Effects of Inspiratory Rise Time on Triggering Work Load During Pressure-Support Ventilation: A Lung Model Study

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BACKGROUND: The rise in inspiratory flow is important during patient-triggered ventilation. Many ventilators incorporate a function to control the time to reach the targeted airway pressure (inspiratory rise time). However, it has not been clarified how inspiratory rise time affects inspiratory work load under various ventilator settings. In a bench study we investigated the effect of inspiratory rise time on inspiratory work load during pressure-support ventilation (PSV).

METHODS: We studied 6 ICU ventilators. We measured flow and pressure at the airway opening ($P_{ao}$) at PEEP of 5 cm H2O, pressure-support of 5 cm H2O and 10 cm H2O, 4 triggering sensitivities, and inspiratory drives 300 mL, 500 mL, and 700 mL. The inspiratory-rise-time setting was not consistent between the ventilators, and we chose 3 inspiratory-rise-time levels with each ventilator. The inspiratory delay time (DT) was defined as the time between the onset of inspiration and the return of $P_{ao}$ to baseline, and was divided into 2 parts at the point of the lowest $P_{ao}$: before the lowest $P_{ao}$ (DT1), and after the lowest $P_{ao}$ (DT2). As an indicator of inspiratory work load we calculated the pressure-time-product (PTP) of the $P_{ao}$ over the DT. PTP was also divided into PTP1 and PTP2, at the point of the lowest $P_{ao}$. RESULTS: Short inspiratory rise time reduced DT2, PTP1, and PTP2, regardless of the pressure-support level, triggering sensitivity, or inspiratory drive. However, the inspiratory-rise-time setting did not affect DT1. The PTP1, PTP2, and DT2 values differed significantly among the ventilators. A combination of short inspiratory rise time, high PSV, and sharp triggering sensitivity resulted in the smallest PTP and DT values. CONCLUSIONS: Short inspiratory rise time decreased inspiratory work load, regardless of the pressure-support level, triggering sensitivity, or inspiratory drive. Inspiratory work load can be maximally lowered by a combination of a short inspiratory rise time, a sharp triggering sensitivity, and a high inspiratory pressure-support level for a given patient’s inspiratory effort. Key words: inspiratory rise time; pressure-support ventilation; pressure-time-product; inspiratory delay time. [Respir Care 2010;55(7):878–884. © 2010 Daedalus Enterprises]
Demonstrated that the inspiratory assistance increased and patient’s inspiratory work load decreased under short inspiratory rise time.\textsuperscript{4-7} However, the relationship between the inspiratory-rise-time setting and inspiratory work load under various ventilator settings has not been fully clarified.\textsuperscript{8} The aim of this bench study was to investigate the effects of combinations of inspiratory rise time and other ventilator settings on inspiratory work load during pressure-support ventilation (PSV), using a lung model that simulated spontaneous breathing. We hypothesized that short inspiratory rise time would reduce inspiratory work load, regardless of the magnitude of inspiratory drive or ventilator settings such as the pressure-support level or triggering sensitivity. We also searched for the optimal combination of inspiratory rise time and other ventilatory settings to decrease inspiratory work load.

**Methods**

This research was performed at the University of Tokushima Graduate School, Tokushima, Japan.

**Lung Model**

We used a 2-bellows-in-a-box type lung model, with a compliance of 27.2 mL/H\textsubscript{2}O and a resistance 12.0 cm H\textsubscript{2}O/\textsubscript{L/s} (Fig. 1). Details of this lung model were described before.\textsuperscript{6,9} Briefly, the lung model consisted of 2 bellows placed in a plastic air-tight box and simulated spontaneous breathing with different inspiratory drives. The upper bellows, lower bellows, and the space between the bellows and box represented the lung, diaphragm, and pleural cavity, respectively. The diaphragm bellows was connected to a T-tube, and jet flow was injected into it to create negative pressure in the bellows. The jet flow was created by wall-gas source, pressure regulator, and proportional solenoid valve, which was regulated by a computer. A movement of the diaphragm bellows inflated the lung bellows. During the expiratory phase the diaphragm bellows was opened to the atmosphere and returned to the original position.

We set the lung model at a respiratory rate of 15 breaths/min and an inspiratory time of 1.0 s. The jet flow was adjusted to create tidal volumes (V\textsubscript{T}) of 300 mL, 500 mL, and 700 mL, at which the pressures generated during the first 0.1 s of an airway occlusion were 3.5 cm H\textsubscript{2}O, 5.8 cm H\textsubscript{2}O, and 10.3 cm H\textsubscript{2}O, respectively. The lung model was connected to the ventilator through a standard ventilator circuit (Tytco Healthcare, Mirandola, Italy), an 8-mm inner-diameter endotracheal tube (Portex, Keene, New Hampshire), and a heat-and-moisture exchanger (Hygrobac S, Mallinckrodt Dar, Tyco Healthcare, Mirandola, Italy).

