Evaluation of Resistance in 8 Different Heat-and-Moisture Exchangers: Effects of Saturation and Flow Rate/Profile

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INTRODUCTION: When endotracheal intubation is required during ventilatory support, the physiologic mechanisms of heating and humidifying the inspired air related to the upper airways are bypassed. The task of conditioning the air can be partially accomplished by heat-and-moisture exchangers (HMEs). OBJECTIVES: To evaluate and compare with respect to imposed resistance, different types/models of HME: (1) dry versus saturated, (2) changing inspiratory flow rates. MATERIALS AND METHODS: Eight different HMEs were studied using a lung model system. The study was conducted initially by simulating spontaneous breathing, followed by connecting the system directly to a mechanical ventilator to provide pressure-support ventilation. RESULTS: None of the encountered values of resistance (0.5–3.6 cm H₂O/L/s) exceeded the limits stipulated by the previously described international standard for HMEs (International Standards Organization Draft International Standard 9360-2) (not to exceed 5.0 cm H₂O with a flow of 1.0 L/s, even when saturated). The hygroscopic HME had less resistance than other types, independent of the precondition status (dry or saturated) or the respiratory mode. The hygroscopic HME also had a lesser increase in resistance when saturated. The resistance of the HME was little affected by increases in flow, but saturation did increase resistance in the hydrophobic and hygroscopic/hydrophobic HME to levels that could be important at some clinical conditions. CONCLUSIONS: Resistance was little affected by saturation in hygroscopic models, when compared to the hydrophobic or hygroscopic/hydrophobic HME. Changes in inspiratory flow did not cause relevant alterations in resistance. Key words: heat-and-moisture exchangers, respiratory mechanics, resistance, mechanical ventilation. [Respir Care 2005;50(5):636–643. © 2005 Daedalus Enterprises]

Introduction

During spontaneous breathing, inspired air is warmed and humidified during passage through the nasal and oral cavities. The upper airways are responsible for the delivery of gas at approximately 32°C and a relative humidity of more than 90% to the lower respiratory tract at the tracheal carina. Upon reaching the alveolar level, inspired air is warmed to body temperature (about 37°C) and has achieved 100% saturation with water vapor. The point at which gases reach body temperature and full saturation is known as the isothermic saturation boundary. The isothermic saturation boundary can and does move up and down the respiratory tract as ambient conditions change or when there is a change in the patient’s disease state. When positive-pressure ventilation is delivered through oro/naso endotracheal intubation or via tracheostomy tube, the physiologic mechanisms of heating and humidifying the air related to the upper airways are bypassed. Dry gas delivery has been associated with damage to the tracheobronchial mucosa and undesirable clinical manifestations. So it is vital to precondition the inspired air in order to provide adequate heating and humidification.
Methods

A respiratory system analog (Fig. 1) was constructed, using a training test lung (model 1600, Michigan Instruments, Grand Rapids, Michigan) and a Bear lung model (Bear Medical Systems, Palm Springs, California). The training test lung has 2 compartments. We connected the first compartment to a Bear 1000 mechanical ventilator (Bear Medical Systems, Palm Springs, California), and the second compartment was displaced by the first compartment with the aid of a lift bar. The second compartment was connected to the Bear lung model, which is a bellows within a rigid box. In our analog, the bellows represents the lung, and the space between the rigid box and the bellows represents the pleural cavity.

There are no clear standards in mechanical models about the effort simulation that should be used. In a pilot study we tried to design efforts in order to obtain 3 different levels of airway occlusion pressure 0.1 s after the onset of inspiratory effort (P_{0.1}), to simulate normal and high demand situations. The arbitrary efforts that we used were based on the findings of this pilot study. The Bear ventilator was used to simulate 3 levels of inspiratory effort, by adjusting pressure levels and slopes in pressure control mode: effort 1 (E1): change in pressure (ΔP) = 18 cm H₂O and slope = −3; effort 2 (E2): ΔP = 22 cm H₂O and slope = 0; effort 3 (E3): ΔP = 26 cm H₂O and slope = +4. The effort levels were set to deliver normal P_{0.1} (3.3 cm H₂O), an effort above normal P_{0.1} (6.1 cm H₂O), and a high P_{0.1} (8.0 cm H₂O), respectively. To achieve these targets, the compliance of the first compartment of the training test lung was set at 54 mL/cm H₂O. The compliance of the second compartment of the training test lung, representing the thoracic cage, was set at 200 mL/cm H₂O, resulting in a respiratory system compliance of 60 mL/cm H₂O. Constant settings for each effort level were respiratory frequency 12 breaths/min, inspiratory time 1 s, and positive end-expiratory pressure 0 cm H₂O.

