

# Efficacy of a Heated Passover Humidifier During Noninvasive Ventilation: A Bench Study

Anne E Holland PhD, Linda Denehy PhD, Catherine A Buchan BN,  
and John W Wilson MBBS PhD

**BACKGROUND:** Noninvasive positive-pressure ventilation (NPPV) delivers air at a high flow, which is associated with airway mucosal drying and impaired airway functioning. **OBJECTIVES:** To examine the effects of mechanical ventilation parameters on relative humidity and absolute humidity during NPPV, and to evaluate the effect of a heated passover humidifier on relative humidity, absolute humidity, and ventilator performance during NPPV. **METHODS:** We performed a bench study to assess the effects of inspiratory positive airway pressure (IPAP) of 10 cm H<sub>2</sub>O, 15 cm H<sub>2</sub>O, and 20 cm H<sub>2</sub>O, respiratory rates of 12 breaths/min and 24 breaths/min, and inspiratory-expiratory ratios of 1:2 and 1:3 on relative and absolute humidity. The measurements were obtained on room air and with a heated humidifier at medium and maximum heater settings. **RESULTS:** Without humidification, the relative humidity in the NPPV circuit (range 16.3–26.5%) was substantially lower than the ambient relative humidity (27.6–31.5%) at all ventilatory settings. Increasing the IPAP decreased the relative humidity (Spearman's rho = 0.67, p < 0.001). Changing the respiratory rate or inspiratory-expiratory ratio had no significant effect. Both relative and absolute humidity increased with humidification, and the air was fully saturated at the maximum heater setting. Delivered IPAP was reduced by 0.5–1 cm H<sub>2</sub>O during humidification. **CONCLUSIONS:** NPPV delivers air with a low relative humidity, especially with high inspiratory pressure. Addition of a heated humidifier increases the relative and absolute humidity to levels acceptable for nonintubated patients, with minimal effect on delivered pressure. Consideration should be given to heated humidification during NPPV, especially when airway drying and secretion retention are of concern. *Key words:* mechanical ventilation, humidification, humidity, noninvasive ventilation. [Respir Care 2007;52(1):38–44. © 2007 Daedalus Enterprises]

## Introduction

Anne E Holland PhD is affiliated with the School of Physiotherapy, La Trobe University, and with the Department of Physiotherapy, Alfred Hospital, Melbourne, Australia. Linda Denehy PhD is affiliated with the School of Physiotherapy, University of Melbourne, Melbourne, Australia. Catherine A Buchan BN and John W Wilson MBBS PhD are affiliated with the Department of Allergy, Immunology and Respiratory Medicine, Alfred Hospital, Melbourne, Australia. John W Wilson MBBS PhD is also affiliated with the Department of Medicine, Monash University, Melbourne, Australia.

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Correspondence: Anne E Holland PhD, Physiotherapy Department, Alfred Hospital, Commercial Road, Melbourne 3004, Victoria, Australia. E-mail: a.holland@alfred.org.au.

The performance of the human airway is dependent on adequate humidification of the inspired air.<sup>1</sup> Sufficient levels of both absolute humidity (the mass of water in a unit volume of air at a given temperature) and relative humidity (the amount of water carried by the air as a percentage of its maximum water-carrying capacity at that temperature) are required for optimal airway functioning.<sup>2</sup> When

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inspired humidity is reduced, more heat and moisture are lost from the airway mucosa to the gas. A number of adverse effects of reduced inspired humidity on mucociliary function have been demonstrated, including decrease or cessation of ciliary function,<sup>3–5</sup> increased mucus viscosity,<sup>6</sup> and inflammation of the airway mucosa.<sup>7</sup>

Mucociliary dysfunction has been demonstrated in vivo with less than 30 min exposure to dry air.<sup>1</sup>

Noninvasive positive-pressure ventilation (NPPV) delivers inspired air at a very high flow. It has been suggested that this may compromise the airway's ability to adequately heat and humidify inspired air.<sup>8</sup> Despite its widespread use, there has been little examination of delivered humidity under NPPV. One case study reported inspissated secretions that caused life-threatening airway obstruction during NPPV with high-flow oxygen entrained, an adverse event that the authors attributed to inadequate humidification.<sup>9</sup> However, the level of humidity being delivered was not quantified. Consensus statements and guidelines for NPPV use contain conflicting recommendations regarding added humidification,<sup>10–12</sup> which reflects the paucity of published data.

