The Effects of Passive Humidifier Dead Space on Respiratory Variables in Paralyzed and Spontaneously Breathing Patients

Robert S Campbell RRT FAARC, Kenneth Davis Jr MD, Jay A Johannigman MD, and Richard D Branson RRT

BACKGROUND: Passive humidifiers have gained acceptance in the intensive care unit because of their low cost, simple operation, and elimination of condensate from the breathing circuit. However, the additional dead space of these devices may adversely affect respiratory function in certain patients. This study evaluates the effects of passive humidifier dead space on respiratory function. METHODS: Two groups of patients were studied. The first group consisted of patients recovering from acute lung injury and breathing spontaneously on pressure support ventilation. The second group consisted of patients who were receiving controlled mechanical ventilation and were chemically paralyzed following operative procedures. All patients used 3 humidification devices in random order for one hour each. The devices were a heated humidifier (HH), a hygroscopic heat and moisture exchanger (HHME) with a dead space of 28 mL, and a heat and moisture exchanger (HME) with a dead space of 90 mL. During each measurement period the following were recorded: tidal volume, minute volume, respiratory frequency, oxygen consumption, carbon dioxide production, ratio of dead space volume to tidal volume (V_D/V_T), and blood gases. In the second group, intrinsic positive end-expiratory pressure was also measured. RESULTS: Addition of either of the passive humidifiers was associated with increased V_D/V_T. In spontaneously breathing patients, V_D/V_T increased from 59 ± 13 (HH) to 62 ± 13 (HHME) to 68 ± 11% (HME) ($p < 0.05$). In these patients, constant alveolar ventilation was maintained as a result of increased respiratory frequency, from 22.1 ± 6.6 breaths/min (HH) to 24.5 ± 6.9 breaths/min (HHME) to 27.7 ± 7.4 breaths/min (HME) ($p < 0.05$), and increased minute volume, from 9.1 ± 3.5 L/min (HH) to 9.9 ± 3.6 L/min (HHME) to 11.7 ± 4.2 L/min (HME) ($p < 0.05$). There were no changes in blood gases or carbon dioxide production. In the paralyzed patient group, V_D/V_T increased from 54 ± 12% (HH) to 56 ± 10% (HHME) to 59 ± 11% (HME) ($p < 0.05$) and arterial partial pressure of carbon dioxide (P_{aCO_2}) increased from 43.2 ± 8.5 mm Hg (HH) to 43.9 ± 8.7 mm Hg (HHME) to 46.8 ± 11 mm Hg (HME) ($p < 0.05$). There were no changes in respiratory frequency, tidal volume, minute volume, carbon dioxide production, or intrinsic positive end-expiratory pressure. DISCUSSION: These findings suggest that use of passive humidifiers with increased dead space is associated with increased V_D/V_T. In spontaneously breathing patients this is associated with an increase in respiratory rate and minute volume to maintain constant alveolar ventilation. In paralyzed patients this is associated with a small but statistically significant increase in P_{aCO_2}. CONCLUSION: Clinicians should be aware that each type of passive humidifier has inherent dead space characteristics. Passive humidifiers with high dead space may negatively impact the respiratory function of spontaneously breathing patients or carbon dioxide retention in paralyzed patients. When choosing a passive humidifier, the device with the smallest dead space, but which meets the desired moisture output requirements, should be selected. [Respir Care 2000;45(3):306–312] *Key words: passive humidifier, dead space, respiratory function, mechanical ventilation, alveolar ventilation, humidification, respiratory equipment.*

Background

Humidification of inspired gases following tracheal intubation for mechanical ventilation is required to prevent the untoward effects of cool, dry gases on the tracheobronchial epithelium.[1–3] For nearly 4 decades, heated humidification has been the preferred method of conditioning inspired gases. In the past decade, passive humidifiers (PHs,

The authors are affiliated with the Department of Surgery, University of Cincinnati, Cincinnati, Ohio.

