Flow dynamics using high-frequency jet ventilation in a model of bronchopleural fistula†

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Editor’s key points
- High-frequency jet ventilation (HFJV) is often considered the ventilation technique of choice for patients with a bronchopleural fistula.
- This study found that higher jet frequencies and lower driving pressures may reduce air leak.
- The benefits of HFJV may be lost in patients with severe parenchymal lung disease.

Background. Positive pressure ventilation in patients with a bronchopleural fistula (BPF) is associated with variable, unpredictable gas leaks that can impair gas exchange. The optimum settings for high-frequency jet ventilation in this scenario are unclear. We investigated flow dynamics with BPFs of 2 and 10 mm, at various positions and with different jet ventilator settings in a bench-top model.

Methods. A 2 or 10 mm length fistula was created at proximal, middle, or distal sites in standard artificial ventilator ‘test’ lungs and cadaveric porcine lungs. The effects of alterations in frequency, applied pressure, and on entrained, expired, and leak volumes were determined using gauge and differential pressure sensors.

Results. Entrained, delivered, and leak volumes were affected markedly by ventilator settings, particularly frequency: leaks were much greater at frequencies $<100$ min$^{-1}$. The leak/expired volume ratio varied between 0% and 92%. Leak and entrained volumes increased progressively with more proximally situated fistulae, whereas the measured expired volume decreased. Leak volumes with a 2 mm fistula were approximately half that of a 10 mm fistula across all ventilator frequencies. All volumes increased with increased driving pressure. The optimum injection time varied depending on BPF position and the accepted compromise between leak and expired volumes. Entrained volume contributed up to 50% of the total tidal volume.

Conclusions. These data suggest that gas leak will be minimized and ventilator volumes maintained during jet ventilation using frequencies $>200$ min$^{-1}$ and lower driving pressures, but confirmatory clinical studies are required. Values displayed by the jet ventilator are unreliable.

Keywords: bronchial fistula; high-frequency jet ventilation; pulmonary ventilation; respiration, artificial

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A bronchopleural fistula (BPF) is defined as an abnormal tract (fistula) between the bronchial tree and pleural cavity. It is a complication of surgical lung resection, and the incidence after lobectomy or pneumonectomy is 0.8–15%.1,2 The management of ventilation for patients with a BPF undergoing surgery, or respiratory support in intensive care, is often complex and several methods may be used. High-frequency jet ventilation (HFJV) is a useful technique for managing patients with BPF and acute lung injury or other conditions associated with reduced lung compliance. Advantages are that airway pressures and leak volumes are limited,3–5 there is a potential reduction in alveolar shear stresses, and cardiovascular effects are less.6–8 HFJV has some disadvantages such as the potential to produce pulmonary barotrauma, and complications resulting from misplacement of the jet cannula, including gastric rupture, pneumomediastinum, and tension pneumothorax.9–13

However, perhaps one of the main limitations to its more widespread use in clinical practice is that there is no reliable method available for accurate monitoring of ventilation. The delivered and entrained gas volumes generated during HFJV, and the subsequent gas leaks in the presence of a BPF, are not measured directly but are estimated by an internal flow sensor. The accuracy of these estimations varies according to the ventilator driving pressure, inspiratory to expiratory ratio, and applied frequency. Furthermore, there is no device for measuring volume or pressure at the exhaust port of the jet.
adaptor. Nonetheless, it is widely accepted that one of the benefits of HFJV is the low distal airway pressures it produces. Although some studies have evaluated different methods of monitoring airway gases and entrained volumes during HFJV, the results have been contradictory. Furthermore, there are no specific data on entrained gas flows and volumes when HFJV is used in the presence of a BPF. Consequently, the optimal ventilator settings for HFJV are unknown, especially when used in patients with a BPF. Our hypothesis was that leak and entrained gas flows would be affected by both the characteristics of the fistula and the settings applied during HFJV, and there may be optimal HFJV settings to minimize the leak through a BPF, independent of the BPF position.

The objectives of this study were: (i) to establish a model to determine gas flows and delivered tidal volumes during HFJV in order to (ii) understand how a simulated BPF of different size and position affected delivered ventilation using HFJV. Specific aims were to determine: (i) the effect of the size and position of BPF on gas flow through the lung and leak pressures, and (ii) the contribution of entrained volume to total tidal volume.

