

Factors Affecting Oxygen Delivery With Bi-Level Positive Airway Pressure

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INTRODUCTION: Portable pressure ventilators, or bi-level ventilators, do not typically have an oxygen control, and thus supplemental oxygen is usually administered by adding it into the mask or the circuit. We conducted this study to test the hypothesis that delivered oxygen concentration using this configuration is affected by the choice of leak port, oxygen injection site, and ventilator settings. **METHODS:** A lung model simulating spontaneous breathing was connected to the head of a manikin. An oronasal mask was attached to the manikin. A single-limb circuit was attached to the mask and a bi-level ventilator. Three leak ports were compared: leak in the mask, plateau exhalation valve with mask leak port occluded, and leak port in the circuit with mask leak port occluded. Bi-level positive airway pressure (BiPAP) settings of 10/5, 15/5, 20/5, 15/10, 20/10, and 25/10 cm H₂O were used at respiratory rates of 15 and 25 breaths/min. Oxygen was added into the mask or into the circuit at the ventilator outlet, using flows of 5 and 10 L/min. Carbon dioxide was added into the lung model to produce an end-tidal P_{CO₂} of either 40 or 75 mm Hg. **RESULTS:** Delivered oxygen concentration was not affected by respiratory rate ($p = 0.22$) or end-tidal P_{CO₂} ($p = 0.74$). The oxygen concentration was greater when oxygen was added into the circuit with the leak port in the mask ($p < 0.001$), whereas oxygen concentration was greater when oxygen was added into the mask with the leak port in circuit ($p = 0.005$). Oxygen concentration was significantly lower with the leak port in the mask ($p < 0.001$), with a higher inspiratory positive airway pressure ($p < 0.001$), and with a higher expiratory positive airway pressure ($p < 0.001$). The highest oxygen concentration was achieved with oxygen added to the mask, with the leak port in the circuit, and with the lowest settings of inspiratory (10 cm H₂O) and expiratory (5 cm H₂O) positive airway pressure. **CONCLUSIONS:** Delivered oxygen concentration during BiPAP is a complex interaction between the leak port type, the site of oxygen injection, the ventilator settings, and the oxygen flow. Because of this, it is important to continuously measure arterial oxygen saturation via pulse oximetry with patients in acute respiratory failure who are receiving noninvasive ventilation from a bi-level ventilator. *Key words:* noninvasive positive-pressure ventilation, oxygen delivery, BiPAP, bi-level. [Respir Care 2004;49(3):270–275. © 2004 Daedalus Enterprises]

Introduction

High-level evidence supports the use of noninvasive positive-pressure ventilation in appropriately selected pa-

tients with acute respiratory failure.^{1–5} Most of these patients need supplemental oxygen in addition to ventilatory support. The fraction of inspired oxygen (F_{IO₂}) can be precisely controlled on ventilators commonly used for crit-

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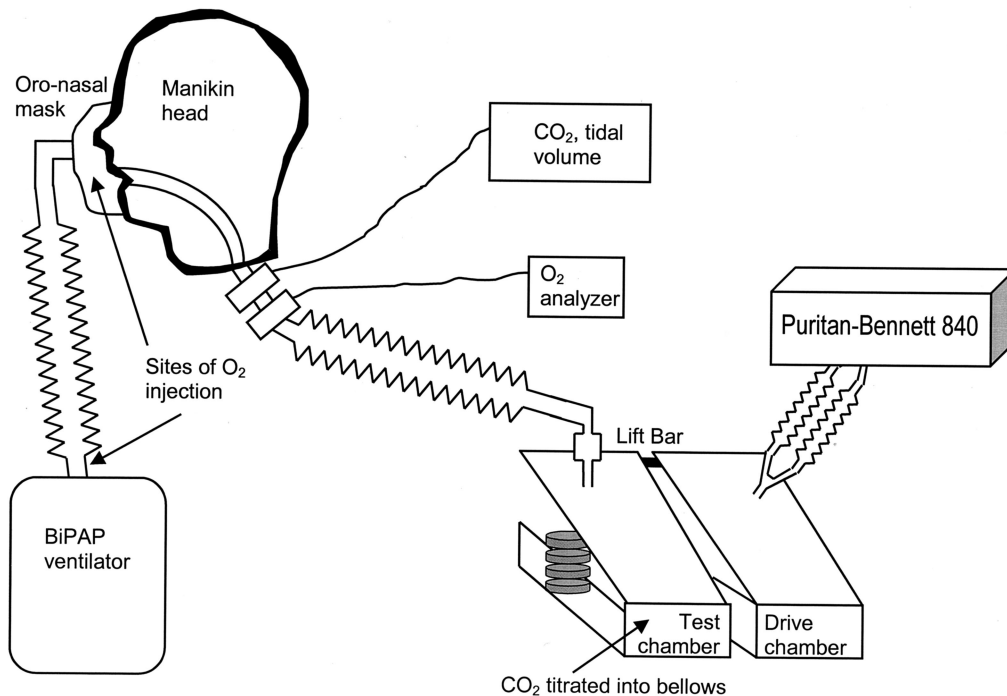


