CHAPTER 9

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

D.N. Ghista¹, R. Pasam², S.B. Vasudev³, P. Bandi⁴ & R.V. Kumar⁵

¹School of MPE, Nanyang Technological University, Singapore.
²Department of Bioengineering, University of Illinois at Chicago, USA.
³Department of Biomedical Engineering, University of South Florida, Tampa, USA.
⁴Department of Population Health Sciences, University of Wisconsin, Madison, USA.
⁵Department of Pulmonary Medicine, Mediciti Hospitals, Hyderabad, India.

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.
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, $P_m > P_{al}$ 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.

$$RV' + \frac{V}{C} = P_L(t) - P_e = P_N(t), \tag{1}$$

wherein:

(i) the driving pressure, $P_L = P_m - P_p$

(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) $V = V(t) - V_e$ (wherein $V_e$ is the end-expiratory lung volume)

(iv) $P_e$ is the end-expiratory pressure
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 $P_L = P_e + B \sin(\omega t)$, $P_N = B \sin(\omega t)$. The governing equation (1) then becomes:

$$R_a \dot{V} + \frac{V}{C_a} = P_N = B \sin(\omega t).$$  (2)

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

$$V(t) = \frac{BC_a \{\sin(\omega t) - \omega k_a \cos(\omega t)\}}{1 + \omega^2 k_a^2} + H e^{-t/k_a},$$  (3)

wherein:

(i) $k_a (= R_a C_a)$ 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) $\omega$ 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 $dV/dt = 0$ at $t = 0$. Applying this initial condition to our differential equation (3), the constant $H$ is obtained as:

$$H = \frac{BC_a \omega k_a}{1 + \omega^2 k_a^2}.$$  (4)

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

$$V(t) = \frac{BC_a \{\sin(\omega t) - \omega k_a \cos(\omega t)\}}{1 + \omega^2 k_a^2} + \frac{BC_a \omega k_a}{1 + \omega^2 k_a^2} e^{-t/k_a}.$$  (5)

Figure 2 illustrates typical data of $V$, $\dot{V}$ 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 $dV/dt = 0$ in eqn. (5), we obtain:

$$\cos(\omega t) + \omega k_a \sin(\omega t) = e^{-t/k_a}.$$  (6)
For $t = \tau_m$, $V(t)$ 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 $e^{\omega \tau_m}$ is of the order of 10 to 2. At $t = \tau_m$, at which the lung volume is maximum, we note from Fig. 2 that $\tau_m$ is of the order of 2 s. Hence $\tau_m/k_a$ is of the order 20–4, so that $e^{-\omega \tau_m}$ 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 $k_a$:

$$\tan (\omega \tau_m) = -1/\omega k_a, \quad (7a)$$

or,

$$k_a = -1/\omega \tan (\omega \tau_m), \quad (7b)$$

wherein:

(i) If $\tan (\omega \tau_m) = -1/\omega k_a$, then

$$\tan (\pi - \omega \tau_m) = 1/\omega k_a, \quad i.e., \pi - \omega \tau_m = \tan^{-1} (1/\omega k_a) \quad (8a)$$

Hence,

$$\tau_m = \frac{\pi - \tan^{-1} (1/\omega k_a)}{\omega}, \quad (8c)$$
or,
\[ t_m = \frac{\pi - \theta}{\omega}, \text{ wherein } \theta = \tan^{-1} \left( \frac{1}{\omega k_a} \right). \] (8d)

Hence, the phase difference between \( t = \frac{\pi}{2\omega} \) at which pressure \( P_N (= B \sin (\omega t)) \) is maximum and \( t_m \) is,
\[ t_m - t = \frac{\pi - \tan^{-1} \left( \frac{1}{\omega k_a} \right)}{\omega} - \frac{\pi}{2\omega}, \] (9a)
or,
\[ \Delta t = \frac{\pi}{2\omega} - \frac{\tan^{-1} \left( \frac{1}{\omega k_a} \right)}{\omega} = \frac{(\pi/2) - \tan^{-1} \left( \frac{1}{\omega k_a} \right)}{\omega}. \] (9b)

From eqn. (8c),
\[ \tan^{-1} \left( \frac{1}{\omega k_a} \right) = \theta = \pi - \omega t_m. \] (10a)

Hence,
\[ \sin \theta = \frac{1}{\sqrt{1 + \omega^2 k_a^2}} \] (10b)
\[ \cos \theta = \frac{\omega k_a}{\sqrt{1 + \omega^2 k_a^2}}. \] (10c)