The testing region was a section of tubings/connectors that represented the airways. We added a resistive element (4.0 cm H₂O/L/s) to simulate resistance similar to that of a normal patient. Flow and pressure sensors were connected to the model immediately before and after the HME; the data were transmitted to a personal computer with an analogic-digital data-acquisition interface (PCI-MIO-16XE-50, National Instruments, Austin, Texas). In this same simulated airway segment, 8 different HMEs were sequentially tested. Our choice of HME was based on the most commonly used units in hospitals of our city (Table I) (Fig. 2). The study was initially conducted while simulating spontaneous ventilation, then the analog was connected to a mechanical ventilator (model 840, Nellcor Puritan Bennett, Carlsbad, California) to simulate pressure-support ventilation (PSV) set at 10 cm H₂O. Software developed in LabView (National Instruments, Austin, Texas) was used for the analysis. Using customized subprograms, we analyzed 10 cycles for each simulated condition in order to generate a “mean” cycle and to
calculate the imposed resistance due to the HME. Resistance was measured using the isovolume method, based on an analysis of transpulmonary pressure, flow, and volume information; points were chosen in both the inspiratory and expiratory phases of a respiratory cycle when lung volumes were identical and flow rates were about maximal. In the tidal range of volume-change, the elastic component of transpulmonary pressure is the same at these instants. Accordingly, the observed change in the pressure between these points relates solely to flow resistance. The ratio of this pressure change to the corresponding change in flow between these points has been calculated. This value represents an “average” flow resistance for inspiration and expiration.

After basal measurements were obtained from each HME still dry, the HMEs were connected to a nebulizer (micro mist nebulizer #1884, Hudson RCI, Temecula, California) that aerosolized 6.0 mL of 0.9% saline into the HME at a flow of 5.0 L/min O₂. The HMEs were then tested in this saturated state (our definition of saturated for this study). The saline aerosolization amount was empirically determined to obtain a wet weight for the HME similar to the weight attained after 24 hours of use in patients. This weight information was derived from samples of each of the studied HMEs used in different patients after 24 hours of use. These HMEs were then sealed and weighed in a high-precision analytic balance.

Results

Initially we performed repeated measurements under different respiratory mechanics situations with different HMEs, and our model showed excellent reproducibility, with a standard deviation for resistance at 0.019. The measured resistances would certainly be statistically different (p < 0.05) when they differed from each other in more than 2 times the standard error of the mean, based on a 95% confidence interval. Many comparisons were found to be statistically different, but their clinical importance will be considered in the discussion.

The resistance measures during spontaneous ventilation and PSV are shown in Tables 2 and 3. There are clear differences between control and HME, HME models, and between dry versus saturated conditions.

Although increases in efforts resulted in, at times, statistically significant increases (p < 0.05) in resistance, the magnitude of this increase reached a maximum value of 0.28 cm H₂O/L/s. Therefore, we chose to show only the medium effort (E2) in the next set of figures.

Figure 3 displays resistance during spontaneous ventilation in dry and saturated conditions. Figure 4 displays these values during PSV. We observed from these figures that the Portex, G2S, and HCH had lesser resistance levels, independent of their condition (dry or saturated), and there were smaller resistance differences between dry and saturated states. The Pall, Hygroster, Hygrobac S, G compact, and G light models had greater resistance when dry, and resistance increased after saturation. Among these HMEs, G light (both in spontaneous ventilation and PSV) and G compact (PSV) did not present a significant increase in resistance after saturation.

Figure 5 compares resistance of the dry HME when using spontaneous ventilation or PSV. Figure 6 makes the same comparison for the saturated state. We observed that the resistance of the HME had almost no variation with an increase in flow (during PSV), from a clinical point of view.