**Examined Ventilators**

We studied 6 ventilators: e500 (Newport Medical Instruments, Costa Mesa, California); Evita XL (Dräger Medical, Lübeck, Germany); Servo-i (Maquet, Solna, Sweden); Servo 300 (Maquet, Solna, Sweden); PB 840 (Puritan-Bennett/Covidien, Carlsbad, California); and G5 (Hamilton Medical, Reno, Nevada).

The scale for inspiratory rise time differed among the ventilators, and it was impossible to establish an identical setting for all the ventilators. Table 1 shows the inspiratory rise times, triggering sensitivities, and termination criteria we examined with each ventilator. We set PEEP at 5 cm H\textsubscript{2}O, pressure support at 5 cm H\textsubscript{2}O and 10 cm H\textsubscript{2}O, and triggering sensitivity at $-1$ cm H\textsubscript{2}O and $-2$ cm H\textsubscript{2}O and 2 L/min and 4 L/min. With the e500 the lowest triggering sensitivity setting was 2 L/min, and we tested it at 1 L/min and 2 L/min. Pressure-triggering was not available on the Evita XL, and a numerical setting for flow-triggering was not available on the Servo 300. The termination criteria for pressure support were chosen so that premature termination did not occur (see Table 1).

**Measurements and Calibration**

After a stabilization period we measured flow, pressure at the airway opening (P\textsubscript{aw}, between the endotracheal tube and the heat-and-moisture exchanger), alveolar pressure (P\textsubscript{alv}), and pleural pressure (P\textsubscript{pl}) of the lung model (see Fig. 1). The flow was measured with a pneumotachometer (model 3700A, Hans-Rudolph, Shawnee, Kansas) and a differential pressure transducer (TP-602T [± 5 cm H\textsubscript{2}O], Nihon-Koden, Tokyo, Japan). P\textsubscript{aw}, P\textsubscript{alv}, and P\textsubscript{pl} were measured with differential pressure transducers (TP-603T [± 50 cm H\textsubscript{2}O], Nihon-Koden, Tokyo, Japan). We calibrated the pressure transducers at 0 cm H\textsubscript{2}O and 20 cm H\textsubscript{2}O, with a water manometer. All signals were amplified, sent...
to an analog/digital converter, sampled at 100 Hz, and recorded and analyzed with data-acquisition software (WINDAQ, Dataq Instruments, Akron, Ohio).

Studied variables are illustrated in Figure 2. We determined the start of inspiration when the inspiratory flow started to increase. Inspiratory trigger pressure ($\Delta P_{\text{ao}}$) was defined as the difference between the baseline pressure and the lowest $P_{\text{ao}}$. The same value was measured for $P_{\text{alv}}$ and $\Delta P_{\text{pl}}$. The time from the onset of inspiration to the return of $P_{\text{ao}}$ to baseline was defined as the inspiratory delay time (DT). The DT was divided into 2 components: the time from the onset of inspiration to the lowest $P_{\text{ao}}$ ($DT_1$), and the time from the lowest $P_{\text{ao}}$ to baseline ($DT_2$). As an indicator of patient inspiratory work load we calculated the pressure-time-product (PTP) of the $P_{\text{ao}}$-time curve below baseline. PTP was also divided into values during $DT_1$ (PTP1) and during $DT_2$ (PTP2). Peak inspiratory flow was measured from the flow waveform. $VT$ was calculated by integrating flow.

### Statistical Analysis

Three consecutive breaths were analyzed. Data are expressed as mean $\pm$ SD. Comparisons were performed with analysis of variance. When significant differences were observed, post hoc analysis was performed with the Bonferroni test. Differences were considered significant when $P < .01$. All statistical analysis was performed with statistics software (SPSS 11.01, SPSS, Chicago, Illinois).

### Results

Figure 3 shows representative $P_{ao}$ waveforms when inspiratory-rise-time setting was the shortest and the longest for each ventilator. $DT_2$ was shorter and $\Delta P_{ao}$ was smaller with the shortest inspiratory rise time than with the longest inspiratory rise time with all ventilators.

