Effects of Gas Leak on Triggering Function, Humidification, and Inspiratory Oxygen Fraction During Noninvasive Positive Airway Pressure Ventilation*

Eriko Miyoshi, MD; Yuji Fujino, MD; Akinori Uchiyama, MD; Takashi Mashimo, MD; and Masaji Nishimura, MD

Objectives: During noninvasive positive pressure ventilation (NPPV), the gas leak that commonly occurs around the mask can render NPPV ineffective. We evaluated the effects of gas leak on inspiratory trigger function during NPPV with bilevel pressure and ICU ventilators. In addition, we evaluated the effects of gas leak on fraction of inspired oxygen (FiO2) and humidification.

Methods: Air leak was created at the airway opening of a model lung by establishing several different-size holes in the circuit. During simulated spontaneous breathing, we evaluated inspiratory trigger performance of two bilevel pressure ventilators (BiPAP Vision and BiPAP S/T-D; Respironics; Murrysville, PA) and two ICU ventilators (Puritan-Bennett 7200ae and Puritan-Bennett 840; Tyco Healthcare; Mansfield, MA). Inspiratory delay time and inspiratory trigger pressure were analyzed. FiO2 at the airway opening and inside the model lung were evaluated during BiPAP S/T-D ventilation at supplemental oxygen flows of 3, 6, 9, 12, and 15 L/min. Measured oxygen concentration was compared to mathematically predicted levels. Finally, using two heated humidifiers, we evaluated the effect of gas leak on humidification.

Results: The bilevel pressure ventilators triggered properly at all levels of gas leak, and inspiratory triggering was more effective than with the ICU ventilators. Delivered FiO2 with the BiPAP S/T-D ventilator was affected by gas leak and could be predicted mathematically unless the gas leak was large. With large gas leaks, although relative humidity was maintained, absolute humidity decreased.

Conclusion: Gas leak affected triggering of ICU ventilators, FiO2 of the BiPAP S/T-D ventilator, and humidity with both types of humidifiers.

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Key words: gas leak; humidification; inspiratory fraction of oxygen; noninvasive positive pressure ventilation; triggering function

Abbreviations: AH = absolute humidity; DT = inspiratory delay time; FiO2 = fraction of inspired oxygen; NPPV = noninvasive positive pressure ventilation; PEEP = positive end-expiratory pressure; PI = inspiratory trigger pressure; PIP = peak inspiratory pressure; RH = relative humidity; RR = respiratory rate

Noninvasive positive pressure ventilation (NPPV) has been widely used to provide mechanical ventilation to patients with a number of acute and chronic conditions: chronic respiratory failure caused by restrictive thoracic diseases, and exacerbation of COPD, and some forms of acute respiratory failure. NPPV can reduce the incidence of endotracheal intubation, thus avoiding complications associated with invasive positive pressure ventilation such as nosocomial infections, mechanical injury to the upper airway, and the need for sedation. During NPPV, a nasal or face mask is used as an interface with the mechanical ventilator instead of an endotracheal tube. Perfect sealing of the mask is rarely accomplished during NPPV, and gas leak around the mask can compromise the effectiveness of ventilation. However, NPPV ventilators can compensate for leaks, and the presence of air leaks decreases rebreathing of exhaled gas. Although most ICU ventilators lack the ability to compensate for leaks, they are also used for the administration of...
NPPV. We hypothesized that the presence of air leaks would affect triggering of ICU ventilators to a greater extent than bilevel pressure ventilators. Gas leaks, we also hypothesized, would affect the efficiency of system humidifiers and the fraction of inspired oxygen (FiO₂) delivered by a bilevel pressure ventilation system (BiPAP S/T-D; Respironics; Murrysville, PA). In this study, we evaluated the effects of air leak on triggering, humidification, and FiO₂ in bilevel pressure ventilators and ICU ventilators.

**Materials and Methods**

*Lung Model and Ventilators*

We used a custom-made bellows-in-a-box model lung to simulate spontaneous breathing (Fig 1). The lung consisted of two lung compartments within a rigid box. The space around the compartments simulated the pleural space. The diaphragm compartment bellows was connected to a T-tube through which gas flow was injected to create a Venturi-establishing negative pleural pressure resulting in inspiration of the lung bellows. The source gas was connected to a custom-made pressure regulator and a proportional solenoid valve (SMC Corporation; Indianapolis, IN). The solenoid valve controlled by a function generator (H3BF; Omron; Tokyo, Japan), regulated jet flow, respiratory rate (RR), and inspiratory time. Compliance of the lung model was alterable by changing a spring in the bellows. This lung model has been described in detail in previous publications. Using this model lung, we evaluated the inspiratory triggering capabilities of two ICU ventilators (Puritan-Bennett 7200ae and Puritan-Bennett S40; Tyco Healthcare; Mansfield, MA) and two bilevel pressure ventilators (BiPAP S/T-D and BiPAP Vision; Respironics).

