Moisturizing and mechanical characteristics of a new counter-flow type heated humidifier

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Background. During mechanical ventilation effective conditioning of inspired air is important. In this respect, conventional humidifiers do not perform optimally. By design, a counter-flow-type humidifier should improve humidification and heating, but may increase resistance.

Methods. We investigated mechanical impedance and work of breathing (using pressure-flow characteristics and additional pressure–time product) of a new counter-flow-type humidifier, a conventional heated humidifier, and a passive heat and moisture exchanger (HME) in physical models of the respiratory system. We investigated moisturizing performance (amount of vaporized water at different air flows and ventilatory frequencies) of the two heated humidifiers. Ease of breathing through both heated humidifiers was investigated in 12 healthy volunteers blinded to the type of humidifier.

Results. Moisturizing performance of the conventional heated humidifier was flow-independent (approximately 32.5 mg vaporized water per breath at inspiratory flow rates of 30–120 litre min⁻¹, \(P > 0.05\)) but decreased (10%; \(P < 0.0001\)) with increasing ventilatory rates (12–20 min⁻¹). In contrast, moisturizing performance of the counter-flow-type humidifier (approximately 33.5 mg vaporized water per breath) was both flow- and rate-independent (\(P = 0.75\)). In addition, the counter-flow humidifier caused less physical work (approximately 25%) and resistance (approximately 50%) (both \(P < 0.05\)) than the other two devices. The passive HME displayed the least favourable mechanical characteristics. Ten of 12 volunteers felt breathing through the counter-flow humidifier easier than through the heated humidifier (\(P < 0.05\)).

Conclusion. Compared with a conventional humidifier, the new counter-flow-type humidifier displayed improved air conditioning and mechanical characteristics. Its lower resistance, particularly at low airflows, should be of clinical benefit during spontaneous breathing and triggered assisted ventilation.

**Keywords**: airway, resistance; equipment, heat and moisture exchanger; equipment, heated humidifiers; humidification, efficiency; ventilation, mechanical ventilation support

Accepted for publication: December 5, 2006

During mechanical ventilation with tracheal intubation, the upper airways no longer contribute to humidification and warming of the inspired air. This makes active humidification and heating of inspired air mandatory during mechanical ventilation to prevent functional and morphological injury of the ciliary cells of the tracheo-bronchial tree caused by desiccation.¹⁻³

In clinical practice, passive and heated humidifiers are used for this purpose. Passive humidifiers are of the heat and moisture exchanger (HME) type. Although this type of humidifier is relatively inexpensive and its application may reduce the incidence of ventilator-associated pneumonia,⁴ it does not reliably maintain temperature and humidity of inspired air at higher inspiratory flows,⁵⁻⁷ and it may increase ventilatory requirements, work of breathing, and intrinsic positive end-expiratory pressure by increasing inspiratory and expiratory resistance.⁸⁻⁹

Heated humidifiers have the advantage of maintaining temperature and humidity of the inspired air relatively constant over a wide range of inspiratory flows.¹⁰ Although
their technical design assures lower resistance to airflow than that of the passive humidifiers, they still exhibit a small but real respiratory load.\textsuperscript{10, 11} During demand-flow ventilatory support, the relatively small additional respiratory impedance is clinically negligible. However, spontaneously breathing critically ill patients may not be able to sufficiently increase their work of breathing to overcome even this relatively small additional respiratory load.

Conventional heated humidifiers use a heating plate to evaporate water (Fig. 1A). In contrast, a recently introduced heated humidifier uses the counter-flow principle to humidify air (Fig. 1B). The inner structure of this humidifier possesses a specially developed micro-structural surface, which is coated with water. This creates a large surface area that enhances adsorption of water by passing through air which, in turn, is expected to increase the efficacy of humidification. At the same time, the design is equally expected to increase resistance to airflow.

In this study, we compared the moisturizing and mechanical load characteristics of: (i) the new type humidifier working on the counter-flow principle, (ii) a conventional heated humidifier, and (iii) a passive humidifier. We hypothesized that the new type humidifier has (a) better moisturizing characteristics than the conventional heated humidifier and (b) better load characteristics than the passive humidifier, but not when compared with the conventional heated humidifier.