Studies of the effects of nasal continuous positive airway pressure (CPAP) indicate that heated passover humidification can restore relative humidity to values similar to those of room air<sup>13</sup> and may enhance treatment adherence.<sup>14</sup> NPPV has a similar mode of delivery to CPAP, but NPPV has a wider range of adjustable ventilatory parameters, including inspiratory and expiratory pressure, respiratory rate, and inspiratory time. These factors influence delivered humidity during other forms of ventilation, both with and without a humidifier, because of variations in flow rate and changes in the time that air is exposed to water in the humidification chamber. Higher delivered pressure lowers relative and absolute humidity.<sup>15</sup> During mechanical ventilation, the effectiveness of a heated humidifier is reduced with high minute ventilation, high inspiratory flow, and increased inspiratory time.<sup>16–18</sup> The effects on humidification of altering these parameters during NPPV have not been evaluated.

The humidifier's temperature can be altered by raising or lowering the temperature of the humidifier's hot plate. Although it might be expected that the highest hot-plate setting will provide the most effective humidification, a variety of practices have been reported, with both medium<sup>19</sup> and maximum<sup>20</sup> heater settings. The optimal heated humidifier temperature during NPPV is unknown.

Some authors have expressed concern that heated passover humidifiers may impair ventilator performance.<sup>12</sup> During CPAP the delivered pressure was as much as 3.3 cm H<sub>2</sub>O lower with a heated passover humidifier.<sup>21</sup> The potential for such deleterious effects during NPPV needs to be evaluated.

The aims of this bench study were to determine the effects of NPPV on the relative and absolute humidity of delivered air over a range of ventilatory parameters, and to evaluate the effect of a heated passover humidifier on delivered humidity and pressure during NPPV.

## Methods

### Equipment

NPPV was provided with a bi-level positive-airway-pressure (BiPAP) ventilatory support device (BiPAP Synchrony, Respironics, Murrysville, Pennsylvania), which can deliver BiPAP in both spontaneous and timed modes and thus allows a set machine-generated respiratory rate. The BiPAP device was connected to a standard 180-cm length of smooth-bore tubing and a swivel exhalation port (Whisper, Respironics, Murrysville, Pennsylvania) that was capped at the patient end. This is a fixed-orifice exhalation port, with which the amount of leak flow through the orifice depends on the pressure in the circuit, providing a continuous leak that ranges from 14 L/min at 5 cm H<sub>2</sub>O to 30 L/min at 20 cm H<sub>2</sub>O. A disposable bacterial filter (Suregard, RJ and VK Bird, Melbourne, Victoria, Australia) was used between the tubing and the BiPAP device to replicate patient conditions. The technical specifications of this filter state that it is 99.72% effective at flows of up to 750 L/min and has a dead space of 50 mL.

The humidifier (HC100 with HC300 water chamber, Fisher and Paykel, Breakfast Creek, Australia) was connected in series with the BiPAP device, via a 60-cm length of smooth-bore tubing.

A T-piece connector was inserted between the tubing and exhalation port so that humidity and temperature could be measured at the point in the circuit where a patient mask would usually be inserted. Temperature and relative humidity were measured with a handheld humidity and dew-point meter and field calibrator (HMI41 with HMI45 probe, Vaisala, Helsinki, Finland), which has an accuracy of  $\pm 1\%$  for relative humidity of 0–90%,  $\pm 2\%$  for relative humidity of 90–100%, and temperature accuracy of  $\pm 0.3^\circ\text{C}$  in the range of 0–40°C. The response time (90%) of the HMI45 probe is 15 s at 20°C. Absolute humidity is calculated by the device, based on temperature and relative humidity measurements, according to the standard formula.<sup>22</sup> In accordance with the manufacturer's instructions, the probe was mounted horizontally to prevent condensation from dripping down the probe and saturating the sensor.