To evaluate FiO₂ and humidification during gas leak, we used a mechanical lung model (TTL; Michigan Instruments; Grand Rapids, MI). The resistance of the mechanical lung model was set at 5 cm H₂O/L/s, and the compliance was set at 50 mL/cm H₂O. This lung model was used to evaluate FiO₂ during NPPV with the BiPAP S/T-D ventilator and humidification with the BiPAP Vision ventilator.

**Gas Leak**

Gas leak was created at the airway opening of the lung model with holes of several sizes. As illustrated in Figure 2, the extent of gas leak was nonlinearly related to pressure and flow. Eleven different gas leaks were established at an airway pressure of 5 cm H₂O. Actual leakage ranged from 1.1 to 44.2 L/min. FiO₂ and humidification were evaluated at three levels of gas leak with an airway pressure of 5 cm H₂O: minor, 1.1 L/min; medium, 11.3 L/min; and major, 34.5 L/min.

**Measurements and Calibration**

A pneumotachometer (model 4700 [0 to 160 L]; Hans-Rudolph; Kansas City, MO) calibrated by measuring and integrating the flow signal from a 2-L supersyringe (Hans-Rudolph) was placed at the airway opening of the model lung. A pressure transducer (model TP603T [± 50 cm H₂O]; Nihon Kohden; Tokyo, Japan) calibrated at 0 cm H₂O and 20 cm H₂O using a water manometer was used to monitor the pressure at the airway opening. A mass spectrometer (MGA-1100; GE Medical Sys-
tems; Waukesha, WI) was used to measure oxygen concentrations at the airway opening and inside the bellows. We compared actual F\textsubscript{io2} measures with theoretical results predicted by the formula: 21% + 3% × supplemental oxygen flow (liters per minute).\textsuperscript{14} A hygrometer (Moirscope; Skynet; Tokyo, Japan) was used to measure temperature and relative humidity (RH) at the lung model airway opening. Ambient temperature and humidity were also measured since bilevel ventilators compress room air for delivery during NPPV. All signals were amplified, digitized, and recorded at 100 Hz per signal using data acquisition software (WINDAQ; Dataq Instruments; Akron, OH). Three breaths were analyzed, and average values were used.

**Experimental Protocol**

Each ventilator via a standard ventilator circuit without a humidifier was attached to the custom-made lung model for triggering evaluation. Spontaneous breathing was simulated at an RR of 10 breaths/min, inspiratory time of 1.0 s, and peak inspiratory flow of 60 L/min. A resistor (Michigan Instruments) of 5 cm H\textsubscript{2}O/L/s or 20 cm H\textsubscript{2}O/L/s was connected to the model lung. ICU ventilators were set in the assist/control mode, and bilevel pressure ventilators were set in the spontaneous/timed mode, both with a positive end-expiratory pressure (PEEP) of 5 cm H\textsubscript{2}O, peak inspiratory pressure (PIP) of 15 cm H\textsubscript{2}O, and F\textsubscript{io2} of 0.21. Using the flow-triggering function, inspiratory triggering sensitivity was set to the most sensitive level that did not result in self-triggering. The time between the start of inspiration to the point of minimum airway pressure was recorded as inspiratory delay time (DT). Inspiratory trigger pressure (PI) was recorded as the difference between the baseline pressure and the maximum subbaseline pressure established during triggering of inspiration but described as a positive value.

The BiPAP S/T-D ventilator was connected to the mechanical lung model via the standard circuit recommended by the manufacturer for F\textsubscript{io2} evaluation. The ventilator settings were timed mode; peak inspiratory pressure (PIP), 15 cm H\textsubscript{2}O; PEEP, 5 cm H\textsubscript{2}O; RR, 20/min; and percentage of inspiratory time, 40%. Supplemental oxygen was administered at 3, 6, 9, 12, and 15 L/min into the ventilator circuit at the gas outlet of the ventilator. The humidification capability of two heated humidifiers (PMH1000; Pacific Medico; Tokyo, Japan; and MR290; Fisher & Paykel; Auckland, New Zealand) were evaluated during ventilation with the BiPAP Vision ventilator. Each humidifier was connected to the mechanical lung model via a standard circuit as recommended by the manufacturer. A humidifier heater (MR730; Fisher & Paykel) was used. The ventilator was set in the spontaneous/timed mode; F\textsubscript{io2}, 0.21; PIP; 15 cm H\textsubscript{2}O; PEEP, 5 cm H\textsubscript{2}O; and RR, 20 breaths/min.