Methods

We studied the recently introduced counter-flow-type heated humidifier (HumiCare\textsuperscript{w} 200, Gründler, Freudenstadt, Germany), a conventional heated humidifier (MR850, Fisher & Paykel, Panmure, Auckland, New Zealand), and a passive humidifier (AQUA + FH, Teleflex Medical, Temecula, CA, USA).

Humidification performance

The moisturizing performance of both types of heated humidifiers was assessed in a physical lung model that was driven by a ventilator (Evita 2, Dräger Medical, Lübeck, Germany) (Fig. 2A). The lung model consists of two interconnected water-filled compartments. The first compartment is sealed; the second is open to atmosphere. During inspiration, pressure increases in the sealed compartment, which displaces water into the second compartment. The resulting difference in water level generates a hydrostatic pressure that drives expiration. This lung model was chosen because it is unaffected by humidity.

The two heated humidifiers were placed into the inspiratory limb of the respiratory circuit (Fig. 2A). Operating temperature of both humidifiers was 37°C. Inspiratory flow rates ($V_I$) of 30, 60, 90, and 120 litre min$^{-1}$ at ventilatory frequencies of 12 and 20 min$^{-1}$ were used. Tidal volume was kept constant at 700 ml. Every hour, the humidifier and its water-refilling tank were weighed using a precision balance (LP 62005, Sartorius AG Göttingen, Germany). The amount of water vaporized during the past hour was calculated as the difference between the momentary weight and that measured in the previous hour. Weight measurements were made three times for each of the four inspiratory flow rates resulting in 12 measurements per humidifier at each ventilatory frequency. The amount of vaporized water per breath was calculated by dividing the 1-h weight difference by the ventilatory frequency and measurement duration.

Physical work–pressure–time product (PTP)

The mechanical load of all three humidification devices was assessed by measurements of physical work and PTP. For this purpose, a ventilator (Evita 2) delivered...
continuous positive airway pressure (CPAP) of 5 cmH\textsubscript{2}O to an active lung model. As part of this model, a flow generator (LS4000, Draeger Medical, Lübeck, Germany) simulated the active muscle component of the respiratory system (Fig. 2B). To mimic spontaneous breathing, the flow generator was connected to a lung compliance model (ISO 5369/87\textsuperscript{12}) consisting of a rigid, non-distensible air chamber filled with copper–wool exhibiting a compliance of 54 ml cmH\textsubscript{2}O\textsuperscript{2}. To model a resistance, an antibacterial filter (Bact Trap, Pharma Systems AB, Knivsta, Sweden) was attached to the outlet of the lung model ($R = 2.05 \text{ mbar s litre}^{-1}$ at 60 litre min$^{-1}$, manufacturer’s information). The flow generator was set to deliver a sinusoidal flow pattern with a tidal volume of 700 ml at a rate of 24 min$^{-1}$. An identical rate was used for impedance measurements (see below). A pneumotachograph (Fleisch No. 2, Metabo, Epalinges, Switzerland) was placed between the CPAP-delivering system and lung model (Fig. 2B). The two active humidifiers were placed in the inspiratory limb, the passive humidifier distally to the Y-piece of the CPAP-delivering system.

Physical work ($w$) dissipated during the passage of air through a device during a single inspiration was calculated

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**Fig 2** (a) Experimental set-up for assessment of humidification performance of the heated humidifiers. A ventilator (Evita 2) delivered volume-controlled ventilation to a moisture-proof physical lung model. (b) Model used for measurements of work of breathing. A ventilator (Evita 2) delivered continuous positive pressure (CPAP). $R =$ bacterial filter. $V =$ Fleisch pneumotachograph. $P =$ pressure transducer. HME = heat and moisture exchanger. (c) Model used for measurements of mechanical impedance. The lung simulator delivered a sinusoidal flow. $V =$ Fleisch pneumotachograph. $P =$ pressure transducer. HME = heat and moisture exchanger.
by integrating the product of pressure \( (p) \) and flow \( (\dot{V}) \) over time:

\[
w = \int_{\text{Inspiration}} \Delta p \cdot \dot{V} \, dt \quad (1)
\]

