Artificial Ventilation of a Canine Model of Bronchopleural Fistula

Irvin Mayers, M.D., F.R.C.P.(C),* Richard Long, M.D., F.R.C.P.(C),†
Peter H. Breen, M.D.,‡ L. D. H. Wood, M.D., Ph.D.§

The authors studied the abnormalities of gas exchange and lung mechanics in a canine model of bronchopleural fistula during intermittent positive pressure ventilation (IPPV) and high-frequency oscillatory ventilation (HFOV). The left lower lobe bronchus was opened to atmosphere and it was determined that end expired volume was best maintained at frequencies of 45–50 breaths/min. during IPPV. Comparing alternating periods of IPPV and HFOV in six dogs (Group 1) at matched airway opening pressure (P_a), we found that P_a decreased significantly to 68 ± 14 mmHg and 69 ± 24 mmHg, respectively, on opening the fistula. In a second group of six dogs (Group 2), when P_a was increased by additional bias flow into the ventilatory circuit during both IPPV and HFOV, P_a increased significantly to 89 ± 12 mmHg and 87 ± 8 mmHg, respectively. Repeating Group 2 studies after induction of oleic acid low-pressure pulmonary edema demonstrated that conventional IPPV was associated with large intrapulmonary shunts. HFOV, however, maintained gas exchange at near baseline values. For both Group 1 and Group 2, the calculated gas flow through the fistula was significantly less at all levels of airway pressure during HFOV. The authors conclude that HFOV offers advantages over conventional IPPV in the maintenance of oxygenation and in the reduction of gas leak through the fistula. (Key words: End-expiratory pressure, Hypoxia. Lung: edema. Ventilation: high frequency oscillatory; intermittent positive pressure.)

BRONCHOPLEURAL FISTULA complicates about 2% of pneumonectomies, and this complication is associated with a mortality approaching 20%. As well as surgical correction, current therapy of a large, persistent bronchopleural fistula includes independent ventilation of each lung, plugging the leak under bronchoscopic control, the addition of positive end-expired pressure (PEEP) to the pleural surface, and high-frequency ventilation. In order to better understand the associated abnormalities of lung mechanics and gas exchange, we studied a canine model of bronchopleural fistula during intermittent positive-pressure ventilation (IPPV) and during high-frequency oscillatory ventilation (HFOV). We postulated that the loss of volume through the fistula and the associated gas-exchange abnormalities might be improved with HFOV. We also tested the efficacy of IPPV with an additional inspiratory flow in the maintenance of gas exchange in this model. The effects of IPPV on oxygenation and leak rate through the fistula (V_LEAK) were compared with HFOV at high and at low levels of airway opening pressure (P_a). We also compared IPPV and HFOV following induction of low-pressure pulmonary edema where the gas-exchange problems would be worsened. We found that the primary determinant of oxygenation was the level of airway pressure and not ventilator mode. We also found that the V_LEAK was lower during HFOV for any given level of airway pressure.

Methods

ANIMAL PREPARATION

Twelve mongrel dogs (21 ± 2 kg) were anesthetized (pentobarbital 30 mg/kg) and intubated with a cuffed endotracheal tube. They were mechanically ventilated at a tidal volume (V_T) of 20 ml/kg (Harvard® ventilator) with room air. A port near the endotracheal tube was connected by low-compliance tubing to an air phase transducer (Validyne DP45-28®) to measure P_a. Ventilator frequency (f) was set to maintain Pao2 between 30–35 mmHg. Throughout the remainder of the experiment anesthesia was maintained with intermittent doses of pentobarbital (50–100 mg). A large-bore catheter was inserted into the femoral artery and connected to a Statham® pressure transducer to measure blood pressure. A second catheter was inserted into the femoral vein for fluid and drug administration. Arterial blood samples were analyzed at 37°C (Corning 165-2®) for Pao2, Paco2, and pH and were corrected for dog body temperature. Heating blankets were used to maintain dog body temperature near 37°C.

