INCREASE IN RESISTANCE OF IN-LINE BREATHING FILTERS IN HUMIDIFIED AIR

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SUMMARY

A study has been performed to measure the resistance of Pall Ultipor BB50 filters when exposed to humidified air for 48 h during artificial ventilation by an Engstrom Erica ventilator fitted with a Bennett Cascade Mk2 humidifier. A marked increase in resistance was demonstrated. A hypothesis is presented as to the aetiology of these findings together with details of minor modifications to the system which allow the use of these filters under clinically acceptable conditions.

The use of in-line breathing filters during artificial ventilation, although not proven conclusively (du Moulin and Hedley-White, 1982), is thought to protect the patient from organisms present in the ventilator, and the ventilator from infection in the patient. In addition, in the Intensive Care Unit, patients may require mechanical ventilation for prolonged periods, and often develop severe opportunistic infections of the respiratory tract. With the recent acquisition of Engstrom Erica ventilators and Bennett Cascade Mk2 humidifiers, we were aware of having a system with no inbuilt filter protection.

It was considered that Ultipor BB50 filters would protect the patient, and the environment, if they were placed in the ventilator circuit, one on the patient side of the humidifier and a second on the expiratory port of the ventilator. The life of the filters, as given by the manufacturers (Pall Biomedical U.K.), is 48 h.

An initial trial was carried out on one patient over a period of several days with the filters in situ. It was noticed on several occasions that, after about 12–24 h, there was an increase in the peak inspiratory pressure, of the order of 10–15 cm H₂O, as measured at the inspiratory port of the ventilator. Moreover, it was observed that the pressures returned to normal values when the filters were removed and replaced. These changes were noticed on three consecutive occasions on this one patient, although there was no change in the tidal volume delivered by the ventilator. The decision to implement this study was made following a further incident, in the same patient who, as his lung function improved, was allowed to breathe spontaneously in the Extended Mandatory Minute Volume mode of the ventilator as part of the process of weaning. Following institution of this mode of ventilation the patient was seen to be breathing well, requiring no additional mandatory breaths from the ventilator. Twelve hours later, however, he was observed to be in considerable respiratory difficulty. He was making strong inspiratory efforts, but was unable to register any tidal volume on the display of the ventilator. Acting as a fail-safe device, the EMMV mode of the ventilator had taken over and was delivering the full preset minute volume to the patient. It was noticed that the pressure gauge was displaying a peak inspiratory pressure of 55 cm H₂O, during mandatory breaths, and there was also a marked expiratory retard, which was preventing the pressure decreasing to zero during expiration. Immediate removal of both filters led to a decrease in peak pressure to 30 cm H₂O and a return of pressure to zero during expiration.

MATERIALS AND METHODS

A test circuit was set up using an Engstrom Erica ventilator equipped with a Bennett Cascade Mk2 humidifier and attached to a Medishield Ventilator Performance Analyser, acting as a model lung (fig. 1). Two Ultipor BB50 filters were used in the circuit, one placed horizontally on the patient side of the humidifier and the second on the expiratory port of the ventilator. The temperature sensing probe of the humidifier was placed in the circuit at the catheter mount (fig. 1).

The pressure was measured in the patient circuit through an air-filled system using 18-gauge needles pushed through the ventilator tubing and connected to two Elcomatic 705A transducers and an Elcoma-
tic EM720A twin channel recorder. The frequency response of the system was measured by the step response method after pressurizing to 30 mm Hg with air. The delay time was found to be 0.04 s with no overshoot. The sites of measurement were, proximally, at the inspiratory port of the ventilator and, distally, at the patient end in the catheter mount (fig. 1). The recorder was run at a speed of 25 mm s⁻¹. Measurements were recorded in mm Hg and later converted to cm H₂O (conversion factor 1.36).

The ventilator was set to deliver a tidal volume of 600 ml at a rate of 16 b.p.m., giving a peak inspiratory pressure of around 20 cm H₂O. The inspiratory flow pattern was set to "constant flow", the I:E ratio to 1:2, and the inspiratory flow rate was adjusted to the middle of the "normal range" on the ventilator (no nominal range being given). These settings gave a good plateau on the pressure tracing. The ventilator was operated only in the Controlled Mechanical Ventilation mode with FIO₂ 0.4. The humidifier was filled with sterile water and adjusted to give a temperature of 35°C at the catheter mount. Before any readings were made from the circuit the humidifier was filled to a constant level and the system allowed to reach a constant temperature. No changes were made to any of these settings during the tests, each of which was run for a continuous period of 48 h. Regular recordings were obtained from the two pressure transducers during each test. A control recording was made at the beginning and end of each test without the filters in place.

