6}$$

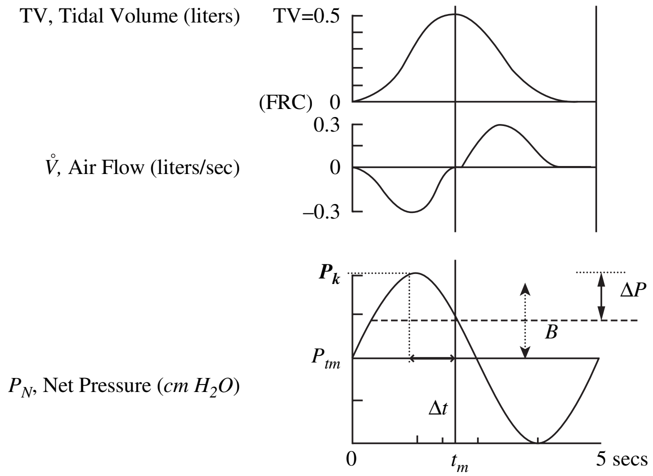

Figure 2: Lung-ventilatory model data shows air flow ($\mathring{V}$) and volume (V) and net pressure (P_{N}). Pause pressure ($P_{t_{\mathrm{m}}}$) occurs at t_{m}, at which the volume is maximum ($TV =$ tidal volume). Δt is the phase difference between the time of maximum volume and peak pressure (P_{k}), it also the time lag between the peak and pause pressures. B is the amplitude of the net pressure waveform P_{N} applied by the ventilator. This P_{N} oscillates about P_{e} with an amplitude of B.

For $t = t_{\mathrm{m}}$, $V(t)$ is maximum and equal to TV. Now in a normal person k_{a} is of the order of 0.1, and 0.5 in ventilated patients with respiratory disorders, which is relevant to our study of COPD patients. Hence the term $\mathrm{e}^{t/k_{\mathrm{a}}}$ is of the order of $10t$ to $2t$. At $t = t_{\mathrm{m}}$, at which the lung volume is maximum, we note from Fig. 2 that t_{m} is of the order of 2 s. Hence $t_{\mathrm{m}}/k_{\mathrm{a}}$ is of the order 20–4, so that $\mathrm{e}^{-t/k_{\mathrm{a}}}$ is of the order of e^{-20} to e^{-4}, which is very small and hence negligible. Hence from eqn. (6), we obtain the following expression for k_{a}:

$$\tan(\omega t) = -1/\omega k_{\mathrm{a}}, \tag{7a}$$

or,

$$k_{\mathrm{a}} = -1/\omega \tan(\omega t_{\mathrm{m}}), \tag{7b}$$

wherein:

(i) If $\tan(\omega t_{\mathrm{m}}) = -1/\omega k_{\mathrm{a}}$, then (8a)

$$\tan(\pi - \omega t_{\mathrm{m}}) = 1/\omega k_{\mathrm{a}}, \text{ i.e., } \pi - \omega t_{\mathrm{m}} = \tan^{-1}(1/\omega k_{\mathrm{a}}) \tag{8b}$$

Hence,

$$t_{\mathrm{m}} = \frac{\pi - \tan^{-1}(1/\omega k_{\mathrm{a}})}{\omega}, \tag{8c}$$

or,

$$t_{\rm m} = \frac{\pi - \theta}{\omega}, \text{ wherein } \quad \theta = \tan^{-1}(1/\omega k_{\rm a}). \tag{8d}$$

Hence, the phase difference between $t = \pi/2\omega$ at which pressure $P_{\rm N}$ $(= B\sin(\omega t))$ is maximum and $t_{\rm m}$ is,

$$t_{\rm m} - t = \frac{\pi - \tan^{-1}(1/\omega k_{\rm a})}{\omega} - \frac{\pi}{2\omega}, \tag{9a}$$

or,

$$\Delta t = \frac{\pi}{2\omega} - \frac{\tan^{-1}(1/\omega k_{\rm a})}{\omega} = \frac{(\pi/2) - \tan^{-1}(1/\omega k_{\rm a})}{\omega}. \tag{9b}$$

From eqn. (8c),

$$\tan^{-1}(1/\omega k_{\rm a}) = \theta = \pi - \omega t_{\rm m}. \tag{10a}$$

Hence,

$$\sin\theta = \frac{1}{\sqrt{1 + \omega^2 k_{\rm a}^2}} \tag{10b}$$

$$\cos\theta = \frac{\omega k_{\rm a}}{\sqrt{1 + \omega^2 k_{\rm a}^2}}. \tag{10c}$$