Correspondence: Robert S Campbell RRT FAARC, Department of Surgery, University of Cincinnati, 231 Bethesda Avenue, Cincinnati OH 45267-0558. E-mail: Robert.Campbell@UC.edu.

also known as "artificial noses") have gained some popularity because of their low cost and simple operation.[4,5] During introduction of PHs to our practice, we became concerned about the potential for increase in the work of breathing (WOB) due to the inherent flow resistance of the device.[6] This increased resistance was studied by others and found to have a small, clinically unimportant effect on respiratory function under normal conditions.[7–9] However, clinically important differences have been reported in the case of accumulated secretions or water in the PH.[10–11] More recently, several reports have shown that PH dead space may adversely affect respiratory mechanics, blood gases, and WOB.[12–14] We evaluated the effects of two PHs, one with a small dead space (28 mL) and one with a larger dead space (90 mL), on respiratory mechanics, lung volumes, and blood gases during spontaneous and controlled mechanical ventilation.

Materials and Methods

All patients were in the surgical intensive care unit at the University of Cincinnati. Informed consent was obtained from the patient or next of kin prior to study entry. Two groups of patients were studied. Group I consisted of 15 patients considered to be weaning from mechanical ventilation and who were receiving ≤ 5 cm H_2O positive end-expiratory pressure, fraction of inspired oxygen ≤ 0.50, and pressure support of 10 cm H_2O. All Group I patients were recovering from acute lung injury and breathing spontaneously at near minimal ventilatory support during the study. Group II consisted of 11 patients receiving controlled mechanical ventilation who were pharmacologically paralyzed and sedated following operative procedures.

Each patient used 3 humidification devices in random order for a period of one hour each. The devices included a heated humidifier (HH, an MR 730, Fisher & Paykel, Panmure, New Zealand), a hygroscopic heat and moisture exchanger (HHME, a Humid-Vent 2, Gibeck, Indianapolis, Indiana), and a heat and moisture exchanger (HME, an Extended Use HME, Mallinckrodt, Pleasanton, California). The HH was a passover device set to maintain proximal airway temperature at 34° C. A conventional (not a heated-wire) 60-inch breathing circuit (Hudson-RCI, Temecula, California) was used during all 3 study periods. The HHME and HME were placed between the endotracheal tube and circuit Y-piece. The HH was removed from the circuit when each PH was in use. The resistance of each device was measured at a constant flow of 1 L/s using a calibration analyzer (RT-200 Timeter Calibration Analyzer, Allied Health Care Products, St Louis, Missouri) prior to use. The dead space of each PH was measured according to International Organization for Standardization standard 9360.[4] Table 1 shows characteristics of the 3 devices.

Patients were maintained in the semi-Fowler's position throughout the study. All patients were ventilated using a Puritan-Bennett 7200ae ventilator (Mallinckrodt, Pleasanton, California), and ventilator settings remained constant during the study periods. Each ventilator used was up-to-date with regard to preventive maintenance schedules, and the flow and volume monitoring accuracy was assured within 10% prior to data collection. Pressure-triggering was used during the entire study period to eliminate bias flow in the breathing circuit, and the sensitivity was set to the lowest level that would not result in auto-triggering. All patients in Group II were ventilated using volume-controlled mandatory breaths. When a new humidification device was placed, a complete extended self test was performed to assure circuit integrity (eliminate leaks) and calculate circuit compressible volume. Airway pressures, volumes, and flows were measured using sensors integral to the ventilator. Data for these measurements were an average of the values obtained over the last 5 minutes of each one-hour period. Continuous measurements of oxygen consumption ($\dot{V}_{O_2}$) and carbon dioxide production ($\dot{V}_{CO_2}$) were accomplished using a commercially available, indirect calorimeter (Delta Trac, Sensormedics, Yorba Linda, California). The fraction of inspired oxygen was stabilized by using an inspiratory mixing chamber (MRM 250, Fisher & Paykel, Panmure, New Zealand),[15] and expiratory gases were collected from the expiratory port of the ventilator. The accuracy of the calorimeter is $\pm 3\%$ for $\dot{V}_{CO_2}$ and $\pm 7\%$ for $\dot{V}_{O_2}$.[16,17] Values for $\dot{V}_{O_2}$ and $\dot{V}_{CO_2}$ are based on an average of the last 10 minutes of each one-hour period. Mixed expired carbon dioxide ($P_{\bar{E}CO_2}$) was measured during the final 3 minutes of observation. During the final minute, an arterial blood gas sample was drawn and immediately analyzed for pH, P_{aO_2}, and P_{aCO_2}. Dead space to tidal volume ratio (V_D/V_T) was calculated using the Bohr equation:

$$V_D/V_T = \frac{P_{aCO_2} - P_{\bar{E}CO_2}}{P_{aCO_2}}$$

Table 1.   Characteristics of the Three Humidification Devices Used in the Study

Device	Resistance (cm H_2O/L/s)	Dead Space (mL)
Heated humidifier	0.47	N/A
HHME	1.5	28
HME	1.6	90

HHME = hygroscopic heat and moisture exchanger.
HME = heat and moisture exchanger.

Table 2. Patient Characteristics

	Group I ($n = 15$)	Group II ($n = 11$)
Age (years)	37 ± 12	54 ± 15
Gender (male/female)	9/6	8/3
Weight (kg)	86 ± 9	83 ± 12
Height (cm)	164 ± 18	152 ± 17
Duration of ventilation (days)	11 ± 3	1 ± 2

Dead space ventilation was calculated as the product of minute ventilation and V_D/V_T. Alveolar ventilation was calculated as the difference between minute ventilation and dead space ventilation. The ventilatory equivalents for oxygen and carbon dioxide were measured by dividing the minute ventilation by the $\dot{V}_{O_2}$ and $\dot{V}_{CO_2}$, respectively. In patients receiving controlled mechanical ventilation, intrinsic positive end-expiratory pressure ($PEEP_I$) was measured using the expiratory port occlusion technique.[18] $PEEP_I$ was measured twice, with 2–3 minutes between measurements. $PEEP_I$ was the last measurement to be accomplished at the end of each study period.

All data are reported as mean $\pm$ standard deviation. Data were compared using analysis of variance, and a $p < 0.05$ was considered significant.

Results

Table 1 shows the resistance and dead space characteristics of each humidification device. Table 2 shows patient characteristics.

Spontaneously Breathing Patients (Group I)

The addition of either an HHME or an HME increased respiratory frequency, compared to breathing via an HH. This increase in frequency was accompanied by increased V_T in the HME group. Minute ventilation, V_D/V_T, and the ventilatory equivalent of both oxygen and carbon dioxide were significantly greater with the HME than with the HH ($p < 0.05$). Alveolar ventilation remained constant during all 3 study periods. Although respiratory frequency, minute ventilation, and V_D/V_T were higher with HHME than with HH, the differences did not reach statistical significance. There were no changes in blood gases between study periods resulting from the humidification techniques employed. Figure 1 shows the relationship between minute ventilation, alveolar ventilation, and dead space volume in spontaneously breathing patients resulting from each humidification technique. All data for Group I patients are shown in Table 3 as mean $\pm$ standard deviation.

Table 3. Comparison of Ventilatory and Blood Gas Parameters in Spontaneously Breathing Patients, Using Three Humidification Devices

Variable	HH	HHME	HME
Frequency (breaths/min)	22.1 ± 6.6	24.5 ± 6.9	27.7 ± 7.4*
Tidal volume (mL)	411 ± 61	400 ± 52	428 ± 67†
Minute volume (L/min)	9.1 ± 3.5	9.9 ± 3.6	11.7 ± 4.2*
P_{aO_2} (mm Hg)	98.3 ± 31.4	93.9 ± 28.9	96.5 ± 33.4
P_{aCO_2} (mm Hg)	40.1 ± 8.6	41.7 ± 8.9	42.3 ± 7.5
$\dot{V}_{O_2}$ (mL/min)	300 ± 86	294 ± 85	300 ± 93
$\dot{V}_{CO_2}$ (mL/min)	261 ± 79	258 ± 77	259 ± 83
$\dot{V}_E/\dot{V}_{O_2}$ (L/L V_{O_2})	30.3 ± 6.8	33.7 ± 7.4	39.0 ± 8.6*
$\dot{V}_E/\dot{V}_{CO_2}$ (L/L V_{CO_2})	34.9 ± 6.9	38.4 ± 6.4	45.2 ± 7.6*
V_D/V_T (%)	59 ± 13	62 ± 13	68 ± 11*

