HEAT AND MOISTURE EXCHANGERS IN ARTIFICIAL VENTILATION

An Experimental Study of the Effect of Gas Leakage

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Humidification of inspired gases during spontaneous breathing and artificial ventilation is well established (Chamney, 1969; Boys and Howells, 1972; Weeks, 1975; Chalon et al., 1979, 1981) and a variety of humidifiers is available (Sara, 1965; Sara and Currie, 1965; Hayes and Robinson, 1970; Reynolds, 1974; Weeks, 1975; Hayes, 1978). A less expensive method is the use of heat and moisture exchangers (HME)—which conserve humidity (Toremalm, 1960; Mapleson, Morgan and Hillard, 1963; Shanks and Sara, 1973; Steward, 1976; Walker and Bethune, 1976; Oh, Thompson and Hayward, 1981; Weeks, 1981), possibly with fewer hazards than have been encountered with heated humidifiers (Klein and Graves, 1974; Bancroft, 1982), and with the advantage that electrical or gas power is not required for their operation. Although possible and actual drawbacks have been described (Buckley, 1984; DHSS, 1986), HME have become increasingly popular and have supplanted heated humidifiers in some instances (Bethune and Shelly, 1985). HME relying on condensation-evaporation alone have been evaluated (Walker and Bethune, 1976; Oh, Thompson and Hayward, 1981; Weeks, 1981; ECRI, 1983), as have others which have hygroscopic additives (Gedeon and Mebius, 1979; Revenas and Lindholm, 1979; Hay and Miller, 1982; Stoutenbeck, Miranda and Zandstra, 1982) and also one which is claimed to be hydrophobic (Bethune and Shelly, 1985).

The performance of HME is generally less flexible, and of a lower order of efficiency, than that of heated humidifiers. They have, nevertheless, been found satisfactory in clinical practice, even though their water output has been confirmed (Weeks and Ramsey, 1983; Ogino, Kopotic and Mannino, 1985) as being less than had formerly been thought necessary for adult patients (Editorial, 1979). Moreover, a recent report suggested that an adult HME modified for neonatal application was satisfactory in use (Duncan, 1985) and since then a purpose-designed neonatal HME has been introduced (ICOR AB, Sweden).

HME have been used with continuous positive airway pressure (CPAP) and positive end-expiratory pressure (PEEP), the latter often accompanying artificial ventilation in adults, children and neonates. During the artificial ventilation of neonates it is customary to use a tracheal tube the diameter of which is, by intention, smaller than that which would fit snugly at the level of the cricoid cartilage (Sweeney, Allen and Steven, 1973), in order to avoid trauma to the mucosa, local mucosal swelling and stenosis after removal (Allen and Steven, 1965, 1972; Stocks, 1966; Markham, Blackwood and Conn, 1967; Owen-Thomas, 1967; Abbott, 1968; Hatch, 1968).

We investigated the effect of the inevitable leak...
around the tracheal tube on the performance of
the HME by devising an investigation in which a
lung model was ventilated by intermittent positive
pressure ventilation (IPPV) at tidal volumes and
frequencies of ventilation encountered in clinical
practice. Leaks, which simulated those associated
with ventilation through a tracheal tube forming
an imperfect seal at the level of the cricoid carti-
lage, were permitted.

MATERIALS AND METHODS
The test apparatus was arranged as shown in
figure 1. A Barnet Mk III ventilator (Philips
Medical Ltd) was used to ventilate a Lung
Ventilator Function Analyser (LVFA) (Medi-
shield Limited) which was maintained at a
temperature of 37 °C by immersion in a water
bath. The gas inside the LVFA was humidified by
the addition of a small quantity of water before the
start of the tests, and saturation in the static
condition was confirmed by measurement before
and after each test. A flow splitting valve was
interposed between the HME and the LVFA to
separate the inspired and expired gas flows, as
described by Weeks (1974). Humidity and
temperature were measured continuously in the
inspiratory and expiratory limbs of the valve, by
hygrometers ("Si-grometer", Moisture Control
and Measurement Ltd) and Type K Cr/Al
thermocouples (Kane and May Ltd).

Previous work had confirmed the suitability of
the hygrometer for the measurement of breathing
system humidity (Tilling, Hancox and Hayes,
1983). The measurements represented the in-
spired and expired humidities and temperatures
in the test system.