Fig. 2 shows the clinical lung-volume response dynamics in response to the now net ventilatory driving pressure ($P_{\rm N}$). Referring to Fig. 2, $t_{\rm m}$ denotes the time at which the lung volume is maximum. Since ω (the frequency of the oscillatory pressure profile applied by the ventilator) and $t_{\rm m}$ (the time at which $V(t) = TV$) are known, we can evaluate the model parameter $k_{\rm a}$, from eqns. (10a, b, c). Hence, from eqns. (5) and (6) we obtain:

$$V(t = t_{\rm m}) = TV = \frac{BC_{\rm a}\{\sin(\omega t) - \omega k_{\rm a}\cos(\omega t)\}}{1 + \omega^2 k_{\rm a}^2} + \frac{BC_{\rm a}\omega k_{\rm a}}{1 + \omega^2 k_{\rm a}^2} {\rm e}^{-t/k_{\rm a}}. \tag{11a}$$

Therein, based on eqn. (6), at $t = t_{\rm m}$ the second term,

$$H = \frac{BC_{\rm a}\omega k_{\rm a}}{1 + \omega^2 k_{\rm a}^2} {\rm e}^{-t_{\rm m}/k_{\rm a}} \approx 0. \tag{11b}$$

Hence, eqn. (11a) becomes:

$$V(t = t_{\rm m}) = TV = \frac{BC_{\rm a}\{\sin(\omega t) - \omega k_{\rm a}\cos(\omega t)\}}{1 + \omega^2 k_{\rm a}^2}. \tag{12}$$

Now, in eqn. (12) if we put

$$N = \sin(\omega t) - \omega k_{\rm a}\cos(\omega t) \tag{13a}$$

then, from eqns. (8d, 10b, c), eqn. (13a) becomes:

$$N = \sin(\theta) - \omega k_{\rm a}\cos(\theta) = \frac{1}{\sqrt{1 + \omega^2 k_{\rm a}^2}} + \frac{\omega^2 k_{\rm a}^2}{\sqrt{1 + \omega^2 k_{\rm a}^2}}, \tag{13b}$$

or,

$$N = \sqrt{1 + \omega^2 k_a^2}. \quad (13c)$$

Then, based on eqns. (13a) and (13c), eqn. (12) becomes:

$$V(t = t_m) = TV = \frac{BC_a}{\sqrt{1 + \omega^2 k_a^2}}. \quad (14)$$

4 Determining lung compliance (C_a) and air-flow resistance (R_a)

Now, as shown in Fig. 2, the peak pressure (P_k) is the maximum pressure in the lungs during inspiration. The pause pressure is defined to occur when $V(t)$ is maximum, i.e. (at $t = t_m$) at the end of inspiration. The peak pressure occurs when the driving pressure is maximum at $t = \pi/2\omega$, while the pause pressure occurs when the lung volume is maximum, i.e. at the end of inspiration, when $t_m = (\pi - \theta)/\omega$. It can be interpreted that there is always a phase lag of Δt between pause and peak pressures, which is described by eqn. (9). It is known that the driving pressure (P_L) is given as $P_L = P_e + B \sin(\omega t)$, which leads us to:

$$\text{Peak Pressure}\,(P_k) = P_{L_{\text{at}\, t=\pi/2\omega}} = P_e + B \quad (15)$$

$$\text{Pause Pressure}\,(P_{t_m}) = P_{L_{\text{at}\, t=(\pi-\theta)/\omega}} = P_e + B \sin\left\{\omega\left(\frac{\pi - \theta}{\omega}\right)\right\}, \quad (16)$$

$$\text{or, Pause Pressure}\,(P_{t_m}) = P_e + B \sin\theta. \quad (17)$$

Based on eqn. (10b), eqn. (17) becomes:

$$\text{Pause Pressure}\,(P_{t_m}) = P_e + \frac{B}{\sqrt{1 + \omega^2 k_a^2}}. \quad (18)$$

Then, from eqns. (15) and (18):

(i)

$$P_k - P_{t_m} = \Delta P = B - B\sin\theta = B(1 - \sin\theta), \quad (19a)$$

or,

$$B = \frac{P_k - P_{t_m}}{(1 - \sin\theta)} = \frac{\Delta P}{(1 - \sin\theta)}, \quad (19b)$$

(ii)

$$P_e = P_k - B = \frac{P_{t_m} - P_k \sin\theta}{(1 - \sin\theta)}, \quad (20)$$

wherein, $\sin\theta$ is given by eqn. (10b).