### Procedure

The study was conducted in an air-conditioned room without windows and with the door closed, to maintain constant environmental conditions. All measurements were conducted by the same investigator, over 3 days. Figure 1 shows the experimental setup.

We evaluated the effect on temperature and humidity of pressure level, respiratory rate, and inspiratory time. The following ventilatory settings were evaluated: inspiratory

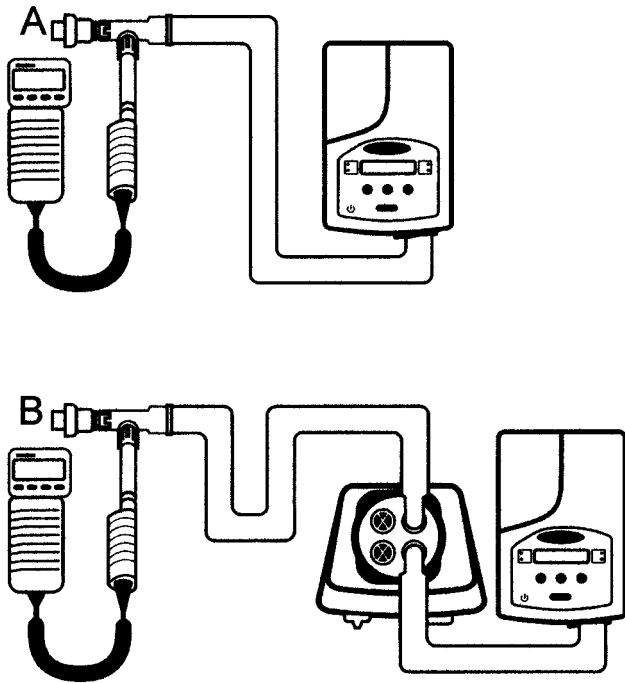


Fig. 1. Experimental setup (A) without humidifier and (B) with humidifier.

positive airway pressures (IPAP) of 10 cm H<sub>2</sub>O, 15 cm H<sub>2</sub>O, and 20 cm H<sub>2</sub>O; respiratory rates of 12 breaths/min and 24 breaths/min; and inspiratory-expiratory ratios of 1:2 and 1:3. Those values correspond to inspiratory times of 1.6 s and 1.25 s, respectively, at 12 breaths/min, and to 0.8 s and 0.6 s at 24 breaths/min. Expiratory positive airway pressure (EPAP) was maintained at 5 cm H<sub>2</sub>O throughout. The 12 possible combinations of these settings were studied 3 times each, in random order. Randomization was carried out with custom software, based on a pseudo-random-number generator.

Relative humidity, temperature, and absolute humidity were recorded every minute until steady state was achieved for each testing condition. Steady state was defined as consistency of readings over 5 consecutive minutes, such that relative humidity varied less than 2% and temperature varied by less than 0.3°C. Ambient temperature and relative humidity were recorded prior to each of the 12 conditions, prior to inserting the probe into the circuit.

We evaluated the effects of a heated humidifier on relative and absolute humidity and temperature after the measurements on room air, to ensure that the probe and the circuit remained completely dry throughout the room air condition. Measurements were obtained with the humidifier on a medium setting of 5 (H5, measured temperature range 23.3–24.9°C). The same 12 combinations of ventilatory settings were studied in random order. Steady state was determined as previously described. All 12 measurements were then repeated in random order, with the hu-

midifier on its maximum temperature setting of 9 (H9, measured temperature range 24.6–25.9°C).

A calibrated manometer was used to measure the maximum inspiratory and expiratory pressure delivered at each of the 12 ventilatory settings. Each setting was studied in random order on 2 occasions. Pressure was measured prior to the exhalation port, at the same point at which humidity measures were obtained. Measurements were obtained first without a humidifier in the circuit, and then repeated with the humidifier in the same configuration as previously described.