Additional–PTP (PTP\text{add}) during a single inspiration was calculated by integrating the negative values of difference between CPAP and pressure at the model’s outlet over time:

\[
\text{PTP}_{\text{add}} = - \int_{\text{Inspiration}} (p - \text{CPAP})_{(>0)} \, dt \quad (2)
\]

When airway pressure decreases below CPAP as a result of the patient’s effort to overcome that part of the respiratory load that is not compensated for by the ventilator, the integral becomes negative. Thus, to obtain positive values, the term needs to be multiplied by \(-1\).

The pressure reduction across the humidifiers was measured using differential pressure transducers (1210A, ICSensors, Milpitas, CA, USA) at a sampling rate of 100 Hz. Before each measurement, the water reservoirs of the heated humidifiers were refilled, and the devices were heated to operating temperature. The passive humidifier was saturated with water by flushing it with humidified air at 60 litre \( \text{min}^{-1} \) for at least 45 min. Ten respiratory cycles were analysed for each condition. All measurements were repeated six times after complete dismantling and reassembling of the set-up.

**Mechanical impedance**

The lung simulator was used as a flow generator (Fig. 2c). It was set to deliver a sinusoidal flow pattern with a peak flow rate of 120 litre \( \text{min}^{-1} \) at a rate of 24 \( \text{min}^{-1} \), and was connected to the inspiratory port of the respective humidifier via a Fleisch pneumotachograph. To prevent aspiration of humidified air by the lung simulator, a one-way valve was placed between the pneumotachograph and flow generator. This valve assured the cyclic replenishment of the flow generator with ambient dry air. Pressure-flow characteristics of the heated humidifiers were analysed in the absence and presence of the tubing system recommended by the manufacturer. In case of the HME, we arbitrarily used the tubing of the counter-flow humidifier. Mechanical impedance of the humidifiers was determined by applying an expanded Rohrer’s equation\(^\text{13}\) that accounts for inertance:\(^\text{14}\)

\[
\Delta p = K_1 \cdot \dot{V} + K_2 \cdot \dot{V}^2 + I \cdot \ddot{V} \quad (3)
\]

where \( \Delta p \) is the pressure difference across the humidifier, \( K_1 \) and \( K_2 \) Rohrer’s coefficients, \( I \) inertance, \( \dot{V} \) flow and \( \ddot{V} \) volume acceleration. Dividing equation (3) by flow results in:

\[
R = \frac{\Delta p - I \cdot \ddot{V}}{\dot{V}} = K_1 + K_2 \cdot \dot{V} \quad (4)
\]

where \( R \) is the flow-dependent resistance. We used least squares fit to determine Rohrer’s coefficients \( K_1 \) and \( K_2 \), and \( I \) of the devices during the positive flow phase (inspiration phase). In addition, resistance at \( \dot{V} = 60 \text{ litre min}^{-1} \) (R1) was calculated.

**Perception**

To investigate whether differences in breathing resistance between the active humidifiers would be of clinical relevance, we performed a two-alternative forced-choice study in 12 healthy volunteers (female, \( n=5 \); male, \( n=7 \); age, mean 34 years, range 24–53 years; weight, mean 70 kg, range 55–95 kg; height, mean 177 cm, range 162–189 cm). None of the volunteers had a known history of lung disease or smoking, or were taking respiratory or cardiovascular medication. The study was approved by the local ethics committee, and informed written consent was obtained from each participant.