In eqn. (19b), since P_k, and P_{t_m} as well as $\theta(=\pi - \omega t_m)$ are measurable, hence B can be evaluated. Then from eqn. (14), we can evaluate the averaged lung compliance (C_a), because k_a has already been evaluated by eqn. (7b). Hence, based on eqns. (14), (10b) and (19b), we obtain:

$$C_a = \frac{TV\sqrt{1+\omega^2 k_a^2}}{B} = \frac{TV}{B\sin\theta} = \frac{TV(1-\sin\theta)}{\Delta P \sin\theta}. \tag{21}$$

Hence, from eqns. (21) and (10a) the average value of airflow resistance (R_a) can be evaluated as:

$$R_a = k_a/C_a = \frac{\Delta P \sin\theta(1/\omega\tan\theta)}{TV(1-\sin\theta)} = \frac{\Delta P\cos\theta}{TV\omega(1-\sin\theta)}. \tag{22}$$

For our patients, the computed values of the parameters are:

$$R_a = 9 - 43\,\mathrm{cmH_2O\,s/L} \tag{23}$$
$$C_a = 0.020 - 0.080\,\mathrm{L/cmH_2O}.$$

Now, that we have determined the expressions for R_a and C_a, the next step is to develop an integrated index incorporating these parameters.

5 Formulating a lung-ventilatory index (*LVI*) incorporating R_a and C_a

We believe that the correlations between averaged airflow resistance (R_a), averaged lung compliance (C_a), tidal volume (TV), respiratory rate (RF), and maximum inspiratory pressure or peak pressure (P_k) could be used as a possible indicator for determining lung status in a mechanically ventilated COPD patient with acute respiratory failure. We hence propose that a composite index (LVI) incorporating these isolated parameters can have a higher predictive power. For this purpose, we note that patients with COPD have higher R_a, lower C_a, lower TV, higher P_k and higher respiratory rate (or frequency) RF. If we want the lung-ventilatory index (LVI) to have a high value for a COPD patient and further increasing LVI for deteriorating lung status and decreasing LVI for improving lung status in a mechanically ventilated COPD patient in acute respiratory failure, then the lung-ventilatory index (LVI) can be expressed as:

$$LVI = \frac{R_a(RF)P_k}{C_a(TV)}. \tag{24}$$

Let us obtain the order-of-magnitude values of LVI for a mechanically ventilated COPD patient in acute respiratory failure (by using representative computed values of the parameters R_a, C_a, RF, TV, and P_k) in order to verify that the formula for

LVI (eqn. (22)) can enable distinct separation in mechanically ventilated COPD patients in acute respiratory failure.

$$LVI\ (Intubated\,\text{COPD}) = \frac{[15\,\text{cmH}_2\text{O s/L}][0.33\,\text{s}^{-1}][20\,\text{cmH}_2\text{O}]}{[0.035\,\text{L/cmH}_2\text{O}][0.5\,\text{L}]}.$$
$$= 5654\,(\text{cmH}_2\text{O/L})^3, \qquad (25)$$

wherein,

$$R_\text{a} = 15\,\text{cmH}_2\text{O s/L} \qquad C_\text{a} = 0.035\,\text{L/cmH}_2\text{O} \qquad RF = 0.33\,\text{s}^{-1}$$
$$TV = 0.5\,\text{L} \qquad P_\text{k} = 20\,\text{cmH}_2\text{O}.$$

Now, let us obtain the order of magnitude of *LVI* (by using representative computed values of R_a, C_a, RF, TV, and P_k) as above for a COPD patient with improving lung status just before successful discontinuation.

$$LVI\ (Outpatient\,\text{COPD}) = \frac{[10\,\text{cmH}_2\text{O s/L}][0.33\,\text{s}^{-1}][12\,\text{cmH}_2\text{O}]}{[0.05\,\text{L/cmH}_2\text{O}][0.35\,\text{L}]}$$
$$= 2263\,(\text{cmH}_2\text{O/L})^3, \qquad (26)$$

wherein,

$$R_\text{a} = 10\,\text{cmH}_2\text{O s/L} \quad C_\text{a} = 0.050\,\text{L/cmH}_2\text{O} \quad RF = 0.33\,\text{s}^{-1}$$
$$TV = 0.35\,\text{L} \qquad P_\text{k} = 12\,\text{cmH}_2\text{O}.$$

Hence, for *LVI* to reflect lung-status improvement in a mechanically ventilated COPD patient in acute respiratory failure, it has to decrease to the range of *LVI* for an outpatient COPD patient at the time of discontinuation. Additionally, we now write:

$$LVI(t) = LVI_0 \mathrm{e}^{-\kappa t}, \qquad (27)$$

wherein:

(i) LVI_0 represents the value of *LVI* at the time of admission of the patient to the respiratory care unit.
(ii) the coefficient κ, represents the rate of improvement (or deterioration) of the patient's lung status; $\kappa = 0$ implies no change in lung condition.
(iii) the coefficient κ (the rate of decrease of *LVI* or improvement in lung status) will be positive with deteriorating lung condition and negative for improving lung condition.