Calculation of the resistance of the circuit was obtained by analysis of the pressure–time tracing obtained from the transducer situated at the inspiratory port of the ventilator (Nunn, 1969) (fig. 2) and applying the formula:

\[ \text{Resistance (cm H}_2\text{O litre}^{-1}\text{s}) = \frac{(\text{peak pressure} - \text{plateau pressure}) \times t}{VT} \]

where \( t \) = inspiratory time in seconds and \( VT \) = tidal volume in litres.

![Fig. 1. Diagram of the experimental circuit showing positioning of the filters and pressure transducers. Insp. Fil. = inspiratory filter; Exp. Fil. = expiratory filter.](image1)

![Fig. 2. Pressure tracing demonstrating calculation of the circuit resistance (see text for formula) from pressure (mm Hg) and time (s) where \( t \) = total inspiratory time, \( P_{\text{peak}} \) = peak pressure and \( P_{\text{plateau}} \) = plateau pressure. The calculations assume a constant flow rate in inspiration.](image2)
During the inspiratory phase of the ventilator cycle a pressure was generated in the system, from the compliance of the system plus the resistance (peak pressure). During the plateau phase there was no flow in the system and the pressure measured was entirely a result of the compliance of the system (plateau pressure). The pressure difference measured from the tracings (peak pressure – plateau pressure) was attributable to the resistance to flow of the humidifier and filter. The formula calculates the resistance across the humidifier and filter as being equal to the pressure decrease across the humidifier and filter (peak pressure – plateau pressure), divided by the mean flow through the system during the inspiratory phase (tidal volume/inspiratory time). The calculation assumes a constant flow rate during inspiration. In the tracings which showed a marked increase in resistance this calculation could only be used as an approximation as the flow decreased towards the end of inspiration and the plateau area became unclear.

Because the flow across the expiratory filter was not constant, in contrast to the inspiratory filter where a constant flow has been assumed, it was not possible to measure quantitatively the resistance of the expiratory filter. However, by examining the decay of the pressure obtained by the transducer at the catheter mount during the expiratory phase, it was possible to assess any significant increase in resistance of the filter as a decrease in the gradient of the curve. If the expiratory time was prolonged sufficiently a positive pressure would be evident throughout the ventilator cycle.

Tidal volume, minute volume and static compliance were recorded from the ventilator display.

Following the results of the first study, and detailed discussion with Pall Biomedical, a second study was undertaken in an attempt to decrease the increase in resistance found in the circuit using the method already described. In the second study several minor modifications were made to the test circuit. The positioning of both filters was changed, the inspiratory filter being placed vertically on the humidifier by the use of an extension tube, and a water trap was placed between the expiratory filter and the expiratory port of the ventilator. The temperature-sensing probe of the humidifier was placed in the inspiratory limb of the patient tubing, in contrast to the catheter mount where it was sited in the first study (fig. 3).

RESULTS

First study

Six test runs were performed (table I). The temperature of the water in the humidifier bowl was measured as 60 °C following equilibrium, when the temperature at the catheter mount was 35 °C. In all
instances an increase in peak inspiratory pressure (as measured at the inspiratory port of the ventilator) could be seen during the 48-h period, indicating an increase in the resistance of the inspiratory filter. The mean maximum increase in inspiratory pressure was 17 cm H$_2$O (range 8–36). The resistance of the expiratory filter was assessed from the pressure recordings from the transducer at the catheter mount. An increase in the resistance of the expiratory filter would decrease the flow rate, lead to an increase in expiratory time and ultimately result in a positive pressure throughout the ventilator cycle. This was observed on the pressure tracings as a decrease of the gradient during the expiratory phase (fig. 4), and in three of the six investigations a positive pressure was noted throughout the ventilator cycle, the maximum positive expiratory pressure being 6 mm Hg (approx 8 cm H$_2$O). There was no change in the performance of the lung model as measured by the compliance of the circuit during any of the studies.

The increase in the resistance of the filters was demonstrated on three occasions as early as 12 h after the commencement of the test (table I, nos 2, 5 and 6). On all but one occasion (table I, no. 3) the increase in resistance at 48 h was greater than that which could be regarded as acceptable and, in all instances, was greater than the manufacturer's specification which describes the pressure decrease across the new filters as 0.8 cm H$_2$O at a flow rate of 50 litre min$^{-1}$.

The preset tidal volume was delivered in all experiments throughout the full 48 h. In runs 1 and 5 (table I) there were marked increases in the resistance of both filters leading to a prolonged inspiratory time, an increase in the peak inspiratory pressure and a loss of the plateau phase during inspiration. This is seen diagrammatically in figure 4. In addition, it was found that there was a marked expiratory retard giving rise to a positive pressure throughout the ventilator cycle. In contrast, the picture seen in run 2 was slightly different in that only the inspiratory filter demonstrated an increase in resistance, and hence the decrease in pressure during expiration remained normal (fig. 5).

