High-frequency, Small-volume Ventilation during Thoracic Surgery

James A. Glenski, M.D.,* Matthew Crawford, B.S., M.B., F.F.A.R.A.C.S.,† and Kai Rehder, M.D.‡

Surgical conditions during conventional mechanical ventilation (CMV) and pulmonary gas exchange were compared with those during high-frequency ventilation (HFV) in 24 patients undergoing anesthesia for intrathoracic surgery. HFV at an oscillatory frequency of 3 Hz and a delivered gas volume of 1.3–1.9 ml/kg provided excellent surgical conditions for peripheral lung procedures. However, surgical conditions for procedures on the major airways or mediastinal structures were unsatisfactory during HFV. Adequate pulmonary gas exchange was achieved with HFV when the chest was open. Further evidence is presented for expiratory flow limitation during HFV. Expiratory flow limitation seems to occur particularly in patients with chronic obstructive airway disease, leading to increased lung volume. Currently, the authors do not recommend HFV for routine use during anesthesia for thoracic surgery. (Key words: Surgery: thoracic. Ventilation: gas exchange; high-frequency; mechanical.)

Three major forms of high-frequency ventilation exist. These are high-frequency, positive-pressure ventilation (HFPPV), high-frequency jet ventilation (HFJV), and high-frequency ventilation (HFV), sometimes also referred to as high-frequency oscillation (HFO). During HFPPV, modified conventional mechanical ventilators, which operate at rates typically ranging from 60 to 150 breaths/min, are used. HFJV involves the rapid delivery of small pulses of gas via a cannula in the upper airway at frequencies ranging between 150 to 300 breaths/min. During HFV, gas is delivered to the airways by different devices, such as loudspeakers, ball-valve interruptors, or piston pumps. With HFV, oscillatory frequencies as high as 3000/min have been used.

Previously, we have shown that HFV can maintain adequate pulmonary gas exchange in anesthetized volunteers3 and in patients undergoing elective orthopedic or abdominal surgery.4 We did not recommend the routine use of HFV for this type of surgery because we believed that the disadvantages outweighed the advantages. It has been reported that, compared with conventional mechanical ventilation (CMV), HFJV and HFPPV may provide superior surgical conditions during certain types of thoracic surgery while maintaining similar to better pulmonary gas exchange.5–7 This investigation evaluated thoracic surgical conditions and pulmonary gas exchange during HFV.

Methods

Twenty-four anesthetized patients (24 to 76 yr, 52 to 113 kg) undergoing elective thoracotomies were studied. Eleven patients were operated on while in the left and 13 while in the right lateral decubitus position. Preoperative pulmonary function tests were performed in 12 patients; nine of these had obstructive and two had restrictive lung disease. Pulmonary function studies were normal in one patient. The remaining patients had no pulmonary function testing performed before the operation, but clinically had normal lung function for their ages, as assessed by history and physical examination. A pneumectomy was performed in one patient, a lobectomy in 12 patients, and a wedge resection in 11 patients.

Anesthesia was induced with intravenously administered thiopental sodium. The trachea was intubated with an oral cuffed endotracheal tube (8 to 9 mm ID) after the intravenous administration of succinylcholine chloride. CMV was instituted with a tidal volume of 8–10 ml/kg, a rate of 8–10 breaths/min, and 0 cm H2O of end-expiratory pressure. Anesthesia was maintained with isoflurane or enflurane vaporized in oxygen, and muscle paralysis was maintained by pancuronium bromide. Supplemental morphine sulfate or fentanyl citrate was administered intravenously.