**Results**

**Triggering Evaluation**

Table 1 shows DT and PI for each leak level on all ventilators. The Puritan-Bennett 7200ae and Pur-
tan-Bennett 840 showed uncontrollable self-triggering when the gas leak was >18 L/min at end-expiration. The BiPAP Vision and BiPAP S/T-D adequately compensated for all leaks, and PI and DT were not affected by any air leak (Fig 3, top, A, and bottom, B; Table 1), nor by either airway resistance (only data for 5 cm H$_2$O/L/s are presented in Table 1).

FIO$_2$ Evaluation

Figure 4 shows representative waveforms for FIO$_2$ and airway pressure at the airway opening of the lung model (top, A) and inside the bellows (bottom, B) during medium leak. FIO$_2$ at the airway opening varied greatly during each ventilatory cycle. Table 2 shows values for FIO$_2$ at the airway opening (maximum and minimum), FIO$_2$ inside the bellows, and predicted FIO$_2$. Figure 5 shows the relation between the measured FIO$_2$ inside the bellows and the predicted FIO$_2$. Except at the highest tested level of air leak (major), FIO$_2$ inside the bellows was close to the values predicted by the formula.

Humidification Evaluation

Throughout the protocol, ambient temperature and RH were approximately 24°C and 50%. Table 3 shows data for temperature and RH at the airway opening of the lung model. With both humidifiers, RH was maintained close to 100% regardless of leak. Temperature, however, with the PMH1000 heated humidifier declined to close to the ambient temperature with an absolute humidity (AH) of approximately 22 mg/L. The MR290 maintained temperature at approximately 30°C and AH at approximately 30 mg/L, although both declined slightly at high leaks.

Discussion

Major findings of this study are that bilevel pressure ventilators could adequately compensate for all levels of leak evaluated, while ICU ventilators were not able to cope with large leaks. As the leak increased, the bilevel ventilation inspiratory triggering response was not affected. The FIO$_2$ delivered by the BiPAP S/T-D was affected in ways not predicted by the formula when the gas leak was large. The MR290 was able to maintain temperature and humidity under all leak conditions.

NPPV is widely used to assist patients with both acute and chronic respiratory failure and is believed to decrease the rate of intubation, length of ICU stay, and mortality. However, ventilatory support with NPPV is not always successful. When, instead of an endotracheal tube a face mask is used, air leak through and around the mask is inevitable. When a nasal mask is used, larger leaks occur as gas escapes through the mouth. A variety of other problems, such as eye irritation and patient discomfort, are associated with air leak. In this study, we hypothesized that air leak during NPPV caused dysynchrony between patient and ventilator, fluctuation of inspired oxygen concentration, and unsatisfactory humidification of inspiratory gas. To evaluate the effects of gas leak, others have evaluated the affect of only a single level of leak using a swivel connector (Wisper Swivel Connector; Respironics)$^{15}$ or two levels of leaks.$^{16}$ This is the most comprehensive evaluation of the impact of leaks during NPPV to date.

It is not unusual to use ICU ventilators for NPPV, but trigger sensitivity must be titrated to avoid autotriggering due to gas leaks. When autotriggering

<table>
<thead>
<tr>
<th>Leakage, L/min</th>
<th>Puritan-Bennett 7200ae</th>
<th>Puritan-Bennett 840</th>
<th>BiPAP ST-D</th>
<th>BiPAP Vision</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DT, s</td>
<td>PI, cm H$_2$O</td>
<td>DT, s</td>
<td>PI, cm H$_2$O</td>
</tr>
<tr>
<td>0</td>
<td>0.107</td>
<td>5.033</td>
<td>0.080</td>
<td>4.569</td>
</tr>
<tr>
<td>1.1</td>
<td>0.097</td>
<td>4.992</td>
<td>0.080</td>
<td>4.569</td>
</tr>
<tr>
<td>2.5</td>
<td>0.110</td>
<td>4.902</td>
<td>0.080</td>
<td>4.468</td>
</tr>
<tr>
<td>3.1</td>
<td>0.100</td>
<td>4.962</td>
<td>0.080</td>
<td>4.287</td>
</tr>
<tr>
<td>7.8</td>
<td>0.110</td>
<td>4.882</td>
<td>0.073</td>
<td>4.206</td>
</tr>
<tr>
<td>11.3</td>
<td>0.110</td>
<td>4.800</td>
<td>0.060</td>
<td>3.970</td>
</tr>
<tr>
<td>18.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>19.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>22.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>25.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>34.5</td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>44.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</table>

