RESISTANCE OF HUMIDIFIERS, AND INSPIRATORY WORK IMPOSED BY A VENTILATOR-HUMIDIFIER CIRCUIT

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SUMMARY
The pressures and resistances of a bubble humidifier (Bennett Cascade) and a blow-by humidifier (Fisher and Paykel) were measured and computed at gas flow rates from 4.5 to 100 litre min$^{-1}$. Pressures increased with flows, with the Bennett pressures being greater at all flows. The resistance of the Fisher-Paykel increased with flows, but remained less than that of the Bennett. An inverse resistance-flow relationship was seen with the Bennett up to a flow of 35 litre min$^{-1}$. The work of breathing through a Servo 900C ventilator-humidifier circuit was computed, using a lung model. Work was performed by the Servo 900C on the lung, especially with the Fisher-Paykel circuit. The Bennett circuit required considerably greater (3.7 times more) inspiratory work. Thus the Bennett Cascade humidifier may present an unacceptable inspiratory load during spontaneous breathing.

KEY WORDS
Airway, resistance to breathing. Equipment. humidifiers

The need for airway humidification in long-term mechanical ventilation is unquestioned. Heated water reservoir humidifiers are used in ventilator circuits to provide water vapour with little or no aerosol. There are two basic types of heated humidifiers: bubble or cascade, and pass-over or blow-by [1]. In bubble humidifiers, gas is dispersed through heated water, whereas in blow-by humidifiers, gas passes over the water surface. The Bennett Cascade (Bennett Medical Equipment, U.S.A.) and the Fisher-Paykel humidifiers (Fisher and Paykel Medical, New Zealand) are the most commonly used heated bubble and blow-by heated humidifiers, respectively.

It is recognized that successful weaning from mechanical ventilation may be determined by the heavy inspiratory load of some breathing systems [2, 3], but there is little published literature on the contribution of humidifiers to the work of spontaneous breathing. This study was undertaken to compare the flow resistances of the Bennett Cascade and Fisher-Paykel humidifiers, and the inspiratory work of a ventilator circuit with each humidifier.

MATERIALS AND METHODS
The resistances of a Bennett Cascade humidifier and a Fisher-Paykel humidifier (MR 500) were studied under constant flow conditions. Both humidifiers were filled with water, but remained unheated. Wall source air was passed into the inlet hose of each humidifier via a RT-200 Calibration Analyzer (Timeter Instrument Corp., PA, U.S.A.). The gas flow rate was set successively at 4.5, 7, 10, 15 and 20 litre min$^{-1}$, and thereafter at 10-litre min$^{-1}$ increments to a maximum of 100 litre min$^{-1}$. At each constant gas flow rate, pressures were measured at both the inlet and outlet, using a differential strain gauge pressure transducer (Motorola MPX 10DP). Resistive pressure at each flow rate was given by the pressure decrease. Three sets of pressure and flow measurements were recorded with each humidifier. With the Fisher-Paykel circuit, a new disposable water chamber was used for each set of measurements.

Work of breathing was studied using a Servo 900C ventilator (Siemens Elema, Sweden). The Servo 900C was set to cater for spontaneous breathing (continuous positive airway pressure...
RESISTANCE AND WORK OF HUMIDIFIERS

Modified Cape ventilator (TC50)

Gould oscilloscope recorder

Pressure-flow transducers

Humidifier

Servo 900C ventilator

Fig. 1. Schematic diagram of model lung to simulate spontaneous breathing. The Servo 900C ventilator was set to the "CPAP" mode.

(CPAP) mode), with a triggering sensitivity marginally greater than 0 cm H₂O. Spontaneous ventilation was simulated using a modified Cape TC 50 ventilator (Cape Engineering, England), adjusted to simulate a tidal volume of 600 ml at a rate of 15 b.p.m. and with a peak inspiratory flow of about 45 litre min⁻¹ (fig. 1). Airway pressures and flows were measured at the patient airway, using a strain gauge pressure transducer (Motorola MPX 10DP) and a platinum hot wire flow transducer (Ohmeda SE 302T). The pressure and flow transducers were calibrated with the RT-200 Calibration Analyzer. Simultaneous pressure and flow signals were digitized at a rate of 200 s⁻¹ and recorded and displayed on an oscilloscope (Gould DSO 1604).

Work of breathing imposed by the whole breathing system was derived from the pressure-flow values. The product of pressure (P) and flow (V) gives instantaneous power (W) at that moment. Power over a defined time interval (T₀–T₁) is given by integration of P. V over that time. Work during that time interval is then given by

$$ W = \int_{T_0}^{T_1} P \cdot V \, dt $$

This method of determining work done has been described previously [2, 4]. Inspired tidal volume (VT) was derived from integration of flow during the inspiratory phase T₁. Work of breathing was converted to J/litre of ventilation.