As inspiratory rise time became shorter, both PTP1 and PTP2 decreased with all ventilators, regardless of inspira-
tory drive, pressure-support level, or triggering sensitivity ($P < .01$) (Fig. 4). The PTP$_1$ values were smallest with the PB 840 and the Servo 300, and largest with the G5. The PTP$_2$ values were smallest with the PB 840 and largest with the G5. The effect of inspiratory rise time change on PTP$_2$ was more apparent than the effect on PTP$_1$ with most ventilators. The combined effects of adjusting the triggering sensitivity, pressure support, and inspiratory-rise-time setting on PTP are shown in Figure 5. Optimizing each of the triggering sensitivity, pressure support, and inspiratory rise time decreased PTP by 9%, 31%, and 28%, on average, respectively. When optimizing all, PTP decreased by 83%.

DT$_1$ did not change significantly between the various inspiratory-rise-time settings with any of the ventilators (Fig. 6). In contrast, as inspiratory rise time became shorter, DT$_2$ decreased with all the ventilators, regardless of inspiratory drive, pressure-support level, or triggering sensitivity ($P < .01$). The effect of inspiratory rise time change on DT$_2$ differed among the ventilators ($P < .01$). The DT$_2$ values were smallest with the G5. The combined effects of adjusting the triggering sensitivity, pressure support, and inspiratory-rise-time setting on DT are shown in Figure 7. Optimizing each of the triggering sensitivity, pressure support, and inspiratory-rise-time setting on DT are shown in Figure 7. Optimizing each of the triggering sensitivity, pressure support, and inspiratory rise time decreased DT by 2%, 10%, and 30%, on average, respectively. When optimizing all, DT decreased by 47%.
As inspiratory rise time became shorter, $\Delta P_{ao}$ decreased with all the ventilators, regardless of inspiratory drive, pressure-support level, or triggering sensitivity ($P < .01$) (Fig. 8). The $\Delta P_{ao}$ values were smallest with the PB 840 and largest with the G5. The combined effects of adjusting the triggering sensitivity, pressure support, and inspiratory-rise-time setting on $\Delta P_{ao}$ are shown in Figure 9. Optimizing each of the triggering sensitivity, pressure support, and inspiratory rise time decreased $\Delta P_{ao}$ by 9%, 28%, and 9%, on average, respectively. When optimizing all, $\Delta P_{ao}$ decreased by 66%.

Table 2 shows the results for DT, DT1, DT2, PTP, PTP1, PTP2, $\Delta P_{ao}$, $\Delta P_{alv}$, $\Delta P_{pl}$, and peak inspiratory flow, which were pooled for all inspiratory effort and pressure-support levels, for the shortest inspiratory rise time and the most sensitive triggering. PTP and PTP2 were smallest with the PB 840 and largest with the G5 ($P < .01$).

Discussion

The main findings of this bench study are:
1. Short inspiratory rise time reduced PTP1, PTP2, and PTP, regardless of the inspiratory drive, pressure-support level, or triggering sensitivity, with all the ventilators.
2. DT2 decreased as inspiratory rise time decreased, whereas DT1 did not.
3. PTP1, PTP2, and DT2 were different among these ventilators.
4. A combination of short inspiratory rise time, high pressure-support, and sharp triggering sensitivity gave the smallest PTP and DT values.

Bonmarchand et al reported that short inspiratory rise time decreased the work of breathing (WOB) in patients with obstructive4 and restrictive5 diseases, when the pressure-support level was fixed in each patient. However, they compared very slow inspiratory rise times (1.0 s, 1.25 s, and 1.5 s) to modest inspiratory rise times (0.1 s and 0.25 s). The range of clinically used inspiratory-rise-time setting is not that wide: inspiratory rise time longer than 1.0 s is too slow for most patients. The ventilators we investigated in the present study exhibited better performance, probably because we used a clinically realistic range of inspiratory rise times.

To evaluate the effect of inspiratory rise time on pre-trigger and post-trigger events separately,2 we divided PTP and DT into 2 components at the lowest $P_{ao}$. DT1 did not...
change significantly among the different inspiratory-rise-time settings (see Fig. 3). DT$_1$ consisted mainly of the DT from the start of inspiratory effort to triggering of the ventilator, and short inspiratory rise time did not affect this measurement. In contrast, as inspiratory rise time shortened, DT$_2$ decreased with all the ventilators. Shorter inspiratory rise time decreased the WOB, as evidenced by the decreased DT$_2$ and PTP$_2$. Because DT$_1$ was a pre-trigger event, it was reasonable that DT$_1$ increased with less sensitive triggering but did not increase with longer inspiratory rise time. However, short inspiratory rise time decreased ΔP$_{ao}$ in all ventilators, whereas DT$_1$ was not affected by inspiratory rise time. The supplied flow could not exceed the demand immediately after the inspiratory triggering, and the P$_{ao}$ continued to drop more with longer inspiratory rise time. Therefore, as inspiratory rise time shortened, PTP$_1$ and ΔP$_{ao}$ decreased with no change of DT$_1$.