Fig. 2 shows the clinical lung-volume response dynamics in response to the now net ventilatory driving pressure \( (P_N) \). Referring to Fig. 2, \( t_m \) denotes the time at which the lung volume is maximum. Since \( \omega \) (the frequency of the oscillatory pressure profile applied by the ventilator) and \( t_m \) (the time at which \( V(t) = TV \)) are known, we can evaluate the model parameter \( k_a \), from eqns. (10a, b, c). Hence, from eqns. (5) and (6) we obtain:
\[ V(t = t_m) = TV = \frac{BC_a \sin (\omega t) - \omega k_a \cos (\omega t)}{1 + \omega^2 k_a^2} + \frac{BC_a \omega k_a}{1 + \omega^2 k_a^2} e^{-t/k_a}. \] (11a)

Therein, based on eqn. (6), at \( t = t_m \) the second term,
\[ H = \frac{BC_a \omega k_a}{1 + \omega^2 k_a^2} e^{-t_m/k_a} \approx 0. \] (11b)

Hence, eqn. (11a) becomes:
\[ V(t = t_m) = TV = \frac{BC_a \sin (\omega t) - \omega k_a \cos (\omega t)}{1 + \omega^2 k_a^2}. \] (12)

Now, in eqn. (12) if we put
\[ N = \sin (\omega t) - \omega k_a \cos (\omega t) \] (13a)
then, from eqns. (8d, 10b, c), eqn. (13a) becomes:
\[ N = \sin (\theta) - \omega k_a \cos (\theta) = \frac{1}{\sqrt{1 + \omega^2 k_a^2}} + \frac{\omega^2 k_a^2}{\sqrt{1 + \omega^2 k_a^2}}. \] (13b)
or,

\[ N = \sqrt{1 + \omega^2 k_a^2}. \]  

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

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

### 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. \((t = t_m)\) 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 \(\Delta t\) 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:

- **Peak Pressure** \((P_k)\) given by:

\[ P_k = P_{\text{at } t = \pi/2\omega} = P_e + B \]  

- **Pause Pressure** \((P_{tm})\) given by:

\[ P_{tm} = P_{\text{at } t = (\pi - \theta)/\omega} = P_e + B \sin\left(\omega\left(\frac{\pi - \theta}{\omega}\right)\right), \]

or, **Pause Pressure** \((P_{tm})\) given by:

\[ P_{tm} = P_e + B \sin\theta. \]

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

\[ P_{tm} = P_e + \frac{B}{\sqrt{1 + \omega^2 k_a^2}}. \]

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

(i) \(P_k - P_{tm} = \Delta P = B - B \sin\theta = B(1 - \sin\theta),\)

or,

\[ B = \frac{P_k - P_{tm}}{(1 - \sin\theta)} = \frac{\Delta P}{(1 - \sin\theta)}, \]

(ii) \(P_e = P_k - B = \frac{P_{tm} - P_k \sin\theta}{1 - \sin\theta},\)

wherein, \(\sin\theta\) is given by eqn. (10b).
In eqn. (19b), since $P_k$, and $P_{m}$ 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:

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

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

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

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

\begin{align*}
R_a &= 9 - 43 \text{ cmH}_2\text{O s/L} \\
C_a &= 0.020 - 0.080 \text{ L/cmH}_2\text{O}.
\end{align*}  \hspace{1cm} (23)

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:

$$LVI = \frac{R_a(RF)P_k}{C_a(TV)}.$$  \hspace{1cm} (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.

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

wherein,

\[
R_a = 15 \text{ cmH}_2\text{O s/L} \quad C_a = 0.035 \text{ L/cmH}_2\text{O} \quad RF = 0.33 \text{ s}^{-1} \quad TV = 0.5 \text{ L} \quad P_k = 20 \text{ cmH}_2\text{O}.
\]

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.

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

wherein,

\[
R_a = 10 \text{ cmH}_2\text{O s/L} \quad C_a = 0.050 \text{ L/cmH}_2\text{O} \quad RF = 0.33 \text{ s}^{-1} \quad TV = 0.35 \text{ L} \quad P_k = 12 \text{ cmH}_2\text{O}.
\]

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:

\[
LVI(t) = LVI_0 e^{-\kappa t}, \tag{27}
\]

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 \(\kappa\), represents the rate of improvement (or deterioration) of the patient’s lung status; \(\kappa = 0\) implies no change in lung condition.