We can also formulate an index (*LII*) for overall lung-status improvement or deterioration as:

$$LII(\%) = \frac{LVI\ (\text{at entry or intubation}) - LVI\ (\text{at discharge or extubation})}{LVI\ (\text{at entry})} \times 100. \qquad (28)$$

6 Evaluating lung-ventilatory index (*LVI*)

6.1 *LVI* characteristics

Now, that we have formulated *LVI,* let us verify for selected patient data that *LVI* is indicative of lung-status improvement or deterioration. For this purpose, we have categorized the intubated patients into two categories, (i) patients who were successfully discontinued and (ii) patients who failed discontinuation. Table 1 provides the range of *LVI* values for the two categories, wherein for all successful discontinuations the *LVI* is close to the value for an outpatient COPD patient.

In Table 1 all patients who were successfully discontinued have *LVI* at discontinuation in the range of 1194–4589 $(cmH_2O/L)^3$. Similarly, patients with failed discontinuation have *LVI* at discontinuation in the range of 7144–15658 $(cmH_2O/L)^3$, thus *LVI* is indicating a clear separation between successful and failed discontinuation. It is also observed that the rate of lung-status improvement was faster after successful discontinuation, due to reduced dead space by mechanical ventilation of CABG patients. In Fig. 3, we have provided the distribution of *LVI* at outcome for successful and failed discontinuation of mechanically ventilated COPD patients in acute respiratory failure (approximated as a normal distribution). In Fig. 4, we have provided *LVI* characteristics for four patients, indicating their lung-status.

6.2 Comparing the efficacies of R_a and C_a with *LVI*

Now, let us evaluate the significance of R_a and C_a with lung status. In Table 2, we have provided information on the values of R_a and C_a at discontinuation for the two classes of patients. In Figs. 5 and 8, we have provided R_a and C_a characteristics for the same four patients discussed in Fig. 4. We observe that patients with successful discontinuation had (i) R_a at discontinuation in the range of 9–14 cmH_2O s/L compared to 17–23 cmH_2O s/L in failed-discontinuation cases, and (ii) C_a for successful discontinuation in the range of 0.03–0.08 L/cmH_2O compared to 0.028–0.042 L/cmH_2O in failed-discontinuation cases.

Figure 5 shows the time variation in R_a of successfully extubated patients (SEPs) and the unsuccessfully extubated patients (UEPs). It is noted that R_a decreases

Table 1: Range of *LVI* values at intubation and outcome.

Outcome	Number	Age (Years)	Sex (M/F)	Time of intubation (Hrs)	*LVI* at intubation $(cmH_2O/L)^3$	*LVI* at outcome $(cmH_2O/L)^3$
Successful Discontinuation	6	54–74	6/0	11–55	3959–13568	1194–4589
Failed Discontinuation	7	64–83	5/2	29–88	3350–21152	7144–15658

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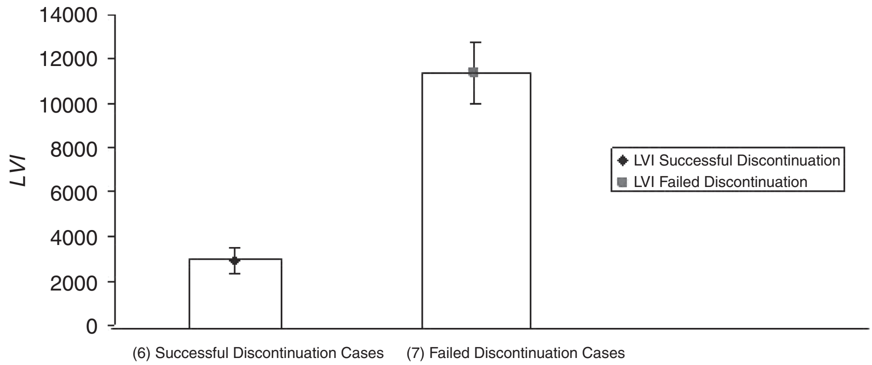

Figure 3: Distribution of *LVI* at discontinuation for patients with failed and successful discontinuation. For the 6 successfully discontinued cases, the *LVI* was (2900) ± (567) $(cmH_2O/L)^3$; for the 7 failed-discontinuation cases the *LVI* was (11400) ± (1433) $(cmH_2O/L)^3$. It is observed that *LVI* indicates clear separation between failed and successful discontinuation.