Following muscle paralysis (succinylcholine 100 mg), a wide thoracotomy was performed through the left fifth intercostal space. On opening the pleural space, 3–4 cmH2O PEEP was added to the expiratory line of the Harvard® ventilator (Emerson® PEEP valve). Using cautery, an opening was made in the lateral wall of the left
Fig. 1. Ventilatory cycles during IPPV are depicted schematically. Airway opening pressure ($P_{aw}$) is represented along the y-axis and time is represented along the x-axis. The solid lines represent ventilation at a frequency of 15 breaths/min. When the fistula is opened to atmosphere (arrow), the end expired pressure progressively decreases until it reaches atmospheric pressure. The interrupted lines depict the effect of increasing frequency to 45 breaths/min. On opening the fistula, the end expired pressure again decreases but the rapid ventilatory rate prevents it from reaching to atmospheric pressure. This formed the basis for the rapid ventilatory rates used during IPPV with the fistula open to atmosphere.

lower-lobe bronchus. A flexible tube (length 4.0 cm, ID 7 mm) was inserted through the opening in the wall of the bronchus, and the flared end of the tube was pulled against the bronchial wall. The tube was then secured with a purse-string suture with the tube at an angle of 90° to the long axis of the bronchus. The tube was clamped closed to atmosphere and the lungs were reinflated, ensuring that the left lower lobe was also inflated. A wide sternotomy was performed to ensure that pleural pressure was equal to atmosphere.

In six dogs a Swan-Ganz® catheter was positioned in the right atrium via the right external jugular vein. This was used for administration of oleic acid in the studies that included induction of low-pressure pulmonary edema. Following administration of the oleic acid, the catheter was then directed into a branch of the pulmonary artery and, with the balloon inflated, a pulmonary capillary wedge pressure (PCWP) could be obtained.

Ventilator Parameters

When the fistula was opened to the atmosphere during IPPV, f was increased to 45–50 breaths/min and $V_T$ was reduced to 10 ml/kg. Figure 1 outlines the rationale for the IPPV settings that were chosen. During HFOV, $P_{acO_2}$ was set by adjustment of $V_T$ or f on the oscillator (Metrex Instruments, Brampton, Ontario). The HFOV circuit (fig. 2) is similar to that described by Thompson et al. Briefly, a fresh gas flow (FGF) (bias flow) enters through the line labeled FGF in, is oscillated, and exits through the line labeled FGF out. A flexible connector was interposed between FGF in and a pressure port near the endotracheal tube. During HFOV, $P_{aw}$ was measured statically by simultaneously clamping the fistula and the flexible connector. During IPPV, mean $P_{aw}$ was obtained by electronically meaning the pressure signal over several respiratory cycles. During HFOV, $P_{aw}$ could be independently adjusted by altering the bias flow. In order to affect increases in $P_{aw}$ during IPPV, we added a bias flow to the inspiratory line of the Harvard® ventilator (fig. 2). The flow rate through the bias line was controlled by a flowmeter and the fractional inspired $O_2$ concentration ($FiO_2$) was controlled with a Bennett air–oxygen mixer.

Measurements

The $V_{LEAK}$ was calculated as the difference between inspired and expired ventilation during HFOV, timed volumes (30–60 s) were collected at the FGF out line (fig. 2) and at the FGF in lines. The timed volumes were collected in a Latex® meteorologic balloon and measured in

HFOV

VENTILATOR

FGFout FGF in $P_{aw}$ BPF clamp

LUNG

IPPV

VENTILATOR

EXP.

FRESH GAS FLOW $P_{aw}$ BPF INS.

LUNG

Fig. 2. Ventilator circuit and model. The upper panel shows the HFOV circuit with the fistula (BPF) at the left lower lobe bronchus. Airway pressure ($P_{aw}$) is measured at the pressure port after clamping the fistula and the flexible tubing (shown by X). Fresh gas enters at the inflow line (FGFin), is oscillated by the ventilator, and leaves the circuit at the outflow line (FGFout). The lower panel shows the IPPV circuit. The pressure port ($P_{aw}$) and fistula (BPF) are also schematically represented. During Group 2 experiments, a fresh gas flow line was connected to the circuit to allow increases in airway pressure during period IPPV 2 and during IPPV + FGF.
a water-sealed spirometer (Collins, Braintree, MA). Because the oscillator circuit was a closed system, the difference between flows at FGFin and FGFout was equal to the gas flow through the fistula.