*All data determined at resistance of 5 cm H$_2$O/L/s. Gas leak is expressed as air flow at airway pressure of 5 cm H$_2$O. Due to unavoidable self-triggering, DT and PI could not be determined with the Puritan-Bennett 7200ae and Puritan-Bennett 840 when gas leak was >18 L/min.
occurs, dyssynchrony between the patient and ventilator is unavoidable. This leads to discomfort during NPPV, poor ventilation, and frequently failure of NPPV. Using a lung model, Bunburaphong et al\textsuperscript{17} compared the performance of nine portable home care ventilators to an ICU ventilator. They concluded that most of the portable ventilators were able to appropriately respond to high ventilatory demands and provided better inspiratory triggering than the ICU ventilator. Our results corroborate this finding. Although we were able to titrate the inspiratory triggering sensitivity on the ICU ventilators to cope with medium leaks, this does not imply that ICU ventilators can be safely used with large leaks. Great care should be taken when ICU ventilators are employed to provide NPPV, especially by nasal mask or nasal pillows because dyssynchrony between the patient and the ventilator is common. As a result, gas leak can lead to failure of NPPV.

Some bilevel pressure ventilators have integrated F\textsubscript{io2} control functions. However, to increase the F\textsubscript{io2} on most bilevel pressure ventilators, oxygen must be titrated into the ventilator circuit. Theoretically, both the size of the leak and the minute ventilation are factors that affect the oxygen concentration when oxygen is titrated into the circuit. Our results demonstrate that F\textsubscript{io2} in the mask also fluctuated when gas leak was absent. This is a result
of the constant flow of oxygen vs the variable flow delivered by the bilevel ventilator during inspiration. We considered the $\text{FiO}_2$ inside the bellows as equivalent to the actual inspired oxygen by patients in clinical situations. Inside the bellows, except at the largest tested leak, $\text{FiO}_2$ values were close to those predicted by the formula (Fig 4). Thys et al\textsuperscript{18} reported that $\text{FiO}_2$ with bilevel pressure ventilators depended on three factors: the point where oxygen is added into the circuit, the level of inspiratory positive airway pressure, and the oxygen flow rate. In our study, the site of oxygen administration and ventilator settings were constant. Since we used a mass spectrometer to measure $\text{FiO}_2$, it was possible to assess, during the entire ventilatory cycles, the fluctuations of $\text{FiO}_2$ under all leak conditions. Despite these fluctuations, our findings reveal that the actual $\text{FiO}_2$ inspired by patients is likely to be constant and predictable using the formula. Thus actual $\text{FiO}_2$ levels can be reasonably well predicted if the ventilator set-up is as we described.

The human nasopharynx is remarkably well able to affect the warming and humidification of inspired air. Rouadi et al\textsuperscript{19} reported that dry and cold gas was completely humidified to 100% RH on its way through the nasopharynx. When patients breathe via

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**FIGURE 4.** *Top, A:* With a moderate leak and oxygen flow of 9 L/min, waveforms for airway pressure ($\text{Paw}$) and $\text{FiO}_2$ measured at the airway opening are illustrated. $\text{FiO}_2$ varied greatly during the ventilatory cycle. *Bottom, B:* Waveforms for airway pressure ($\text{Paw}$) and $\text{FiO}_2$ measured inside the model lung with a moderate gas leak and oxygen flow of 9L/min. $\text{FiO}_2$ was essentially constant.
an endotracheal tube, inspiratory gas bypasses the nasopharynx. American National Standards and International Organization of Standardization recommend an AH level of inspired gas of > 33 mg/L in patients whose supraglottic airways are bypassed.\textsuperscript{20,21} During NPPV, although inspiratory gas does pass through the upper airway, patients often complain of dryness and pain in the nasopharynx when inspiratory gas is dry. Proper humidification of inspiratory gas during NPPV is essential. When using the MR290 humidifier, although AH was lower than the recommended value of 33 mg/L, the temperature at the airway opening was higher than when using the PMH1000. Moreover, with the MR290, temperature was not significantly affected by the amount of gas leak. Although there are no agreed-on standards for humidification during NPPV, compared with the PMH1000 the MR290 can be expected to be more effective in avoiding patient discomfort.