The inflow and outflow gas streams were
separated in order to overcome the limitations
imposed by the response times of both humidity
and temperature sensors (Berger and Balko,
1973). The outputs from the temperature and
humidity sensors were taken to a microcomputer
(Commodore Business Machines Model 4032)

Fig. 1. Diagram of test apparatus showing lung ventilator function analyser (lung simulator) and the
positioning of the transducers in the flow splitting valve. To simulate a leak around the uncuffed tracheal
tube, a leak was introduced at the valve A.
EFFECT OF GAS LEAKAGE ON HME PERFORMANCE

TABLE I. Details of four tests in which a Lung Ventilator Function Analyser was ventilated through an adult Heat and Moisture Exchanger, without and with a leak between the two pieces of equipment

<table>
<thead>
<tr>
<th>Test</th>
<th>Frequency (b.p.m.)</th>
<th>Measured tidal volume (ml ± 2%) Before leak</th>
<th>Measured tidal volume (ml ± 2%) After leak</th>
<th>Leak (% ± 4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>25</td>
<td>54</td>
<td>40</td>
<td>25.9</td>
</tr>
<tr>
<td>2</td>
<td>25</td>
<td>195</td>
<td>168</td>
<td>13.8</td>
</tr>
<tr>
<td>3</td>
<td>25</td>
<td>226</td>
<td>184</td>
<td>18.5</td>
</tr>
<tr>
<td>4</td>
<td>25</td>
<td>460</td>
<td>405</td>
<td>11.9</td>
</tr>
</tbody>
</table>

Four tests were conducted with a leak between the HME and the LVFA. In each case the leak was introduced after 30 min and the test continued for a further 30 min. The ventilator settings are shown in table I. The errors quoted in the table are based on an uncertainty of ± 2% in the reading of the respirometer, as quoted in the manual supplied with the respirometer.

The variations in inspired and expired humidity with respect to time are displayed graphically in figures 2–5. The results, summarized in table II, show the mean values of humidity before and after the introduction of a leak. Each result is the mean (± 1 SD) of 60 readings.

RESULTS

The validity of using a lung model which does not maintain constant humidity in the expired gas under all conditions will be contested, but the matter can only be settled by making measurements on patients. The figure for energy loss in expired breath of normally breathing adults, published by Walker, Wells and Merrill (1961), was compared with the results of tests 1–4. In our model, the rate of energy loss in the expired breath was found by adding together the power passed to

![Expired humidity vs. time](image-url)

![Inspired humidity vs. time](image-url)

FIG. 2. Inspired and expired humidity with inspired tidal volume of 54 ml and a 25.9% leak at the tracheal tube after 30 min.

DISCUSSION

The variations in inspired and expired humidity with respect to time are displayed graphically in figures 2–5.
the HME and the power lost to the room (table III). Walker and colleagues quote a net loss from the respiratory tract of "about" 16.9 W, which is of an order comparable to the power losses measured in our tests of 2.24 W, 7.56 W, 8.89 W, 19.81 W for tests 1, 2, 3 and 4, respectively.

The tidal volume settings were chosen to cover the ranges expected in small paediatric, and adult, practice. The results in table II show that the standard deviation is greater after the introduction of a leak than previously. The reason is apparent in the continuous recordings of humidity. In all cases, whereas inspired humidity was constant for the first 30 min of test, it decreased steadily during

**Fig. 3.** Inspired and expired humidity with an inspired tidal volume of 195 ml and a 13.8% leak at the tracheal tube after 30 min.

**Fig. 4.** Inspired and expired humidity with inspired tidal volume of 226 ml and an 18.5% leak at the tracheal tube after 30 min.
EFFECT OF GAS LEAKAGE ON HME PERFORMANCE

Fig. 5. Inspired and expired humidity with inspired tidal volume of 460 ml and an 11.9% leak at the tracheal tube after 30 min.