(iii) the coefficient \(\kappa\) (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:

\[
LII(\%) = \frac{LVI \text{ (at entry or intubation)} - LVI \text{ (at discharge or extubation)}}{LVI \text{ (at entry)}} \times 100, \tag{28}
\]
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 (cmH₂O/L)³. Similarly, patients with failed discontinuation have LVI at discontinuation in the range of 7144–15658 (cmH₂O/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 cmH₂O s/L compared to 17–23 cmH₂O s/L in failed-discontinuation cases, and (ii) $C_a$ for successful discontinuation in the range of 0.03–0.08 L/cmH₂O compared to 0.028–0.042 L/cmH₂O 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>
<thead>
<tr>
<th>Outcome</th>
<th>Number</th>
<th>Age (Years)</th>
<th>Sex (M/F)</th>
<th>Time of intubation (Hrs)</th>
<th>$LVI$ at intubation (cmH₂O/L)³</th>
<th>$LVI$ at outcome (cmH₂O/L)³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Successful Discontinuation</td>
<td>6</td>
<td>54–74</td>
<td>6/0</td>
<td>11–55</td>
<td>3959–13568</td>
<td>1194–4589</td>
</tr>
<tr>
<td>Failed Discontinuation</td>
<td>7</td>
<td>64–83</td>
<td>5/2</td>
<td>29–88</td>
<td>3350–21152</td>
<td>7144–15658</td>
</tr>
</tbody>
</table>
Figure 3: Distribution of LVI at discontinuation for patients with failed and successful discontinuation. For the 6 successfully discontinued cases, the LVI was \((2900) \pm (567) \text{ (cmH}_2\text{O/L)}^3\); for the 7 failed-discontinuation cases the LVI was \((11400) \pm (1433) \text{ (cmH}_2\text{O/L)}^3\). 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\(_2\)O s/L and decreased only slightly at discontinuation to 10.82 cmH\(_2\)O 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\(_2\)O/L\(^3\)), i.e. it is significantly closer to the
Table 2: Range of $R_a$ and $C_a$ at intubation and outcome.

<table>
<thead>
<tr>
<th>Outcome</th>
<th>$R_a$ at intubation cmH$_2$O/L</th>
<th>$R_a$ at outcome cmH$_2$O/L</th>
<th>$C_a$ at intubation L/cmH$_2$O</th>
<th>$C_a$ at outcome L/cmH$_2$O</th>
<th>$k_i$ at intubation s</th>
<th>$k_i$ at outcome s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Successful Discontinuation</td>
<td>14–32</td>
<td>9–14</td>
<td>0.03–0.047</td>
<td>0.030–0.080</td>
<td>0.42–1.50</td>
<td>0.27–1.12</td>
</tr>
<tr>
<td>Failed Discontinuation</td>
<td>14–25</td>
<td>17–23</td>
<td>0.03–0.037</td>
<td>0.028–0.042</td>
<td>0.42–0.925</td>
<td>0.47–0.99</td>
</tr>
</tbody>
</table>

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$_2$O 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$_2$O and for failed extubation is 0.028–0.042 L/cmH$_2$O, 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.
Indicator for Lung Status

Successful Discontinuation
Failed Discontinuation

Figure 6: Distribution of $R_a$ at discontinuation for successful and failed discontinuation. $R_a = (11.5) \pm (0.83)$ (cmH$_2$O S/L) for the 6 successful-discontinuation cases, and $(20) \pm (1)$ (cmH$_2$O 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$_2$O) for the 6 successful-discontinuation cases, and $(0.034) \pm (0.0027)$ (L/cmH$_2$O) 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 (cmH$_2$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 ($\kappa$)

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 $\kappa$ at intubation and outcome.

<table>
<thead>
<tr>
<th>Outcome</th>
<th>Number</th>
<th>Age (Years)</th>
<th>Sex (M/F)</th>
<th>Time of intubation (Hrs)</th>
<th>$LII$ (%) at outcome</th>
<th>$\kappa$ at outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>Successful Discontinuation</td>
<td>6</td>
<td>54–74</td>
<td>6/0</td>
<td>11–55</td>
<td>26–86 %</td>
<td>0–0.18</td>
</tr>
<tr>
<td>Failed Discontinuation</td>
<td>7</td>
<td>64–83</td>
<td>5/2</td>
<td>29–88</td>
<td>−101–49 %</td>
<td>−0.045–0.015</td>
</tr>
</tbody>
</table>

Figure 9: The distribution of $\kappa$ 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, $\kappa$ indicates appreciable separation between successful and failed discontinuations.

The coefficient $\kappa$ corresponds to the rate of improvement or deterioration in lung status. It is to be noted that for a patient with improving lung condition, $\kappa$ will be positive and vice versa. We have observed that in most patients, $\kappa$ decreased immediately after the first few hours of mechanical ventilation, and later on varied somewhat and stabilized before successful discontinuation. Hence, we propose that $\kappa$ 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 $\kappa$ 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
indicated that $LII$ and $\kappa$ 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 $\kappa$, in combination is as follows. Starting with evaluation of $LVI$ at the time of intubation, we can employ $LII$ and $\kappa$ 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 $\kappa$ 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