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**TABLE I. First study. Increase in resistance of inspiratory filter with time (cm H$_2$O litre$^{-1}$).** *Approximation—see text*

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**Fig. 4. Pressure tracing, first study. A: Inspiratory port of ventilator; B: catheter mount.** An increase in peak pressure can be seen to develop over 48 h in A. Note, in B, a decrease in the gradient of the curve during expiration signifying a decrease in flow rate leading to the development of a positive pressure throughout the cycle. Note the gradual loss of the plateau phase and increase in inspiratory time. Marker is 1 s.
Second study

Six test runs were performed. The water temperature in the humidifier bowl was found to be at 46 °C following equilibrium. An increase in the resistance of the inspiratory filter in the new position was demonstrated in all instances (table II), but the magnitude of the increase was smaller, the mean increase in resistance being 3.25 cm H₂O litre⁻¹ s at 24 h (range 2.2-4.3) and 6.7 cm H₂O litre⁻¹ s at 48 h (range 3.8-9.0) compared with a mean maximum increase at 48 h of 17.5 cm H₂O litre⁻¹ s in the first study. In no case was there any detectable increase in the resistance of the expiratory filter.

DISCUSSION

The investigation has demonstrated that a large increase in resistance can develop when these filters are used with this particular equipment, unless considerable care is taken in their positioning. In the first study the filters were used as recommended originally by the manufacturers and a hazard developed. The use of a modified circuit reduced considerably the increase in resistance (fig. 6).

The position of the filters in the circuit was chosen to provide full protection for the patient from contamination in the inspiratory side of the circuit. At the time the study was performed only one humidifier was available for each ventilator and, although the ventilator tubing was changed daily, this was not possible with the humidifier. Positioning the inspiratory filter at the inspiratory port of the ventilator was considered and would undoubtedly be associated with little, if any, increase in resistance. However, in this position, the patient would not be protected from any source of infection in the humidifier and the filters are marketed as being suitable for use in humidified air because of their hydrophobic properties. Therefore, it was felt appropriate to try to achieve the lowest possible resistance while maintaining the filters in the circuit between the patient and the humidifier.

Since this study the manufacturers have stated that, in normal use, the resistance of the inspiratory filter, in humidified air, can be expected to increase by a maximum of 4 cm H₂O litre⁻¹ s per 24 h. Although there is no breakdown in the hydrophobic properties of the filter material, the passage across the filter of warm humidified air produces condensation within the pores of the material, leading to a gradual increase in the measured resistance. The increase quoted by the manufacturers is within the

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**FIG. 5. Pressure tracing, second study. Increases in peak pressure can be seen in A. Note, in B, that the gradient of the curve during expiration remains normal, signifying a normal flow rate and that the pressure decreases to zero during expiration. Marker is 1 s.**
limits of clinical acceptability at 24 h, and was verified in the second study in five of the six experiments.

The marked increase in the resistance of the inspiratory filter seen in the original study is thought to have occurred because of two factors. First, the weight of the patient tubing caused tilting of the filter and allowed a considerable amount of condensation to accumulate, so decreasing markedly the surface area available for gas flow and, in addition, allowing water to be forced into the filter material during the inspiratory cycle (fig. 7).

The temperature of the water in the humidifier in the first study was 15°C higher than in the modified circuit, causing an acceleration of the rate of condensation within the filter material. The differences seen in the water temperature in the two studies is a function of the mode of operation of the Bennett Cascade Mk2 humidifier which is servo-controlled by a distally-placed temperature probe. By placing the probe in the catheter mount (first study) it was subject to the cooling effect of the expired gas passing across it and this led to an excessive increase in the temperature of the water in the humidifier bowl. The positioning of the temperature probe in the inspiratory limb of the patient circuit overcame this problem as only inspired gas passes across it. In the clinical situation the expired air is often warmer than the inspired air and the position of the probe is not critical. From observations in our patients we can show no change in the water bath temperature with the probe in either position in the circuit. Therefore the position of the probe can be excluded as a sole cause for the observed phenomenon.

The performance of the expiratory filter in the first study cannot be explained fully. Any increase in resistance of this filter, which produces expiratory retard and positive pressure throughout the ventilator cycle, is unacceptable. It was thought that one possible explanation could be the collection of water within the expiratory mechanism of the ventilator, allowing water to settle on top of the expiratory filter. However, this is unlikely and was not demonstrated during these experiments. Moreover, since using a water trap between the filter and the ventilator (second study) we have been unable to detect any increase in the resistance of this filter.

We conclude, that, with our equipment, the Pall Ultipor BB50 filters require careful positioning if their resistance is to remain acceptable. Nevertheless, in the revised circuit the resistance measured,
although satisfactory at 24 h, was higher than desirable at 48 h, and this is of particular importance if the patient is receiving Intermittent Mandatory Ventilation. We recommend that the inspiratory filter should be changed at least every 24 h and a close watch kept for any signs of an excessive increase in resistance. It would be preferable if a clearer explanation for the increase in expiratory resistance could be given and this needs further investigation.

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REFERENCES