During IPPV the gas flow through the fistula was calculated as the difference between the inspired flow and expired flow. Timed expired volumes were collected at the expiratory line and flows through the line were derived. Inspiratory gas flow (Vi) was calculated as the product of VT and f. Frequency was obtained from the oscillograph record and VT from the settings of the Harvard® ventilator. The VT settings of the ventilator, previously calibrated against the spirometer, were accurate to within 5%. In the experiments in which additional fresh gas was added to the IPPV circuit, the additional gas flow was measured as a timed-volume collection, as described for HFOV measurements. This additional gas flow was added to the calculated IPPV inspiratory flow.

**Experimental Protocol**

Following the sternotomy, 10–15 min were allowed for the animals to stabilize. The animals were divided into two groups of six dogs. All animals were ventilated for four 30-min periods of IPPV alternating with HFOV in the sequence IPPV1, HFOV1, IPPV2, and HFOV2 (table 1). In the first six dogs (Group 1), mean PAO was low during both IPPV periods and during both HFOV periods. In the second six dogs (Group 2), mean PAO was also low during IPPV1 and HFOV1 but was increased during IPPV2 and HFOV2. Between each period the fistula was closed to atmosphere and the animals received three lung inflations to total lung capacity (TLC) as determined by a transpulmonary pressure (Ptp) of 25–30 cmH2O.

In Group 1, baseline measurements were made with the fistula closed (period C). These included blood pressure, rectal temperature, blood gases, and PAO. The animals then received the four periods of ventilation. At the end of each 30-min period, all baseline measurements were repeated and fistula gas flow was measured as well. During IPPV1 and IPPV2, mean PAO was a function of ventilator settings and the gas flow through the fistula. The mean PAO during HFOV1 and HFOV2 was set to equal the mean PAO of the preceding IPPV period by adjusting the bias flow.

Group 2 animals were treated similarly to Group 1 during periods C, IPPV1, and HFOV1. During period IPPV2, the mean PAO was increased by adding a bias flow to the inspiratory line of the IPPV circuit (fig. 2). The mean PAO during IPPV2 was set to match the mean PAO of the fistula-closed period. During period HFOV2 the mean PAO was set equal to the mean PAO of period IPPV2 by adjusting the bias flow rate.

**Table 1. Experimental Protocol**

<table>
<thead>
<tr>
<th>Group 1</th>
<th>PAO*</th>
<th>Group 2</th>
<th>PAO</th>
</tr>
</thead>
<tbody>
<tr>
<td>IPPV1</td>
<td>low</td>
<td>IPPV1</td>
<td>low</td>
</tr>
<tr>
<td>HFOV1</td>
<td>low</td>
<td>HFOV1</td>
<td>low</td>
</tr>
<tr>
<td>IPPV2</td>
<td>low</td>
<td>IPPV2</td>
<td>high</td>
</tr>
<tr>
<td>HFOV2</td>
<td>low</td>
<td>HFOV2</td>
<td>high</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Oleic acid administered</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>IPPV + FGF</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>HFOV</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>IPPV</td>
<td></td>
</tr>
</tbody>
</table>

Each period lasted 30 min. The fistula was closed and the lungs were inflated between periods. Only in Group 2 experiments was oleic acid administered following period HFOV2. See text for further discussion.

* Mean airway opening pressure.