TABLE II. Results: mean values of humidity before and after the introduction of a leak

<table>
<thead>
<tr>
<th>Test</th>
<th>Initial VT (ml)</th>
<th>Leak (%)</th>
<th>Mean inspired humidity (g m⁻³)</th>
<th>Mean expired humidity (g m⁻³)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Before leak</td>
<td>After leak</td>
</tr>
<tr>
<td>1</td>
<td>54</td>
<td>25.9</td>
<td>21.89 ± 0.2</td>
<td>19.09 ± 1.23</td>
</tr>
<tr>
<td>2</td>
<td>195</td>
<td>13.8</td>
<td>21.34 ± 0.23</td>
<td>14.95 ± 2.15</td>
</tr>
<tr>
<td>3</td>
<td>226</td>
<td>18.5</td>
<td>22.06 ± 0.31</td>
<td>15.11 ± 2.47</td>
</tr>
<tr>
<td>4</td>
<td>460</td>
<td>11.9</td>
<td>23.31 ± 0.61</td>
<td>19.82 ± 1.16</td>
</tr>
</tbody>
</table>

TABLE III. Rates of energy transfer (power) to the patient, the HME and the atmosphere, and losses to the HME and atmosphere expressed as percentage of total available power

<table>
<thead>
<tr>
<th>Test</th>
<th>Power to patient (W)</th>
<th>Power to HME (W)</th>
<th>Power loss to room (W)</th>
<th>Power losses (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>To room</td>
</tr>
<tr>
<td>1</td>
<td>1.9 ± 0.04</td>
<td>1.66 ± 0.04</td>
<td>0.58 ± 0.02</td>
<td>25.9 ± 1.6 -14.5 ± 2</td>
</tr>
<tr>
<td>2</td>
<td>5.87 ± 0.13</td>
<td>6.51 ± 0.15</td>
<td>1.05 ± 0.04</td>
<td>13.9 ± 0.9 9.8 ± 4</td>
</tr>
<tr>
<td>3</td>
<td>6.85 ± 0.15</td>
<td>7.24 ± 0.16</td>
<td>1.65 ± 0.07</td>
<td>18.6 ± 1.3 5.3 ± 4</td>
</tr>
<tr>
<td>4</td>
<td>15.84 ± 0.35</td>
<td>17.41 ± 0.40</td>
<td>2.40 ± 0.10</td>
<td>12.1 ± 0.8 9.0 ± 4</td>
</tr>
</tbody>
</table>

The largest leak in terms of proportion of initial tidal volume occurred in test 1; that is, with the smallest tidal volume (54 ml) selected. In this instance, there were only small decreases in values of inspired and expired humidity. The greatest decrease in humidity was obtained in tests 2 and 3 with tidal volumes of 195 ml and 226 ml, whereas the largest tidal volume (460 ml) pro-

the latter part of the test when the leak was present. Thus, it appears that when an HME is used instead of a conventional heated humidifier in a breathing system in which there is a gas leak around the tracheal tube, the inspired humidity is lower than would be expected from manufacturers' data or from the results of tests in which no leak has been simulated.
duced a relatively smaller decrease in inspired humidity on the introduction of a leak of some 12%.

The results demonstrate that a leak between the HME and the LVFA causes a decrease in the humidity of the inspired gases. In figures 2–5 the differences in humidity between the inspired and expired gases were related to the “efficiency” of the HME. The two characteristics diverge after the introduction of a leak—revealing decreasing efficiency.

In the case of the smallest tidal volume (54 ml), expired humidity was unaffected by the leak, even though the inspired humidity decreased. To explain this it is suggested that, with very small tidal volumes, the LVFA may be able to make good humidity and temperature losses from its own reserves; that is, water vapour has time to diffuse from within the LVFA and increase water vapour pressure of the incoming gas before it is expired. Therefore, the temperature and humidity of the expired gas remain unaltered (i.e. its specific energy—energy per unit volume is the same, see Appendix). With larger tidal volumes there is insufficient time for the LVFA to saturate the incoming gas. Therefore, expired gas humidity and temperature decrease, compounding the effects of lower energy release in the HME.

Table III shows the power (or rate of energy transfer) to the HME, that returning to the patient and that lost to the atmosphere. Values were calculated from the results (see Appendix) for humidity and temperature shown in table III, using well-established thermodynamic relationships (Goff and Gratch, 1946; Goff, 1949; Institution, 1973; Institute, 1975). The errors quoted are based on the combined random errors in temperature, humidity and flow measurements.

In this table, the power losses to the surrounding atmosphere and those in the HME are shown as percentages of the total available power. The large errors in these results are attributable to the small volumes being measured and the small differences between the tidal volumes measured before and after the introduction of the leak. The percentage power losses to the surroundings are the same as the percentage volume losses from the system.

