

## High-frequency Small-volume Ventilation in Anesthetized Humans

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

Pulmonary gas exchange during conventional mechanical ventilation (CMV) (tidal volume 10 ml/kg, rate 8-10 breaths/min) was compared with that during high-frequency small-volume ventilation (HFV) in 67 patients undergoing anesthesia for various surgical procedures. HFV was studied at oscillation frequencies ranging from 3 to 18 Hz with stroke volumes of 0.8 to 2.2 ml/kg. Adequate pulmonary gas exchange was achieved with CMV and HFV, and the efficiency of oxygenation, that is, (A-a)D<sub>O<sub>2</sub></sub>, was similar in the two conditions. During HFV, the lung volume was higher than during CMV in most patients. Muscle paralysis did not significantly change either Pa<sub>CO<sub>2</sub></sub> or Pa<sub>O<sub>2</sub></sub>. In general, increasing fresh gas flow into the HFV system above approximately 10 l/min resulted in little reduction in Pa<sub>CO<sub>2</sub></sub>, but reduction of fresh gas flow below approximately 6 l/min increased Pa<sub>CO<sub>2</sub></sub> progressively. Currently, we do not recommend HFV at 12-18 Hz for routine use during anesthesia for orthopedic or abdominal surgery. (Key words: Lungs: gas exchange. Ventilation: high frequency; mechanical.)

HIGH-FREQUENCY small-volume ventilation (HFV) provides adequate pulmonary gas exchange in subjects with normal or abnormal lungs.<sup>1-4</sup> Some authors reported arterial oxygenation to be improved with HFV over that observed with conventional mechanical ventilation (CMV).<sup>2,3</sup>

Butler *et al.*<sup>2</sup> suggested that this improved oxygenation may be due to better matching of ventilation to perfusion ( $\dot{V}/\dot{Q}$ ). Since the induction of anesthesia increases the mismatching of  $\dot{V}/\dot{Q}$ ,<sup>5,6</sup> we examined whether HFV also improves oxygenation in anesthetized humans. We found no difference in the efficiency of oxygenation between these two modes of ventilation. In addition, we were interested in the practicality of HFV in the operating room.

\* Special Clinical Fellow in Anesthesiology, Mayo Clinic and Mayo Foundation.

† Professor of Anesthesiology and Physiology, Mayo Medical School.

Received from the Departments of Anesthesiology and Physiology and Biophysics, Mayo Clinic and Mayo Foundation, Rochester, Minnesota. Accepted for publication September 21, 1984. Supported in part by National Heart, Lung and Blood Institute research grant HL-21584 and grants from Ohio Medical Products, Madison, Wisconsin, and Siemens Medical Systems, Iselin, New Jersey.

Address reprint requests to Dr. Rehder: Department of Anesthesiology, Mayo Clinic, 200 First Street SW, Rochester, Minnesota 55905.

### Methods

Sixty-seven anesthetized patients (21 to 78 yr, 44-150 kg) were studied. All but four of the patients were undergoing elective orthopedic procedures on a lower extremity; four were general surgical patients. The patients were lying in the supine (n = 60) or lateral decubitus position (n = 7). Most patients (n = 53) had a tourniquet applied to the limb upon which to be operated. Twenty-seven patients had a significant smoking history (1.5-75 pack-years), and three had a history of juvenile asthma. Preoperative pulmonary function tests were performed in only four cases, and the results were abnormal in one. The other patients had clinically normal lung function for their ages as assessed by history and physical examination. The study was approved by the institutional review board, and a written informed consent was obtained from each patient before the study. Only patients who were scheduled for general anesthesia and who required endotracheal intubation as part of their routine anesthetic management were selected.

Anesthesia was induced with thiopental sodium given intravenously. The trachea was intubated with a cuffed wire spiral endotracheal tube (8-10 mm ID) after succinylcholine chloride was administered intravenously. CMV was instituted (tidal volume 10 ml/kg, rate 8-10 breaths/min, 0 end-expiratory pressure). Anesthesia was maintained with halothane, enflurane, or isoflurane vaporized in either 30, 50, or 100% oxygen, the balance being nitrous oxide.

The high-frequency ventilator system consisted of a variable-stroke piston pump (9.6 cm ID) driven by a variable-speed electric motor. The pump was connected by reinforced silastic tube (12.5 mm ID, 60 cm long) to one port of a four-port connector (fig. 1). The gas volume (ml) remaining in the HFV pump at top dead center was  $[110 + (130 \text{ minus stroke volume})/2]$ . Another port of the four-port connector accepted a 9-mm ID 2.8-m-long, noncompressible outlet tube (which behaved like a low-pass filter, that is, it offers high impedance to high frequencies but low impedance to low frequencies), the distal end of which was attached to an anesthetic scavenging system. The third port was at-

tached to the endotracheal tube, and the fourth port was fitted with a 2-mm ID orifice, through which fresh humidified gas entered the system. At 1.15 m from the distal end of the outlet tube, a suction port was added in order to change lung volume. The mean pressure in the HFV system was 1.5 cmH<sub>2</sub>O at a fresh gas flow of 10 l/min and without a patient attached to the endotracheal tube. The stroke volume of the HFV pump was determined with a calibrated syringe. The lung volume above FRC during CMV (est.  $\Delta V_L$ ) was estimated to be one-third of the tidal volume. To determine the mean lung volume above FRC ( $\Delta V_L$ ) during HFV, a three-way valve attached to a Wright respirometer was inserted between the four-port connector and the endotracheal tube. Gas could pass either from the pump to the patient's lungs or from the patient's lungs through the Wright respirometer to the atmosphere.