The high-frequency ventilator system consisted of a variable-stroke piston pump (9.6 cm ID) driven by a variable-speed electrical motor (fig. 1). The pump was connected by a reinforced silastic tube (12.5 mm ID, 60 cm long) to a four-port connector. The second port of the connector accepted a 2.8-m long, noncompressible filter tube; the internal diameter of the bias tube used in the first three patients was 9 mm and, in the last 21 patients, 6 mm. The distal end of the bias tube was attached to a Venturi system, which was used to adjust the lung volume during HFV. An anesthetic scavenging system was attached to the Venturi system. The third port of the connector was attached to the endotracheal tube. Humidified oxygen (10 l/min) containing anesthetic vapors entered the system through a 2-mm ID orifice fitted into the fourth...
quency and stroke volume were used before heart rate (ECG), arterial blood pressure, esophageal temperature (thermistor), and $P_{\text{co2}}$ were recorded. During HFV, delivered gas volume and $P_{\text{aCO2}}$ were measured. Immediately thereafter, an arterial blood sample was obtained for measurement of pH and of oxygen ($P_{\text{aO2}}$) and carbon dioxide ($P_{\text{aCO2}}$) tensions; all blood gas tensions were corrected for body temperature. During CMV, arterial blood samples were obtained before thoracotomy or after the thoracotomy wound had been closed. During HFV, arterial blood gas samples were obtained only while the thorax was open.

In all but eight patients, CMV was continued after the pleural cavity was opened so that the operating conditions with both modes of pulmonary ventilation could be compared by the surgeon. To measure delivered volume, HFV was instituted temporarily while the chest was closed in eight patients.

All patients were visited throughout their hospital stay to determine the incidence of complications. $P_{\text{aCO2}}$ and $P_{\text{aO2}}$ were tested for differences using the Student's $t$ test for paired data. The $(P_{\text{aCO2}} - P_{\text{aO2}})$ difference between patients with chronic obstructive airway disease and patients with clinically normal pulmonary function was tested using an unpaired Student's $t$ test; $P < 0.05$ was considered significant. Results are reported as the mean ± standard deviation.

**Results**

For peripheral lung work, operating conditions during HFV at 3 Hz were judged by the thoracic surgeons to be superior to those during CMV in all patients. The lung could be manipulated easily and had little or no tendency to encroach upon the surgical field, except in two patients in whom pronounced hyperinflation occurred with HFV. These patients had chronic obstructive airway disease, and the hyperinflation of the lungs could be minimized by increasing the suction at the distal end of the bias tube. Surgery around the hilum or mediastinal structures was associated with a large mediastinal "bounce," which made surgical work difficult. Changes in the large diameter airways with each oscillation made surgery on the major airways almost impossible. At frequencies greater than 3 Hz, the vibration of the surgical field was annoying and offered little or no advantage over the conditions during CMV.

Adequate pulmonary gas exchange was maintained with both CMV and HFV (table 1). Small but progressive increases in $P_{\text{aCO2}}$ occurred in the first three patients. This problem was eliminated by replacing the 9.0-mm ID bias tube with one having the same length but an ID of 6.0 mm. There were no significant differences in systemic arterial pressure, pulse rate, or body temperature between the two modes of ventilation.
TABLE 2. Pump Settings and Respiratory Variables during High-frequecy Ventilation at 3 Hz

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Stroke volume (ml/kg)</td>
<td>2.1 ± 0.2</td>
</tr>
<tr>
<td>Delivered gas volume (ml/kg)</td>
<td>1.6 ± 0.3</td>
</tr>
<tr>
<td>Mean airway pressure ($P_{aw}$) (cm H$_2$O)</td>
<td>4.2 ± 2.3*</td>
</tr>
<tr>
<td>Occlusion pressure ($P_{occ}$) (cm H$_2$O)</td>
<td>7.8 ± 2.4</td>
</tr>
<tr>
<td>$P_{aw} - P_{es}$ (cm H$_2$O)</td>
<td></td>
</tr>
<tr>
<td>Patients with chronic obstructive</td>
<td>6.1 ± 2.5†</td>
</tr>
<tr>
<td>airway disease</td>
<td></td>
</tr>
<tr>
<td>Patients with clinically normal</td>
<td>1.8 ± 1.9</td>
</tr>
<tr>
<td>pulmonary function</td>
<td></td>
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</tbody>
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Mean ± SD.
* Significantly less than occlusion pressure ($P < 0.01$).
† Significantly greater than in patients with clinically normal pulmonary function ($P < 0.01$).