An interesting result of test 1 (using the smallest tidal volume of 54 ml) was the return of more energy to the LVFA from the HME than was delivered from the LVFA to the HME. This can only be explained by assuming that energy from the surroundings was utilized by the HME or that an exothermic chemical reaction in the hygroscopic additive had a significant effect. In either case, this went some way towards offsetting the proportionally very large power loss to the surroundings in this test (25.91%), and to reducing the overall power loss to 11.4%. Thus, it may be inferred that, in different ambient conditions or when an HME with a hygroscopic additive is not being used, the power loss could be worse, thereby leading to a greater decrease in the humidity of the inspired gas. In the other three tests losses in the HME were additional to those resulting from leakage of gas. In the other three tests losses in the HME were additional to those resulting from leakage of gas. Tables II and III clearly demonstrate that the total power loss was related to the observed decrease in the humidity of the inspired gas. The largest decrease in the humidity of the inspiratory gas was seen in the results of tests 2 and 3 (table II), which had the highest total power loss (table III).

**CONCLUSION**

When an HME is included in a breathing system with an uncuffed tracheal tube and, especially, if the tube is substantially smaller than that permitted by the cricoid opening, the inspired humidity may be reduced. The results indicate that the magnitude of the reduction is affected by the proportion of the inspired volume which escapes from the tracheal leak and by changes in the inspired tidal volume. We suggest that ventilatory frequency, environmental conditions and the type of HME used (hygroscopic or non-hygroscopic) may also have important effects. More specific tests would be needed to establish mathematical correlations between any of these factors and the reduction of inspired humidity.

Calculations of power loss reveal that, in terms of energy loss from the patient, the effect of the leak around the tracheal tube is unimportant, amounting to between only 14% and 35% (i.e. power loss to room from table III, as a percentage of the total power loss in the expirate). However, the losses are superimposed on losses resulting from the donation of energy to inspired gases, if these are not supplied at the required energy level.

The principal effect of the energy loss by way of the leak is that on HME performance and, hence, on the humidity of the inspired gas. This, in turn, may be expected to cause greater energy loss from the respiratory mucosa than would otherwise be the case.
**APPENDIX**

An HME can only conserve as much of the patient's own heat and moisture as is delivered to it in the exhaled breath. It is convenient to think of this as the energy contained in the gas as a result of its moisture content and temperature. A gas with a given humidity and temperature has an energy content specified by that humidity and temperature which may be expressed in J/kg of gas, and this energy content, called enthalpy, can be calculated or obtained from tables. If a proportion of this energy bypasses the device (that is, if it passes directly to the atmosphere around the outside of the tracheal tube) then the energy which escapes is no longer available to be conserved.

The enthalpy is a measure of the total energy which is available in the gas. A substance has a certain finite amount of energy at any temperature including absolute zero, but in order to make calculations uniform the zero point (datum) of enthalpy is usually taken as 0 °C. Specific enthalpy \( h \) of a moist gas is equal to the sum of the enthalpy of the air and the enthalpy of the water vapour:

\[
h = ha + g.hg
\]

where \( h = \) total specific enthalpy (J kg\(^{-1}\)), \( ha = \) specific enthalpy dry air (J kg\(^{-1}\)), \( hg = \) specific enthalpy water vapour (J kg\(^{-1}\)), and \( g = \) moisture content of the air (kg kg\(^{-1}\)).

At constant pressure the enthalpy values are functions of the temperature of the air and water and these values can be found in tables or calculated (Institution, 1973).

The total energy of a given mass of gas is then easily calculated:

\[
E = h \times m
\]

where \( E = \) energy (J), \( h = \) specific enthalpy (J kg\(^{-1}\)) and \( m = \) mass of gas (kg), or from a given volume:

\[
E = h \times d \times v
\]

where \( h = \) specific enthalpy (J kg\(^{-1}\)), \( d = \) gas density (kg m\(^{-3}\)), and \( v = \) gas volume (m\(^3\)).

It is evident from examination of equations (2) and (3) that the total energy may be varied by adjusting the mass \( m \) or volume \( v \) while maintaining the specific enthalpy at a constant value.

Power loss (rate of energy transfer) is calculated:

\[
P = h \times v \times d
\]

where \( P = \) power (W), \( h = \) enthalpy (J kg\(^{-1}\)), \( v = \) volume flow (m\(^2\) s\(^{-1}\)) and \( d = \) density (kg m\(^{-3}\)).

**ACKNOWLEDGEMENTS**

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**REFERENCES**


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