During both CMV and HFV, fractional inspired oxygen concentration ( $F_{I_{O_2}}$ ) of the fresh gas was monitored constantly (polarography).  $F_{I_{O_2}}$  was 0.5 in all patients except those of Group 3 (described below).

After 20 to 30 min of CMV or HFV at constant frequencies and stroke volumes, heart rate (ECG), arterial blood pressure (strain gauge), esophageal temperature (thermistor), and  $F_{I_{O_2}}$  were recorded. Thereafter, an arterial blood sample was analyzed for pH and oxygen and carbon dioxide tensions; all blood gas tensions were corrected for body temperature. After this, if the patient was on HFV, ( $\Delta V_L$ ) was determined in triplicate.

The 67 patients were subjected to different experimental protocols. Some patients participated in more than one protocol (table 1). All patients were visited throughout their hospital stay to determine the incidence of complications.

### Procedures

#### COMPARISON BETWEEN CMV AND HFV (GROUP 1)

Forty patients were subdivided into three subsets according to oscillatory frequency ( $f$ ), stroke volume (SV), and  $\Delta V_L$  during HFV (table 1). The first two subsets of patients had similar stroke volumes and frequencies but differed in  $\Delta V_L$ . The third subset of patients were oscillated at 18 Hz and with a reduced SV. Gas flow during HFV in Group 1 ranged from 6 to 12 l/min.

#### EFFECT OF OSCILLATORY FREQUENCY (GROUP 2)

The effect of changing the oscillatory frequency and stroke volume combination was studied in 10 patients whose lungs were oscillated at 12 Hz and then at 5 Hz. Because of time limitation, only seven of the 10 patients

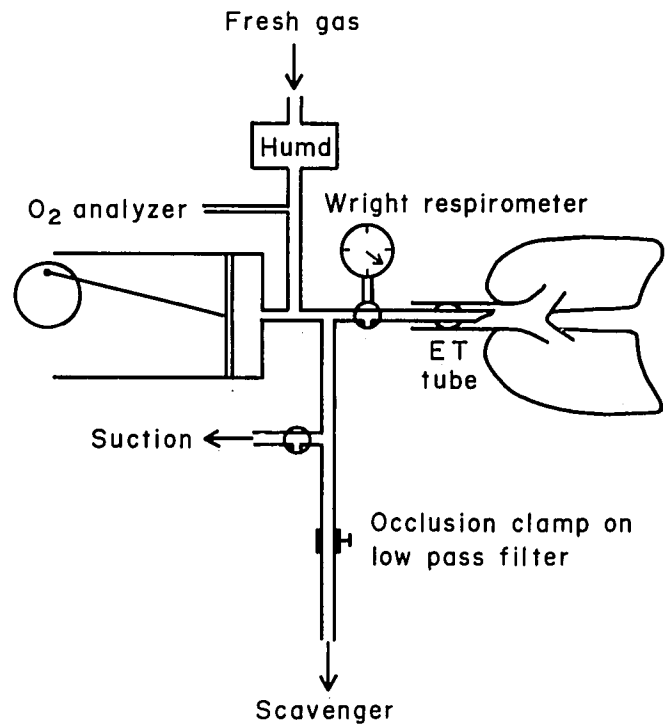


FIG. 1. Diagram of HFV system. Humd = humidifier; ET tube = cuffed wire spiral endotracheal tube. Suction or occlusion clamp were used to alter airway pressure. Fractional inspired oxygen concentration was monitored continuously by polarography (O<sub>2</sub> analyzer). Wright respirometer was used to measure intermittently lung volume above FRC ( $\Delta V_L$ ).

also were studied at 3 Hz. The stroke volume was adjusted in an attempt to produce similar arterial carbon dioxide tensions ( $P_{a_{CO_2}}$ ) at all oscillatory frequencies.  $\Delta V_L$  was adjusted to be similar at all oscillatory frequency-stroke volume combinations by adjusting the suction on the outlet tube.

After adjustment of the lung volume, airway occlusion pressure ( $P_{occ}$ ) was determined in all patients of Group 2 by occluding the airway for approximately 5 s during HFV.