Discussion

HMEs have had growing acceptance in recent years because of their low cost, simplicity of use, reduction in...
circuit condensate, avoidance of an energy source, and in some HMEs, microbiological filtration. Several studies have been published that tested HME characteristics, employing the models of HME available at that time, under a range of conditions/techniques with the use of respiratory-system mechanical simulators.22–24,28,35,44

Adding an HME to the patient’s respiratory system does increase airway resistance15,23–26 and work of breathing15,22,25–30. This increase in resistance can be ignored in patients with normal lungs having low airway resistance that is clinically unimportant; therefore, an increase in resistance caused by an HME may not be a factor for patients with normal pulmonary parenchyma. But, theoretically, a resistance of 1.78 cm H2O/L/s (mean resistance found in our study) or of 3.60 cm H2O/L/s (maximum value of resistance found), could in some clinical settings, such as patients with chronic obstructive pulmonary disease, together with the intrinsically high resistance in the airways of these patients and the endotracheal-tube resistance, lead to increased WOB and to the development of dynamic hyperinflation.41

Previous studies stated that the international standard for the HME (International Standards Organization Draft International Standard 9360-2) has set a maximum increase of resistive pressure not to exceed 5.0 cm H2O with a flow of 1.0 L/s, even when saturated.24,33 The imposed resistance by an HME ranged, in our study, between 0.50 cm H2O/L/s (G2S dry, spontaneous ventilation, low effort) and 3.60 cm H2O/L/s (Hygrobac S saturated, spontaneous ventilation, high effort). None of our encountered values of resistance exceeded the limits stipulated by the international standard for the HME (International Standards Organization Draft International Standard 9360-2).

Table 2. Resistance Without HME (Control) and With 8 Different HMEs During Spontaneous Ventilation

<table>
<thead>
<tr>
<th>Inspiratory Effort</th>
<th>Control</th>
<th>Pall</th>
<th>Hygroster</th>
<th>Hygrobac S</th>
<th>Portex</th>
<th>G compact</th>
<th>G light</th>
<th>G2S</th>
<th>HCH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry</td>
<td>E1</td>
<td>0.283</td>
<td>2.157</td>
<td>2.314</td>
<td>2.005</td>
<td>0.964</td>
<td>2.325</td>
<td>1.710</td>
<td>0.793</td>
</tr>
<tr>
<td></td>
<td>E2</td>
<td>0.316</td>
<td>2.251</td>
<td>2.368</td>
<td>2.074</td>
<td>1.067</td>
<td>2.392</td>
<td>1.813</td>
<td>0.857</td>
</tr>
<tr>
<td></td>
<td>E3</td>
<td>0.345</td>
<td>2.336</td>
<td>2.417</td>
<td>2.141</td>
<td>1.161</td>
<td>2.453</td>
<td>1.908</td>
<td>0.915</td>
</tr>
<tr>
<td>Saturated</td>
<td>E1</td>
<td>NA</td>
<td>2.842</td>
<td>3.311</td>
<td>3.788</td>
<td>0.994</td>
<td>3.088</td>
<td>1.93</td>
<td>1.154</td>
</tr>
<tr>
<td></td>
<td>E2</td>
<td>NA</td>
<td>2.936</td>
<td>3.357</td>
<td>3.842</td>
<td>1.102</td>
<td>3.082</td>
<td>2.021</td>
<td>1.229</td>
</tr>
</tbody>
</table>

HME = heat-and-moisture exchanger
E1 = low effort
E2 = medium effort
E3 = high effort
NA = not applicable

Table 3. Resistance Without HME (Control) and With 8 Different HMEs During Pressure-Support Ventilation

<table>
<thead>
<tr>
<th>Inspiratory Effort</th>
<th>Control</th>
<th>Pall</th>
<th>Hygroster</th>
<th>Hygrobac S</th>
<th>Portex</th>
<th>G Compact</th>
<th>G Light</th>
<th>G2S</th>
<th>HCH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry</td>
<td>E1</td>
<td>0.365</td>
<td>2.392</td>
<td>2.475</td>
<td>2.196</td>
<td>1.216</td>
<td>2.499</td>
<td>2.004</td>
<td>0.996</td>
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<tr>
<td></td>
<td>E2</td>
<td>0.387</td>
<td>2.454</td>
<td>2.509</td>
<td>2.246</td>
<td>1.315</td>
<td>2.552</td>
<td>2.101</td>
<td>1.050</td>
</tr>
<tr>
<td></td>
<td>E3</td>
<td>0.405</td>
<td>2.498</td>
<td>2.537</td>
<td>2.293</td>
<td>1.387</td>
<td>2.598</td>
<td>2.173</td>
<td>1.092</td>
</tr>
<tr>
<td>Saturated</td>
<td>E1</td>
<td>NA</td>
<td>2.929</td>
<td>3.323</td>
<td>3.765</td>
<td>1.262</td>
<td>2.851</td>
<td>2.075</td>
<td>1.287</td>
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<tr>
<td></td>
<td>E2</td>
<td>NA</td>
<td>2.947</td>
<td>3.339</td>
<td>3.701</td>
<td>1.355</td>
<td>2.765</td>
<td>2.165</td>
<td>1.342</td>
</tr>
<tr>
<td></td>
<td>E3</td>
<td>NA</td>
<td>2.942</td>
<td>3.347</td>
<td>3.655</td>
<td>1.425</td>
<td>2.791</td>
<td>2.224</td>
<td>1.368</td>
</tr>
</tbody>
</table>

