FIG. 1. A localized skin burn and blister formation developed underneath the photo-transmitter side of a pulse oximeter probe on the left great toe of a 3-month-old infant (case 1).

a 70° C LED, one ear pressure necrosis, and one ultraviolet skin tanning (with a fiberoptic model). This indicates that the probes used in pulse oximetry requires special attention and frequent probe site inspection.

REFERENCES

1. Solimano AJ, Smyth JA, Mann TK, Albersheim, SG, Lockitch G: Pulse oximetry advantages in infants with bronchopulmonary dysplasia. Pediatrics 78:844–849, 1986
2. Deckerdt R, Steward DJ: Non-invasive arterial hemoglobin saturation versus transcutaneous oxygen tension monitoring in the preterm infant. Crit Care Med 12:936–938, 1984
3. Jennis MS, Peabody JL: No burns, no gradient-pulse oximetry, an alternative to transcutaneous PO_2 (abstract). Clin Res 33:139A, 1985
4. Miyasaka K: Use of non-invasive oximetry during the induction of anesthesia in children, Pulse Oximeter. Edited by Payne JP, Severinghaus JW. New York, Springer-Verlag, 1986, pp 95–100

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High-frequency Jet Ventilation During Thoracic Surgical Procedures

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Several modalities of ventilation have been proposed to prevent or minimize hypoxemia during thoracotomy,[1,2] including ventilation at supraphysiologic frequencies.[3–5] Since the differences among these modalities which utilize elevated rates are considerable,[6] we examined the impact of high-frequency jet ventilation (HFJV), administered at various rates, on gas exchange in patients undergoing thoracic surgery, both while the chest cavity was open and while it was closed.

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MATERIALS AND METHODS

The subjects were 120 patients scheduled for open thoracotomy involving resection of lung parenchyma or thoracic esophagus. The research protocol was approved by the Institutional Review Board, and written consent was obtained from each patient. All were premedicated with morphine, 5 mg im, and atropine, .4 mg im, approximately 1 h before surgery. Anesthesia was induced with sodium thiopental, 4 mg/kg iv, and succinylcholine, 1 mg/kg, and was maintained with an oxygen-nitrous oxide mixture (40:60–50:50), supplemented with intravenous fentanyl, droperidol, pancuronium bromide, and sodium thiopental as needed. Endotracheal intubation was performed with an 8–8.5-mm diameter National Catheter Hi-Lo® disposable endotracheal tube. This device had an extruded lumen that permitted measurement of airway pressure 5–6 centimeters above the carina. The airway pressure port was connected to a pressure transducer and a monitoring oscilloscope through an air-filled catheter. Inspired oxygen concentration (F_{IO_2}) was measured with a paramagnetic oxygen analyzer placed between the ventilator Y-connector and the endotracheal tube. ECG was displayed on a monitor oscilloscope, and radial arterial and central venous pressures were directly measured *via*

TABLE 1. Patients from Whom Samples were Obtained, at Each Respiratory Frequency, in Experimental Conditions 1 (IPPV; Closed Chest), 3 (HFJV; Immediately After the Chest was Opened), 5 (HFJV; Immediately Before Resuming IPPV), and 6 (IPPV; Before the Chest was Reclosed)

	Experimental Condition			
	1	3	5	6
HFJV Rate	Number of Patients			
100	12	13	7	7
150	13	12	9	9
180	10	7	6	6
24	10	8	6	6
Total	45	40	28	28

indwelling catheters. Mean airway pressure (Paw), heart rate, and vascular pressure values were tabulated from the digital display of the monitors.