#### EFFECT OF INSPIRED OXYGEN CONCENTRATION (GROUP 3)

At an oscillatory frequency of 12 Hz, 14 patients were studied at an  $F_{I_{O_2}}$  of 0.3, and nine of them also were studied at an  $F_{I_{O_2}}$  of approximately 1; the  $F_{I_{O_2}}$  was less than 1 because of the presence of the volatile agents. For the purpose of this study, we will refer to this as  $F_{I_{O_2}} = 1.0$ . The stroke volume and fresh gas flow was kept constant in each patient during HFV. The sequence of measurements was CMV at  $F_{I_{O_2}} = 0.3$ , HFV at  $F_{I_{O_2}} = 0.3$ , HFV at  $F_{I_{O_2}} = 1.0$ , and CMV at  $F_{I_{O_2}} = 1.0$ . Again  $P_{occ}$  was measured in all patients of Group 3.

TABLE 1. Conditions and Variables during HFV, Mean (Range)

Group	Study	n	SV (ml/kg)	f (Hz)	FI <sub>O<sub>2</sub></sub>	$\dot{V}_{FG}$ (l/min)	$\Delta V_L$ , HFV, (l)	Est. $\Delta V_L$ * (CMV (l))	Paralysis
1	Comparison between CMV and HFV	22	1.2 (1.0-1.2)	12	0.5	9.7 (6-12)	0.2 (0.1-0.3)	0.2 (0.2-0.3)	13 yes 9 no
		11	1.2 (1.0-1.2)	12	0.5	9.6 (6-10)	0.6 (0.3-0.9)	0.3 (0.2-0.4)	1 yes 10 no
		7	0.9 (0.8-1.1)	18	0.5	9.7 (9-10)	0.5 (0.3-1.1)	0.3 (0.2-0.4)	3 yes 4 no
2	Effect of oscillatory frequency	10	1.2	12	0.5	10	0.4	0.3 (0.2-0.3)	10 no
		10	2.0 (1.8-2.2)	5	0.5	10	0.4 (0.2-0.8)	0.3 (0.2-0.3)	1 yes 9 no
		7	2.1 (1.9-2.2)	3	0.5	10	0.3 (0.2-0.8)	0.3 (0.2-0.3)	7 no
3	Effect of FI <sub>O<sub>2</sub></sub>	14	1.2 (1.2-1.7)	12	0.3 or 1.0	10	0.5 (0.2-1.3)	0.3 (0.2-0.3)	14 no
4	Effect of muscle paralysis	10	1.1 (0.8-1.2)	12 or 18	0.5	10	0.5 (0.2-1.2)	0.3 (0.2-0.4)	10 yes 10 no
5	Effect of $\dot{V}_{FG}$ on PaCO <sub>2</sub>	14	1.2 (1.0-1.2)	12	0.5	7.8 (3-12)	0.2 (0.1-0.4)	0.2 (0.2-0.3)	14 yes

SV = stroke volume; f = oscillatory frequency; FI<sub>O<sub>2</sub></sub> = fractional inspired oxygen concentration;  $\dot{V}_{FG}$  = fresh gas flow; and  $\Delta V_L$  = lung volume above FRC.

$$* \text{ Est. } \Delta V_L = \frac{V_T}{3}$$

EFFECT OF MUSCLE PARALYSIS (GROUP 4)

Arterial blood gas tensions were determined before and after muscle paralysis (0.1 mg/kg pancuronium bromide or 0.25 mg/kg metacurine iodide) in 10 patients whose lungs were oscillated at either 12 or 18 Hz. In each patient, stroke volume and fresh gas flow were identical before and after the administration of the muscle relaxant.

EFFECT OF FRESH GAS FLOW ON PaCO<sub>2</sub> (GROUP 5)

Fresh gas flow was varied between 3 and 12 l/min in 14 patients, while stroke volume and oscillatory frequency (12 Hz) were kept constant. To prevent respiratory efforts stimulated by increased PaCO<sub>2</sub>, neuromuscular blockade was used in all patients of Group 5. Arterial blood samples were drawn after 20-30 min of constant fresh gas flow.

Calculations

Alveolar oxygen tension (PA<sub>O<sub>2</sub></sub>) was calculated from the alveolar air equation, assuming R = 0.8 and the FI<sub>O<sub>2</sub></sub> to be equal to that of the fresh gas:

$$PA_{O_2} = PI_{O_2} - \frac{PA_{CO_2}}{R}, \text{ for } FI_{O_2} \leq 0.5, \quad (1)$$

assuming PI<sub>CO<sub>2</sub></sub> and PI<sub>anesth</sub> = 0 mmHg

$$PA_{O_2} = PI_{O_2} - Pa_{CO_2} \text{ for } FI_{O_2} = 1 \quad (2)$$

All results were tested for statistical significance using Student's *t* test for paired data.

Results

GENERAL RESULTS

Operating conditions during HFV were neither superior nor inferior to those during CMV, as judged by the orthopedic surgeons. In the four patients undergoing abdominal surgery, vibrations of the surgical field at 12 and 18 Hz were considered by the general surgeons to be annoying.

In many patients, secretions could be aspirated from the trachea 5-10 min after initiation of HFV. In all patients mean lung volume was above FRC during HFV. In general, the mean lung volume was larger during HFV than during CMV. In all patients during HFV, vibrations of the right side of the chest appeared by palpation to be greater than of the left side.