HME = heat-and-moisture exchanger
E1 = low effort
E2 = medium effort
E3 = high effort
NA = not applicable
Their recovering ability is dependent on materials within the HME, and there are 3 basic types of HME: hygroscopic, hydrophobic, and combined (hygroscopic-hydrophobic). The hygroscopic HMEs (HHME: Portex, G2S, and HCH) contain materials of low thermal conductivity, impregnated with a hygroscopic chemical. The hydrophobic HME (HMEF: Pall) has a larger surface area, because of pleating of the material. The HMEF has a substance covering the filter that prevents the water’s exodus during exhalation, and the HMEF serves as an efficient microbiologic filter as well. The combined HMEs (hygroscopic-hydrophobic) (HHMEF: Hygroster, Hygrobac S, G compact, and G light) have humidification properties and the bacterial-retention properties of the filter membrane. In the HHMEF, the hygroscopically-treated material is located between the patient’s airway and the filter.
classical groups of HMEs, in agreement with Thiéry et al.40

When we compared dry with saturated HMEs for each effort level and ventilation mode, we observed that the types/models of HME influenced the resistance measurements. The main factor is the hydrophobic membrane, because the HHME (without hydrophobic membrane) showed a distinct behavior compared to the others (HMEF, HHMEF), presenting less resistance in all situations and less effect on resistance when saturated.

The hydrophobic components seem to have an important role in causing higher resistance values. The HMEs with a hydrophobic membrane (HMEF and HHMEF) show an increase in resistance after saturation, although this phenomenon differed among models. Except for the G light, this increase in resistance ranged between 0.69 cm H2O/L/s and 1.80 cm H2O/L/s for the low effort during simulated spontaneous ventilation. In high-demand situations, this additional increase in resistance could cause iatrogenic increases in airway pressure. G light, although belonging to the HHMEFs, was the model that had the least resistance in this group when dry, and also exhibited a smaller increase when saturated in each ventilatory mode. When PSV was used, G compact also had little change in resistance when saturated.

As seen in the tables/figures, only by saturating an HME do we produce a significant increase in resistance. If secretions become entrapped inside the HME, this could lead to a significant further increase in resistance. Therefore, when an HME is in use and secretions become abundant, a heated humidifier should be used to replace the HME. Other studies have reported increases of resistance with the use of HME when they were filled with secretions,34 blood,36 or water.23

One of the limitations of our study was the use of saline to saturate the HME. Although we tried to simulate the weight-gain observed in patients, the saturation with saline may be different than the humidity exchange that happens in patients during the respiratory cycle. Thus, the magnitude of our results may not reflect exactly the clinical situation, although this consideration does not change the interpretation of our findings.

HMEF and HHMEF models displayed significant increases in resistance after saturation, but they had little increase in resistance due to increased inspiratory flow. Overall, we observed that HMEs had little variation in resistance in response to an increase in flow (when pressure support and/or higher efforts were used). Some studies23,35 have reported significant increases in resistance when flow was increased. In our study, although there was an increase in resistance as a function of flow, the magnitude of this increase was smaller than that observed in other studies and certainly of little clinical importance.

The fact that different HME models were used in our study can partially explain these findings.

In our study, the only objective was to analyze respiratory mechanics, and, based on our findings, HHMEs are slightly better suited for patients with disorders of respiratory mechanics, because they show low resistance when dry and little variation in resistance with saturation. It is important to remember, though, that other factors can influence the choice of an HME, such as humidification capacity and microbiological filter ability.

We must not forget that factors that increase resistance of the ventilator-patient circuit, like the endotracheal tube and/or the presence of humidification devices, are often neglected when respiratory system mechanics are determined. This lack of consideration can result in errors in therapy, such as a delay in weaning from mechanical ventilation.

Conclusions

1. None of the encountered values of resistance (dry or saturated HME) exceeded the limits stipulated by the international standard for the HME (International Standards Organization Draft International Standard 9360–2).