Fig. 1. Experimental setup. BiPAP = bi-level positive airway pressure.

ically ill patients. Such ventilators, however, do not perform well in the presence of mask leaks, which invariably occur during noninvasive positive-pressure ventilation. Portable pressure ventilators, or bi-level ventilators, compensate well for leaks and are commonly used to provide noninvasive positive-pressure ventilation.⁶ Many of those ventilators, however, do not have an oxygen control, and thus supplemental oxygen is usually administered by adding it into the mask or the circuit.

Bi-level ventilators operate with a leak port in the system, which also serves as the exhalation port for the patient. The size of the port is fixed and leak varies according to the pressure in the system. This port can be incorporated directly into the mask or into the circuit near the connection to the mask. We have anecdotally noted differences in arterial oxygen saturation with different leak port types when the same flow of oxygen was added. An extensive literature search uncovered only one report that addressed this issue.⁷ In that study oxygen delivery was reported to be greater when oxygen was added into the circuit near the ventilator rather than at the mask. The mask used in that study incorporated the exhalation port in the mask. In a report published after we completed the present study, Thys et al⁸ reported that the delivered oxygen concentration was greatest when oxygen was added into the circuit between the ventilator and the exhalation port. Interestingly, they reported lower delivered oxygen concentrations when oxygen was added either at the ventilator outlet or at a site between the exhalation port and the mask. Neither of these studies reported the effect of ox-

xygen administration directly into the mask. We conducted the present study to test the hypothesis that delivered oxygen concentration during bi-level positive airway pressure (BiPAP) is affected by the choice of leak port, oxygen injection site, and BiPAP settings.

Methods

A model was constructed to allow simulated spontaneous ventilation with BiPAP (Fig. 1). A ventilator (model 840, Puritan-Bennett, Pleasanton, California) was attached to one chamber of a dual-chamber test lung. A lift bar was placed between the chambers so that the ventilator triggered a simulated spontaneous breathing effort in the second chamber, which was connected to the head of a manikin. The drive ventilator was only used to trigger the initiation of the inspiratory phase of the BiPAP ventilator. Once the breath was triggered, inflation of the test chamber was controlled by the BiPAP ventilator. This experimental setup was similar to that used previously in our laboratory to study heliox delivery and aerosol bronchodilator delivery during noninvasive ventilation.^{9,10} Carbon dioxide was titrated into the lung model to produce an end-tidal P_{CO_2} of 40 or 75 mm Hg. A mainstream monitor (NICO, Novametrix, Wallingford, Connecticut) was inserted between the manikin and the lung model to measure volume delivery and end-tidal P_{CO_2} . Oxygen was measured adjacent to the site of volume and carbon dioxide measurement (model 7820, Puritan-Bennett, Carlsbad, California).