Methods

As previously presented and published in abstract form, our study model comprised a high-frequency jet ventilator (Monsoon 2.4e, Acutronic, Switzerland) connected to a reinforced tracheal tube (Mallinkrodt™, Covidien plc, Dublin, Ireland) via a jet adaptor (Mercury Medical, Clearwater, FL, USA) and connected to an artificial test lung or porcine lung model, which was enclosed within an airtight acrylic box. Two gauge pressure (MPX10GP, Freescale Semiconductor Inc., Austin, TX, USA), and two differential pressure (MPX10DP, Freescale Semiconductor Inc.) sensors were interfaced with a four channel differential oscilloscope (Picoscope 4424a, Pico Technology Ltd, St Neots, Cambridgeshire, UK), linked to a laptop computer, capturing four pressure signals simultaneously with a sampling size of 80 Ms s⁻¹ (Mega samples per second) (Fig. 1, Supplementary Figure S1). In order to determine the gas volumes generated during HFJV, in particular the entrained volume, we performed experiments to measure the pressures both at the emergence of the jet and at the simulated thoracic wall. The following measurements were made:

- Airway pressure 5 cm distal to the jet.
- Flow into the exhaust port, including entrained flow.
- Total flow out of the exhaust port, including jet pulse, entrained volume, and fraction.
- Leak volume and pressure (the pressure of the gas leak at the inferior monitoring port).

Measurements were made while monitoring the driving pressure, respiratory rate, and proportion of time during the injection phase. These variables were altered during different series of experiments. The order of experiments was to use the default settings first (IT 40%, driving pressure 1.5 bar) followed by different driving pressures (1 bar, then 2 bar) followed by different IT% (20% then 60%). Additional details are available in Supplementary Figure S3. We tested and refined the experimental model using a 2 litre ventilator test lung (Intersurgical, Wokingham, UK) before further measurements using cadaveric pig lungs. The interval between experiments was ~5 min. At the start of each experiment, the oscilloscope traces were calibrated to zero. After the prepared left pig lung was placed into the acrylic box and the box sealed, HFJV was commenced and a further period of 1 min elapsed before data were collected to allow the system to stabilize.

All cadaveric porcine lungs were taken from healthy adult Large Breed pigs of ~100 kg weight (Vascutek, Renfrewshire, UK). The pigs were slaughtered in accordance with UK Home Office regulations, to allow harvesting of their heart valves for routine supply to UK cardiac units. The lungs, which would normally be destroyed, were supplied to us for research purposes. The approximate weight of the 18 lungs used was 0.7 kg and approximate dimensions (including trachea) were 45 cm x 40 cm. A right pneumonectomy was performed at the distal point of the right main bronchus, and this was then closed with a tie to make an airtight seal. The formation of the BPF was completed using a scalpel blade at a point dependent on the desired fistula position. The distal incision was made just proximal to the position of the tie, the middle fistula was created at the carina, and the proximal fistula at a point halfway up the trachea. All incisions were horizontal and for the large BPF was 10 mm in length.

For each series of experiments, three readings were taken at intervals of 1 min and the lungs were refrigerated overnight at 4°C to allow repetition of experiments the following day. The prepared lungs were neither ventilated nor inflated during storage in the refrigerator. This allowed six readings for each lung experiment with a new lung prepared for each investigation. One set of lungs was left complete in order to investigate the effect of HFJV on an intact pair of pig lungs and for reference purposes.

The ‘test’ lungs were standard 2 litre ventilator test lung reservoir bags (Intersurgical, Wokingham, UK), length 26 cm when deflated. A horizontal 10 mm hole was created using a scalpel at the distal end of the bag, and 13 and 6.5 cm from the proximal opening to represent a distal, middle, and proximal fistula, respectively.

Data were exported to a data spreadsheet (Windows Excel 2007) for analysis using Riemann integration. Each experiment was performed six times and data are presented as mean (sd).

Results

The effect of ventilator frequency in artificial test lung and pig lung models

When applying HFJV in intact lung models, using either an artificial test lung (Fig. 2a) or a cadaveric pig lung (Fig. 2a), there was an almost exponential decrease in measured and entrained tidal volumes as ventilator frequency increased, with absolute values similar in both models. There was a marked difference between the measured expired volume and the tidal volume estimated by the jet ventilator (Fig. 2a and d). In both models, the entrained volume contributed almost 50% to the expired tidal volume at low frequencies (< 100 min⁻¹). As entrainment...
decreases at higher frequencies, the injection pulse volume accounted for an increasing proportion of total tidal volume, exceeding 80% at frequencies > 300 min⁻¹.