Complications associated with the study included a mild tracheitis that persisted for 2 days in one patient. This patient had chronic obstructive lung disease (FEV<sub>1</sub>/VC = 67%) and showed a large  $\Delta V_L$  (1,100 ml). Two patients with no known lung disease developed systemic arterial hypotension accompanied by some facial venous congestion. After the substitution of CMV for HFV, expiratory wheezing was heard on auscultation, and an increased impedance to lung inflation was noted. HFV

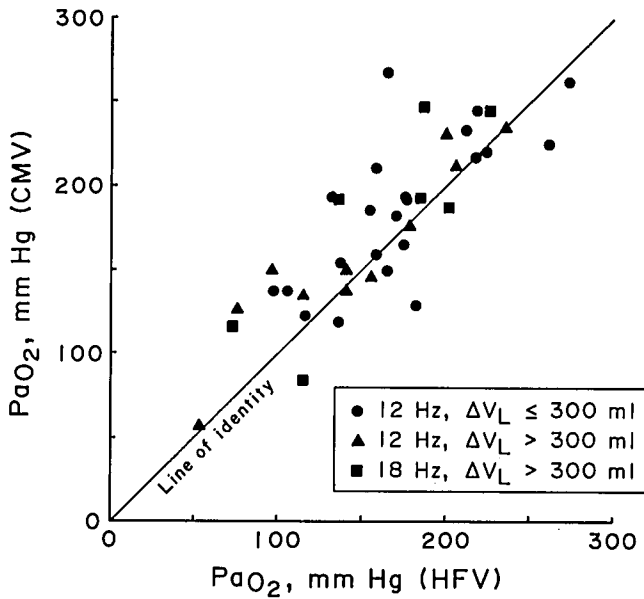


FIG. 2. Arterial oxygen tensions ( $P_{aO_2}$ ) determined in 40 patients of Group 1 after at least 20 min of constant conventional mechanical ventilation (CMV) or at least 20 min of constant high-frequency ventilation (HFV). Arterial oxygen tension during CMV was significantly higher than during HFV ( $P < 0.05$ ) in all three subsets.

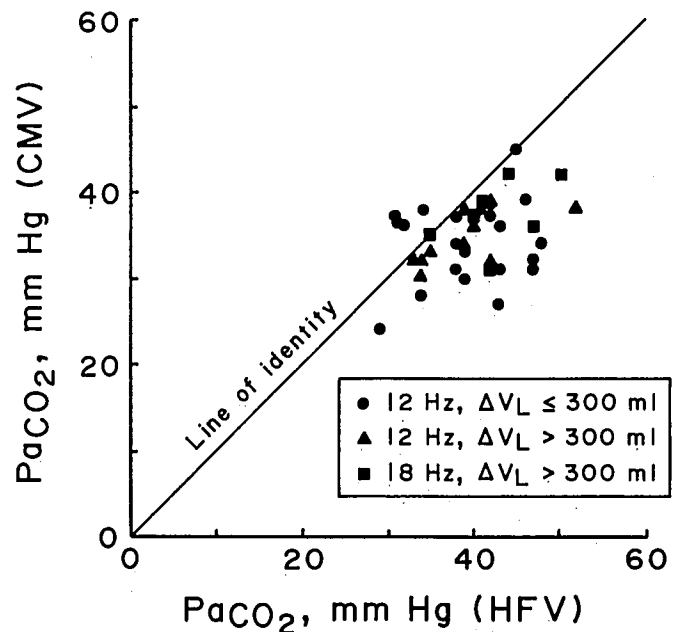


FIG. 3. Arterial carbon dioxide tensions ( $P_{aCO_2}$ ) determined in the 40 patients of Group 1.  $P_{aCO_2}$  was significantly higher during HFV than CMV, but all values were within clinically acceptable limits.

was reinstated successfully in one of these patients, after the level of anesthesia was deepened. In the other patient, HFV was abandoned, since two further attempts of HFV resulted again in systemic arterial hypotension and wheezing. No postoperative respiratory complications occurred in these two patients. In two patients, the tip of the endotracheal tube migrated down into the right main bronchus during HFV, but vibrations still were seen over the left side of the chest.

#### COMPARISON BETWEEN CMV AND HFV (GROUP 1)

Patients whose  $\Delta V_L$  increased moderately during HFV did not respond differently to HFV than did patients with larger increases in  $\Delta V_L$ . The two oscillation frequency-stroke volume combinations studied in Group 1 had no significantly different effect on blood pressure, heart rate, or blood gas tensions ( $P > 0.05$ ).  $P_{aO_2}$  was significantly lower (fig. 2) and  $P_{aCO_2}$  (fig. 3) was significantly higher ( $P < 0.05$ ) during HFV than during CMV. However, no significant difference in  $(A-a)D_{O_2}$  was observed between CMV and HFV (fig. 4). Mean arterial blood pressure was significantly higher ( $P < 0.05$ ) during HFV than during CMV (table 2); esophageal temperature was not different between CMV and HFV.