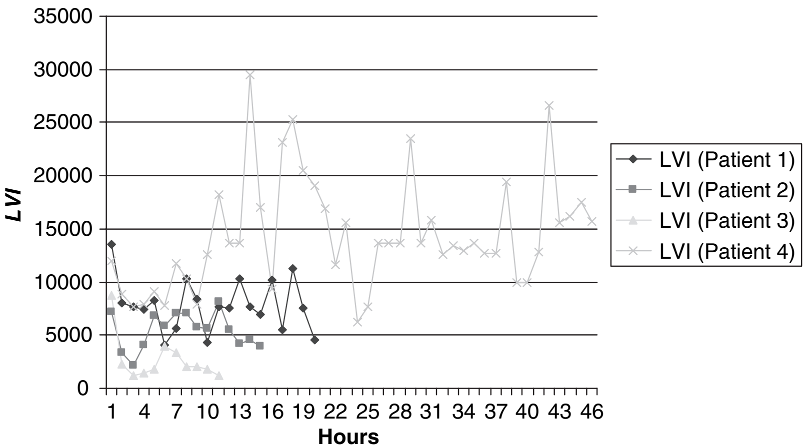

Figure 4: *LVI* showing lung status in four mechanically ventilated COPD patients in acute respiratory failure. Note that Patients 1, 2 and 3 were successfully discontinued and patient 4 failed discontinuation.

steadily in SEPs but continues to be high in the UEPs. The distribution of R_a (in Fig. 6), graphically illustrates the distinct separation of unsuccessfully and successfully extubated patients. Yet in the case of patient 2 in (Fig. 5) the resistance at intubation was 12.38 cmH_2O s/L and decreased only slightly at discontinuation to 10.82 cmH_2O s/L within the period of 15 hours of intubation to a value corresponding to that of an outpatient COPD patient. However, for this patient—2, the *LVI* changes from 7300 to 4500 $(cmH_2O/L)^3$, i.e. it is significantly closer to the

Table 2: Range of R_a and C_a at intubation and outcome.

Outcome	R_a at intubation cmH_2Os/L	R_a at outcome cmH_2Os/L	C_a at intubation L/cmH_2O	C_a at outcome L/cmH_2O	k_a at intubation s	k_a at outcome s
Successful Discontinuation	14–32	9–14	0.03–0.047	0.030–0.080	0.42–1.50	0.27–1.12
Failed Discontinuation	14–25	17–23	0.03–0.037	0.028–0.042	0.42–0.925	0.47–0.99

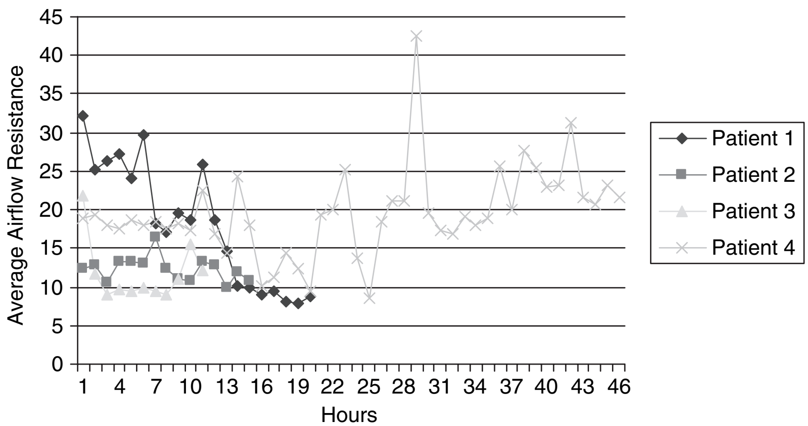

Figure 5: The variations in R_a for four mechanically ventilated patients indicating that Patient 1, 2, and 3 are all discontinued at lower values 8–10 cmH_2O s/L, i.e. closer to outpatient COPD values. It is also observed that the average airflow resistance is higher for deteriorating lung condition.

outpatient COPD patient *LVI* at successful discontinuation, thus indicating that R_a is less sensitive to the change in lung status compared to *LVI* .