The main limitation of our study is the fact that we used a lung model. During each protocol, the simulated leakage was constant; this is not true in clinical practice. The results we obtained could lead to the unjustified conclusion that, in practical use, ICU ventilators cope well with gas leak. In clinical situations, gas leak from the mask changes in response to airway pressure swings and patient movement. In the present study, we chose flow triggering and adjusted the base flow and trigger sensitivity according to the amount of gas leak. At the bedside, however, it would be impossible to carry out such fine titration of inspiratory trigger sensitivity to compensate for gas leak when using ICU ventilators. Furthermore, when there is a gas leak, psychological response must be considered since gas leak may affect ventilatory demand. Additionally, we only investigated two levels of system resistance to simulate the effect of increased airway resistance on inspiratory triggering in the presence of gas leak. A much wider range of airway resistance would be observed in clinical prac-

<table>
<thead>
<tr>
<th>Leakage</th>
<th>None</th>
<th>Minor</th>
<th>Medium</th>
<th>Major</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>39.9/23.8; 30.7</td>
<td>38.8/23.4; 29.6</td>
<td>34.0/22.6; 28.2</td>
<td>28.9/21.7; 23.4</td>
</tr>
<tr>
<td>6</td>
<td>58.5/28.2; 40.0</td>
<td>56.9/27.3; 40.2</td>
<td>47.1/25.5; 36.7</td>
<td>35.0/24.0; 27.6</td>
</tr>
<tr>
<td>9</td>
<td>78.8/34.8; 52.3</td>
<td>76.7/33.1; 50.8</td>
<td>60.0/29.2; 46.9</td>
<td>45.5/26.6; 32.0</td>
</tr>
<tr>
<td>12</td>
<td>90.3/41.7; 61.0</td>
<td>89.0/38.7; 60.0</td>
<td>70.3/32.4; 54.4</td>
<td>53.2/28.9; 36.5</td>
</tr>
<tr>
<td>15</td>
<td>97.7/50.0; 70.0</td>
<td>95.8/45.3; 68.0</td>
<td>80.4/36.2; 63.2</td>
<td>59.7/31.4; 41.2</td>
</tr>
</tbody>
</table>

*Data are presented as maximum/minimum $F_{iO_2}$, %: $F_{iO_2}$ inside the bellows, % unless otherwise indicated. Gas leak (at airway pressure of 5 cm $H_2O$): minor, 1.1 L/min; medium, 11.3 L/min; major, 34.5 L/min. Predicted $F_{iO_2}$ values were calculated using the formula: 21% + 3% × supplemental oxygen flow (liters per minute).
tice. Our results may also be affected by the constant respiratory demand of our model. The ventilatory demand varies considerably over time. Finally, we only evaluated the effect of gas leak at one lung model compliance clearly changes in patient compliance could affect the level of leak in a particular patient.

In conclusion, the amount of gas leak during NPPV affects synchrony with the mechanical ventilator, FiO₂, and humidity. FiO₂ can be predicted using a formula unless gas leak is large. Gas leak had a minimal effect on humidification by the humidifiers evaluated.

REFERENCES
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Table 3—Temperature and RH at Various Gas Leaks With the PMH 1000 and MR 290 Heated Humidifiers at the Airway Opening of the Model Lung*

<table>
<thead>
<tr>
<th>Leakage</th>
<th>PMH1000</th>
<th>MR290</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>24.80/99.98 (22.8)</td>
<td>30.14/99.98 (30.6)</td>
</tr>
<tr>
<td>Minor</td>
<td>25.02/99.98 (23.1)</td>
<td>30.56/99.98 (31.3)</td>
</tr>
<tr>
<td>Medium</td>
<td>24.98/99.98 (23.0)</td>
<td>30.18/99.98 (30.6)</td>
</tr>
<tr>
<td>Major</td>
<td>24.23/99.98 (22.1)</td>
<td>29.66/99.98 (29.8)</td>
</tr>
</tbody>
</table>

*Data are presented as temperature, °C/RH, % (AH, mg/L). Gas leak (at airway pressure of 5 cm H₂O): minor, 1.1 L/min; medium, 11.3 L/min; major, 34.5 L/min.