The mean delivered gas volume was 76% of the stroke volume produced by the HFV-pump (table 2), ranging from 58 and 100% (i.e., no resonant amplification of delivered volume occurred). $P_{es}$ was significantly less than $P_{occ}$. Patients with chronic obstructive airway disease had significantly larger differences in ($P_{occ} - P_{es}$) than did patients with clinically normal lungs. The largest difference was noted in a patient with obstructive airway disease ($FEV_1/VC = 0.55$), in which ($P_{occ} - P_{es}$) = 9 cm H$_2$O.

Pressure tracings obtained during initiation of HFV showed larger amplitudes during expiration than during inspiration (fig. 2, left upper panel). Inspiratory and expiratory pressure tracings became more similar a few seconds after initiation of HFV. Large changes in expiratory flow occurred when tracheal pressure was least (see arrow in fig. 2, left lower panel). Differences between inspiratory and expiratory flow patterns at the initiation of HFV were more common in patients with chronic obstructive airway disease than in patients with clinically normal lungs, and these differences were less obvious at higher mean airway pressures (that is, at higher lung volumes) (fig. 3).

The only complication associated with the study was bronchospasm, which developed in one patient while in the recovery room. The bronchospasm responded to intravenously administered aminophylline, and the patient's subsequent postoperative course was uneventful. One patient died from an acute myocardial infarction 3 d after surgery.

**Discussion**

In anesthetized-paralyzed patients undergoing thoracic surgery in the lateral decubitus position, HFV resulted in 1) adequate pulmonary gas exchange, 2) excellent surgical conditions for peripheral lung surgery, and 3) unsatisfactory surgical conditions for mediastinal or major airway surgery.

Because of the briefness of the surgical procedures and the desire to achieve a quasi-steady-state, arterial blood for blood gas analyses could be obtained during CMV only while the thorax was closed and during HFV only while the thorax was open. The efficiency of pulmonary gas exchange of these two modes of ventilation, therefore, cannot be compared. However, adequate pulmonary gas exchange was provided during HFV in all patients. Moreover, during HFV with the thorax open, $PaO_2$ was not significantly different from the $PaO_2$ during CMV after the chest had been closed.

The rationale for using HFV during intrathoracic surgery was to improve surgical conditions without resultant hypoxemia. In our experience, HFV was not associated with hypoxemia (an association that is often seen with one-lung anesthesia). However, the surgical conditions for procedures involving the mediastinum and large airways were inferior to the conditions that can be obtained with one-lung anesthesia because of the changes in airway diameters. In our hands, HFV is not a suitable alternative for use in mediastinal or major airway procedures. The
large changes in airway diameter may be of functional importance because a fraction of the delivered gas volume may be lost through the shunting of the delivered volume to airway distension.

Previous work has suggested that expiratory flow limitation may occur during HFV.1,2,10 During HFV, increases in lung volume were demonstrated by Rehder et al.1 in healthy anesthetized volunteers, and by Crawford and Rehder2 in anesthetized patients. Tracheal pressure tracings and the asymmetry between the inspiratory and expiratory flow during initiation of HFV suggest expiratory flow limitation. This expiratory flow limitation could contribute to the increases in lung volume. Interestingly, Paco2 was always higher than Pao2.

In conclusion, HFV resulted in adequate pulmonary gas exchange during thoracic surgery. HFV improved surgical conditions for peripheral lung work. However, during HFV, surgical conditions were unsatisfactory for mediastinal or major airway procedures. We do not recommend HFV as a routine procedure during thoracic surgery because we believe the disadvantages of HFV outweigh the advantages. The disadvantages include 1) monitoring heart and breath sounds with an esophageal stethoscope is difficult during HFV; 2) the adequacy of ventilation cannot be judged from the motion of the chest or lung; 3) the use of anesthetic gases is high; and 4) assessment of lung volume is difficult.

References