Data were analysed by linear and polynomial regression and a comparison between the two humidifiers was made using analysis of variance; P < 0.01 was considered significant.

RESULTS

The three sets of pressure recordings with each humidifier were nearly identical. The coefficient of variation for the pressure recordings ranged from 0.1 to 2.8% except at the smallest flows. At a flow rate of 4.5 litre min⁻¹, the coefficient of variation was 5.9% for the Fisher-Paykel and 8.7% for the Bennett Cascade. Resistive pressures increased with greater flows (fig. 2, table I). The pressure:flow curves were fitted with a second order polynomial with r = 0.999 for the Bennett

![Fig. 2. Pressure-flow curves of Bennett Cascade humidifier (O) and Fisher-Paykel humidifier (●). Pressures of the Bennett are greater at all gas flows.](image)
TABLE I. Pressures and resistances of Fisher-Paykel (F-P) and Bennett Cascade (Bennett) humidifiers related to gas flow rates

<table>
<thead>
<tr>
<th>Mean flow (litre min(^{-1}))</th>
<th>Mean pressure (kPa)</th>
<th>Mean resistance (kPa litre(^{-1}) s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>F-P</td>
<td>F-P</td>
<td>Bennett</td>
</tr>
<tr>
<td>4.5</td>
<td>0.003</td>
<td>0.045</td>
</tr>
<tr>
<td>7.0</td>
<td>0.011</td>
<td>0.053</td>
</tr>
<tr>
<td>10.0</td>
<td>0.025</td>
<td>0.063</td>
</tr>
<tr>
<td>15.3</td>
<td>0.042</td>
<td>0.097</td>
</tr>
<tr>
<td>20.8</td>
<td>0.084</td>
<td>0.120</td>
</tr>
<tr>
<td>30.0</td>
<td>0.147</td>
<td>0.168</td>
</tr>
<tr>
<td>40.0</td>
<td>0.221</td>
<td>0.221</td>
</tr>
<tr>
<td>50.5</td>
<td>0.326</td>
<td>0.263</td>
</tr>
<tr>
<td>60.6</td>
<td>0.463</td>
<td>0.322</td>
</tr>
<tr>
<td>70.2</td>
<td>0.621</td>
<td>0.395</td>
</tr>
<tr>
<td>80.5</td>
<td>0.779</td>
<td>0.463</td>
</tr>
<tr>
<td>90.5</td>
<td>0.968</td>
<td>0.516</td>
</tr>
<tr>
<td>100.7</td>
<td>1.157</td>
<td>0.571</td>
</tr>
</tbody>
</table>

FIG. 3. Resistance–flow curves of Bennett Cascade humidifier (○) and Fisher–Paykel humidifier (●). The Bennett has an inverse relationship for flows up to 35 litre min\(^{-1}\).

Cascade and \( r = 1.000 \) for the Fisher–Paykel. Resistive pressure at each flow rate with the Bennett Cascade was always greater compared with the Fisher–Paykel (\( P < 0.001 \)).

Calculated resistances (table I) were plotted against flow rate (fig. 3). The Bennett Cascade’s resistance was high initially, but decreased sharply with increasing flows up to 35 litre min\(^{-1}\). Thereafter, it remained relatively constant at a mean of 0.66 kPa litre\(^{-1}\) s. With the Fisher–Paykel, resistance showed a small linear increase with increasing flow (\( r = 0.998 \)) but was always less than the Bennett’s resistance (\( P < 0.001 \)). Resistances at 45 litre min\(^{-1}\) were 0.22 kPa litre\(^{-1}\) s for the Fisher–Paykel, and 0.64 kPa litre\(^{-1}\) s for the Bennett Cascade.

In the work of breathing experiments, the lung model produced identical curves in each ventilatory cycle for both flow and pressure. The flow curves of the Servo 900C system with each humidifier are shown in figure 4. Simulated inspiration was accorded a negative polarity for easier visualization. The expiratory flow curves were identical and the inspiratory curves almost identical for the two humidifiers. However, corresponding inspiratory pressure curves (fig. 5) were different. The Bennett Cascade generated larger negative inspiratory pressures (maximum of \(-0.43\) kPa) than the Fisher–Paykel (maximum of \(-0.24\) kPa). Computed inspired \( V'\) was 680 ml.