HH = heated humidifier.
HHME = hygroscopic heat and moisture exchanger.
HME = heat and moisture exchanger.
P_{aO_2} = arterial partial pressure of oxygen.
P_{aCO_2} = arterial partial pressure of carbon dioxide.
$\dot{V}_{O_2}$ = oxygen consumption.
$\dot{V}_{CO_2}$ = carbon dioxide production.
$\dot{V}_E/\dot{V}_{O_2}$ = ratio of minute ventilation to oxygen consumption.
$\dot{V}_E/\dot{V}_{CO_2}$ = ratio of minute ventilation to carbon dioxide production.
V_D/V_T = ratio of dead space volume to tidal volume.
*$p < 0.05$ HH vs HME.
†$p < 0.05$ HME vs HHME.

Controlled Mechanical Ventilation Patients (Group II)

The addition of either an HHME or an HME increased both V_D/V_T and P_{aCO_2} and decreased alveolar ventilation, compared to HH, and the difference was statistically significant when comparing HH to HME ($p < 0.05$). There were no changes in P_{aO_2}. Figure 2 shows the relationship between minute ventilation, alveolar ventilation, and dead space volume in paralyzed patients receiving controlled mechanical ventilation, with each of the humidification techniques employed. By virtue of the study design, minute ventilation, frequency, and V_T remained constant between study periods. There were no differences in $PEEP_I$. All data for Group II patients are shown in Table 4 as mean $\pm$ standard deviation.

Discussion

Passive humidifiers have had growing acceptance in recent years because of their low cost, simple operation, and elimination of circuit condensate.[5] Concern over adverse ventilatory effects of PHs has predominately been aimed at the increased resistance imposed by the foam or paper insert.[9–11] Those studies, however, failed to show significant changes in the WOB associated with PH resistance, in the absence of partial occlusion by secretions,
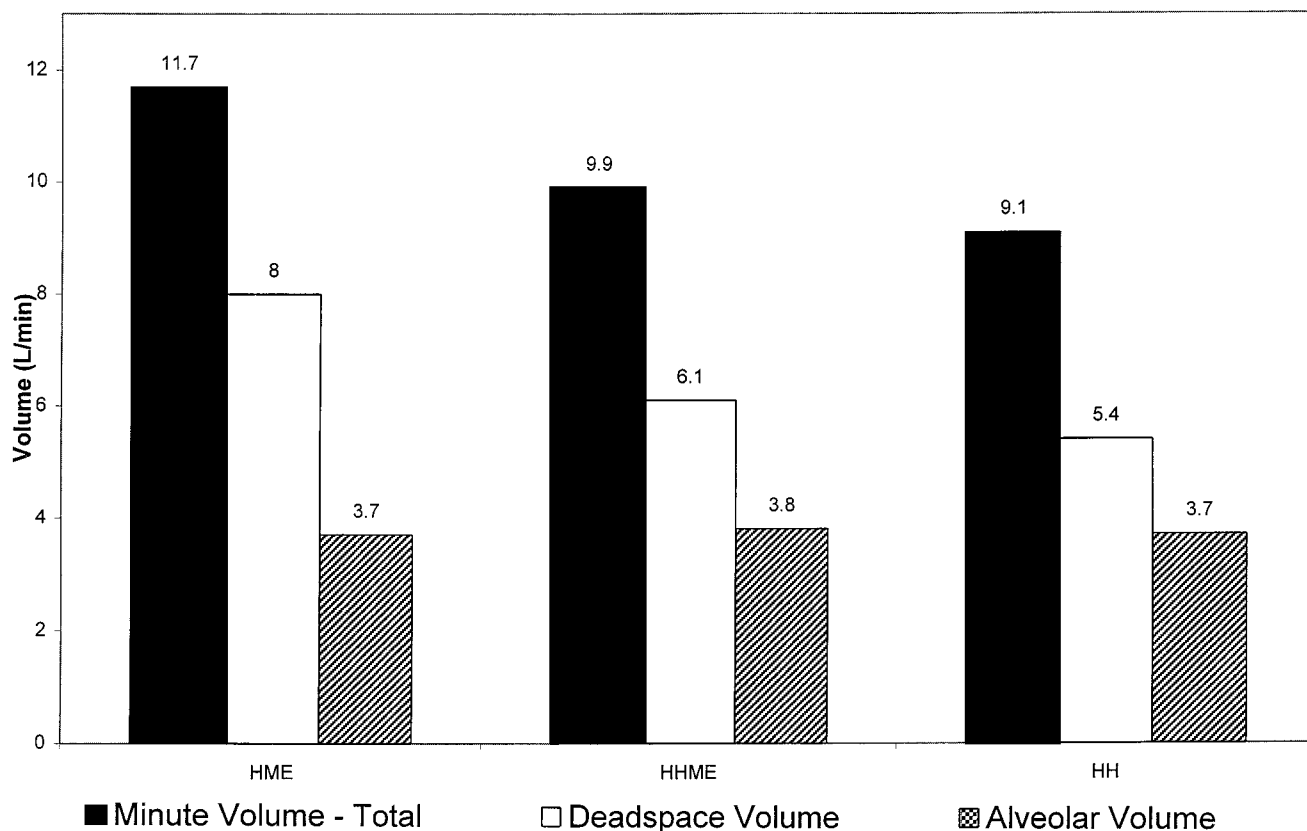
Fig. 1. Relationship between minute ventilation, dead space volume, and alveolar ventilation in spontaneously breathing patients, resulting from each humidification technique.