#### EFFECT OF OSCILLATORY FREQUENCY (GROUP 2)

No significant differences were found in  $P_{aO_2}$ ,  $(A-a)D_{O_2}$ , mean arterial blood pressure and heart rate

between CMV and HFV at 12, 5, or 3 Hz (table 3). There was also no significant difference noted in  $\Delta V_L$  and  $P_{occ}$  among the different frequencies during HFV. We attempted to select appropriate stroke volumes in order to keep  $P_{aCO_2}$  similar during all conditions. How-

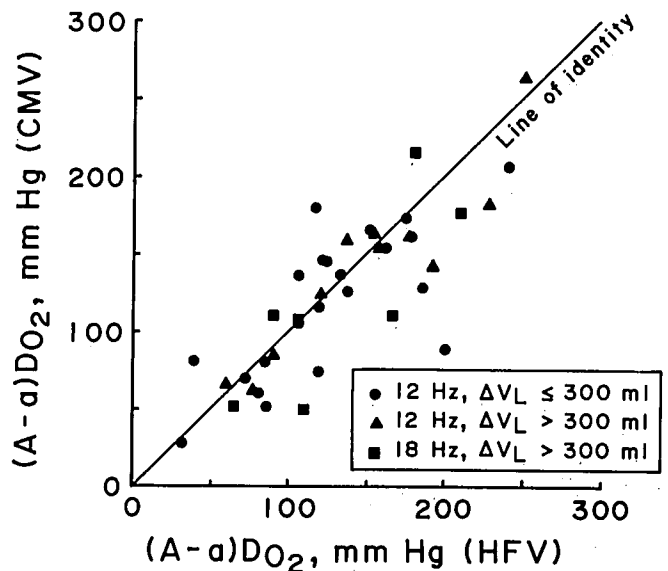


FIG. 4. Alveolar-arterial oxygen tension differences [ $(A-a)D_{O_2}$ ] determined in the 40 patients of Group 1. There was no significant difference in  $(A-a)D_{O_2}$  determined during CMV or HFV in each of the three subsets.

TABLE 2. Comparison between CMV and HFV, Group 1 (Mean  $\pm$  SD)

	CMV	HFV
Heart rate (beats/min)	75 $\pm$ 14	77 $\pm$ 15
Mean arterial blood pressure (mmHg)	79 $\pm$ 10	87 $\pm$ 10*

\* Significantly different from CMV value (paired *t* test,  $P < 0.05$ ).

ever,  $P_{aCO_2}$  was significantly higher ( $P < 0.05$ ) at 12 Hz than during CMV or HFV at 5 or 3 Hz, that is, the delivered gas volume was too small at 12 Hz.

#### EFFECT OF INSPIRED OXYGEN CONCENTRATION (GROUP 3)

$P_{aO_2}$  was significantly less ( $P < 0.05$ ) during HFV than during CMV at  $FI_{O_2}$  0.3 but not at  $FI_{O_2}$  1.0. No differences were seen in  $P_{aCO_2}$ , (A-a) $D_{O_2}$ , mean arterial blood pressure, or heart rate between CMV and HFV at  $FI_{O_2}$  0.3 or  $FI_{O_2}$  1.0 (table 4).

#### EFFECT OF MUSCLE PARALYSIS (GROUP 4)

Muscle paralysis during HFV resulted in no significant change in  $P_{aCO_2}$  or  $P_{aO_2}$ . There was no significant change in  $\Delta V_L$  before or after paralysis.

#### EFFECT OF FRESH GAS FLOW ON $P_{aCO_2}$ (GROUP 5)

$P_{aCO_2}$  was reduced in all but one patient when fresh gas flow was increased (fig. 5). In general, increases in gas flow above approximately 10 l/min resulted in little reduction in  $P_{aCO_2}$ , while reductions in fresh gas flow below approximately 6 l/min increased  $P_{aCO_2}$  progressively. Lung volume above FRC did not change signifi-

TABLE 3. Effect of Oscillatory Frequency, Group 2 (Mean  $\pm$  SD)

	CMV (n = 10)	HFV		
		12 Hz (n = 10)	5 Hz (n = 10)	3 Hz (n = 7)
$P_{aO_2}$ (mmHg)	157 $\pm$ 41	151 $\pm$ 43	139 $\pm$ 41	152 $\pm$ 50
$P_{aCO_2}$ (mmHg)	37 $\pm$ 6	42 $\pm$ 6*	38 $\pm$ 7	36 $\pm$ 6
(A-a) $D_{O_2}$ (mmHg)	141 $\pm$ 41	141 $\pm$ 44	157 $\pm$ 45	148 $\pm$ 54
$\overline{BP}$ (mmHg)	88 $\pm$ 7	93 $\pm$ 16	90 $\pm$ 15	91 $\pm$ 13
HR (beats/min)	71 $\pm$ 17	73 $\pm$ 18	72 $\pm$ 17	79 $\pm$ 25
$\Delta V_L$ (ml)	272 $\pm$ 36†	403 $\pm$ 226	395 $\pm$ 232	329 $\pm$ 196
$P_{occ}$ (cmH <sub>2</sub> O)	—	8.3 $\pm$ 2.5	8.2 $\pm$ 2.8	7.5 $\pm$ 2.2

$P_{aO_2}$  = arterial oxygen tension;  $P_{aCO_2}$  = arterial carbon dioxide tension; (A-a) $D_{O_2}$  = alveolar-arterial difference in oxygen tension;  $\overline{BP}$  = mean arterial blood pressure; HR = heart rate;  $\Delta V_L$  = mean lung volume above FRC; and  $P_{occ}$  = airway occlusion pressure.