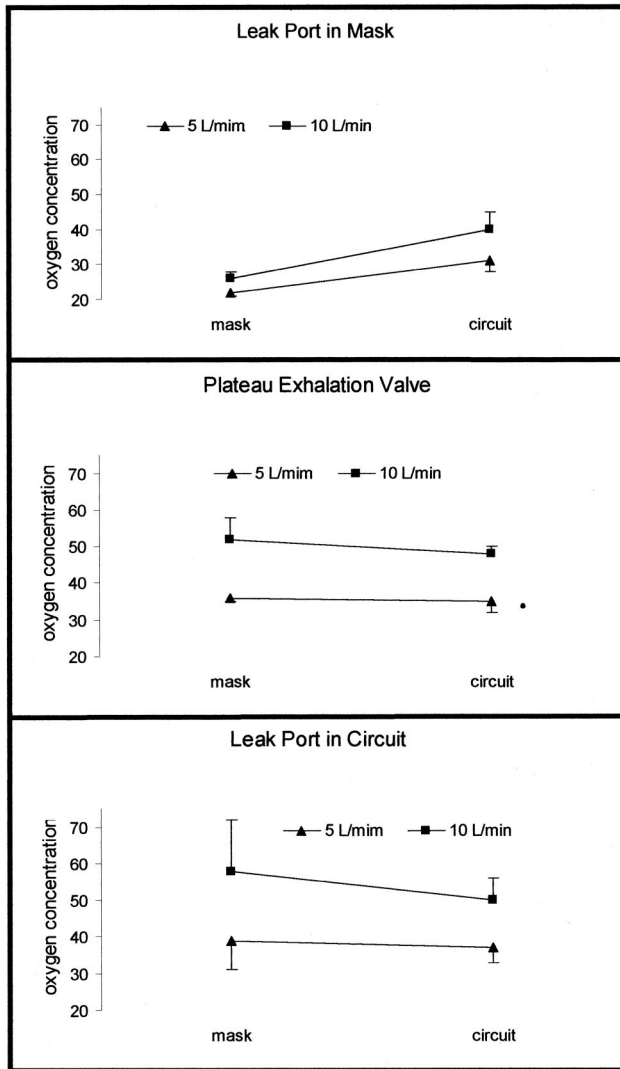


Fig. 2. Effect of leak port and site of oxygen injection on measured oxygen concentration at oxygen flows of 5 and 10 L/min, and with oxygen added into the mask or into the circuit. Data are pooled for all variables other than those of interest.

An oronasal face mask (Mirage, Resmed, San Diego, California) was secured to the manikin face in a manner similar to that used clinically. A single-limb circuit was attached to the mask and the ventilator (Synchrony BiPAP, Respironics, Pittsburgh, Pennsylvania). We evaluated 3 popular devices with leak ports that have different leakage characteristics: (1) the leak port in the Mirage mask, (2) the Plateau Exhalation Valve (Respironics, Pittsburgh, Pennsylvania) with the Mirage mask leak port occluded, and (3) the BiPAP Disposable Circuit (Respironics, Pittsburgh, Pennsylvania) leak port incorporated into circuit and Mirage mask leak port occluded. We used BiPAP settings of 10/5, 15/5, 20/5, 15/10, 20/10, and 25/10 cm H₂O in conjunction with respiratory rates of 15 and 25 breaths/min. Oxygen was added into the mask or into the

circuit at the ventilator outlet, using flows of 5 and 10 L/min.

Flow through each leak port type was measured in the following manner. The patient connection distal to the leak port was occluded. Flow and pressure were measured immediately proximal to the leak port with the NICO monitor. The Synchrony BiPAP ventilator was set for continuous positive airway pressures of 5, 10, 15, and 20 cm H₂O. Pressure and flow were recorded from the NICO monitor signal, and leak flow was plotted as a function of pressure.

Statistical analysis consisted of descriptive statistics and analysis of variance. Where appropriate, post-hoc analysis was conducted with Scheffé's test. Differences were considered statistically significant when $p < 0.05$. Commercially available software (SPSS version 11.5, SPSS, Chicago, Illinois) was used for statistical analysis.

Results

Neither P_{CO_2} ($p = 0.77$) nor respiratory rate ($p = 0.29$) significantly affected the measured oxygen concentration, so these data were pooled for all subsequent analysis. The measured oxygen concentration was significantly greater with a flow of 10 L/min than with a flow of 5 L/min ($p < 0.001$). The measured oxygen concentration was lower with the leak port incorporated into the mask than with the other 2 leak ports ($p < 0.001$ by Scheffé's test) (Fig. 2). There was no significant difference between measured oxygen concentration with the Plateau Exhalation Valve and the leak port incorporated into the circuit ($p = 0.14$ by Scheffé's test). With the mask leak port the measured oxygen concentration was greater when oxygen was added into the circuit ($p < 0.001$). With the leak port in the circuit the measured oxygen concentration was greater when oxygen was added into the mask ($p = 0.005$). With the plateau exhalation valve the measured oxygen concentration was not significantly different for the 2 oxygen injection sites ($p = 0.086$). The measured oxygen concentration was lower with higher inspiratory positive airway pressure (IPAP) and expiratory positive airway pressure (EPAP) settings ($p < 0.001$), regardless of the difference between IPAP and EPAP settings (ie, the level of pressure support) (Fig. 3).

Figure 4 shows the relationship between leak flow and pressure. The change in flow as pressure increased was greater for the leak port in the mask (slope = 2.4) than for the leak port in the circuit (slope = 0.92) or for the plateau exhalation valve (slope = -0.06).