### Statistical Analyses

The data obtained were not normally distributed, and nonparametric statistics were used for all the analyses. The relationships between variables were assessed with Spearman's rho ( $r_s$ ). The differences between the room air, H5, and H9 conditions were examined with the Mann-Whitney U test or Kruskal-Wallis test. Pearson's chi-square test was used to determine the relationships between categorical variables. The significance level was set at  $p < 0.05$ . The data were analyzed with statistics software (SPSS 11.0, SPSS, Chicago, Illinois).

### Results

#### Effects of NPPV on Humidity and Temperature

Ambient relative humidity ranged from 27.6% to 31.5% on the testing days. In contrast, relative humidity during NPPV without humidification ranged from 16.3% to 26.5%. There was a weak but significant relationship between ambient relative humidity and circuit relative humidity during NPPV ( $r_s = 0.38$ ,  $p = 0.02$ ), which indicates a lower relative humidity during NPPV under conditions of low ambient relative humidity. Figure 2 shows the relationship of relative humidity to inspiratory pressure. Increasing the IPAP significantly decreased the relative humidity ( $r_s = -0.67$ ,  $p < 0.001$ ). Respiratory rate ( $r_s = -0.23$ ,  $p = 0.18$ ) and inspiratory time ( $r_s = -0.13$ ,  $p = 0.44$ ) had no significant effect on relative humidity.

Temperature measured prior to the exhalation port ranged from 23.9°C to 29.4°C, which exceeded ambient temperature at all ventilatory settings (ambient temperature range 21.6–22.8°C). Increasing IPAP was associated with increasing temperature ( $r_s = 0.88$ ,  $p < 0.001$ ). However, respiratory rate ( $r_s = 0.09$ ,  $p = 0.6$ ) and inspiratory time ( $r_s = 0.02$ ,  $p = 0.90$ ) had no effect on temperature during NPPV.

Absolute humidity measured prior to the exhalation port during NPPV was in the range 4.8–5.3 g/m<sup>3</sup>. There was a significant relationship between absolute humidity and ambient relative humidity ( $r_s = 0.70$ ,  $p < 0.001$ ). There was a trend toward reduced absolute humidity with increased IPAP ( $r_s = -0.32$ ,  $p = 0.05$ ), although absolute humidity

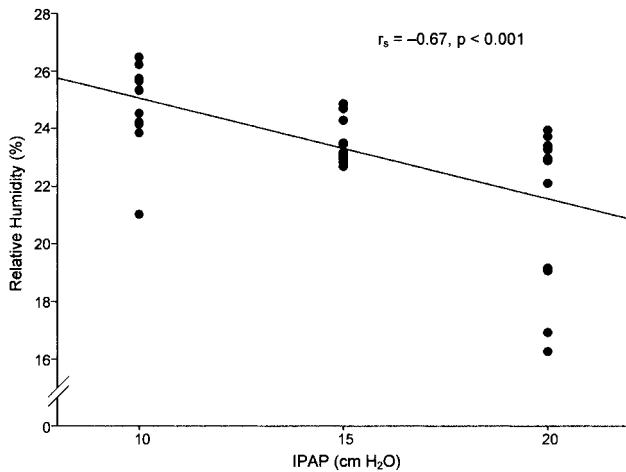


Fig. 2. Effect of inspiratory pressure on relative humidity during bi-level positive airway pressure. IPAP = inspiratory positive airway pressure.  $r_s$  = Spearman's rho.

was better preserved than relative humidity, because of the higher temperature with higher IPAP. Manipulation of respiratory rate ( $r_s = -0.05$ ,  $p = 0.79$ ) and inspiratory time ( $r_s = -0.04$ ,  $p = 0.82$ ) had no relationship to absolute humidity during NPPV.

**Effect of a Heated Passover Humidifier on Humidity During BiPAP**

The addition of a heated passover humidifier substantially increased the relative humidity of air delivered during NPPV (Fig. 3). Relative humidity was significantly higher with H5 than with room air ( $p < 0.001$ ), and there was a further increase in relative humidity from H5 to H9 ( $p < 0.001$ ). With the humidifier, increasing the IPAP still reduced the relative humidity, both at H5 ( $r_s = -0.48$ ,  $p = 0.003$ ) and at H9 ( $r_s = -0.572$ ,  $p < 0.001$ ); however, Figure 3 shows that the absolute magnitude of this effect was smaller at H9 than at H5. Increasing the IPAP was also associated with increased temperature at H5 ( $r_s = 0.85$ ,  $p < 0.001$ ), but there was no significant association between IPAP and temperature at H9 ( $r_s = 0.28$ ,  $p = 0.1$ ).