blood, or saline. More recently, PH dead space has been implicated as a source of ventilatory impairment.[12–14]

Our findings indicate that increasing PH dead space increases V_D/V_T. In spontaneously breathing patients, this requires increased minute ventilation to maintain constant alveolar ventilation and P_{aCO_2}. In our patients, this increase was mainly accomplished by increasing respiratory frequency. During controlled mechanical ventilation, the increase in V_D/V_T resulted in a small but statistically significant increase in P_{aCO_2}, indicating decreased alveolar ventilation. These findings are consistent with the work of Le Bourdelles et al,[12] Pelosi et al,[13] and Iotti et al.[14]

Pelosi et al compared the effects of two PHs on ventilatory mechanics and volumes in 14 patients ventilated using pressure support ventilation.[13] Characteristics of the HHMEs used in that study were: dead space 95 mL and resistance 1.9 cm H_2O/L/s, and dead space 65 mL and resistance 2.5 cm H_2O/L/s. All patients in that study were recovering from acute lung injury. They found that both HHMEs increased minute ventilation approximately 2.5 L/min over that seen with HH use.[13] These authors also found that patient WOB increased 66% with the larger HHME and 37% with the smaller HHME, compared to HH. Pelosi et al also noted that the pressure generated in

the first 100 milliseconds ($P_{0.1}$) of inspiration significantly increased during use of the HHMEs. During use of the large HHME, $P_{0.1}$ doubled, and during use of the small HHME, $P_{0.1}$ increased by 60%. Their findings indicate that the additional minute ventilation required to overcome the increased dead space significantly impacts patient WOB. In an effort to overcome the increased patient WOB, the authors increased the pressure support level. The use of pressure support returned WOB per breath to baseline values, but the WOB per minute remained elevated. The authors suggested that an additional 10 cm H_2O pressure support should eliminate the increased WOB caused by increased HHME dead space.[13]