Subjects were instructed to breathe quietly through a mouthpiece, inhaling through the mouth but exhaling through the nose to avoid rebreathing of expired air. The mouthpiece was connected via a tubing system to one of the two heated humidifiers (referred to as ‘device A’ and ‘device B’). Identical tubing was used throughout. The sequence of testing was randomized, with the humidifier being tested first always referred to as ‘device A’. After a minute of undisturbed breathing, humidifiers were switched by connecting the distal part of the tubing system to the alternative humidifier. The humidifiers were switched three times. Before each switch, the subjects were told that there would now be a switch from ‘device A’ to ‘device B’ or vice versa. At the end of the trial, the subjects were asked whether breathing had felt easier or more difficult with device A or B. In accordance with the forced-choice technique, we did not offer the alternative ‘no difference’.

**Statistical analysis**

We used Student’s \( t \)-test and \textit{anova} with Fisher’s \textit{plsd} for \textit{post hoc} testing using StatView 5.01 software (SAS Institute, Cary, USA). For analysis of data from the subject study, we calculated the probability of the binomial distribution (Pearson–Neyman test). The number of volunteers was determined by means of an \textit{a priori} power analysis. Twelve subjects were required to achieve a power of 0.9. Statistical significance was assumed for \( P<0.05 \).
Results

Moisturizing performance

The amount of water vaporized per breath by the new counter-flow-type humidifier was independent of flow rate ($P=0.753$) and ventilatory frequency ($P=0.764$) (Table 1). The amount of water vaporized by the conventional humidifier was also independent of flow rate ($P=0.398$), but dependent on ventilatory frequency ($P<0.0001$). Whereas the amount of vaporized water was similar at a ventilatory frequency of 12 min$^{-1}$, at a higher ventilatory frequency of 20 min$^{-1}$, the new type humidifier vaporized 10–13% more water than the conventional humidifier ($P<0.0001$).

Work of breathing

The three humidifiers caused significantly different amounts of physical work (Fig. 3A). Compared with the counter-flow-type humidifier (HC200), physical work of the conventional heated (MR850) and the passive humidifier (HME) was higher by approximately 25 and 55%, respectively ($P<0.0001$ between all devices). PTP$\text{add}$ was similar between both types of heated humidifiers ($P=0.859$) (Fig. 3B), which was more than twice as low as that caused by the passive humidifier ($P<0.0001$).

Mechanical impedance

In the absence of any tubing system, all humidifiers displayed small and comparable inerties (I) (Table 2). Attachment of the respective dedicated tubing system increased inertia 10–12-fold. The assembled device (humidifier + tubing system) of the counter-flow humidifier displayed a 50% larger inertia than the conventional humidifier ($P<0.0001$) (Table 2).

At a flow rate of 60 litre min$^{-1}$, in the absence of any tubing, system resistances ($R$) varied between humidifiers by a factor of 2–5 (all differences $P<0.0001$), with the counter-flow humidifier (HC200) exhibiting the lowest and the passive humidifier (HME) the highest resistance (Table 2). Attachment of the dedicated tubing system increased resistance 1.5-fold (passive humidifier, HME), 2-fold (conventional humidifier, MR850), and 3.5-fold (counter-flow humidifier, HC200) (all increases $P<0.0001$). The resulting resistances of the assembled devices (humidifier + tubing system) were comparable between counter-flow and conventional humidifier, which, in turn, were approximately half that of the passive humidifier ($P<0.0001$).

Absolute resistance and the effect of adding a tubing system on resistance were clearly flow dependent (Fig. 4). Without or with tubing system attached, resistances of both heated humidifiers were lower at low flow rates (3 litre min$^{-1}$) than at high flow rates (90 litre min$^{-1}$) ($P<0.05$; Fig. 4). With no tubing system attached, increasing the flow rate from 3 to 90 litre min$^{-1}$ increased the resistance of both humidifiers by five- to seven-fold. At both flow rates, resistance of the counter-flow humidifier was approximately two times lower than that of the conventional humidifier ($P<0.05$). Depending on flow rate and type of humidifier, attachment of the tubing system increased resistances by two- to five-fold. However, whereas resistances of the assembled devices were comparable at the higher flow rate ($P=0.109$), at the low flow rate, resistance of the counter-flow humidifier was lower than that of the conventional humidifier by about 35% ($P=0.033$).