Respiratory rate had no effect on relative humidity at either H5 ( $r_s = 0.03$ ,  $p = 0.88$ ) or H9 ( $r_s = 0.06$ ,  $p = 0.71$ ). Likewise, inspiratory time did not affect relative humidity at either H5 ( $r_s = -0.61$ ,  $p = 0.72$ ) or H9 ( $r_s = 0.15$ ,  $p = 0.38$ ). Circuit relative humidity during NPPV was correlated with ambient relative humidity at H5, but no effect of ambient relative humidity was evident at H9 (Fig. 4).

Absolute humidity was increased by addition of the humidifier, with a greater effect at H9 (range 21.28–23.56  $g/m^3$ ) than at H5 (range 16.42–20.70  $g/m^3$ ,  $p < 0.001$  vs H9). There were no significant effects from inspiratory pressure, respiratory rate, or inspiratory time at H5 or H9. Ambient

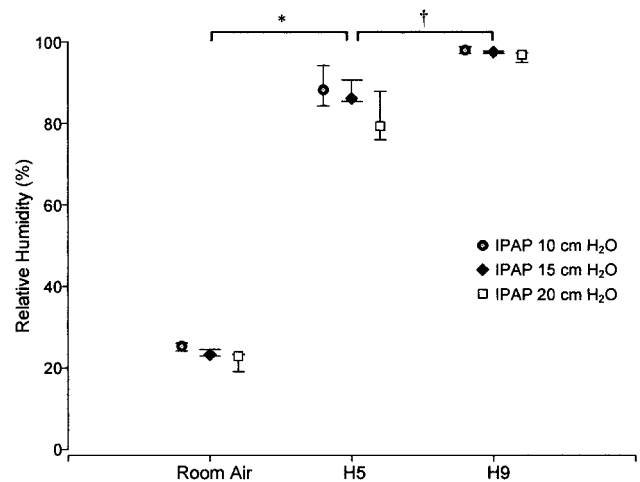


Fig. 3. Effect of heated passover humidification and inspiratory pressure on relative humidity during bi-level positive airway pressure. IPAP = inspiratory positive airway pressure. H5 = humidifier at medium heater setting. H9 = humidifier at maximum heater setting. The values are medians and interquartile ranges. \*  $p < 0.001$  for room air versus H5. †  $p < 0.001$  for H5 versus H9.

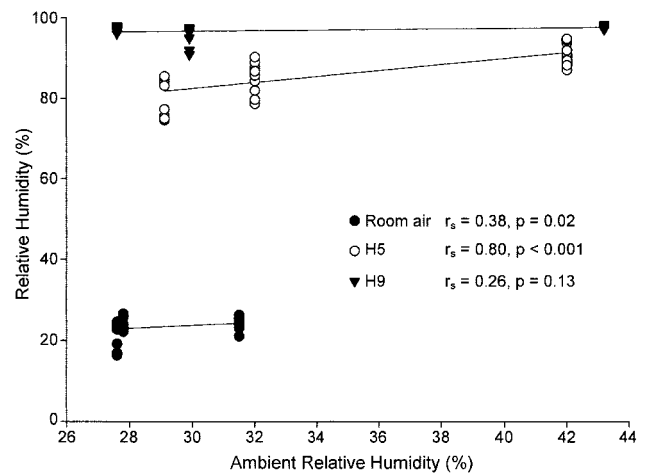


Fig. 4. Effect of ambient relative humidity on relative humidity in the delivered gas, with and without a heated humidifier. The values are individual measurements, with regression lines. H5 = humidifier at medium heater setting. H9 = humidifier at maximum heater setting.  $r_s$  = Spearman's rho.

relative humidity had a strong association with absolute humidity during H5 ( $r_s = 0.89$ ,  $p < 0.001$ ). There was a slight association between ambient relative humidity and absolute humidity at H9 ( $r_s = 0.45$ ,  $p = 0.006$ ), but the absolute magnitude of this association was very small, with absolute humidity ranging from 22.5  $g/m^3$  to 23.0  $g/m^3$ .

