The estimation of work of breathing (WOB) is one of the most important respiratory function tests during partial ventilatory support. The measurement of WOB allows assessment of the efficiency of ventilatory assist and patient-ventilator synchrony. The total WOB (WOBtot) can be considered as the sum of three components: work used to inflate the lung, work used to displace the diaphragm and chest wall, and work used to contract the respiratory muscles. During partial ventilatory assist, there is a time delay between the start of inspiratory effort and the onset of gas entry into the lungs. During this triggering time, ventilatory muscles have to perform the work (WOBtr) to lower the circuit airway pressure to the onset sensitivity level. In general, WOB can be calculated using the pressure-volume (P-V) loop. However, during the delay period, no volume displacement occurs, because a machine cycle will not be initiated until the sum of machine's set trigger sensitivity and auto-PEEP are overcome by patient's inspiratory effort. Although the estimations of triggering capability of various ventilators have been reported. The determination of WOBtr and its dependence on lung mechanics have never been evaluated (to our knowledge). Our mechanical lung model was designed to simulate spontaneous breathing during different trial conditions with various lung compliance (CL) and airway resistance (Raw). The WOBtr was calculated by direct measurement of pressure changes and the resultant volume displacement of the diaphragm bellows from the P-V loops.

Our first objective was to quantify WOBtr at various pressure support (PS) levels, CL and Raw. A bias flow system has been incorporated in some ventilators (New Port E-200, NMI, United States; Bear 5, Bear Corp., United States; and CV-4000, IMI, Japan). In this system there is fresh gas flow during the triggering phase of inspiration in the pressure support ven-

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**Estimation of Triggering Work of Breathing (Konyukov et al)**

\[ G_{cw} = \text{chest wall compliance}; CF = \text{continuous flow}; CL = \text{lung compliance}; FRC = \text{functional residual capacitance}; I/E = \text{inspiratory/expiratory ratio}; P_{aw} = \text{airway pressure}; P_{drin} = \text{driving pressure}; P_{pl} = \text{pleural pressure}; PS = \text{pressure support}; P_{V} = \text{pressure-volume}; RV = \text{airway resistance}; V_{drin} = \text{driving volume}; WOB = \text{work of breathing}; WOB_{tot} = \text{total work of breathing}; WOB_{tr} = \text{triggering work of breathing} \]
ventilation (PSV) and synchronized intermittent mandatory ventilation (SIMV) modes. This additional gas flow ranges from 0 to 30 L/min. When spontaneous inspiratory effort reduces the airway pressure to reach the set pressure sensitivity level, a demand valve opens further to meet the patient inspiratory flow demand. Thus, bias-flow was proposed to be useful for minimizing patient’s efforts to open the demand valve. However, recent studies revealed that the triggering delay becomes longer in the presence of the bias flow during assist ventilation.\textsuperscript{10,14} Apparently, there has been no study that quantitatively examined the use of bias flow during PSV. The second purpose of this study was to determine the efficacy of PSV in conjunction with bias flow.

**Materials and Methods**

**Apparatus**

Our lung model has been detailed in the previous communication.\textsuperscript{15} In brief, two bellows were suspended in series by the springs inside an airtight plastic cylinder (Fig 1). The sealed space between the bellows and the cylinder represented the pleural space in which the pressure was subatmospheric. The upper and lower bellows represented the lungs and diaphragm, respectively. The inspiratory effort was provided by the movement of the diaphragm bellows through the Venturi effect created by the jet flow.Expiration occurred passively when the jet flow was terminated, and the lower bellows was opened to the atmosphere, returning to the original volume state (FRC). The driving pressure, respiratory rate, and inspiratory-expiratory ratio can be adjusted by changing the function of the jet-flow generator. The $C_L$ and chest wall compliance ($C_{CW}$) can be adjusted by changing the elasticity of the springs inside both bellows. Airway resistance can be varied as 5, 20, or 50 cm H$_2$O/L/s by changing the diameter of a resistor interposed between the lung model and a ventilator. The negative pressure ($P_{d,in}$) and the resultant volume change inside the diaphragm bellows ($V_{d,in}$) were simultaneously measured with a pressure transducer and a hot-wire flowmeter (Minato ATD 105, Osaka, Japan), respectively. The pleural pressure ($P_{pl}$), postresistance lung bellows pressure which was taken to represent alveolar pressure ($P_{aw}$), and airway pressure ($P_{aw}$) were simultaneously measured with a pressure transducer. All variables were monitored and recorded on a multichannel strip-chart recorder (Omicorder, Sanei, Tokyo, Japan) and a personal computer (PC-386LX, Epson, Japan).