Table 1 Amount of vaporized water (mg) per respiratory cycle. Values are means (SD). HC200, counter-flow-type humidifier; MR850, conventional humidifier; $V_{I}$, inspiratory flow rate. *$P<0.0001$ vs ventilatory frequency of 12 min$^{-1}$.

<table>
<thead>
<tr>
<th>$V_{I}$ (litre min$^{-1}$)</th>
<th>Ventilatory frequency</th>
<th>HC200</th>
<th>MR850</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>12 min$^{-1}$</td>
<td>20 min$^{-1}$</td>
<td>12 min$^{-1}$</td>
</tr>
<tr>
<td>30</td>
<td>33.1 (0.1)</td>
<td>33.3 (0.6)</td>
<td>32.9 (1.0)</td>
</tr>
<tr>
<td>60</td>
<td>33.8 (0.8)</td>
<td>33.7 (0.2)</td>
<td>32.6 (0.3)</td>
</tr>
<tr>
<td>90</td>
<td>33.6 (0.8)</td>
<td>33.3 (0.3)</td>
<td>32.3 (0.1)</td>
</tr>
<tr>
<td>120</td>
<td>33.1 (0.5)</td>
<td>33.4 (0.2)</td>
<td>32.4 (0.2)</td>
</tr>
</tbody>
</table>

Fig 3 (A) Physical work exhibited by the counter-flow type (HC200), the conventional (MR850), and the passive humidifier (HME) during inspiration. Bars and whiskers are means (SD). *$P<0.001$ between all humidifiers. (B) Additional PTP ($\text{PTP}_{\text{add}}$) produced by the humidifiers during inspiration. Bars and whiskers are means (SD). #$P<0.05$ passive humidifier (HME) compared with both heated humidifiers (HC200 and MR850).
Volunteer study

Ten of the 12 blinded volunteers rated breathing through the counter-flow humidifier easier compared with the conventional humidifier ($P=0.019$).

Discussion

The main findings of this investigation can be summarized as follows: (a) the new counter-flow-type heated humidifier showed better moisturizing and mechanical characteristics than the conventional active humidifier; (b) the superior humidification characteristics of the counter-flow-type humidifier were independent of flow and ventilatory frequency and (c) airflow resistance and physical work varied with the type of humidifier and flow rate. These results confirm our hypothesis that the new type humidifier has better moisturizing characteristics than the conventional heated humidifier and better load characteristics than the passive humidifier. However, as resistance at low flow rates with the attached tubing system and physical work of the counter-flow humidifier were lower than that of the conventional humidifier, the results do not confirm our hypothesis that load characteristics of the counter-flow humidifier would be inferior to that of the conventional heated humidifier.

Although the passive humidifier exhibited lower resistances than the previously reported, they were still the highest of the three devices, resulting in the highest physical work during inspiration. Of the two heated humidifiers, with no tubing the new counter-flow type demonstrated a significantly lower resistance. However, after attachment of dedicated tubing systems, total resistances were comparable. The larger per cent increase in resistance of the new type humidifier in response to the tubing attachment was caused by different tube geometries. While the tubing dedicated to the conventional humidifier was 150 cm long and had an inner diameter of approximately 22 mm, the tubing dedicated to the new type humidifier was 165 cm long and had an inner diameter of approximately 16 mm.

Despite the relatively larger increase in resistance in response to the attachment of the tubing, the new type humidifier exhibited advantages of potential clinical relevance over the conventional one. Most importantly, resistance was two times smaller at low flow rates. Such low flow rates characterize the beginning of inspiration and the triggering of the ventilator. This superior pressure-flow characteristic of the counter-flow-type humidifier should thus be of benefit in all situations of non-supported spontaneous breathing (including home care ventilation).

![Fig 4](image-url)

**Table 2** Inertance ($I$) and resistance ($R$) at a flow of 60 litre min$^{-1}$. Values are means (SD). HC200, counter-flow-type humidifier; MR850, conventional humidifier; HME, passive humidifier; −, absent tubing system; +, present tubing system. *$P<0.0001$ compared with no tubing system. **$P<0.0001$ between all groups.