Power curves for both humidifiers are shown in figure 6. Positive values denote the power required to overcome the resistance of the system, whereas negative values are the power inherent in the
RESISTANCE AND WORK OF HUMIDIFIERS

FIG. 5. Pressure curves of a simulated spontaneous breath from a Servo 900C ventilator with a Fisher–Paykel (dotted line) and a Bennett Cascade (solid line) humidifier in circuit. Expiratory curves are identical and shown here to precede inspiration. Inspiratory curves show extremely rapid pressure changes. The Bennett Cascade generated greater negative pressures.

FIG. 6. Computed power curves of a simulated spontaneous breath from a Servo 900C ventilator with a Fisher–Paykel (dotted line) and a Bennett Cascade (solid line) humidifier in circuit. Expiration is represented here to precede inspiration. Negative power values denote work done on the lung by the breathing system. The Bennett Cascade required greater power during inspiration.

Table II. Work done \((J/litre^{-1})\) during a simulated spontaneous breath using a Servo 900C ventilator system with the specified humidifier in-line

<table>
<thead>
<tr>
<th>Humidifier</th>
<th>Inspiratory phase</th>
<th>Expiratory phase</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fisher–Paykel</td>
<td>-0.032</td>
<td>0.140</td>
<td>0.108</td>
</tr>
<tr>
<td>Bennett Cascade</td>
<td>0.087</td>
<td>0.137</td>
<td>0.224</td>
</tr>
</tbody>
</table>

system because of an assist effect of the ventilator (see below). Work done during a simulated spontaneous breath is given in Table II. Inspiratory work \((W_i)\) with a Bennett Cascade in the circuit was 0.087 J litre\(^{-1}\); with the Fisher–Paykel circuit it was -0.032 J litre\(^{-1}\).

DISCUSSION

Previous studies have reported values for work of breathing in ventilators and tracheal tubes [2, 3, 5–15], but reports on humidifiers are few. This is somewhat surprising, as humidifiers were designed originally for mechanical and assisted ventilation, and not specifically for spontaneous breathing. Dennison and co-workers [5] studied the resistances of eight circuits, including two with a Bennett Cascade humidifier, but tracheal tubes were attached. Mecklenburg and colleagues [2] reported on the resistance and work of breathing of the Kontron ventilator and its humidifier, a bubble device. Our present study compared the Bennett Cascade with the Fisher–Paykel, a blow-by humidifier.

With both humidifiers, increasing resistive pressures were produced by increasing flows. Greater resistive pressures were seen with the Bennett Cascade as expected, as it requires gas to be drawn through water. The curvilinear pressure–flow curve obtained with the Bennett Cascade was similar to that reported by Dennison and co-workers for a Bennett Cascade circuit with a 9-mm tracheal tube [5].

When resistances were computed, the Bennett Cascade demonstrated an inverse relationship between resistance and flow for flow rates less than 35 litre min\(^{-1}\) (fig. 3). This phenomenon was reported also by Dennison and co-workers [5] and may be caused by the complex passage of gas through the Bennett Cascade. Gas is drawn through water in its chamber and then through a grid, creating froth [1] which decreases re-
sistance to gas flow. Low gas flows may produce proportionately less froth and thus meet with greater resistance. As a corollary, if sufficient froth is produced by adequate flows, resistance remains relatively constant. This resistance was demonstrated in our study to be 0.66 kPa litre\(^{-1}\) s with flows greater than 35 litre min\(^{-1}\) (fig. 3).

The Fisher–Paykel humidifier, on the other hand, has gas passing over the water surface [1]. Resistance would be expected to be less than that of bubble humidifiers. In addition, it incorporates filter paper wicks to increase water surface area effectively. Thus increased flow rates are likely to increase turbulence within the unit, giving rise to increases in resistance. The resistance increases were small in this study.

There are no specifications for a maximum resistance to flow applicable to humidifiers, as far as we know. Nunn recommended an upper limit of about 0.6 kPa litre\(^{-1}\) s at a flow rate of 30 litre min\(^{-1}\) for a breathing system [16]. The resistance of the Fisher–Paykel alone at the same flow was 0.17 kPa litre\(^{-1}\) s (with a maximum of 0.57 kPa litre\(^{-1}\) s at 100 litre min\(^{-1}\)). However, the resistance of the Bennett Cascade was considerably greater than the recommended upper limit at low flows, and approximated that limit with flows greater than 30 litre min\(^{-1}\). Consequently, the resistance of a ventilator circuit with a Bennett Cascade humidifier would be considerably greater than 0.6 kPa litre\(^{-1}\) s.