**The effect of an artificial BPF**

In the presence of an artificial BPF, a similar relationship between measured tidal volumes and ventilator frequency was observed. Displayed tidal volumes were also greater than measured volumes and were numerically similar, irrespective of fistula size or position (Fig. 3A–D). The entrained and leak volumes were similar with a fistula at ‘middle’ (level of the carina) and ‘distal’ (right main bronchial stump) sites but were both much larger with a ‘proximal’ (tracheal) fistula (Fig. 3A–C). Consequently, the measured expired tidal volumes were similar irrespective of fistula position. The effect of fistula position was small (all leak volumes <20 ml) at a frequency >200 min⁻¹, but leak volume increased at lower frequencies, especially with a more proximal fistula.

**The effect of alterations in fistula size and position**

With the formation of a larger fistula (10 mm), a similar pattern was seen as respiratory frequency increased. The entrained volumes were smaller with both the distal and middle fistulae and subsequently the expired tidal volumes were smaller (Fig. 3D and E). However, the machine tidal volumes displayed by the jet ventilator did not change noticeably, irrespective of size or position of the fistula and were consistently greater than the measured expired volumes. There were no data from the proximal 10 mm fistula as the pig lung remained collapsed, with no effective ventilation. A tabulated comparison of leak volumes against ventilator frequency for 2 and 10 mm distal, middle, and proximal fistulae is presented in Supplementary Table S1.

**The effect of altering jet ventilator driving pressure in the presence of a fistula**

When the jet ventilator driving pressure was increased between 1.0 and 2.0 bar, the entrained, leak, and expired tidal volumes all increased. A similar pattern of decreased entrained, leak, and expired volumes with increasing ventilator frequency was seen. The leak volumes were similar across the respiratory frequencies for driving pressures of 1.0 and 1.5 bar but were markedly raised for a driving pressure of 2.0 bar particularly at frequencies <150 min⁻¹. The entrained volumes were smallest for a driving pressure of 1.0 bar but largest for a driving pressure of 1.5 bar (Fig. 4A–F). These patterns were similar when ventilating with a ‘middle’-situated fistula (Supplementary Fig. S2).
The effect of altering injection time percentage on measured volumes

A similar relationship between ventilator frequency and entrained, expired, and leak volumes was observed at injection times of 20%, 40%, and 60%. However, the increase in entrained volumes at lower frequencies was greatest with an injection time of 40%, with a corresponding increase in expired volumes, particularly at frequencies <100 min⁻¹. Nonetheless, leak volumes were negligible at frequencies >150 min⁻¹ (Fig. 5A–C). With an injection time of 60%, the entrained and leak volumes decreased further compared with 20% and 40%. At frequencies >250 min⁻¹ and a 60% injection time, the high airway pressures encountered caused activation of the ventilator cessation function. Ventilation was halted and therefore no data could be recorded.
The effect of varying injection time percentage on leak volumes at proximal, middle, and distal fistula sites

Absolute leak volumes were higher when ventilating the model with a proximal or middle fistula. Leak volumes were higher with a 40% injection time with a distal fistula throughout the recorded range of frequencies, but absolute leak volumes were low at frequencies >120 min⁻¹. A similar pattern occurred with a middle fistula, but the absolute leak volumes
were greater, and increasing injection time to 60% produced the highest leak volumes. Leak volumes were lowest with a 20% injection time irrespective of the fistula position, although the differences between 20% and 40% injection time were low with a distal or middle fistula. With a proximal fistula, leak volumes were higher for all the injection times studied, but remained comparatively low at frequencies >200 min⁻¹ with injection times of 20% and 40% (Fig. 6).

The relevance of leak volumes is greater if they are considered in relation to the corresponding expired volumes (Table 1) as in clinical practice there is often a compromise between maintaining gas distal delivery and minimizing leak volumes. This can be

![Fig 4](https://academic.oup.com/bja/article-abstract/112/2/355/285521)
Flow dynamics during HFJV in a model of BPF