\* Significantly different from CMV values and values at 5 and 3 Hz (paired *t* test,  $P < 0.05$ ).

† Est.  $\Delta V_L = \frac{V_T}{3}$ .

cantly with changes in fresh gas flow. The maximum change was 0.2 l.

## Discussion

### GENERAL COMMENTS

The important findings are 1) HFV can be performed with nearly standard anesthetic apparatus in the operating room (except for the HFV pump and the four-port connector); 2) HFV maintains adequate pulmonary gas exchange in anesthetized recumbent humans with or without muscle paralysis; 3) HFV does not improve efficiency of oxygenation over that of CMV; and 4) HFV has no apparent advantage over CMV. The disadvantages of HFV are that 1) monitoring of heart and breath sounds with an esophageal stethoscope is impossible; 2) adequacy of ventilation cannot be estimated from the movement of the thorax; 3) chest wall vibrations cannot be relied upon as an indication of correct endotracheal tube position; 4) consumption of gaseous anesthetics is higher during HFV than during CMV because of the high fresh gas flow; and 5) assessing the lung volume is difficult.

During HFV,  $P_{occ}$  was elevated consistently. The increase in lung volume ( $\Delta V_L$ ) during HFV may be caused by expiratory flow limitation by the fluid mechanical behavior of the HFV circuit or a combination of both.<sup>7,8</sup> At the low lung volumes existing in anesthetized recumbent man (near RV), expiratory flow limitation may occur at relatively low flows. That two patients who had the highest  $\Delta V_L$  had either obstructive lung disease or developed expiratory wheezing appears to be consistent with the hypothesis that expiratory flow limitation may occur during HFV in recumbent anesthetized humans.

Two patients with no known lung disease developed expiratory wheezing during HFV, a finding that also has been observed during high-frequency jet ventilation.<sup>9</sup> The wheezing could not be heard during HFV, possibly because of HFV-associated noise transmitted to the chest; it became apparent only after HFV had been discontinued. One other patient developed expiratory wheezing during CMV; this was treated successfully with aminophylline. HFV did not produce expiratory wheezing in this patient, and his pulmonary gas exchange was improved during HFV. Three patients with a history of juvenile asthma who had normal pulmonary functions and were taking no medication at the time of this study did not develop expiratory wheezing nor did they experience exceptionally large increases in lung volume.

In several patients, copious amounts of secretions were aspirated from the lumen of the endotracheal tube shortly after initiation of HFV. The effect of HFV on

secretions is still unclear. In anesthetized dogs, mucociliary clearance is slower during HFV than during CMV.<sup>10</sup> However, increased mobilization of secretions may occur during HFV, since sputum is a thixotropic-like substance—that is, with agitation, it may become less viscous.<sup>11</sup>

Surgical conditions were not improved during HFV at oscillation frequencies of 12 or 18 Hz. In four patients who had upper abdominal surgery, HFV at 12 and 18 Hz caused annoying vibrations of the surgical field. At 3 Hz, however, oscillations were considerably less. Some surgeons believed that operating conditions during HFV at 3 Hz were superior to those during CMV.

### PULMONARY GAS EXCHANGE

Tidal volume and frequency for CMV and stroke volume and oscillatory frequency for HFV were chosen in an attempt to produce normocapnia. With both modes of ventilation, a wide range of PaCO<sub>2</sub>, which were within the clinically acceptable range, occurred—that is, it was equally difficult to predict the settings necessary to achieve normocapnia.

The mean (A-a)D<sub>O<sub>2</sub></sub> was above normal with both modes of ventilation, confirming previous findings of impaired oxygenation during anesthesia.<sup>5,12,13</sup> Both increased mismatching of ventilation to perfusion ( $\dot{V}/\dot{Q}$ ) and increased right-to-left intrapulmonary shunting ( $\dot{Q}_s/\dot{Q}_t$ ) follow induction of general anesthesia.<sup>5,6</sup> Since pulmonary gas exchange was not improved during HFV at FI<sub>O<sub>2</sub></sub> of either 0.3 or 1.0, the mechanisms underlying the increased  $\dot{V}/\dot{Q}$  mismatching and increased  $\dot{Q}_s/\dot{Q}_t$  apparently were not affected significantly by HFV. This is in contrast to reports of patients who are in respiratory insufficiency, who may apparently experience an improvement in gas exchange during HFV, presumably on the basis of reduced  $\dot{V}/\dot{Q}$  mismatching.<sup>2</sup>

Altering the combination of stroke volume and oscillatory frequency did not significantly improve the efficiency of oxygenation in anesthetized humans. A significantly better oxygenation during HFV at low oscillation frequencies than during CMV has been observed, however, in anesthetized dogs.<sup>14</sup> Since surgical conditions may be improved with HFV at 3 Hz, further investigation at low oscillation frequencies is required.