Le Bourdelles et al compared blood gases and ventilatory volumes during ventilation using an HH and an HHME (dead space 75 mL). All patients in this study were spontaneously breathing on 10–15 cm H_2O pressure support. They found that during HHME use, minute ventilation increased from 8.1 ± 0.8 L/min to 9.3 ± 0.8 L/min, with V_T remaining constant and respiratory frequency increasing from 19 ± 2 breaths/min to 21 ± 2 breaths/min. They also found that, despite the increase in minute ventilation, P_{aCO_2} increased from 42 ± 2 mm Hg to 44 ± 2 mm Hg.[12] Le Bourdelles et al did not measure WOB, V_D/V_T, or
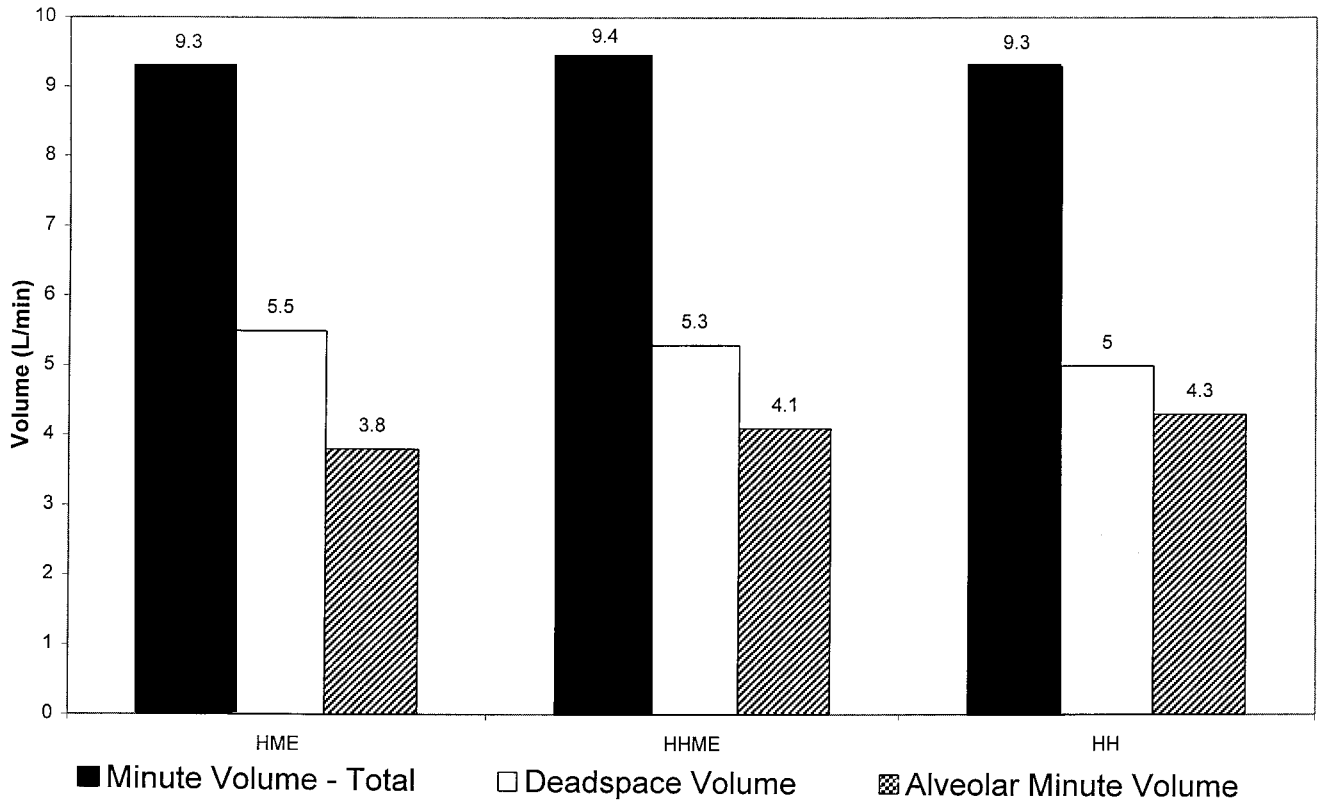
Fig. 2. Relationship between minute ventilation, dead space volume, and alveolar ventilation in paralyzed patients receiving controlled mechanical ventilation, resulting from each humidification technique.

V_{CO_2}. The authors suggested that, though in most patients the addition of HHME dead space is probably insignificant, patients with respiratory muscle fatigue could be negatively affected during weaning.