Fig 5 The effect of varying inspiratory time as a percentage of each cycle (IT %) on delivered and leak volumes in the artificial test lung with a 10 mm distal hole. Data presented as mean (sd). Each experiment repeated six times. There was little effect of alterations in IT on expired volumes at frequencies > 200 min⁻¹ with a 10 mm distal fistula (a–c). All volumes were increased at low frequencies with an IT of 40% compared with 20%. When IT was set at 60%, the proportion of entrained volume decreased compared with 20 and 40% IT, and the expired volumes were correspondingly reduced. At frequencies > 250 min⁻¹ and a 60% IT, the high airway pressures encountered caused the ventilator shut-off mechanism to halt ventilation and therefore no data were recorded.
Fig 6 The effect of varying IT (as a percentage of each cycle) on leak volumes in the artificial test lung at a proximal, middle, and distal sites, with a driving pressure of 1.5 bar. Data presented as mean (SD). Each experiment repeated six times. Changing IT had little effect on leak volumes with a distal fistula, particularly at frequencies > 150 min⁻¹ (A). However, leak volumes were highest with a 40% IT at frequencies < 120 min⁻¹ compared with 20 and 60% IT. A similar pattern occurred with a middle fistula, but the absolute leak volumes were greater, and increasing IT to 60% produced the highest leak volumes (B). With a proximal fistula (C), higher leak volumes occurred with all IT compared with middle and distal fistulae, but with an IT of 20% or 40%, remained relatively low at frequencies > 200 min⁻¹.
Table 1 Comparison of leak and expired volumes when using HFJV at 20, 40, and 60 IT%, 1.5 bar DP, with 10 mm distal, middle, and proximal fistula sites in test lung. Data presented as mean (SD) \((n=6)\). Leak volumes increase with fistula position (proximal -> distal) and injection time percentage (60 -> 20). In general, expired volumes decrease with fistula position (distal -> proximal). The largest expired volumes occurred with an injection time of 40%.

<table>
<thead>
<tr>
<th>Frequency</th>
<th>20% injection time</th>
<th>40% injection time</th>
<th>60% injection time</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Distal Leak</td>
<td>Expired</td>
<td>Middle Leak</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>60</td>
<td>37.8 (0.17)</td>
<td>302 (1.46)</td>
<td>53.1 (0.85)</td>
</tr>
<tr>
<td>80</td>
<td>24.0 (0.45)</td>
<td>221.6 (0.35)</td>
<td>37.6 (0.83)</td>
</tr>
<tr>
<td>100</td>
<td>18.2 (0.26)</td>
<td>179.7 (1.38)</td>
<td>265.6 (0.46)</td>
</tr>
<tr>
<td>120</td>
<td>13.7 (0.30)</td>
<td>159.2 (1.33)</td>
<td>204.0 (0.53)</td>
</tr>
<tr>
<td>140</td>
<td>8.9 (0.50)</td>
<td>134.3 (1.75)</td>
<td>15.0 (0.26)</td>
</tr>
<tr>
<td>160</td>
<td>6.9 (0.10)</td>
<td>118.6 (2.36)</td>
<td>12.3 (0.75)</td>
</tr>
<tr>
<td>180</td>
<td>5.8 (0.26)</td>
<td>107.3 (1.32)</td>
<td>9.4 (0.10)</td>
</tr>
<tr>
<td>200</td>
<td>3.4 (0.06)</td>
<td>98.0 (1.55)</td>
<td>7.5 (0.12)</td>
</tr>
<tr>
<td>220</td>
<td>2.4 (0.26)</td>
<td>92.5 (1.31)</td>
<td>6.3 (0.10)</td>
</tr>
<tr>
<td>240</td>
<td>2.0 (0.12)</td>
<td>85.1 (0.95)</td>
<td>6.0 (0.40)</td>
</tr>
<tr>
<td>250</td>
<td>1.7 (0.21)</td>
<td>82.3 (2.20)</td>
<td>5.6 (0.21)</td>
</tr>
<tr>
<td>300</td>
<td>0.6 (0.10)</td>
<td>67.4 (0.36)</td>
<td>3.1 (0.25)</td>
</tr>
<tr>
<td>350</td>
<td>0.2 (0.03)</td>
<td>60.1 (1.24)</td>
<td>2.0 (0.06)</td>
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</table>
The proportion of delivered gas escaping through the fistula. Look at the ‘leak’ to ‘expired’ tidal volume ratio as this reflects understanding these data from a clinical perspective, it is easier to optimize gas exchange, including delivery of gas to the lung or a porcine lung. There was also a large disparity between ventilator volumes during HFJV whether using an artificial test lung. The ‘fistula’, and the size and shape of the fistula. We found that the proportion of injected and entrained gas leaking during jet ventilation are the entrained and leak volumes, but these are difficult to predict and to quantify. The entrained volume is proportional to the negative pressure generated by the velocity of the jet stream; this depends on friction represented as leak volume as a percentage of the expired volume, that is, leak volume/expired volume ratio \( (L/E) \) ratio. The \( L/E \) ratio was greater with a more proximal fistula, increased with increasing injection time and decreased with increasing injection frequency. With a proximal fistula and 60% injection time, the \( L/E \) ratio was 0.92 (Table 2).