Discussion

The major finding of the present study is that the delivered oxygen concentration with BiPAP is affected by

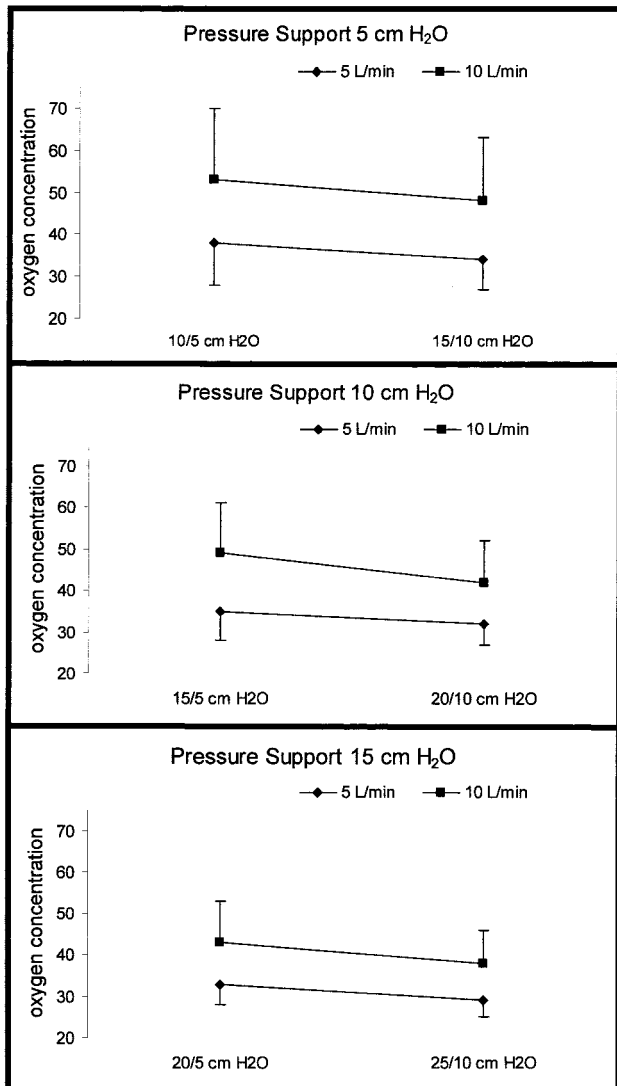


Fig. 3. Effect of ventilator settings on measured oxygen concentration at oxygen flows of 5 and 10 L/min. Data are pooled for all variables other than those of interest.

the type of leak port and the site at which oxygen is added into the circuit. The delivered oxygen concentration was also affected by the IPAP and EPAP settings and the oxygen flow. As shown in Table 1, the highest oxygen concentration was achieved with oxygen added to the mask, with the leak port in the circuit, and with the lowest settings of IPAP and EPAP.

When the leak port was in the mask and oxygen was added into the mask, presumably much of the oxygen was exhausted out the exhalation port, because of the close proximity of the oxygen entrainment site and the leak port. Adding oxygen distally into the circuit allows more time for mixing when the leak port is in the mask. When the leak port was in the circuit, the delivered oxygen concentration was greater when oxygen was added into the mask.

However, the effect of oxygen injection site was less with the leak port in the circuit than with the leak port in the mask. The delivered oxygen concentration was similar with the leak port in the circuit and the plateau exhalation valve.

Conditions that produce greater flow through the circuit produce lower delivered oxygen concentrations. There are 2 lines of evidence for this from our data. First, the lowest oxygen concentrations occurred with the leak port in the mask, which produced the greatest flow in the circuit (see Fig. 4). Second, lower oxygen concentrations occurred with higher pressure settings, which also produce greater flow in the circuit. Another way of stating this is that leakage flow is an important factor affecting oxygen delivery to patients receiving BiPAP therapy. Leakage can occur either through the leak port (intended leak), between the mask and the face (unintended leak), or from the mouth if a nasal mask is used (unintended leak). In our study we were careful to minimize unintended leaks. Although we did not study the effect of unintended leak, we speculate that this would also have the effect of lowering the delivered oxygen concentration. Changes in respiratory drive—another variable that we did not study—may affect flow from the BiPAP ventilator and thus the delivered oxygen concentration.

