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 (Pao) 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 Pao to baseline, and was divided into 2 parts at the point of the lowest Pao: before the lowest Pao (DT₁), and after the lowest Pao (DT₂). As an indicator of inspiratory work load we calculated the pressure-time-product (PTP) of the Pao over the DT. PTP was also divided into PTP₁ and PTP₂, at the point of the lowest Pao. 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]

Introduction

Patient-ventilator synchrony is important to reduce the patient’s inspiratory work load during patient-triggered ventilation.¹ Trigger delay and inspiratory flow are 2 major factors influencing the inspiratory work load.² Flow-triggering function improves the inspiratory work load due to the trigger delay. When inspiratory flow does not meet the patient’s demand, the ventilator cannot appropriately reduce the patient’s inspiratory work load.³ Many ventilators have a function to regulate initial flow, termed inspiratory rise time, because it also regulates the time to reach the targeted airway pressure. Previous studies dem-
onstrated that the inspiratory assistance increased and pa-
tient’s inspiratory work load decreased under short in-
spiratory rise time.4-7 However, the relationship between 
the inspiratory-rise-time setting and inspiratory work load 
under various ventilator settings has not been fully clari-
fied.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 To-
kushima Graduate School, Tokushima, Japan.

Lung Model

We used a 2-bellows-in-a-box type lung model, with a 
compliance of 27.2 mL/H2O and a resistance 12.0 cm H2O/ 
L/s (Fig. 1). Details of this lung model were described 
before.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 bel-
loows, lower bellows, and the space between the bellows 
and box represented the lung, diaphragm, and pleural cav-
ity, respectively. The diaphragm bellows was connected to 
a T-tube, and jet flow was injected into it to create nega-
tive pressure in the bellows. The jet flow was created by 
wall-gas source, pressure regulator, and proportional so-
lenoid valve, which was regulated by a computer. A move-
ment 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 (VT) 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 H2O, 
5.8 cm H2O, and 10.3 cm H2O, respectively. The lung 
model was connected to the ventilator through a standard 
ventilator circuit (Tyco Healthcare, Mirandola, Italy), an 
8-mm inner-diameter endotracheal tube (Portex, Keene, 
New Hampshire), and a heat-and-moisture exchanger (Hy-
grobac S, Mallinkrodt Dar, Tyco Healthcare, Mirandola, 
Italy).

Examined Ventilators

We studied 6 ventilators: e500 (Newport Medical In-
struments, Costa Mesa, California); Evita XL (Dräger Med-
ical, Lübeck, Germany); Servo-i (Maquet, Solna, Sweden); 
Servo 300 (Maquet, Solna, Sweden); PB 840 (Puritan-
Bennett/Covidien, Carlsbad, California); and G5 (Hamil-
ton 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 H2O, pressure support at 5 cm H2O and 10 cm H2O, 
and triggering sensitivity at −1 cm H2O and −2 cm H2O 
and 2 L/min and 4 L/min. With the e500 the lowest trig-
ering sensitivity setting was 2 L/min, and we tested it at 
1 L/min and 2 L/min. Pressure-triggering was not avail-
able on the Evita XL, and a numerical setting for flow-
triggering was not available on the Servo 300. The termi-
nation criteria for pressure support were chosen so that 
preadaptation termination did not occur (see Table 1).

Measurements and Calibration

After a stabilization period we measured flow, pressure 
at the airway opening (Pao, between the endotracheal tube 
and the heat-and-moisture exchanger), alveolar pressure 
(Palv), and pleural pressure (Ppl) 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 H2O], 
Nihon-Koden, Tokyo, Japan). Pao, Palv, and Ppl were mea-
sured with differential pressure transducers (TP-603T 
[± 50 cm H2O], Nihon-Koden, Tokyo, Japan). We cali-
brated the pressure transducers at 0 cm H2O and 20 cm H2O, 
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 ($P_{\text{Pao}}$) was defined as the difference between the baseline pressure and the lowest $P_{\text{Pao}}$. The same value was measured for $P_{\text{Palv}}$ and $P_{\text{Ppl}}$. The time from the onset of inspiration to the return of $P_{\text{Pao}}$ 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 $P_{\text{Pao}}$ (DT$_1$), and the time from the lowest $P_{\text{Pao}}$ to baseline (DT$_2$). As an indicator of patient inspiratory work load we calculated the pressure-time-product (PTP) of the $P_{\text{Pao}}$-time curve below baseline. PTP was also divided into values during DT$_1$ (PTP$_1$) and during DT$_2$ (PTP$_2$). 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 ± 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 $P_{\text{Pao}}$ waveforms when inspiratory-rise-time setting was the shortest and the longest for each ventilator. DT$_2$ was shorter and $\Delta P_{\text{Pao}}$ 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 PTP$_1$ and PTP$_2$ 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 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 e500 and largest 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 decreased DT by 2%, 10%, and 30%, on average, respectively. When optimizing all, DT decreased by 47%. 

Fig. 3. Representative tracings of airway pressure-time curves. The dotted lines represent the shortest inspiratory-rise-time settings. The solid lines represent the longest inspiratory-rise-time settings. The ventilator settings were zero PEEP, pressure support 5 cm H$_2$O, and tidal volume 300 mL. The triggering sensitivities were 4 L/min with the Evita XL and −2 cm H$_2$O with the other ventilators.