The inspired oxygen concentration during HFV is likely to be less than that measured in the fresh gas flow because of rebreathing. Thus, the (A-a)D<sub>O<sub>2</sub></sub> during HFV may have been overestimated. This error is probably small, because increasing the fresh gas, which reduces rebreathing, did not reduce the (A-a)D<sub>O<sub>2</sub></sub>. We ignored the presence of volatile anesthetics in the inspired gas mixture for the calculation of PA<sub>O<sub>2</sub></sub> both during CMV and HFV. Since the inspired concentration of the volatile

TABLE 4. Effect of Inspired Oxygen Concentration, Group 3 (Mean ± SD)

	FI <sub>O<sub>2</sub></sub> 0.3		FI <sub>O<sub>2</sub></sub> 1.0	
	CMV (n = 14)	HFV (n = 14)	CMV (n = 9)	HFV (n = 9)
PaO <sub>2</sub> (mmHg)	101 ± 20	96 ± 21*	332 ± 48	325 ± 54
PaCO <sub>2</sub> (mmHg)	37 ± 3	39 ± 4	37 ± 3	38 ± 3
(A-a)D <sub>O<sub>2</sub></sub> (mmHg)	61 ± 17	64 ± 19	304 ± 51	310 ± 55
$\overline{BP}$ (mmHg)	84 ± 15	86 ± 10	85 ± 14	90 ± 13
HR (beats/min)	77 ± 14	77 ± 15	74 ± 13	78 ± 17
ΔV <sub>I</sub> (ml)	272 ± 52†	498 ± 301	253 ± 51	373 ± 162
P <sub>rec</sub> (cmH <sub>2</sub> O)	—	9.3 ± 3.6	—	8.3 ± 3.3

For definition of symbols, see Table 3.

\* Significantly different from CMV (*P* < 0.05), paired *t* test.

† Est. ΔV<sub>I</sub> =  $\frac{V_T}{3}$ .

anesthetics was the same during both modes of ventilation, comparison of (A-a)D<sub>O<sub>2</sub></sub> between the two modes of ventilation should be valid.

### CARDIOVASCULAR RESPONSE

Mean systemic arterial blood pressure was significantly higher during HFV than during CMV in the patients of Group 1. We have no explanation for this difference, but the surgical stimulus may have been more intense with HFV than with CMV and the higher PaCO<sub>2</sub> also may have contributed to the higher mean arterial blood pressure in these patients.

### THE EFFECT OF MUSCLE PARALYSIS

In anesthetized dogs, HFV reduces total respiratory compliance, a change that can be reversed by succinyl-

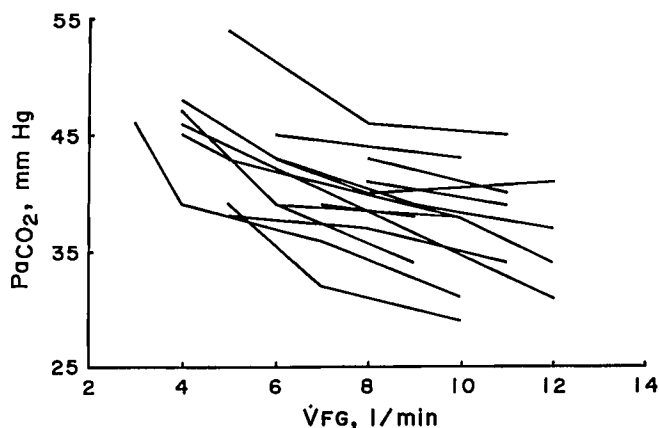


FIG. 5. Arterial carbon dioxide tension (PaCO<sub>2</sub>) plotted as a function of fresh gas flow ( $\dot{V}_{FG}$ ) determined in 14 patients of Group 5. Stroke volume and oscillation frequency were kept constant, while  $\dot{V}_{FG}$  was changed. Note that, in general,  $\dot{V}_{FG}$  less than approximately 6 l/min resulted in an increase in PaCO<sub>2</sub>, whereas  $\dot{V}_{FG}$  more than approximately 10 l/min resulted in little decrease of PaCO<sub>2</sub>.

choline;<sup>15</sup> the activation of chest wall proprioceptors may be the underlying mechanism for the decreased compliance. If total respiratory compliance also is reduced during HFV after the induction of anesthesia, then at constant settings of the pump, the fraction of the stroke volume delivered to the lungs should increase after muscle paralysis. Hence, with an unchanged combination of frequency and stroke volume, one would anticipate a decrease in the  $P_{aCO_2}$  after muscle paralysis, unless  $CO_2$  production had changed. A decrease in  $P_{aCO_2}$  did not occur. We suggest that HFV did not significantly decrease the compliance of the respiratory system in anesthetized humans.