Two previous studies evaluated oxygen delivery with a noninvasive positive-pressure ventilator. Waugh and De Kler⁷ compared the delivered oxygen concentration with oxygen added either at the outlet of the ventilator or at the inlet to the mask. They compared a variety of IPAP and EPAP settings, but all of their experiments were conducted with the leak port in the mask. Similar to our findings, they reported a higher delivered oxygen concentration when oxygen was added into the circuit at the ventilator outlet and lower oxygen concentrations with higher IPAP and EPAP settings. Thys et al⁸ compared various IPAP settings and conducted all of their experiments with the leak port in the circuit. They studied 3 oxygen insertion sites: at the outlet of the ventilator, at the inlet to the mask, and at a midpoint in the circuit. Similar to our findings, they reported lower delivered oxygen concentrations with higher IPAP settings and higher delivered oxygen concentrations with the oxygen added at the ventilator outlet than at the mask inlet. Interestingly, they reported the greatest delivered oxygen concentrations with oxygen added at a midpoint in the circuit. We did not study that oxygen injection site and we question its practicality, given that it would require cutting the circuit to add oxygen. It is noteworthy that neither Waugh and De Kler⁷ nor Thys et al⁸ studied the effect of oxygen injection directly into the mask. Similar to our findings, Thys et al⁸ reported that respiratory rate had no effect on delivered oxygen concentration.

When the leak port is in the mask, it is virtually impossible to measure F_{IO_2} ; it would certainly be impossible to do clinically. The site at which we measured oxygen con-

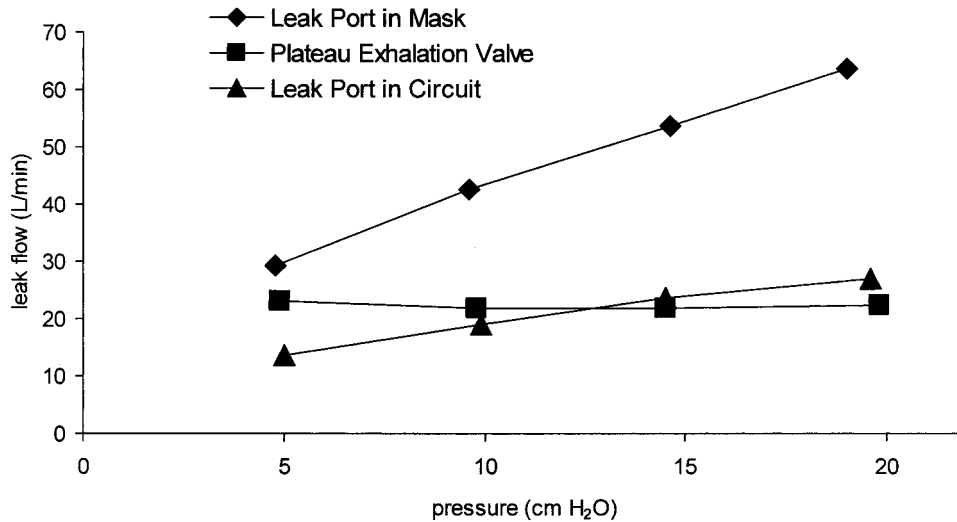


Fig. 4. Leak flow as a function of the leak port type.

centration did not assess F_{IO₂} per se, and it probably reflects simulated tracheal oxygen concentration. Moreover, the analyzer we used has a slow response, so it probably reflected an average of inhaled and exhaled oxygen concentrations. Thus the delivered oxygen concentration we report is slightly lower than the F_{IO₂}. However, the difference between inhaled and exhaled oxygen concentration is usually not more than several percent (within the measurement error of the analyzer that we used). Our experimental setup would have allowed measurement of F_{IO₂} if we had used a rapid-response oxygen analyzer. Because we used an oxygen analyzer with a slow response, we do not know if the oxygen concentration was constant throughout the

inspiratory phase. BiPAP ventilators provide pressure-support ventilation, so the inspiratory flow decreases as inhalation proceeds. Because the flow from the ventilator is decreasing and the added oxygen flow is constant, it is likely that the delivered oxygen concentration is lower at the beginning of inhalation and greater at the end of inhalation. Theoretically, that would mean that the gas delivered to the alveolus (beginning of inhalation) would have a lower oxygen concentration than that delivered to the dead space (end of inhalation). The extent to which that occurs and its clinical importance deserve further study.