In Group 2 dogs, the experimental protocol was extended to examine the interaction of pulmonary edema with a bronchopleural fistula. Following period HFOV2, oleic acid (0.05 ml/kg) was infused through a Swan-Ganz® catheter into the right atrium. The FIO2 was then increased to 0.6, and for the duration of the experiment PCWP was maintained constant with volume infusion (dextran 75) as necessary. After allowing 90 min for the lesion to stabilize, all measurements were repeated with the fistula closed (period C1). The fistula was then opened and the dogs were ventilated for an additional three periods. The first dog to follow this protocol (number 7), died during the initial IPPV period when bias flow was not added to maintain PAO. For the following five experiments (dogs number 8–12), the sequence of ventilatory periods was IPPV with a bias flow (IPPV + FGF), HFOV, and then conventional IPPV (no added bias flow). Between periods the fistula was closed and the lungs were inflated to TLC. During periods IPPV + FGF and HFOV, the mean PAO was prospectively set to match period C1 by adjusting the bias flow. During IPPV without a bias flow, the mean PAO was not prospectively set to a predetermined value.

**Statistics**

Statistical comparisons between Group 1 and Group 2 were made using an unpaired t test. Comparisons between periods within a group were made with an analysis of variance (ANOVA), and when applicable, Tukey's test for multiple comparisons. A P value less than 0.05 was considered to show a significant difference. Results are presented as mean value ± SD.

**Results**

Group 1. Table 2 shows the effect on mean PAO, PAO2, and PAOCO2 of opening the fistula. Values of both mean PAO and mean PAO2 were significantly lowered during the four
TABLE 2. Ventilatory Variables in Two Groups of Dogs with Normal Lungs

<table>
<thead>
<tr>
<th>Group</th>
<th>C</th>
<th>IPPV₁</th>
<th>HFOV₁</th>
<th>IPPV₂</th>
<th>HFOV₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>PaO₂ (mmHg)</td>
<td>1</td>
<td>35 ± 4</td>
<td>35 ± 2</td>
<td>34 ± 5</td>
<td>32 ± 7</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>34 ± 6</td>
<td>35 ± 5</td>
<td>33 ± 4</td>
<td>30 ± 3</td>
</tr>
<tr>
<td>pH</td>
<td>1</td>
<td>7.30 ± 0.03</td>
<td>7.33 ± 0.04</td>
<td>7.34 ± 0.03</td>
<td>7.34 ± 0.03</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>7.34 ± 0.01</td>
<td>7.35 ± 0.10</td>
<td>7.38 ± 0.05</td>
<td>7.37 ± 0.04</td>
</tr>
<tr>
<td>V₁ (ml/kg)</td>
<td>1</td>
<td>19.7 ± 1.4</td>
<td>10.0 ± 1.0*</td>
<td>2.3 ± 0.3*</td>
<td>10 ± 1.0*</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>20.1 ± 0.8</td>
<td>9.7 ± 1.3*</td>
<td>1.9 ± 0.2*</td>
<td>7.0 ± 2.0*</td>
</tr>
<tr>
<td>frequency (cycles/s)</td>
<td>1</td>
<td>0.22 ± 0.05</td>
<td>0.68 ± 0.07*</td>
<td>10.8 ± 0.8*</td>
<td>0.69 ± 0.08*</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.23 ± 0.07</td>
<td>0.77 ± 0.06*</td>
<td>15.0 ± 2.0*</td>
<td>0.78 ± 0.06*</td>
</tr>
<tr>
<td>PEEP (cmH₂O)</td>
<td>1</td>
<td>4.3 ± 0.7</td>
<td>0.8 ± 0.4*</td>
<td>—</td>
<td>0.7 ± 0.4*</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>4.2 ± 0.4</td>
<td>1.7 ± 1.3*</td>
<td>—</td>
<td>5.1 ± 1.0*</td>
</tr>
<tr>
<td>V̅L̅EAK (l/min)</td>
<td>1</td>
<td>0</td>
<td>7.72 ± 1.11</td>
<td>3.03 ± 1.24*</td>
<td>7.89 ± 1.16</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.95 ± 1.99</td>
<td>8.00 ± 3.12*</td>
<td>17.74 ± 2.29*</td>
<td>14.05 ± 1.80*</td>
</tr>
<tr>
<td>V₁ (l/min)</td>
<td>1</td>
<td>5.1 ± 0.9</td>
<td>8.1 ± 0.9*</td>
<td>4.7 ± 1.4*</td>
<td>8.2 ± 1.0*</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>6.1 ± 1.7</td>
<td>9.7 ± 1.2*</td>
<td>10.8 ± 3.5*</td>
<td>21.7 ± 3.4*</td>
</tr>
<tr>
<td>PaO₂ (mmHg)</td>
<td>1</td>
<td>88 ± 6</td>
<td>70 ± 15*</td>
<td>55 ± 14*</td>
<td>67 ± 14*</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>87 ± 7</td>
<td>67 ± 9*</td>
<td>68 ± 16*</td>
<td>89 ± 12*</td>
</tr>
<tr>
<td>Pet (cmH₂O)</td>
<td>1</td>
<td>6.5 ± 0.9</td>
<td>2.4 ± 0.4*</td>
<td>2.6 ± 0.4*</td>
<td>2.5 ± 0.6*</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>6.4 ± 1.0</td>
<td>3.2 ± 1.3*</td>
<td>3.8 ± 0.6*</td>
<td>6.4 ± 1.0*</td>
</tr>
</tbody>
</table>