#### THE EFFECT OF FRESH GAS FLOW ON $CO_2$ ELIMINATION

Rebreathing of gas occurs during HFV. The amount of rebreathing depends on the fresh gas flow. Removal of  $CO_2$  is thus a function of fresh gas flow and ventilation of the lungs. An increase in  $P_{aCO_2}$  with progressive reductions in fresh gas flow is to be anticipated. However, the level to which fresh gas flow safely can be reduced is not known. We found that, in general, flows in excess of approximately 10 l/min usually were not required to achieve adequate removal of  $CO_2$  with the oscillation frequency-stroke volume combinations employed in this study. If oscillation frequency-stroke volume combination is kept constant,  $P_{aCO_2}$  easily can be increased by reducing the fresh gas flow, but  $P_{aCO_2}$  cannot be reduced much by increasing the flow above 10 l/min.

#### CONCLUSIONS

Adequate pulmonary gas exchange can be maintained with HFV in recumbent anesthetized humans. At oscillatory frequencies ranging between 12 and 18 Hz and stroke volumes of 0.8 to 2.2 ml/kg, surgical conditions and efficiency of oxygenation were not better than with CMV. At 3 Hz, however, surgical conditions may be better than with CMV. Muscle paralysis is not necessary to maintain adequate removal of  $CO_2$  with HFV during anesthesia. Some adjustments in  $P_{aCO_2}$  can be made by altering the flow of fresh gas while stroke volume and oscillatory frequency are unchanged. We do not recommend HFV at 12–18 Hz for routine use during anesthesia for orthopedic and abdominal surgery. Further studies are necessary to examine the value of HFV at other (particularly lower) oscillatory frequencies and to define the role of HFV in other surgical specialities.

The authors thank the orthopedic and general surgeons of the Mayo Clinic for their cooperation in allowing this study to proceed with their patients; Mrs. Kathleen A. Street and Mr. Gerald J. Rach for their technical assistance; Mrs. Carol J. Rodgers for her help in the preparation of the manuscript; and Drs. Robert E. Hyatt, Joseph R. Rodarte, H. Michael Marsh, Delmar J. Gillespie, and Kenneth C. Beck for their helpful comments.

#### References

1. Bohn DJ, Miyasaka K, Marchak BE, Thompson WK, Froese AB, Bryan AC: Ventilation by high-frequency oscillation. *J Appl Physiol Respirat Environ Exercise Physiol* 48:710–716, 1980
2. Butler WJ, Bohn DJ, Bryan AC, Froese AB: Ventilation by high-frequency oscillation in humans. *Anesth Analg* 59:577–584, 1980
3. Marchak BE, Thompson WK, Duffy P, Miyaki T, Bryan MH, Bryan AC, Froese AB: Treatment of RDS by high-frequency oscillatory ventilation: A preliminary report. *J Pediatr* 99:287–292, 1981
4. Kolton M, Cattran CB, Kent G, Volgyesi G, Froese AB, Bryan AC: Oxygenation during high-frequency ventilation compared with conventional mechanical ventilation in two models of lung injury. *Anesth Analg* 61:323–332, 1982
5. Dueck R, Young I, Clausen J, Wagner PD: Altered distribution of pulmonary ventilation and blood flow following induction of inhalational anesthesia. *ANESTHESIOLOGY* 52:113–125, 1980
6. Rehder K, Knopp TJ, Sessler AD, Didier EP: Ventilation-perfusion relationship in young healthy awake and anesthetized-paralyzed man. *J Appl Physiol* 47:745–753, 1979
7. Rehder K, Didier EP: Gas transport and pulmonary perfusion during high-frequency ventilation in humans. *J Appl Physiol* 57:1231–1237, 1984
8. Goldstein D, Slutsky AS, Igram RH, Westerman P, Venegas J, Drazen J:  $CO_2$  elimination by high frequency ventilation (4 to 10 Hz) in normal subjects. *Am Rev Respir Dis* 123:251–255, 1981
9. Carlon GC, Kahn RC, Howland WS, Ray C, Jr, Turnbull AD: Clinical experience with high frequency jet ventilation. *Crit Care Med* 9:1–6, 1981
10. McEvoy RD, Davies NJH, Hedenstierna G, Hartman MT, Spragg RG, Wagner PD: Lung mucociliary transport during high-frequency ventilation. *Am Rev Respir Dis* 126:452–456, 1982
11. Clarke SW, Jones JG, Oliver DR: Resistance to two-phase gas-liquid flow in airways. *J Appl Physiol* 29:464–471, 1970
12. Nunn JF: *Applied Respiratory Physiology*. Second Edition, London, Butterworths, 1977
13. Rehder K, Sessler AD, Marsh HM: General anesthesia and the lung. *Am Rev Respir Dis* 112:541–563, 1975
14. Brusasco V, Knopp TJ, Schmid ER, Rehder K: Ventilation-perfusion relationship during high-frequency ventilation. *J Appl Physiol* 56:454–458, 1984
15. Gillespie DJ, Rodarte JR, Hyatt RE: Respiratory mechanics during ventilation by high frequency oscillation (HFO) (abstract). *Physiologist* 23:1, 1980