**Protocol**

The WOB$_{bt}$ was evaluated at the varied lung mechanics which consisted of the combination of two sets of $C_L$ and three sets of Raw. At each $C_L$, the driving pressure was adjusted to provide the $V_{d,in}$ of 500 ml in T-piece breathing with Raw of 5 cm H$_2$O/L/s. Then the upper bellows was connected to a ventilator (Puritan-Bennett 7200a). The pressure support level was gradually increased from 0 to 45 cm H$_2$O to give a $V_r$ of more than 300 ml. Sensitivity was 2 cm H$_2$O. The end-expiratory bellows pressure was considered to be end-expiratory alveolar pressure, represent-

![Diagram](http://journal.publications.chestnet.org/pdfaccess.ashx?url=/data/journals/chest/21695/ on 04/28/2017)
Table 1—Dependence of PSV on Triggering Delay, WOB\textsubscript{fr}, WOB\textsubscript{tot}, and \textit{Vr} at Various Impedance Lung Models

<table>
<thead>
<tr>
<th>(\text{PS}, \text{cm H}_2\text{O})</th>
<th>(\text{Cl}, 0.05 \text{ L/cm H}_2\text{O} \text{ Raw } 5 \text{ cm H}_2\text{O}/\text{L/s})</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\text{Vr}_{\text{driv}}, \text{ml})</td>
<td>(\text{Cl}, 0.03 \text{ L/cm H}_2\text{O} \text{ Raw } 5 \text{ cm H}_2\text{O}/\text{L/s})</td>
</tr>
<tr>
<td>(\text{Vr}, \text{ml})</td>
<td>(\text{Cl}, 0.05 \text{ L/cm H}_2\text{O} \text{ Raw } 5 \text{ cm H}_2\text{O}/\text{L/s})</td>
</tr>
<tr>
<td>(\text{WOB}_{\text{fr}}, \text{g.m})</td>
<td>(\text{WOB}_{\text{fr}}, \text{g.m})</td>
</tr>
<tr>
<td>(\text{WOB}_{\text{tot}}, \text{g.m})</td>
<td>(\text{WOB}_{\text{tot}}, \text{g.m})</td>
</tr>
</tbody>
</table>

- The \(\text{P}_{\text{driv}}\)-\(\text{V}_{\text{driv}}\) loop, \(\text{V}_{\text{driv}}\)-time, and \(\text{P}_{\text{driv}}\)-time curves were simultaneously obtained. The \(\text{WOB}_{\text{fr}}\) was determined from the \(\text{P}_{\text{driv}}\)-\(\text{V}_{\text{driv}}\) loop as an area enclosed by the \(\text{P}_{\text{driv}}\)-\(\text{V}_{\text{driv}}\) curve and \(\text{V}_{\text{driv}}\)-time value accomplished during the triggering delay (Fig 2). The \(\text{WOB}_{\text{fr}}\) was considered as work done by the ventilator during control mechanical ventilation with the \(\text{V}_{\text{r}}\) value equaled to that at a given PS level. The area enclosed by the \(\text{P}_{\text{aw}}\)-\(\text{V}_{\text{r}}\) curve during the entire inspiratory phase was calculated as \(\text{WOB}_{\text{tot}}\).

Both \(\text{WOB}_{\text{fr}}\) and \(\text{WOB}_{\text{tot}}\) were calculated by a personal computer (PC-386LSX, Epson, Japan).

For the bias flow experiment, driving pressure of the jet-flow generator was adjusted to obtain \(\text{V}_{\text{r}}\) of 500 ml at the PS level of 0 cm H\(_2\)O with no bias flow. Then, bias flow was gradually increased from 0 to 20 L/min. The discrete PS levels of 5, 10, and 15 cm H\(_2\)O were applied to each bias flow rate. This experiment was carried out at \(\text{Cl}, 0.05 \text{ L/cm H}_2\text{O} \text{ Raw } 5 \text{ cm H}_2\text{O}/\text{L/s}\).