All patients were initially ventilated with intermittent positive pressure ventilation (IPPV) at a rate of 10 b/min and tidal volume (Vt) of 12 ml/kg. Exhaled Vt was measured with an ultrasonic spirometer in the expiratory limb of the ventilator circuit. Arterial blood was drawn for measurement of gas tension, using a Corning 178® automatic blood gas analyzer; all values were corrected for body temperature. To normalize Pa_{O_2} for different FI_{O_2}s, the Pa_{O_2}/FI_{O_2} ratio was calculated for each blood gas measurement. After the patient had been turned into the left lateral decubitus position and vital signs had remained stable for at least 10 min, HFJV was begun using a commercially available device (Bear Jet® Ventilator) at one of four rates, 100, 150, 180, or 240 b/min, to which the patient had been allocated before surgery, using a computer-generated table of random numbers. The injector cannula, 5 cm long and 1.62 mm internal diameter, was inserted into the swivel connector of the endotracheal tube. An oxygen/nitrous oxide gas mixture was delivered to the injector cannula from a high pressure blender. Jet entrainment was provided by a continuous flow of fresh gases through the anesthesia circuit having the same concentrations of oxygen and nitrous oxide as were delivered through the injector cannula. Vital signs and blood gas measurements were obtained in the following conditions: 1) during IPPV while the chest was closed, with the patient in lateral decubitus position; 2) during HFJV while the chest was closed, with the patient in the lateral decubitus position; 3) during HFJV, immediately after the chest was open; 4) while the chest was open and the operation in progress (Observations were tabulated every 30 min, up to 4 times. This limitation prevented over-representation from data of unusually protracted surgical procedures, since all values obtained with the chest open at the same respiratory rate were averaged together. The patients were always receiving HFJV); 5) shortly before the chest was closed, while the patient was ventilated with HFJV, but immediately before IPPV was reinstituted; and 6) 10 min after the patient was again ventilated with IPPV, if the chest was still open.

TABLE 2. Allocation of Patients to HFJV Rate Groups

Respiratory Rate on HFJV (bpm)	Initial Randomization	Cancellation of surgery	Actual Number of Cases Completed
100	36	2	34
150	31	2	29
180	30	0	30
240	23	7	16
Total	120	11	109

Data from all patients were available for conditions 2 and 4. For the other conditions, blood samples and other measurements were only obtained when this did not interfere with the orderly and safe progression of anesthetic management. A representative number of samples was, however, available for each respiratory rate (table 1). For each variable and for each respiratory rate, Student's *t* test for paired data was used to compare values obtained under conditions 1 and 2, 2 and 3, and 5 and 6. For each variable, values obtained at different HFJV rates before the chest was opened (condition 2) and during surgery (condition 4) were compared by one-way analysis of variance. If a statistically significant difference existed, values obtained at the respiratory rate of 100 b/min were compared with those obtained at rates of 180 and 240 b/min by Newman-Keul's test. For all statistical tests, a P level ≤ 0.05 was accepted as significant.

RESULTS

Patients allocated to each respiratory frequency group were comparable with regard to age, sex, preoperative respiratory function, and type of surgical procedure. With the exception of intraoperative lung overdistension, no complication could be ascribed to the ventilatory technique. In 11 operations, the planned surgical procedure was canceled, reducing the number of experimental subjects to 109. The smallest number of cases had been randomized to the highest HFJV rate (240 breaths/min), and, since most of the cancellations of surgery also occurred in this group, its final sample size was smaller than the others (table 2).

Consecutive measurements during HFJV and IPPV were obtained in 45 patients before the chest was opened (conditions 1 and 2), and in 28 before it was

TABLE 3. Behavior of Relevant Hemodynamic and Gas Exchange Variables when Patients were Transferred from Volume-cycled Ventilation to HFJV or Viceversa

	Paw	Pa_{CO_2}	$Pa_{O_2}/F_{I_{O_2}}$
Closed chest			
Volume cycled ventilation	23.4 ± 1.8*	38 ± 9	223 ± 32
HFJV	8.3 ± 0.9	42 ± 13	187 ± 26
Open chest			
Volume cycled ventilation	19.6 ± 0.9*	43 ± 13	380 ± 20
HFJV	5.8 ± 0.5	39 ± 8	377 ± 25

Paw = mean airway pressure (cmH_2O); Pa_{CO_2} = arterial Pa_{CO_2} (mmHg), $Pa_{O_2}/F_{I_{O_2}}$ = respiratory index (units). All values are expressed as mean ± standard deviation.
* $P < 0.001$ By t test for paired data.

reclosed (conditions 5 and 6). Arterial blood gases were identical at the beginning of surgery, when patients were transferred from IPPV to HFJV while the chest was still closed; and at the end of the procedure, when patients were returned from HFJV to IPPV while the chest was still open. In fact, neither at the beginning nor at the end of surgery were statistically significant differences in any of the monitored dependent variables observed, except for Paw, which was always lower during HFJV (table 3).