Now, let us observe the dynamics of C_a, which is also deemed to provide separation between normal and COPD patients. Fig. 8, illustrating the C_a dynamics of the same 4 patients, does not show a definitive trend of decreasing C_a, while the C_a for patient—1 even decreased. Also, from Table 2 and Fig. 7, the value for C_a at discontinuation for patients with successful extubation is 0.03–0.08 L/cmH_2O and for failed extubation is 0.028–0.042 L/cmH_2O, indicating that C_a does not provide a clear separation between patients with improving and deteriorating lung status. Hence, we believe C_a by itself cannot be a reliable indicator for assessing lung status in mechanically ventilated COPD patients in acute respiratory failure.

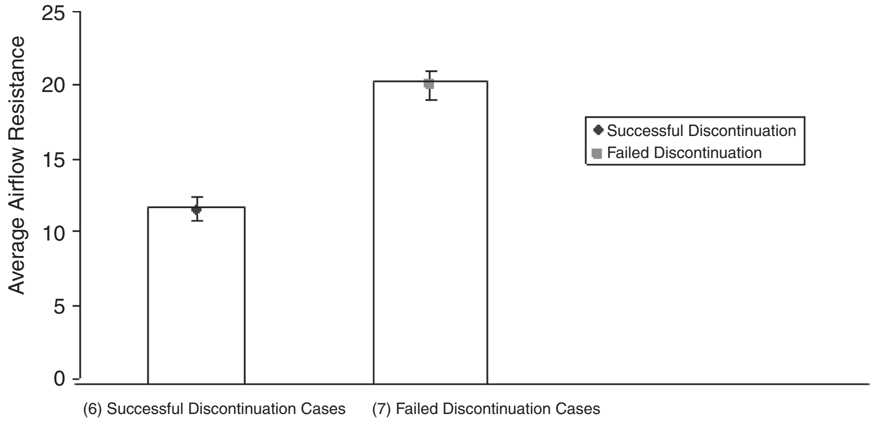

Figure 6: Distribution of R_a at discontinuation for successful and failed discontinuation. $R_a = (11.5) \pm (0.83)$ (cmH_2O S/L) for the 6 successful-discontinuation cases, and $(20) \pm (1)$ (cmH_2O S/L) for the 7 failed-discontinuation cases. Hence, R_a indicates a clear separation between failed and successful discontinuations.

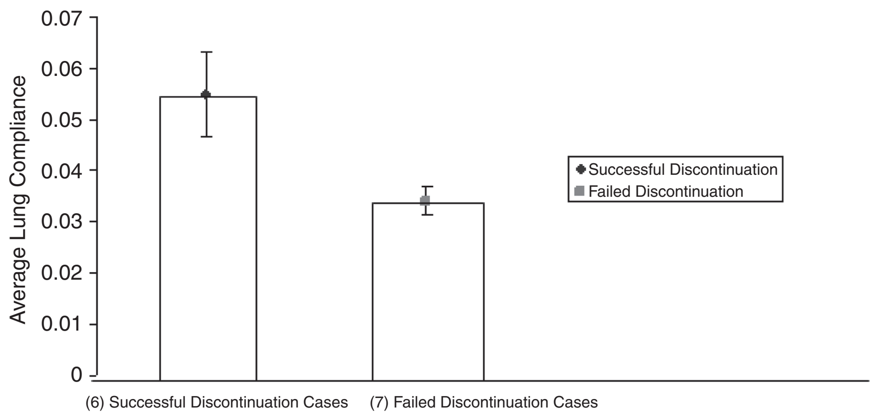

Figure 7: Distribution of C_a at discontinuation for successful and failed discontinuation. $C_a = (0.055) \pm (0.0083)$ (L/cmH_2O) for the 6 successful-discontinuation cases, and $(0.034) \pm (0.0027)$ (L/cmH_2O) for the 7 failed-discontinuation cases. Hence, C_a does not provide a clear separation between failed and successful discontinuations.

6.3 *LVI* as a reliable predictor of ventilator discontinuation

We have noted that *LVI* can, in fact, be a reliable indicator of lung status in a mechanically ventilated COPD patient with acute respiratory failure. *But, can it*