In this study, both short inspiratory rise time and high PSV reduced ΔP$_{ao}$, PTP$_1$, and PTP$_2$, although they did not reduce DT$_1$. Although raising the pressure-support level is commonly used to increase ventilatory assistance, it does not always reduce patient’s inspiratory work load when inspiratory drive is high. To decrease the patient’s inspiratory work load, initial inspiratory flow may be more important than the peak value. Uchiyama et al suggested that increasing initial inspiratory flow was more effective than raising the pressure-support level to preserve inspiratory assistance of PSV in patients with high inspiratory drive. In this study we observed that shortening inspiratory rise time and raising the pressure-support level affected the initial inspiratory flow differently, although both increased peak inspiratory flow. Figure 10 shows representative flow-time waveforms from the PB 840 with 3 combinations of pressure-support (PS) level and the inspiratory-rise-time setting. The increase in initial inspiratory flow was more remarkable with the shorter inspiratory rise time than with the higher pressure-support level.

To our knowledge, this study is the first to demonstrate the combined effects of adjusting inspiratory rise time, triggering sensitivity, and pressure-support level on inspiratory work load. We found that combining all of the best inspiratory rise time, triggering sensitivity, and press-

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**Table 2. Results at the Shortest Inspiratory Rise Time and the Most Sensitive Triggering Setting**

<table>
<thead>
<tr>
<th></th>
<th>e500</th>
<th>Evita XL</th>
<th>Servo-i</th>
<th>Servo 300</th>
<th>PB 840</th>
<th>G5</th>
</tr>
</thead>
<tbody>
<tr>
<td>DT ($s^*$)</td>
<td>0.36 ± 0.14</td>
<td>0.41 ± 0.20</td>
<td>0.41 ± 0.18</td>
<td>0.48 ± 0.20</td>
<td>0.37 ± 0.21</td>
<td>0.52 ± 0.22</td>
</tr>
<tr>
<td>DT$_1$ ($s^*$)</td>
<td>0.21 ± 0.02</td>
<td>0.20 ± 0.03</td>
<td>0.22 ± 0.03</td>
<td>0.23 ± 0.01</td>
<td>0.19 ± 0.06</td>
<td>0.21 ± 0.04</td>
</tr>
<tr>
<td>DT$_2$ ($s^*$)</td>
<td>0.16 ± 0.13</td>
<td>0.21 ± 0.18</td>
<td>0.19 ± 0.17</td>
<td>0.25 ± 0.20</td>
<td>0.18 ± 0.17</td>
<td>0.31 ± 0.19</td>
</tr>
<tr>
<td>PTP (cm H$_2$O)*</td>
<td>0.80 ± 0.68</td>
<td>0.81 ± 0.85</td>
<td>0.84 ± 0.85</td>
<td>0.78 ± 1.10</td>
<td>0.55 ± 0.73</td>
<td>1.53 ± 1.39</td>
</tr>
<tr>
<td>PTP$_1$ (cm H$_2$O)*</td>
<td>0.43 ± 0.25</td>
<td>0.36 ± 0.24</td>
<td>0.37 ± 0.27</td>
<td>0.17 ± 0.36</td>
<td>0.24 ± 0.27</td>
<td>0.55 ± 0.38</td>
</tr>
<tr>
<td>PTP$_2$ (cm H$_2$O)*</td>
<td>0.37 ± 0.44</td>
<td>0.45 ± 0.63</td>
<td>0.47 ± 0.59</td>
<td>0.61 ± 0.76</td>
<td>0.31 ± 0.47</td>
<td>0.98 ± 1.03</td>
</tr>
<tr>
<td>ΔP$_{ao}$ (cm H$_2$O)*</td>
<td>4.87 ± 2.53</td>
<td>3.98 ± 1.94</td>
<td>4.41 ± 2.24</td>
<td>3.86 ± 2.63</td>
<td>2.97 ± 1.53</td>
<td>5.26 ± 2.68</td>
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<tr>
<td>ΔP$_{av}$ (cm H$_2$O)</td>
<td>8.67 ± 3.63</td>
<td>7.73 ± 3.54</td>
<td>7.79 ± 3.77</td>
<td>7.21 ± 3.88</td>
<td>6.56 ± 3.21</td>
<td>8.80 ± 3.72</td>
</tr>
<tr>
<td>ΔP$_{alv}$ (cm H$_2$O)</td>
<td>6.40 ± 2.50</td>
<td>6.05 ± 2.55</td>
<td>5.95 ± 2.55</td>
<td>5.91 ± 2.54</td>
<td>5.32 ± 2.53</td>
<td>6.68 ± 2.72</td>
</tr>
<tr>
<td>PIF (L/min)</td>
<td>69.3 ± 11.8</td>
<td>61.3 ± 10.0</td>
<td>63.2 ± 10.4</td>
<td>59.6 ± 11.0</td>
<td>62.7 ± 9.2</td>
<td>58.2 ± 8.9</td>
</tr>
</tbody>
</table>