* Significant difference from the preceding IPPV period (P < 0.05).
† Difference from Group 1 to Group 2 experiments by t test (P < 0.05).
‡ Difference from control period (C) by ANOVA (P < 0.05).

During IPPV, PEEP could not be measured.

Mean results (±SD) are shown.

V̅L̅EAK = gas flow through the fistula; V₁ = total inspiratory flow; 
P̅aO₂ = mean airway pressure; V̅t = tidal volume; PEEP = positive end-expiratory pressure.

During IPPV₁ and IPPV₂, the V̅L̅EAK was similar. The V̅L̅EAK was not different between periods HFOV₁ and HFOV₂. During either HFOV period, however, the leak rate was lower than during either IPPV period (P < 0.05). The larger leak rate during IPPV necessitated a significantly greater V₁ during IPPV than during HFOV.

Group 2. Table 2 also shows the mean values of P̅aO₂ and 
P̅aCO₂ for Group 2. In Group 2, during periods IPPV₂ and 
HFOV₂ the mean airway pressure was prospectively increased to match that during period C. Figure 3 depicts the changes in P̅aO₂ and P̅aCO₂ from Group 1 to Group 2 as bias flow is added (IPPV₂) or increased (HFOV₂). In Group 1, mean P̅aO₂ was significantly greater during period C when compared with the rest of the periods (P < 0.05 by ANOVA). In Group 2, mean P̅aO₂ was similar during IPPV₂ and HFOV₂ compared with period C, but was significantly less during periods IPPV₁ and HFOV₁. In Group 1, the mean P̅aO₂ decreased significantly on opening the fistula and remained lower than during period C for all four subsequent ventilatory periods. In Group 2, mean P̅aO₂ during periods IPPV₂ and HFOV₂ was similar to period C and significantly greater (by ANOVA) than either periods IPPV₁ or HFOV₁. In general the level of P̅aO₂ paralleled the level of mean P̅et in both Group 1 and Group 2.

In Group 2, the leak rate through the fistula was significantly greater in periods with higher levels of P̅et (IPPV₂ and HFOV₂) than in periods with lower levels of P̅et (IPPV₁ and HFOV₁). When comparing periods with matched levels of P̅et, the leak rate during HFOV was significantly lower than during the matched IPPV periods. Table 2 also shows that V₁ increased from period C to periods IPPV₁ and HFOV₁. V₁ increased further over the preceding periods during periods IPPV₂ and HFOV₂.