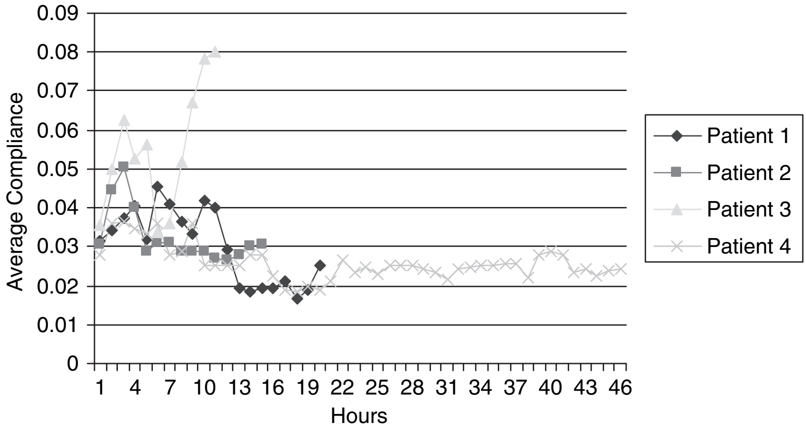

Figure 8: The variations in C_a for four mechanically ventilated patients, indicating that the C_a values for Patients 1, 2 and 4 were all in the lower values and did not change significantly from the time of intubation. Though the lung status for Patients 1 and 2 improved and were successfully discontinued and Patient 4 failed discontinuation.

be used as a predictor for ventilator discontinuation? Now, an ideal predictor of ventilator discontinuation would safely and easily distinguish patients needing discontinuation and continued ventilatory support, which we have successfully indicated with our patient data. Also, it has been speculated that as much as 42% of the time spent by patients on mechanical ventilation are instances when they could have been extubated, and in many cases unnecessary delays in the discontinuation process is associated with further complications.

In this context, we observe that *LVI* has adequately addressed the issue by identifying instances when the patient could potentially be discontinued. For example, in Fig. 4 there are four instances when the *LVI* value for patient 4 is lower than 5000 $(\text{cmH}_2\text{O/L})^3$, and closer to the value for an ideal outpatient COPD patient. This leads us to believe that *LVI* can be a reliable factor in the clinician's judgment to identify patients needing discontinuation.

Thus far, what we have developed leads us to believe that *LVI* is reasonably representative of a reliable index for discontinuation. However, we will be carrying out a more evidence-based clinical approach for validation.

7 Assessing lung-improvement index (*LII*) and rate of lung improvement (κ)

The rationale behind designating *LII* eqn. (24) as an index is not as an indicator for lung status per se, because there are instances when the patient's lung had improved from the time of initial intubation but could not be sustained upon discontinuation. However, *LII* could be representative of the overall lung response to treatment

Table 3: Range of *LII* and κ at intubation and outcome.

Outcome	Number	Age (Years)	Sex (M/F)	Time of intubation (Hrs)	*LII* (%) at outcome	κ at outcome
Successful Discontinuation	6	54–74	6/0	11–55	26–86 %	0–0.18
Failed Discontinuation	7	64–83	5/2	29–88	−101–49 %	−0.045–0.015

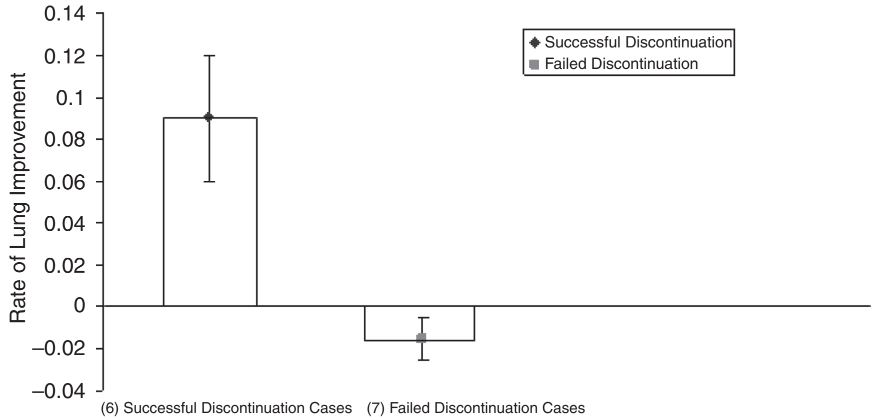

Figure 9: The distribution of κ for patients with successful and failed discontinuation. $\kappa = (0.09) \pm (0.03)$ for the 6 successful-discontinuation cases, and $(-0.015) \pm (0.01)$ for the 7 failed-discontinuation cases. Hence, κ indicates appreciable separation between successful and failed discontinuations.

and medication. The coefficient κ corresponds to the rate of improvement or deterioration in lung status. It is to be noted that for a patient with improving lung condition, κ will be positive and vice versa. We have observed that in most patients, κ decreased immediately after the first few hours of mechanical ventilation, and later on varied somewhat and stabilized before successful discontinuation. Hence, we propose that κ reflects the patient stability in lung status with time, and can provide a clear separation between patients with improving and deteriorating lung status, as indicated by Fig. 9. Table 3, provides information on *LII* and κ for patients with successful and failed discontinuation, while Figs. 9 and 10 illustrate their distributions.