In a study very similar to ours, Iotti et al compared respiratory mechanics, blood gases, and respiratory volumes during use of an HH, an HHME with a flex tube (dead space 60 mL), and an HHME filter (HHMEF) with a dead space of 100 mL.[14] Unique to their study was use of a closed loop controller that automatically adjusted pressure support to maintain a constant $P_{0.1}$. Like our study, they measured V_D/V_T and calculated alveolar ventilation and dead space ventilation. They also measured WOB, airway resistance, $PEEP_I$, and lung compliance. During this study, minute ventilation increased from 10.6 ± 2.3 L during use of an HH, to 10.9 ± 1.6 L during use of an HHME, to 11.9 ± 1.6 L during use of an HHMEF.[14] They also noted a significantly increased total WOB per minute between devices. The total WOB (patient work and ventilator work) was 13.6 ± 8.6 j/min using the HH, 19.2 ± 9.1 j/min using the HHME, and 22.3 ± 9.9 j/min using the HHMEF. Because the closed loop controller increased and decreased pressure support to maintain constant $P_{0.1}$, patient WOB remained constant. Respiratory rate was unchanged, but the required pressure support level increased

from 13 cm H_2O (HH) to 15 cm H_2O (HHME) to 18 cm H_2O (HHMEF) in order to keep $P_{0.1}$ constant. The changes in minute ventilation and dead space ventilation observed by Iotti et al are similar to our results. In their study, alveolar ventilation was kept constant at the cost of a 2 L/min increase in minute volume when using the 100 mL dead space HHMEF. Our results, using an HME with 90 mL of dead space, averaged a 2.6 L/min increase in minute ventilation. In our patients, increased frequency led to higher minute ventilation, whereas in Iotti's patients the ventilator automatically adjusted the pressure support level in order to maintain constant $P_{0.1}$, thus utilizing V_T changes to increase minute ventilation. During constant pressure support, increasing frequency is easier for the patient than increasing V_T.[19]

Another interesting finding in Iotti's study relates to changes in expiratory resistance and total WOB. During use of the large HHMEF, expiratory resistance increased by 30%, yet the total inspiratory WOB increased by 60%. Although we did not measure in vivo airways resistance, no indication of significantly increased resistance could be associated with the HHME or HME, compared to HH, by measurement of peak inspiratory pressure, peak expiratory flow, or $PEEP_I$. We did not directly measure patient mechanical WOB, but indirect measures of patient work (ven-

Table 4. Comparison of Ventilatory and Blood Gas Parameters in Paralyzed Patients, Using Three Humidification Devices

Variable	HH	HHME	HME
Frequency (breaths/min)	11.7 ± 3.1	11.7 ± 3.1	11.7 ± 3.1
Tidal volume (mL)	794 ± 321	801 ± 322	791 ± 312
Minute volume (L/min)	9.3 ± 3.1	9.4 ± 3.2	9.3 ± 3.1
PIP (cm H_2O)	32.6 ± 7.4	32.6 ± 7.0	32.9 ± 7.1
P_{aO_2} (mm Hg)	104 ± 36	104 ± 31	96 ± 34
P_{aCO_2} (mm Hg)	43.2 ± 8.5	43.9 ± 8.7	$46.8 \pm 11.1*$
$\dot{V}_{O_2}$ (mL/min)	308 ± 87	310 ± 87	312 ± 83
$\dot{V}_{CO_2}$ (mL/min)	257 ± 60	254 ± 58	237 ± 57
$\dot{V}_E/\dot{V}_{O_2}$ (L/L V_{O_2})	30.2 ± 7.6	30.3 ± 7.9	29.8 ± 8.3
$\dot{V}_E/\dot{V}_{CO_2}$ (L/L V_{CO_2})	36.2 ± 7.1	37.0 ± 6.9	39.2 ± 7.6
V_D/V_T (%)	54 ± 12	56 ± 10	$59 \pm 11†$
PEEP	0.8 ± 0.4	1.0 ± 0.7	1.1 ± 0.5