Results

The \(\text{WOB}_{\text{fr}}\) and its relationship with lung mechanics during PSV are shown in Table 1. An increase in
PS levels resulted in a gradual increase in VT, auto-PEEP, triggering time, and WOBtr. Regardless of CL and Raw, WOBtr increased proportionally with auto-PEEP levels. Greater WOBtr was attained at the highest auto-PEEP level, and the letter occurred at high airway resistance settings. The WOBtot increased with increasing PS.

The results of WOBtr at each experimental setting and the effects of bias flow on WOBtr are summarized as follows.

1. **WOBtr at Low Lung Compliance (0.03 L/cm H2O)** With Varied Resistance.

A close correlation between WOBtr and auto-PEEP was found with increasing PS levels in all the settings (Table 1), however, to a small extent at low Raw. Auto-PEEP and WOBtr remained unchanged at PS levels from 5 cm H2O to 20 cm H2O at low Raw. In contrast, the highest auto-PEEP and highest WOBtr were attained at the maximum PS level in the high resistance. The triggering time was longest in the high resistance (360 ms) when compared with that at intermediate and low airway resistance (50 to 170 ms).

2. **WOBtr at High Lung Compliance (0.05 L/cm H2O)** With Varied Resistance.

In the high resistance, a high PS level was required to attain the VT of more than 300 ml (Table 1, Fig 3). At a given PS level, WOBtr was proportionally related to the auto-PEEP level (Fig 3). The maximal auto-PEEP (23.8 cm H2O) corresponded to the maximal WOBtr (11.5 g.m). The minimal auto-PEEP was accomplished at the minimal WOBtr of 0.84 g.m. The triggering time ranged from 180 ms at the low auto-PEEP level to 500 ms at the highest auto-PEEP level.

The prolonged triggering time was accompanied by high auto-PEEP level due to high airway resistance.

3. **Effects of Bias Flow on Triggering Time, VT, and WOBtr**

As shown in Table 2, triggering time and WOBtr became larger with increasing bias flow during PSV. Triggering time was longest (590 ms) at the maximal bias flow rate of 20 L/min with PS level of 15 cm H2O, while these values were minimal at the bias flow of 0 L/min and PS of 5 cm H2O. Changes in Psw and the triggering time are shown in Figure 4, indicating that at the same PS level, bias flow did have a significant influence on inspiratory duration and end expiratory airway pressure. The increase in triggering time resulted in proportional increase in WOBtr. The greater WOBtr was attained at the largest triggering time at maximum bias flow with PS level of 15 cm H2O (Table 2).

As driving pressure was held constant at a set VT of 500 ml at PS of 0 cm H2O without bias flow, an increase in PS levels resulted in an increase in VT. Contrary, VT decreased for any PS levels over the studied range of bias flow rates (Table 2). As bias flow rate increased from 0 L/min to 20 L/min, VT decreased from 540 ml to 490 ml and from 650 ml to 590 ml at PS of 5 cm H2O and 15 cm H2O, respectively.

**DISCUSSION**

During partial ventilatory assistance, volumes of gas enter the lung due to transpulmonary pressures generated by a combination of patient effort and ventilator-positive pressure assist. In general, work is the integral of the pressure-volume product. However, during triggering, no volume change occurs. Therefore, WOBtr cannot be estimated using a conventional P-V loop.
The purpose of our study was the quantitative determination of the inspiratory effort required to trigger the ventilator (WOBtr) during partial ventilatory assistance. The WOBtr performed by the respiratory muscles precedes gas entry into the lung. Therefore, WOBtr cannot be measured using the combination of tidal volume and either airway, alveolar, pleural, or esophageal pressures. In this respect, the method used to determine the WOBtr in the current study was different from those of other investigators.1,15,16 In our lung model, volume displacement of the lower bellows was measured as \( V_{\text{rdrv}} \), while the pressure used to produce this volume displacement was defined as \( P_{\text{driv}} \). The onset of the inspiratory effort was taken as the beginning of the negative deflection of the \( P_{\text{driv}} \) on the \( P_{\text{driv}} \)-time curve. After the start of inspiratory effort, airway pressure subsequently dropped to reach the trigger threshold, and then gas flow began to enter into the upper bellows from the ventilator. The WOB was calculated by integrating the \( P_{\text{driv}} \) with respect to \( V_{\text{rdriv}} \) over the triggering time period and this WOB was regarded as WOBtr.