2. Among the HMEs we studied, the HHME had less effect on resistance, when compared to the HMEF and HHMEF models.

3. Changes in inspiratory flow did not cause relevant alterations in resistance. Saturation did, however, increase resistance, mainly in the HMEF and HHMEF models.

REFERENCES


10. Shelly MP, Lloyd GM, Park GR. A review of the mechanisms and
humidification techniques during mechanical ventilation: patient se-
lection, cost, and infection considerations. Respir Care 1996;41(9):
809–816.
12. Ricard JD, Le Miere E, Markowicz P, Lasry S, Saumnon G, Djejdaini
K, et al. Efficiency and safety of mechanical ventilation with a heat
and moisture exchanger changed only once a week. Am J Respir Crit
13. Barnes SD, Normoye DA. Failure of ventilation in an infant due to
increased resistance of a disposable heat and moisture exchanger.
14. Branson RD, Davis K Jr, Campbell RS, Johnson DJ, Porembka DT.
Humidification in the intensive care unit. Prospective study of a new
protocol utilizing heated humidification and a hygroscopic condenser
15. Iotti GA, Olivei MC, Palo A, Galbusera C, Veronesi R, Comelli A,
et al. Unfavorable mechanical effects of heat and moisture ex-
Core textbook of respiratory care practice. St Louis: Mosby; 1994:
441–484.
17. Kirton OC, DeHaven B, Morgan J, Morejon O, Civetta J. A pro-
spective, randomized comparison of an in-line heat moisture ex-
change filter and heated wire humidifiers: rates of ventilator-associated
early-onset (community-acquired) or late-onset (hospital-
acquired) pneumonia and incidence of endotracheal tube occlusion.
Chatburn RL, eds. Respiratory care equipment. Philadelphia: Lip-
of hygroscopic heat and moisture exchangers in intensive care pa-
20. Craven DE, Goularte TA, Make BJ. Contaminated condensate in
mechanical ventilator circuits. A risk factor for nosocomial pneumo-
Dreyfuss D. Comparison of the effects of heat and moisture exchang-
ers and heated humidifiers on ventilation and gas exchange during
1298.
gault PF, Eledjam JJ. Comparison of the effects of heat and moisture
exchangers and heated humidifiers on ventilation and gas exchange
1590–1594.
23. Morgan-Hughes NJ, Mills GH, Northwood D. Air flow resistance
of three heat and moisture exchanging filter designs under wet condi-
289–291.
24. Giarratana V, Monaco E, Vaccher E, Conti G, Faustini A, Conti G.
Use of heat and moisture exchanger (HME) filters in mechanically ventilated ICU patients: influence on airway flow-res-
al. Novel method of evaluation of three heat-moisture exchangers in
138–146.
26. Prasad KK, Chen L. Complications related to the use of a heat and
27. Loeser EA. Water-induced resistance in disposable respiratory-cir-
28. Buckley PM. Increase in resistance of in-line breathing filters in
moisture exchangers on ventilatory pattern and respiratory mechan-
ic in spontaneously breathing patients. Monaldi Arch Chest Dis
Ricard JD. Heat and moisture exchangers in mechanically ventilated
intensive care unit patients: a plea for an independent assessment of
in ventilator-dependent patients. In: Tobin MJ, ed. Principles and
Professions Division; 1998:553–596.
32. Frank NR, Mead J, Ferris Jr. BG. The mechanical behavior of the
1388.
744.
34. Eckerbom B, Lindholm CE. Performance evaluation of six heat and
moisture exchangers according to the Draft International Standard
35. Martin C, Papazian L, Perrin G, Gouin F. Performance
evaluation of three vaporizing humidifiers and two heat and moisture
exchangers in patients with minute ventilation
> 70 L/min. Chest
Effects of heat and moisture exchangers on minute ventilation, ven-
tilatory drive, and work of breathing during pressure-support venti-
1188.
Effects of heat and moisture exchangers on minute ventilation, ven-
tilatory drive, and work of breathing during pressure-support venti-
1188.
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1188.
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tilatory drive, and work of breathing during pressure-support venti-
1188.
Effects of heat and moisture exchangers on minute ventilation, ven-
tilatory drive, and work of breathing during pressure-support venti-
1188.
41. Pelosi P, Solca M, Ravagnan I, Tubiolo D, Ferrario L, Gattinoni L.
Effects of heat and moisture exchangers on minute ventilation, ven-
tilatory drive, and work of breathing during pressure-support venti-
1188.