HH = heated humidifier.
HHME = hygroscopic heat and moisture exchanger.
HME = heat and moisture exchanger.
PIP = peak inspiratory pressure.
P_{aO_2} = arterial partial pressure of oxygen.
P_{aCO_2} = arterial partial pressure of carbon dioxide.
$\dot{V}_{O_2}$ = oxygen consumption.
$\dot{V}_{CO_2}$ = carbon dioxide production.
$\dot{V}_E/\dot{V}_{O_2}$ = ratio of minute ventilation to oxygen consumption.
$\dot{V}_E/\dot{V}_{CO_2}$ = ratio of minute ventilation to carbon dioxide production.
V_D/V_T = ratio of dead space volume to tidal volume.
PEEP = positive end-expiratory pressure.
*p < 0.05 HME and HH vs HHME.
†p < 0.05 HH vs HME.

tilatory equivalent of oxygen and carbon dioxide) may reflect increased metabolic work and decreased efficiency of ventilation with use of the larger dead space PH in Group I (spontaneously breathing) patients, compared to HH.

Despite the fact that HME dead space appears to have the greatest effect on WOB, the resistance of these devices cannot be ignored. The literature conflicts with respect to the effects of PH resistance on respiratory function. Reported adverse effects include increased $PEEP_I$[13,14] and increased expiratory resistance.[10,14] The resistive components of PH use are well known.[6–11] Our initial in vitro analysis of an array of PHs was repeated by several authors using new devices and different techniques.[7–11,20] Normal resistance of a PH is 1.5–3.5 cm H_2O/L/s at 1 L/s. Compared to the resistance of the endotracheal tube, this resistance is relatively small. In fact, Chiaranda et al[7] and Johnson et al[8] found the resistive pressure of PHs clinically unimportant in the absence of secretion accumulation on the PH media. Manthous and Schmidt found that the resistive pressure of the Siemens 153 HHME doubled after 24 hours of use.[10] The Siemens 153 uses a sponge media, which can swell with added moisture, increasing resistance.[6]

Both Pelosi et al[13] and Iotti et al[14] reported increased $PEEP_I$, whereas we observed no $PEEP_I$ change in the current study. There are several reasons for this discrepancy. First, the PHs used in our study did not have filter media.

The devices used in the other studies all had filters, with the exception of the small HHME in the study by Iotti et al.[12–14] Therefore, the devices in our study posed less impediment to expiratory flow. Second, in the other studies, pressure support was increased to supplement V_T and maintain alveolar ventilation. In this instance, higher V_T coupled with increased expiratory resistance would have increased the risk of $PEEP_I$. Increased $PEEP_I$ may also lead to increased patient WOB, because ventilator triggering would become more difficult. Additionally, the patients in our study who had $PEEP_I$ measured were neuromuscularly blocked. In these patients, changes in frequency and inspiration-expiration ratio were not possible and exhalation was always passive.

The effect of $PEEP_I$ caused by PH resistance might be expected to impact respiratory function differently, depending on the presence of obstructive pulmonary disease. In a patient with chronic obstructive pulmonary disease, the additional resistance of a PH might counterbalance the intrinsic flow resistance (similar to pursed-lip breathing) and allow more complete emptying of the lung and thus no net change in end-expiratory alveolar pressure. In a patient with normal airways, any additional expiratory resistance may lead to a net increase in $PEEP_I$. In an earlier study of chronic obstructive pulmonary disease patients, Conti et al failed to find any increase in $PEEP_I$ in a group of patients with chronic obstructive pulmonary disease using an HHME.[21] This may explain the apparent contradiction.

Conclusions

In conclusion, our findings suggest that the increased dead space of a PH can negatively impact ventilatory function by increasing V_D/V_T. In spontaneously breathing patients, alveolar ventilation is maintained by increasing minute ventilation. Minute ventilation is increased by increasing respiratory frequency, which may result in increased WOB. The addition of 5–10 cm H_2O of pressure support may be helpful in normalizing patient WOB and breathing pattern during ventilation with a high dead space PH. In paralyzed patients, the additional dead space may reduce alveolar ventilation, increasing P_{aCO_2}. The effect of PH dead space may be exacerbated during ventilation at low V_T and with larger dead space PH devices. When choosing between available humidification devices, clinicians should consider dead space, in addition to the resistance and moisture output characteristics of each available PH.

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