Fig. 4. Effects of inspiratory rise time on pressure-time product (PTP, see text for definitions of PTP$_1$ and PTP$_2$), with the minimum, medium, and maximum inspiratory-rise-time settings. The inspiratory-rise-time scales differed among the tested ventilators. This figure shows the pooled results from all the modeled inspiratory efforts (300 mL, 500 mL, and 700 mL) and pressure-support levels of 5 cm H$_2$O and 10 cm H$_2$O.

Fig. 5. Combined effects of triggering sensitivity, pressure-support, and inspiratory-rise-time settings on pressure-time product. Worst = the combination of lowest triggering sensitivity, lowest pressure support (5 cm H$_2$O), and slowest inspiratory rise time. TS = with the maximum triggering sensitivity setting. PS = with the maximum pressure-support setting (10 cm H$_2$O). IRT = with the fastest inspiratory rise time. All = the combination of the highest triggering sensitivity, highest pressure support (10 cm H$_2$O), and fastest inspiratory rise time. This figure shows the pooled results from all the ventilators.

Fig. 6. Effects of inspiratory rise time on inspiratory delay time (DT), with the minimum, medium, and maximum inspiratory rise times. This figure shows the pooled results for all the inspiratory efforts (300 mL, 500 mL, and 700 mL) and pressure-support levels of 5 cm H$_2$O and 10 cm H$_2$O.

Fig. 7. Combined effects of triggering sensitivity, pressure-support, and inspiratory-rise-time settings on inspiratory delay time (DT). Worst = the combination of lowest triggering sensitivity, lowest pressure support (5 cm H$_2$O), and slowest inspiratory rise time. TS = with the maximum triggering sensitivity setting. PS = with the maximum pressure-support setting (10 cm H$_2$O). IRT = with the fastest inspiratory rise time. All = the combination of the highest triggering sensitivity, highest pressure support (10 cm H$_2$O), and fastest inspiratory rise time. This figure shows the pooled results from all the ventilators.
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, DT$_1$, DT$_2$, PTP, PTP$_1$, PTP$_2$, $\Delta P_{ao}$, $\Delta P_{alv}$, $\Delta P_{pp}$, 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 PTP$_2$ 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 PTP$_1$, PTP$_2$, and PTP, regardless of the inspiratory drive, pressure-support level, or triggering sensitivity, with all the ventilators.
2. DT$_2$ decreased as inspiratory rise time decreased, whereas DT$_1$ did not.
3. PTP$_1$, PTP$_2$, and DT$_2$ 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 obstructive$^4$ and restrictive$^5$ 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 Pao. The combined effects of triggering sensitivity, pressure-support level, and inspiratory rise time on inspiratory trigger pressure. Worst = the combination of lowest triggering sensitivity, lowest pressure-support (5 cm H$_2$O), and slowest inspiratory rise time. TS = with the maximum triggering sensitivity setting. PS = with the maximum pressure-support setting (10 cm H$_2$O). IRT = with the fastest inspiratory rise time. All = the combination of the highest triggering sensitivity, highest pressure support (10 cm H$_2$O), and fastest inspiratory rise time. This figure shows the pooled results from all the inspiratory efforts (300 mL, 500 mL, and 700 mL).
change significantly among the different inspiratory-rise-time settings (see Fig. 3). DT1 was consistent 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, DT2 decreased with all the ventilators. Shorter inspiratory rise time decreased the WOB, as evidenced by the decreased DT2 and PTP2. Because DT1 was a pre-trigger event, it was reasonable that DT1 increased with less sensitive triggering but did not increase with longer inspiratory rise time. However, short inspiratory rise time decreased $\Delta P_{pa}$ in all ventilators, whereas DT1 was not affected by inspiratory rise time. The supplied flow could not exceed the demand immediately after the inspiratory triggering, and the $P_{pa}$ continued to drop more with longer inspiratory rise time. Therefore, as inspiratory rise time shortened, PTP1 and $\Delta P_{pa}$ decreased with no change of DT1.

In this study, both short inspiratory rise time and high PSV reduced DT2, $\Delta P_{pa}$, PTP1, and PTP2, although they did not reduce DT1. 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.10 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.6 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 pres-

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

<table>
<thead>
<tr>
<th>Ventilator</th>
<th>DT (s)</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>e500</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>DT1 (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>DT2 (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>PTP1 (cm H2O s)</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>PTP2 (cm H2O s)</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>$\Delta P_{pa}$ (cm H2O)</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>
</tr>
<tr>
<td>$\Delta P_{pl}$ (cm H2O)</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>PTF (L/min)</td>
<td>60.3 ± 11.8</td>
<td>51.3 ± 10.0</td>
<td>62.2 ± 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 H2O and 10 cm H2O).

DT = delay time
DT1 = pre-trigger DT
DT2 = post-trigger DT
PTP = pressure-time product
PTP1 = PTP during DT1
PTP2 = PTP during DT2
$\Delta P_{pa}$ = maximum deflection of airway pressure during DT
$\Delta P_{pl}$ = maximum deflection of alveolar pressure during DT
$\Delta P_{pa}$ = maximum deflection of pleural pressure during DT
PIF = peak inspiratory flow

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 al and Thille et al 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.

There were differences between our data and those of Thille et al concerning DT. 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. 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. 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. We examined only a single condition of lung mechanics, which simulated acute respiratory distress syndrome in patients with high resistance. Chatmongkolchart 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.

**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**