**Effect of a Heated Passover Humidifier on Delivered Pressure**

Without humidification, the measured IPAP was 1.0–2.0  $cm H_2O$  lower than the set IPAP. Greater pressure



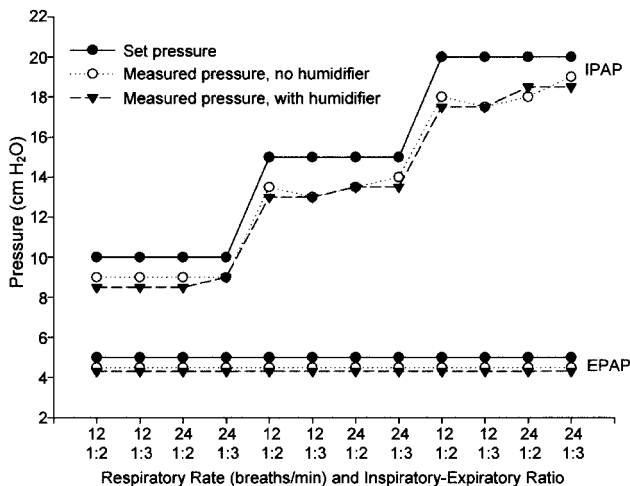


Fig. 5. Effect of a heated humidifier on delivered pressure. IPAP = inspiratory positive airway pressure. EPAP = expiratory positive airway pressure.

reductions occurred at higher IPAP (Fig. 5). Humidification further changed the measured IPAP, by  $-1.0$  cm H<sub>2</sub>O to  $0.5$  cm H<sub>2</sub>O, with a small mean pressure change of  $-0.25$  cm H<sub>2</sub>O. The measured EPAP without the humidifier was  $0.5$  cm H<sub>2</sub>O less than the set EPAP during all recordings. Addition of the humidifier did not change the measured EPAP. Neither respiratory rate nor inspiratory pressure had any effect on measured pressure, with or without the humidifier.

### Discussion

This bench study shows that NPPV delivers air with low absolute and relative humidity. This effect was most prominent with high inspiratory pressure, while respiratory rate and inspiratory time had no effect on delivered humidity. Addition of heated humidification markedly improved delivered humidity, and the most effective humidification was at the highest hot-plate setting. This humidification was achieved with little effect on delivered pressure.

Both relative and absolute humidity decreased with high IPAP, both with and without the humidifier. This is consistent with previous findings during CPAP, where an increase in pressure from  $5.1$  cm H<sub>2</sub>O to  $10.2$  cm H<sub>2</sub>O resulted in lower relative humidity and absolute humidity.<sup>15</sup> Those authors postulated that this was due to greater loss of warm humid air through the exhalation port with the greater flow required to generate higher pressure. The magnitude of this effect in the present study was larger than that reported during CPAP, probably due to the higher pressure and, therefore, higher flow.

No effect of either respiratory rate or inspiratory time on humidity was evident in this study, either with or without the humidifier. This is in contrast with previous bench

studies, in which increased minute ventilation and increased inspiratory time resulted in lower humidity during mechanical ventilation.<sup>17,18</sup> In those studies the 2 components of minute ventilation (tidal volume and respiratory rate) were not studied separately. In the light of the present results it seems likely that the effect of increased minute ventilation on relative humidity is due to increased tidal volume and, hence, higher flow rate. During NPPV, increased tidal volume is delivered by increasing IPAP,<sup>23</sup> and thus the finding of decreased humidity with increased IPAP is consistent with this aspect of the mechanical ventilation literature. Inspiratory times previously examined have been up to 2.5 seconds, and it was with the longer inspiratory times that humidity decrease was observed.<sup>18</sup> The lack of an effect of inspiratory time on humidity in the present study may be related to the shorter inspiratory times we used, which were thought to represent typical physiological values in patients with obstructive lung disease.<sup>24</sup>