* = P < .01 among ventilators. These are the pooled results for all the inspiratory efforts, at 300 mL, 500 mL, and 700 mL, and both pressure-support levels (5 cm H$_2$O and 10 cm H$_2$O).

**DT** = delay time
**DT$_1$** = pre-trigger DT
**DT$_2$** = post-trigger DT
**PTP** = pressure-time product
**PTP$_1$** = PTP during DT$_1$
**PTP$_2$** = PTP during DT$_2$
**ΔP$_{ao}$** = maximum deflection of alveolar pressure during DT
**ΔP$_{av}$** = maximum deflection of alveolar pressure during DT
**ΔP$_{alv}$** = maximum deflection of pleural pressure during DT
**PIF** = peak inspiratory flow

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**Fig. 10.** Representative flow-time curves from the PB 840 with 3 combinations of pressure-support (PS) level and the inspiratory-rise-time setting. The increase in initial inspiratory flow was more remarkable with the shorter inspiratory rise time than with the higher pressure-support level.
sure-support level decreased the inspiratory work load the most (see Figs. 5, 7, and 9). The effects of the combination were greater than the sum of each effect. Uchiyama et al reported that increasing the initial inspiratory flow with maximum inspiratory rise time was more effective than raising the pressure-support level alone in preserving the inspiratory assistance of PSV when inspiratory drive was high. It is reasonable that optimizing triggering sensitivity decreases the inspiratory work load more.

All of our tested ventilators except the G5 showed similar changes in PTP, DT, and inspiratory trigger pressure as we shortened the inspiratory rise time. Richard et al11 and Thille et al12 compared the inspiratory assistance of newer-generation and older ventilators, and of turbine-powered versus gas-powered ventilators. With an enormous amount of data they demonstrated that the improvements in ventilator performance were huge, in comparison with the previous ones, but the progress reached a technical ceiling in recent years. They evaluated PTP over the first 0.3 s and 0.5 s of inspiration, using a 2-chamber type test lung. In contrast, we calculated the PTP below the baseline airway pressure to evaluate the inspiratory work load, using a 2-bellows-in-a-box type test lung and simulated pleural space, as did previous studies.6,9

There were differences between our data and those of Thille et al concerning DT.12 While most of the ventilators in their study had DT ≤ 0.1 s, the DT in our study was 0.3–0.6 s. Although a definite reason was not specified, we speculated it might be due to the different lung model used (2-bellows-in-a-box type), different design to simulate inspiratory effort (negative pressure created in the pleural space), and insertion of a heat-and-moisture-exchanger into the circuit in our study.

Limitations

Since this was a lung model study, direct application of the data to the clinical settings is limited. The relationship between inspiratory rise time and WOB/PTP is not linear, and impact on WOB/PTP cannot be directly transposed to patients.7,8 Prinianakis et al showed that fast inspiratory rise time decreased PTP in patients with chronic obstructive pulmonary disease but was accompanied by substantial air leaks and poor tolerance.8 By using a lung model, however, we could compare a large number of ventilators with each other under multiple simulated clinical situations, which is difficult to do with patients.13 We examined only a single condition of lung mechanics, which simulated acute respiratory distress syndrome in patients with high resistance. Chatmongkolchert et al found results similar to ours when they used a lung model with normal lung mechanics and one pressure-support level and one PEEP setting.14

Conclusions

In this lung model study, shorter inspiratory rise time decreased the inspiratory work load, regardless of the pressure-support level, PEEP setting, triggering sensitivity, or inspiratory drive. To minimize the inspiratory work load, all of the inspiratory rise time, pressure-support level, and triggering sensitivity need to be optimized.

REFERENCES