<table>
<thead>
<tr>
<th>Device</th>
<th>Tubing system</th>
<th>$I$ (cm H$_2$O $s^2$ litre$^{-1}$)</th>
<th>$R$ (cm H$_2$O s litre$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HC200</td>
<td>−</td>
<td>0.006 (0.0018)</td>
<td>0.340 (0.077)$^*$</td>
</tr>
<tr>
<td>HC200</td>
<td>+</td>
<td>0.075 (0.0025)**</td>
<td>1.258 (0.087)$^*$</td>
</tr>
<tr>
<td>MR850</td>
<td>−</td>
<td>0.005 (0.0030)</td>
<td>0.664 (0.027)$^*$</td>
</tr>
<tr>
<td>MR850</td>
<td>+</td>
<td>0.048 (0.0021)**</td>
<td>1.444 (0.033)$^*$</td>
</tr>
<tr>
<td>HME</td>
<td>−</td>
<td>0.008 (0.0017)</td>
<td>1.770 (0.036)$^*$</td>
</tr>
<tr>
<td>HME</td>
<td>+</td>
<td>0.082 (0.0019)**</td>
<td>2.558 (0.019)$^*$</td>
</tr>
</tbody>
</table>
The passive humidifier exhibited the highest resistive load. In contrast to active humidifiers, gas passes through passive humidifiers not only during inspiration but also during expiration increasing resistive loads equally during both phases. Because of its position, distally of the Y-piece, this extra respiratory load cannot be compensated for by ventilatory support, resulting in a larger respiratory load compared with active humidifiers. It has been suggested to use higher inspiratory pressures to compensate for the additional work of breathing caused by passive humidifiers. However, this approach eliminates neither the problem of increased work of breathing during expiration nor that of intrinsic PEEP caused by the high expiratory resistance.

In contrast, the load of both heated humidifiers was partly compensated for by the demand-flow CPAP system as reflected by lower additional PTPs. Between both heated humidifiers, the additional PTPs were comparable despite different impedances. However, without demand-flow support (e.g. when using a passive PEEP valve or in case of pressure measurement in the inspiratory branch of the respiratory system), the additional load of the device cannot be compensated for. In such a case, the higher physical work caused by the conventional humidifier will require a correspondingly larger patient effort compared with using a counter-flow type humidifier. Whereas the healthy patient is likely to be able to generate this additional work of breathing, the critically ill patient and infants and children may fail to do so. In this regard, the new counter-flow-type humidifier clearly performs better.

Our healthy volunteers blinded to the type of heated humidifier rated the resistive load of the new type humidifier lower than that of the conventional humidifier. As we studied healthy, awake volunteers breathing through a mouthpiece, the results are not necessarily applicable to the clinical setting of critically ill unconscious patients breathing through a tracheal tube. Nevertheless, the finding in human volunteers is consistent with that of our in vitro investigation. In addition, tracheotomized patients responded similarly to an extra respiratory load as subjects breathing through a mouthpiece. This combined evidence would thus suggest that the reduced resistance of the new type humidifier may be clinically relevant.

The optimal degree of humidification has not been established. However, as there is evidence that a relative humidity of 100% should be targeted, maximal vaporization of water appears to be indicated, provided supersaturation and transport of droplets are avoided. At times, active humidifiers fail to deliver adequate humidification because of malfunctioning, poor temperature control, or simply omission to refill.

In summary, the new active humidifier functioning on the counter-flow principle demonstrated better humidification and mechanical characteristics compared with the conventional humidifier, independent of flow and ventilatory frequency. A difference in resistance was perceived by blinded human volunteers. As long as active humidifiers are incorporated in a compensating ventilatory support mode, the difference in load characteristics is likely to be clinically irrelevant. However, in all situations of non-supported spontaneous ventilation (such as in home care ventilators), the new design heated humidifier is expected to be of benefit.

Acknowledgement

The authors thank Michael Schuh for his support in performing the measurements. This work was supported by the Deutsche Forschungsgemeinschaft (DFG), Grant No. GU 561/6–1.

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