### Discussion

In this experimental model of a BPF, we found a fairly consistent inverse relationship between entrained and delivered tidal volumes during HFJV whether using an artificial test lung or a porcine lung. There was also a large disparity between the delivered and measured tidal volumes, especially at low frequencies. The extent of the leak varied greatly, depending on the position and size of the fistula, but also in the injection time percentage and the driving pressure. Factors associated with the lowest leak within the parameters of our measurements were a small, distal fistula, respiratory frequency \( > 200 \) min \(^{-1} \), injection time of 40%, and a driving pressure of 1.5 bar.

The principal aim when using HFJV in the management of a BPF is to optimize gas exchange, including delivery of gas to the parts of the lung distal to the fistula where possible. To do this, the leakage through the fistula must be minimized. In order to understand these data from a clinical perspective, it is easier to look at the ‘leak’ to ‘expired’ tidal volume ratio as this reflects the proportion of delivered gas escaping through the fistula. The \( L/E \) ratio depends on the geometry of the interface and ventilator settings [i.e. percentage of injection time, frequency, expired tidal volume \( (VTE) \), the distance of the jet orifice from the ‘fistula’, and the size and shape of the fistula]. We found that the proportion of injected and entrained gas leaking from the fistula was least at high frequencies (Table 1). This suggests that high frequencies are preferable to minimize leakage and increase gas delivery to the lung distal to the fistula.

The \( L/E \) ratio also decreased with increasing IT %, although this effect was less marked the more distal the fistula and leak were from the jet orifice. Another way to consider this is that the \( L/E \) ratio increases as the jet orifice approaches the fistula; this suggests it is better to position the jet orifice proximally to keep the \( L/E \) ratio low. Should the jet orifice be located distal to the fistula, we would expect the \( L/E \) ratio to be minimal since entrainment causes the airway pressures proximal to the jet orifice to drop to near zero or negative values.

Gas exchange during HFJV in clinical practice involves a number of mechanisms: bulk flow, augmented Taylor dispersion, the Pendelluft effect, gas profiling, molecular diffusion, and cardiogenic mixing. A combination of these mechanisms enables effective gas exchange when using HFJV in other clinical scenarios, but the pressures and volumes generated become more important when a BPF is present, because any increase in pressure or volume will increase gas leak through the fistula. One of the main reasons that HFJV (with low levels of auto-PEEP) is recommended for ventilating the lungs of patients with a BPF is because the low tidal volumes generated are assumed to greatly reduce the amount of gas leak through the fistula, although this may not occur in the presence of severe parenchymal lung disease. The tidal volume generated by the jet of gas produced by a high-frequency jet ventilator is determined by several factors, including driving pressure, entrainment ratio, injection time, lung compliance, and airflow resistance. In the presence of a BPF within otherwise normal lungs, the major determinants of the tidal volumes delivered during jet ventilation are the entrained and leak volumes, but these are difficult to predict and to quantify. The entrained volume is proportional to the negative pressure generated by the velocity of the jet stream; this depends on friction

### Table 2 Comparison of leak/expired volume ratios \( (L/E) \) when using HFJV at 20, 40, and 60 IT%, 1.5 bar DP, with 10 mm distal, middle, and proximal fistula sites in test lung. Data presented as mean (n = 6). Leak/expired ratios increase with fistula position (proximal > distal) and injection time percentage (60 > 20) but decreased with increasing frequency.