The present study examined the impact of humidifier hot-plate setting on delivered humidity, the effects of which had not previously been reported. As might be expected, both relative and absolute humidity were significantly higher at H9 than at H5. At H9 the air was almost fully saturated (mean relative humidity of 97%), which is a level desirable for delivered air when a heated humidifier is used.<sup>2</sup> The H9 setting was also more effective in eliminating the drying effects of high pressure and low ambient relative humidity. The implication of this finding is that the highest hot-plate setting that can be tolerated by the patient will provide the most effective humidification. However, in clinical practice the effects of ambient conditions must also be considered: heated air leaving the chamber cools as it passes through unheated tubing to the patient, and condensation in the tubing may occur. As condensation interferes with both patient comfort and ventilator performance,<sup>21</sup> the room temperature should ideally be raised to prevent such effects. Where this is not possible, it may be necessary to reduce the hot-plate temperature to achieve a balance between the most effective humidification and ventilator performance.

A slight decrease in delivered pressure, of up to  $1$  cm H<sub>2</sub>O, was measured with the humidifier in the circuit, the magnitude of which is unlikely to be clinically important. This is in contrast to the results of Bacon and colleagues,<sup>21</sup> who found pressure reductions of up to  $3.3$  cm H<sub>2</sub>O with a cold passover humidifier during CPAP. The different humidification devices used may account for the differences in results, because humidifiers differ widely in their resistance to flow.<sup>16</sup> The results from the present study therefore cannot be extrapolated to other humidification devices. It is possible that heated humidification systems might have additional effects on ventilator performance in vivo, such as interference with inspiratory triggering

and expiratory cycling.<sup>12</sup> Such effects could not be examined in this bench study; therefore, care should continue to be taken that humidifiers do not interfere with NPPV performance.

The optimal level of humidification during NPPV is not known. Unlike during invasive ventilation, patients using NPPV have an intact upper airway and thus retain the ability to condition inspired gas. However, very high air flow and low humidity (as we found in this study), can overwhelm the airway mucosa's capacity to effectively warm and humidify the inspired gas to the level required for optimal mucociliary clearance and airway functioning. Many CPAP users experience symptoms of airway dryness.<sup>14,25,26</sup> An absolute humidity of  $< 10 \text{ g/m}^3$  is associated with upper-airway dryness in CPAP users.<sup>22</sup> The absolute humidity recorded during NPPV in this study was  $4.76\text{--}5.90 \text{ g/m}^3$ , which is well within the range expected to cause airway dryness symptoms. In contrast, the absolute humidities we recorded during heated humidification are close to those recommended for intubated or tracheostomized patients who do not have an intact upper airway,<sup>27</sup> especially at the highest heater setting, and are thus probably more than adequate for nonintubated patients. Previous authors have found that similar levels of absolute humidity are sufficient to eliminate symptoms of upper-airway dryness in CPAP users.<sup>14,19,28</sup>

It is a limitation of this study that it was not performed in vivo, and thus some care must be taken in extrapolating our results to the clinical setting. Expired gas contains higher levels of water than does room air because of incomplete moisture recovery by the airway during expiration,<sup>1</sup> and it is likely that during NPPV not all of this more humid air is lost through the exhalation port. At least some of this moisture may be available to inspired air, so higher humidity may be obtained prior to the exhalation port in vivo. However, in this present study both relative and absolute humidity were not dissimilar to those recorded during in vivo CPAP studies,<sup>13,22</sup> which confirmed that water recovery during expiration is insufficient to prevent symptoms associated with airway drying in human subjects.

### Conclusions

This bench study demonstrates that NPPV delivers air with low relative and absolute humidity, especially with high inspiratory pressure. These low humidities are known to cause symptoms of airway dryness in CPAP users. A heated passover humidifier can raise the humidity to the level associated with abolition of airway dryness symptoms in CPAP users. The highest hot-plate setting delivered the most effective humidification during NPPV. The effects of the tested humidifier on delivered pressure were small and probably not clinically important. These results

indicate that heated passover humidification may be an important addition to NPPV, especially where airway drying and secretion retention are of concern.

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