The presence of auto-PEEP in this model required a greater inspiratory effort to trigger the ventilator. In this respect, auto-PEEP could act as an added threshold load on the respiratory muscles during inspiratory work.8 We found the high correlations between the WOBtr and auto-PEEP level: an increase in auto-PEEP further increased WOBtr in all the experimental settings. As shown in Figure 3, this correlation was especially high in the experiments with the high airway resistance. However, there were two exceptional occasions at PS 5 cm H2O at intermediate airway resistance and \( C_L \) of 0.05 cm H2O, where WOBtr was lower than that at PS level of 0 cm H2O. We speculated that additional inspiratory effort was required to trigger the ventilator at PS level of 0 cm H2O.

Our study demonstrated that an increase in PS level resulted in an increase in auto-PEEP. This may not occur in the clinical situations. When a patient has control over ventilation, the patient’s pressure-supported breaths may result in increased minute ventilation and reduction in inspiratory effort and respiratory rate. As a result, auto-PEEP may be decreased.16-18 In these present experiments, respiratory rate was fixed. Thus, increased PS level resulted in an increase in expired Vr and necessarily led to air trapping and an increase in auto-PEEP. Clinically, a spontaneously breathing patient may be able to compensate for this.

The quantitative estimation of WOBtr showed that triggering work was unexpectedly small in comparison with WOBtr. Indeed, WOBtr was estimated to be less than 6 percent of WOBtr. However, in the experiments with high airway resistance and high compliance lung, high auto-PEEP occurred and triggering time became half of inspiratory supporting time. The absolute value of WOBtr at this setting was 11.5 g.m, which was about 25 percent of the WOB required during the normal spontaneous respiration.

Continuous flow has been suggested to reduce both the airway pressure fluctuations and respiratory work.19,20 In one ventilator (Newport Wave), bias flow is combined with a demand valve. Being governed by a microprocessor, this system can be used in PSV mode with varying bias flow rates. The evidence that this provides an advantage in conjunction with PSV is lacking. Indeed, it may be disadvantageous in patients with severe COPD.21

The investigation of the effect of bias flow with various flow rates during PSV on triggering time and WOBtr was another purpose of our study. The main finding of our study was that in the presence of bias flow, both triggering delay and WOBtr became greater during PSV with the pressure-triggering system (Table 2). Additional effort and time were required in the presence of bias flow to reach an airway pressure level set as a triggering level (Fig 4 and 5). Our data confirmed that continuous gas flow conceivably rendered ventilators less sensitive to a patient’s effort. In patients with weak ventilatory effort, the additional gas flow may prevent the ventilator from sensing the patient’s inspiratory effort. Gurevich and Gelmont10 described their experience of weaning a patient with COPD. In their study, the triggering capabilities of various ventilators were examined. Patient-ventilator asynchrony occurred when the patient was placed on assisted mode with continuous flow. Patients’ efforts were untriggered at the base flow rate of 5 L/min regardless of trigger sensitivity level. Another clinical finding21 was that
the use of PSV was also limited by the employment of continuous in-line nebulizers. These clinical cases in our findings demonstrate that bias flow increases triggering delay and WOBtr.

Bias flow also reduced the pressure support time. Although triggering time was 8 to 9 percent of the whole respiratory cycle without bias flow, it became more than 17 to 30 percent at bias flow of 20 L/min, with support time being shortened. As a result, VT decreased with increasing bias flow rate.

In summary, using the lung model, we have developed the method for the quantitative determination of WOBtr. With this method, we can clarify the relationship between WOBtr and PS level, the respiratory system mechanics, triggering delay, WOBtr, and auto-PEEP. The auto-PEEP was caused by high airway resistance and was found to be the major determinant of WOBtr. In addition, bias flow does not decrease the WOBtr because it interferes with the patient's ability to overcome a demand threshold. We urge caution in the use of bias flow in conjunction with PSV because of the detrimental effect of bias flow on the sensing mechanism requiring additional work to initiate a ventilator-assisted breath.

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