<table>
<thead>
<tr>
<th>Frequency</th>
<th>20% inspiratory time</th>
<th>40% inspiratory time</th>
<th>60% inspiratory time</th>
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<tbody>
<tr>
<td></td>
<td>Distal</td>
<td>Middle</td>
<td>Proximal</td>
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<tr>
<td>60</td>
<td>0.13</td>
<td>0.24</td>
<td>0.54</td>
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<tr>
<td>80</td>
<td>0.11</td>
<td>0.22</td>
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<tr>
<td>100</td>
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<td>0.19</td>
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<td>120</td>
<td>0.09</td>
<td>0.18</td>
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<tr>
<td>140</td>
<td>0.07</td>
<td>0.15</td>
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<td>160</td>
<td>0.06</td>
<td>0.14</td>
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<td>180</td>
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encountered by the jet stream which increases as it travels down the bronchial tree. If pressure were the sole determinant, entrainment would be greatest in the presence of a large proximal fistula when high driving pressures are used; conversely, entrained volumes would be lowest with a small distal fistula and low driving pressure. The leak volume also depends on the velocity and pressure of the gas stream at the fistula. As driving pressure increases, so does the velocity of the gas and since velocity is affected by friction within the conducting airways, a higher driving pressure applied to a more proximal fistula would be expected to produce a larger leak. Our results are consistent with these assumptions and with the findings of Barringer and colleagues who also found increased leak volumes with increased driving pressures when using high-frequency ventilation in a dog model. Their experimental model differed in several ways including the application of negative pressure suction. The data presented here are the first attempt to ascertain the effect of different ventilatory parameters and fistula position on overall ventilation volumes and the contribution of entrained gas. We have not performed any statistical analyses on these data because our study was observational in nature and not intended to address a specific hypothesis.

There are some limitations to our data and urge that extrapolations to clinical practice should be made with caution. The acrylic box used to house the pig lungs and test lungs was a rigid structure, unlike a human thoracic cage. In addition, the dimensions were slightly larger than a human thorax. The porcine lung specimens were supplied to us externally, obtained from animals used to provide heart valves for human transplantation. Only lungs with no overt signs of damage were used. We cannot exclude the possibility that the porcine lung specimens may have had very small unnoticed holes in the lung parenchyma, although we believe that this is unlikely because the results with intact lungs and test lungs were very similar.

The electrical connections for the differential and gauge pressure sensors caused a degree of drift in the oscilloscope trace. However, all the traces were reset to a zero reference point before the start of each experiment. The experimental schedule was constant apart from changing the ventilation method between experiments. All test lungs were identical. The digital flow analyser used to calibrate the flow sensors is considered the gold standard used in clinical practice for calibration of artificial ventilators. At the start of every experiment, all oscilloscope traces were calibrated to zero to eliminate any inaccuracy and all experiments were repeated six times. We also appreciate that leak and entrained volumes may change over time in live animals or in clinical practice for a variety of reasons, but this is outside the scope of this experimental model. The minimal variability with six repeated measurements suggests that no significant changes occurred over time in our model.

The reproducibility of the data acquired from the experimental set up is evident from the very low variability between repeated measurements. Further studies including computational modelling of jet ventilation are required to confirm these findings and assess the effects of changing lung compliance or airway resistance. It is also recognized that other methods of ventilation may be useful in the management of patients with a BPF such as high-frequency oscillatory ventilation and extracorporeal membranous oxygenation, with or without additional specific ventilatory modes that allow spontaneous ventilation. These may have advantages over HFJV in clinical settings, but the aim of this bench-top study was to investigate the important factors pertaining to HFJV and further data are required before comparisons can be made with other methods of ventilation or gas exchange used in practice.

In conclusion, several factors must be considered when using HFJV in the management of a patient with a BPF, in order to provide adequate ventilation while minimizing leak through the fistula. In our model, ventilation volumes (entrained, delivered, and leak) during HFJV were highly dependent on ventilator frequency. Leak volumes were generally low at frequencies > 200 min⁻¹ but also depended on the injection time percentage, driving pressure, the fistula size, and its position in relation to the emergerent jet. If extrapolated to the clinical setting, these data suggest that the ventilator rate should be set at > 200 min⁻¹, driving pressure maintained at 1.5 bar or less, and an injection time of ~40% is applied. The entrained volume can make a large contribution (~40-50%) to the total tidal volume, but these are not monitored by the jet ventilator and clinicians should be aware that the displayed tidal volumes are inaccurate. Further studies are required to confirm these findings in clinical practice.

**Supplementary material**

Supplementary material is available at British Journal of Anaesthesia online.

**Authors’ contributions**

M.J.W.: concept, experimental design data collection, data analysis and interpretation, drafting and revision of manuscript, and approval of final version. E.S.L.: concept, experimental design, data interpretation, revision of manuscript, and approval of final version. J.P.T.: concept, experimental design, data analysis and interpretation, revision of manuscript, and approval of final version.

**Declaration of interest**

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