Figure 4 illustrates the mean values of minute ventilation delivered by the Harvard ventilator and the associated mean P̅aCO₂ for Group 2. P̅aCO₂ was similar between the three periods but the associated minute ventilation decreased significantly from period IPPV₁ to period IPPV₂ (449 ± 74 ml·kg⁻¹·min⁻¹ and 291 ± 131 ml·kg⁻¹·min⁻¹, respectively). During period C neither minute ventilation (284 ± 80 ml·kg⁻¹·min⁻¹) nor P̅aCO₂ were significantly different from period IPPV₂.
EFFECT OF VENTILATOR MODE ON FISTULA FLOW

In figure 5, flow through the fistula is plotted as a function of $P_{ao}$ for each animal. IPPV periods (closed circles) are examined separately from HFOV periods (open circles). These points yielded two distinct regression lines by ANOVA of linear regression ($F = 9.4, P < 0.01$). However, the slopes of the lines were not different using a t statistic.

OLEIC ACID

Table 3 illustrates the values of $P_{aO_2}$ in individual dogs following administration of oleic acid. One animal (number 10) died during period C1 and therefore no further data are available. One animal (number 7) died while receiving conventional IPPV. A $P_{aO_2}$ of 40 mmHg was recorded prior to its death. In the remaining four animals (numbers 8, 9, 11, and 12), when bias flow was used to maintain $P_{ao}$ at levels similar to period C1, then $P_{aO_2}$ was similar to C1 values. This was true for either IPPV or HFOV during which $P_{aO_2}$ was 93% and 90% of period C1 values, respectively. When bias flow was not added during IPPV, the $P_{aO_2}$ decreased to 33% of period C1 values and two animals became so hypoxic that we could not complete the full 30-min ventilatory period.

Although the mean $P_{ao}$ was similar during conventional IPPV and during IPPV with added bias flow (6.3 ± 1.4 cmHgO and 6.8 ± 1.3 cmHgO, respectively), the distribution of the airway pressures during the respiratory cycle tended to be different. Conventional IPPV had greater peak airway pressures than did IPPV with bias flow (13.8 ± 4.4 cmHgO and 10.1 ± 3.1 cmHgO, respectively), but

**Fig. 3.** Mean airway pressure ($P_{aw}$) is shown in the upper panel and $P_{aO_2}$ in the lower panel for Group 1 (open circles and interrupted lines) and Group 2 (closed circles and solid lines). The ventilatory periods are shown along the x-axis (C = fistula closed; I1 = IPPV1; H1 = HFOV1; I2 = IPPV2; and H2 = HFOV2). * represents a difference between Group 1 and Group 2 by t test ($P < 0.05$).

**Fig. 4.** The upper panel illustrates the stability of the $P_{aCO}_2$ in Group 2 during IPPV (C = fistula closed period; I1 = IPPV1 period; I2 = IPPV2 period). $P_{aCO}_2$ was similar between the three ventilatory periods. The lower panel illustrates the associated minute ventilation ($V_{min}$) delivered by the Harvard® ventilator. There was a significant decrease in $V_{min}$ between I1 and I2 ($P < 0.05$). $V_{min}$ was similar between C and I2.
conventional IPPV had lesser values of PEEP than did IPPV with added bias flow (1.9 ± 1.5 cmH2O and 5.1 ± 1.2 cmH2O, respectively). Because of the small number of animals completing all stages of the experiment, statistical tests for significance were not performed.

Discussion

MODEL

We believe this model of bronchopleural fistula allows useful extrapolations to be made to the clinical setting. In our model the pleural pressure was set at atmospheric pressure and, therefore, the pressure driving flow through the fistula was equal to \( P_{ao} \). Also, \( P_{up} \) was equal to \( P_{ao} \). Finally, lung volumes could be inferred from values of \( P_{ao} \) because the product of compliance and \( P_{up} \) is lung volume. In order to obtain reliable measurements of pleural pressure and of volume lost through the fistula, we elected to use an open-chest preparation. The extrapolation of our findings to the clinical setting (i.e., closed chest with chest tube evacuating air) may not be exact but should yield an approximation of clinical findings. Our model, with known pressures and known size and site of fistula, allows comparisons between individual experiments and allows comparison of ventilator mode on lung mechanics and leak rate.