From Table 3 and Fig. 10, we note that some patients with positive response to treatment (i.e. $+LII$) did not necessarily succeed discontinuation. Hence, it is

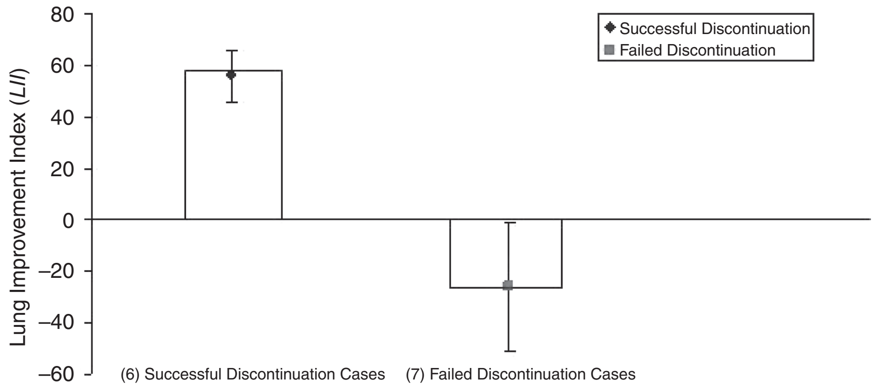

Figure 10: The distribution of the lung-improvement index (*LII*) for patients with successful and failed discontinuations. $LII = (56\%) \pm (10\%)$ for the 6 successful-discontinuation cases, and $(-26\%) \pm (25\%)$ for the 7 failed-discontinuation cases.

indicated that *LII* and κ can show a distinct lung-improvement trend, but may not be regarded as absolute indicators for patient-candidates for successful extubation.

The way in which we could employ *LVI, LII* and κ, in combination is as follows. Starting with evaluation of *LVI* at the time of intubation, we can employ *LII* and κ to designate signs of lung improvement. Then, when *LVI* value persists being less than 3000 $(\text{cmH}_2\text{O/L})^3$ for 2–3 hours, we could decide to extubate the patient.

8 Conclusion

We have shown *LVI*, *LII*, and κ to be reliable indicators for mechanically ventilated COPD patients in acute respiratory failure. We have also indicated how they can be collectively employed to decide on extubating a patient. Now, we need to further testify their efficacies, in assessing COPD therapy in an intensive-care unit, in a larger patient population.

References

[1] Ghista, D.N., Loh, K.M. & Damodharan, M., Lung Ventilation Modeling and Assessment, in "*Human Respiration: Anatomy and Physiology, Mathematical Modeling, Numerical Simulation and Application*", ed. by V. Kulish, WIT Press (Southampton, UK), 2005.

[2] MacIntyre, N.R., Evidence-based Guidelines for Weaning and Discontinuing Ventilatory support by A Collective task Force of the American College of Chest Physicians: Respiratory Care, **47(1)**, 69–90, 2002.

[3] Menzies, R., Gibbons, W. & Goldberg, P., Determinants of weaning and survival among patients with COPD who require mechanical ventilation for acute respiratory failure, *Chest.*, **95(2)**, 398–405, 1989.
[4] Yang, K.L. & Tobin, M.J., A prospective study of indexes predicting the outcome of trials of weaning from mechanical ventilation, *N Engl J Med.*, **324(21)**, 1445–1450, 1991.
[5] Alvisi, R., Volta, C.A., Righini, E.R., Capuzzo, M., Ragazzi, R., Verri, M., Candini, G., Gritti, G. & Milic-Emili, J., Predictors of weaning outcome in chronic obstructive pulmonary disease patients, *Eur Respir J.*, **15(4)**, 656–662, 2000.
[6] Pauwels, R.A., Buist, A.S., Calverley, P.M., Jenkins, C.R. & Hurd, S.S., Global strategy for the diagnosis, management, and prevention of chronic obstructive pulmonary disease. NHLBI/WHO Global Initiative for Chronic Obstructive Lung Disease (GOLD) Workshop summary, *Am J Respir Crit Care Med.*, **163(5)**, 1256–1276, 2001.
[7] Meade, M., Guyatt, G., Cook, D., Griffith, L., Sinuff, T., Kergl, C., Mancebo, J., Esteban, A. & Epstein, S., Predicting success in weaning from mechanical ventilation. *Chest.*, **120(6 Suppl)**, 400S–424S, 2001.
[8] Jubran, A., de Graaff, W.B.V. & Tobin, M.J., Variability of patient-ventilator interaction with pressure support ventilation in patients with chronic obstructive pulmonary disease, *Am J Respir Crit Care Med.*, **152(1)**, 129–136, 1995.