With use of a BiPAP ventilator Thys et al⁸ reported subambient oxygen delivery at low pressures and without

Table 1. Oxygen Concentrations

Oxygen Injection Site	Leak Port	Oxygen Flow (L/min)	Oxygen Concentration (mean ± SD percent)					
			IPAP/EPAP 10/5 cm H ₂ O	IPAP/EPAP 15/5 cm H ₂ O	IPAP/EPAP 20/5 cm H ₂ O	IPAP/EPAP 15/10 cm H ₂ O	IPAP/EPAP 20/10 cm H ₂ O	IPAP/EPAP 25/10 cm H ₂ O
Circuit	Mask	5	33 ± 3	34 ± 2	31 ± 1	30 ± 1	30 ± 2	28 ± 2
		10	41 ± 3	47 ± 4	41 ± 2	38 ± 1	38 ± 4	36 ± 3
	PEV	5	36 ± 1	37 ± 2	35 ± 1	34 ± 1	37 ± 2	34 ± 3
		10	48 ± 2	51 ± 3	49 ± 3	45 ± 3	50 ± 3	44 ± 5
	Circuit	5	37 ± 4	39 ± 6	38 ± 4	38 ± 1	35 ± 1	34 ± 1
		10	51 ± 8	55 ± 11	50 ± 6	49 ± 2	48 ± 4	45 ± 3
Mask	Mask	5	23 ± 1	22 ± 0	22 ± 1	22 ± 0	22 ± 0	22 ± 0
		10	30 ± 2	28 ± 2	26 ± 1	26 ± 1	24 ± 0	24 ± 1
	PEV	5	46 ± 5	38 ± 4	34 ± 3	36 ± 3	33 ± 2	28 ± 2
		10	71 ± 3	54 ± 5	46 ± 3	59 ± 6	47 ± 6	39 ± 4
	Circuit	5	52 ± 3	41 ± 2	36 ± 1	44 ± 4	33 ± 2	29 ± 1
		10	78 ± 3	61 ± 3	52 ± 3	70 ± 9	48 ± 4	39 ± 1

IPAP = inspiratory positive airway pressure
 EPAP = expiratory positive airway pressure
 PEV = plateau exhalation valve

oxygen added to the system. We cannot confirm that finding, because we did not study conditions of no supplemental oxygen flow into the system. In the Thys et al study⁸ that finding was probably due to rebreathing, as has been previously reported. Thus, another factor that may affect the delivered oxygen concentration is rebreathing, which may occur under some conditions with BiPAP.^{11,12} It is interesting to note that we found no significant effect of end-tidal P_{CO_2} on the measured oxygen concentration. Perhaps this means that the risk of rebreathing is lower when oxygen is delivered into the system. This is plausible because the oxygen flow may flush carbon dioxide from the circuit.

Clinical Implications

Our results indicate that the delivered oxygen concentration with BiPAP is a complex interaction of various conditions. Our study was designed to investigate the mechanisms of some factors that might affect the F_{IO_2} during BiPAP; it was not designed to determine the specific F_{IO_2} for various conditions. Accordingly, the data in Table 1 should not be used to predict the specific F_{IO_2} in the clinical setting. It is interesting to note that some changes on the BiPAP ventilator that were intended to improve arterial oxygenation (eg, increased EPAP) might result in a decreased delivered oxygen concentration and thus may be counterproductive. Unfortunately, there is no practical way to monitor the delivered oxygen concentration in systems in which oxygen is added into the mask. When precise oxygen delivery is needed, it is desirable to use a ventilator with an integral oxygen blender. With a system that has the leak port in the mask, oxygen should not be added into the mask, because this results in very low inspired oxygen concentrations. Perhaps most important, pulse oximetry should be used to continuously monitor oxygen saturation during BiPAP therapy when oxygenation is an important aspect of the therapy.¹³

Limitations

This was a bench study and, accordingly, the results should be confirmed clinically. Anecdotally, these results are consistent with our clinical experience. We did not study all variations of oxygen flow, IPAP, and EPAP. Although we studied only 1 BiPAP machine, we suspect that the results would be similar with other commercially available bi-level ventilators. Our intent was not to characterize the delivered oxygen concentration for all settings and devices, but rather to test the general effects of the variables we studied. We also did not study the effect of unintended leakage or changes in respiratory drive, as commonly occur when BiPAP therapy is used clinically.

Conclusions

When administering oxygen with BiPAP therapy, the delivered oxygen concentration is affected by oxygen flow, the site where oxygen is added into the circuit, the position of the leak port, the type of leak port, and the IPAP and EPAP settings. Because of the complex interaction between these variables, it is imperative to continuously measure arterial oxygen saturation, using pulse oximetry, when using this therapy in patients suffering acute respiratory failure.

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