In preliminary experiments we found that measuring the leak rate by a volume collection of gas directly from the fistula site decreased the fistula flow rate by increasing fistula resistance. Therefore, we measured the leak indirectly, as the difference between inspiratory and expiratory flows. In this model the mean fistula leak rates were large, ranging between 81% to 98% of the \( V_i \) during IPPV periods and between 60% to 79% during HFOV periods. Also, in preliminary studies we found that IPPV at slow frequencies (10–12 breaths/min) allowed sufficient time for gas to escape through the fistula and end-expired pressure to decrease to near zero. By increasing IPPV frequency to near the maximal rate the ventilator could deliver (45–50 breaths/min), it was possible to maintain a positive, although low, value of end-expired pressure. During IPPV we could not, however, increase end-expired pressures back to control levels even with complete occlusion of the expiratory line of the ventilator. The HFOV ventilatory circuit allowed an adjustable bias flow of gas and, although increasing the bias flow increased the fistula leak rate, it also set a larger lung volume. The use of a bias flow was therefore extended to the IPPV circuit and similar results were obtained.

We elected to measure mean airway pressure as a static pressure determination. It has been demonstrated that during HFOV, static determinations better reflect alveolar pressures than do dynamic measurements obtained at the airway opening during oscillations.\(^{11}\) Therefore, we elected to match airway pressures obtained dynamically during IPPV with those obtained statically during HFOV.

**GAS EXCHANGE**

The animals ventilated at the low airway pressures tended to be hypoxic. When the airway pressure was increased (Group 2 during IPPV and HFOV), the hypoxia was abolished. When the level of airway pressure was matched between IPPV and HFOV, there were no significant differences in oxygenation. Therefore, we feel that in this model, the level of oxygenation is not deter-

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**Table 3. \( P_{ao} \) in Group 2 Following Oleic Acid Edema**

<table>
<thead>
<tr>
<th>Dog No.</th>
<th>( C_i )</th>
<th>IPPV + FGF</th>
<th>HFOV</th>
<th>IPPV</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>91</td>
<td>—</td>
<td>—</td>
<td>40*</td>
</tr>
<tr>
<td>8</td>
<td>74</td>
<td>56</td>
<td>59</td>
<td>34†</td>
</tr>
<tr>
<td>9</td>
<td>272</td>
<td>263</td>
<td>260</td>
<td>38†</td>
</tr>
<tr>
<td>10</td>
<td>91*</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>11</td>
<td>237</td>
<td>233</td>
<td>304</td>
<td>46</td>
</tr>
<tr>
<td>12</td>
<td>250</td>
<td>228</td>
<td>166</td>
<td>99</td>
</tr>
</tbody>
</table>

Each animal is represented for periods of fistula closed (\( C_i \)), positive pressure ventilations with a fresh gas flow (IPPV + FGF), oscillation (HFOV), and conventional positive pressure ventilation (IPPV).

* Represents the period during which the animal died; †represents inability to complete the full 30-min period. Dog number 7 died during IPPV prior to other periods being attempted and dog number 10 died during \( C_i \). —represents no data available during the period.
minded by ventilator waveform (i.e., IPPV vs. HFOV) but rather is a function of airway pressure.

We extended the study of Group 2 dogs to examine the interaction of pulmonary edema with a bronchopleural fistula. We found that despite increasing the \( F_{O_2} \) to 0.6, the animals became profoundly hypoxic when ventilated by conventional IPPV. We occluded the expiratory limb of the ventilator, but we could not increase PEEP by these means. Presumably, occluding the expiratory limb increased the leak through the fistula without changing end expired lung volumes. This severe hypoxia, however, could be alleviated by ventilation at the higher levels of PEEP made possible by the use of a bias flow during IPPV. The same effect could be achieved by HFOV with increased bias flow. It has been previously demonstrated that in the presence of pulmonary edema, increasing mean \( P_{aw} \) during HFOV improves gas exchange.\(^{10,12,13}\) In our model we could not increase airway pressure except by increasing bias flow. The importance of maintaining lung volumes in the setting of a bronchopleural fistula has been demonstrated clinically\(^{14}\) but the methods suggested previously have included application of some fraction of airway PEEP to the pleural surface. This must result in a reduction of \( P_{aw} \). Our data suggest that decreasing \( P_{aw} \) is associated with worsening hypoxia and cause us to question the clinical efficacy of such maneuvers, especially in the setting of associated pulmonary edema.