The humidifiers were studied also in a simulated clinical setting using a popular modern intensive care ventilator, the Servo 900C. A simulated peak inspiratory flow of 45 litre min\(^{-1}\) was chosen, which approximates to those of stable weaning patients [5, 11]. However, our lung model was not able to produce physiological expiratory flows. Hence computed work done on expiration might be expected to be artificially high. Nevertheless, this did not affect the experiment, as differences in pressure and work of breathing were produced in the inspiratory phase. Our study was not designed to examine natural work against the patient's own compliance and resistance.

The work of breathing for a single breath is expressed appropriately in terms of joules or J/litre of inspiration. Thus the Servo 900C–Bennett Cascade system demanded 3.7 times more work than the Fisher–Paykel system for an inspiratory breath with a peak flow of 45 litre min\(^{-1}\). Nevertheless, the Bennett Cascade's inspiratory work (0.087 J litre\(^{-1}\)) is much less than the 0.544 J litre\(^{-1}\) (0.272 J for 500 ml V\(_r\)) reported for the Kontron ventilator with its humidifier [2].

"Normal" work in breathing directly from atmosphere at rest is about 0.5 J litre\(^{-1}\) [8, 15]. The Servo 900C–Bennett Cascade system thus demanded 17.4% additional work. On the other hand, the Servo 900C–Fisher–Paykel system performed work on the lung. This "reduced work" characteristic of the Servo 900C was reported also by bench [8, 10, 11] and clinical [9] studies on the work of breathing imposed by demand valves of different ventilators. Comparison with our study is difficult, as the circuits in these studies either excluded in-line humidifiers [9] or included tracheal tubes [8, 11] or use of CPAP [10]. The experimental model of Katz, Kraemer and Gjerde included unspecified in-line humidifiers and found that the Servo 900C reduced work by −0.025 to −0.035 J litre\(^{-1}\) at peak flows of 20–60 litre min\(^{-1}\) [8]. A reduced work of −0.02 J litre\(^{-1}\) at a flow of 20 litre min\(^{-1}\) was reported by Bersten and colleagues [11] with a Fisher–Paykel humidifier and a 7-mm tracheal tube. Our value of −0.032 J litre\(^{-1}\) without a tracheal tube, at a flow of 45 litre min\(^{-1}\), is consistent with the values reported above.

The larger negative inspiratory pressures seen with the Servo 900C–Bennett Cascade system confirmed the Bennett's greater resistance. For both humidifiers, an assist effect from the ventilator during the inspiratory phase was obvious. The Servo 900C directs gas into the circuit during inspiration from a pressurized concertina reservoir bag [1, 17]. Hence inspiratory flow can exceed demand, as represented by the increase in airway pressure to greater than that of end-expiration [8] (fig. 5). This would explain the "reduced work" effect of the Servo 900C ventilator.

The pressure flutter during inspiration (fig. 5) can be explained by the inspiratory demand valve of the Servo 900C. This scissors valve is activated by a servo-controlled, rapid cycling stepper motor [17]. A delay of about 0.15 s follows the start of a patient breath before the occluded valve opens [18]. As gas rapidly enters the circuit, a positive pressure is recorded. The gas delivery, patient inspiratory effort, circuit resistance and servo valve result in an inspiratory pressure flutter. This flutter can be significant if the patient's inspiratory flow demands are not met.

Excessive circuit resistance can cause respir-
atory muscle fatigue and prolong weaning from mechanical ventilation. The humidifier and the ventilator’s inspiratory demand valve are the major contributors to the inspiratory resistance of a breathing system. Higher circuit resistances require greater negative intrapulmonary pressures to initiate each spontaneous breath, thus increasing the work of breathing. The peak inspiratory flows of weaning patients are usually about 40–50 litre min\(^{-1}\), but greater flows may be required under stress [5]. If flow from the breathing system is insufficient to meet inspiratory demands, the resistive load on the patient is further increased. This is especially pertinent to the Bennett Cascade humidifier.

In conclusion, the resistance and inspiratory work imposed by the blow-by Fisher-Paykel humidifier is acceptable over the relevant range of patient inspiratory flows. However, the Bennett Cascade humidifier requires much more work for a spontaneous breath, and even by itself, has considerably greater resistances at the same flow rates. These findings confirm our clinical observation that patients are difficult to wean with the Bennett Cascade humidifier. Thus the Bennett Cascade humidifier should not be used for weaning, unless the ventilation mode or gas flow is able to reduce the work of breathing, such as with a Servo 900C. Indeed, the use of bubble humidifiers for spontaneous breathing is questioned.

REFERENCES
10. Samodelov LF, Falke KJ. Total inspiratory work with modern demand valve devices compared to continuous flow CPAP. Intensive Care Medicine 1988; 14: 632–639.