**Alveolar Ventilation**

Even in the presence of a large fistula, we were able to maintain CO\(_2\) elimination. During IPPV in Group 1, the minute ventilation was tripled and this would tend to increase CO\(_2\) elimination. Also, with the large flow through the fistula, there would be minimal alveolar gas in the upper airway down to the level of the fistula and, therefore, anatomic dead space would be reduced. In group 2, the addition of a bias flow to IPPV further decreased dead space. This is implied by a constant \( P_{CO_2} \), despite a decreased minute ventilation delivered by the ventilator from IPPV\(_1\) to IPPV\(_2\) (fig. 4). This may have been due to recruitment of collapsed alveoli caused by the higher airway pressures during IPPV\(_2\). Alternately, the use of a bias flow may have resulted in gas exchange by constant-flow ventilation.\(^{15}\) Lehner et al. were able to maintain adequate \( O_2 \) and CO\(_2\) exchange by constant flows introduced at the level of the carina. Although our model is different, it is possible that the improved gas exchange we observed was a function of constant-flow ventilation in addition to conventional IPPV.

**Leak Rate**

We observed a lower leak rate through the fistula during HFOV when compared with IPPV. The plot of \( V_{LEAK} \) and mean \( P_{aw} \) (fig. 5) describes the pressure–flow characteristics of the fistula. The slopes of the lines are the same. Therefore, at the frequencies we employed during IPPV and HFOV, the impedances to the flow through the fistula are the same. We believe that the decreased flow through the fistula can be explained by the Bernoulli equation.\(^{16}\) This equation can be written as:

\[
P_1 - P_2 = \frac{1}{2} \rho u_2^2 - \frac{1}{2} \rho u_1^2
\]

where \( P_1 \) and \( P_2 \) = pressures (dynes) at location 1 and 2, respectively; \( \rho \) = gas density (g/cm\(^3\)); and \( u_1 \) and \( u_2 \) = gas velocity (cm/s) at location 1 and 2, respectively. (Note that 980 dyn = 1 cmH\(_2\)O). This equation implies that as gas velocity decreases, the lateral pressure exerted by the gas increases. Mean \( P_{aw} \) was measured statically during HFOV (i.e., \( u = 0 \)); therefore, during oscillation the lateral pressure at the left lower lobe would be less than the value of mean \( P_{aw} \). Also, the Bernoulli equation would predict that the driving pressure for leak through a central fistula during HFOV would always be less than alveolar pressure. Using theoretical data from Fredberg\(^{17}\) for gas velocity during HFOV and a value of 1.1 \( \times 10^{-3} \) g/cm\(^3\) for gas density yields a pressure 1 to 2 cmH\(_2\)O lower at the left lower-lobe bronchus (\( u_2 = 1600 \) cm/s) than at the alveolus (\( u_1 < 0.5 \) cm/s). If this explanation is true, then increasing gas velocity during HFOV by increasing oscillator frequency would further increase the Bernoulli pressure drop, and this would be associated with a further reduction in fistula gas flow.

It is not certain that a fistula occurring at a more peripheral site would behave in a similar manner, and extrapolation of these results to such a setting would not be warranted. The obvious treatment of a large bronchopleural fistula is surgical correction. When this is not possible or when an unacceptable time delay is involved, then ventilator management becomes more important. In the setting of a large, central bronchopleural fistula, the use of HFOV appears to offer advantages over conventional IPPV both in reduction of gas lost through the fistula and in the use of a bias flow system to effect increased lung volumes. In the setting where safe HFOV is not available, IPPV at relatively high frequencies in conjunction with an additional fresh gas flow line may offer a reasonable method for acute maintenance of gas exchange.

The authors thank Dr. N. R. Anthonesin for his review of this manuscript and his constructive criticisms.

**References**