In 40 patients, blood gases were measured during HFJV within 10 min after the chest had been opened (condition 3). These values were compared to those obtained with the same ventilatory modality while the pleural space was still sealed (condition 2). A statistically significant decrease of $Pa_{O_2}/F_{I_{O_2}}$ was observed at rates of 100 b/min (closed chest 382 ± 27; open chest 223 ± 38; mean + SEM) and 150 b/min (closed chest 444 ± 38; open chest 268 ± 50), but not at rates of 180 and 240 b/m. There were no differences in Pa_{CO_2} or vital signs.

While the chest was closed and patients ventilated with HFJV (condition 2), Paw increased progressively with higher respiratory rate (fig. 1). Considering values at each individual rate, there was a statistically significant difference between Paw at 100 b/min (5.3 ± .4 mmHg) and 180 b/min (9.2 ± .5 mmHg) and 240 b/min (9.4 ± .9 mmHg). With respect to the $Pa_{O_2}/F_{I_{O_2}}$ ratio (fig. 2), analysis of variance indicated that the differences between respiratory rates were statistically significant; comparison of data obtained at individual rates, however, revealed a significant difference only between 100 b/min (264 ± 16) and 240 b/min (419 ± 37).

Analysis of variance of data obtained every 30 min from all 109 patients, while the chest was opened and surgery in progress (condition 4), indicated that Paw

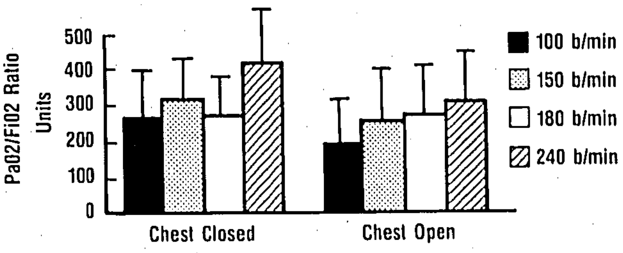

FIG. 1. Mean airway pressure observed at different respiratory rates on HFJV, with the chest both open and closed. There was a significant, progressive increase of Paw with higher respiratory rates. All bars are mean ± standard deviation. Data from all 109 patients.

(fig. 1) and $Pa_{O_2}/F_{I_{O_2}}$ (fig. 2) increased as respiratory rate on HFJV rose from 100 to 240 b/min. When observations at each respiratory rate were considered, Paw at 100 b/min (5.5 ± .2) was significantly lower than at 180 b/min (8.6 ± .3) and 240 b/min (10.7 ± .5). $Pa_{O_2}/F_{I_{O_2}}$ ratio was significantly different only between respiratory rates of 100 b/min (200 ± 10) and 240 b/min (314 ± 19).

DISCUSSION

Only during conditions 2 and 4 were data available from all patients. However, additional data points (conditions 1,3,5, and 6) were available from 28–45 patients, evenly distributed among HFJV rate groups, during all other experimental conditions. Thus, we feel justified in stating that HFJV maintained gas exchange as adequately as did IPPV with the chest both open and closed and at all respiratory rates considered. Also, except for increasing airway pressure, HFJV did not affect any of the physiologic variables monitored. This observation is consistent with findings in patients with acute respiratory failure,[7,8] and confirms previous reports of experimental applications of high-frequency oscillation and high-frequency positive pressure ventilation during thoracic surgery.[3,4] Maintaining good gas exchange in anesthetized patients undergoing thoracotomy is often difficult, since the changes in ventilation and perfusion

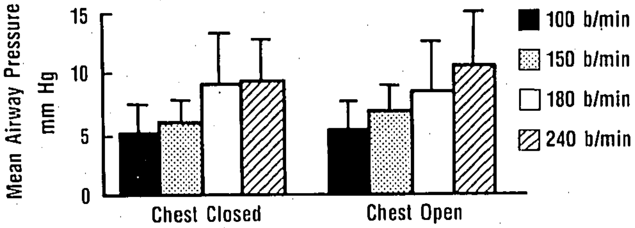

FIG. 2. $Pa_{O_2}/F_{I_{O_2}}$ ratio observed at different respiratory rates during HFJV, with the chest both open and closed. In both cases, $Pa_{O_2}/F_{I_{O_2}}$ at 240 bpm was significantly greater than at 100 bpm. All bars are mean ± standard deviation. Data from all 109 patients.

that occur during surgery are, for the most part, detrimental to lung function.[9,10] The interaction of HFJV and pulmonary mechanics can also affect hemodynamic function and gas exchange. Higher rates and larger volumes reduce alveolar emptying time, and gases are trapped in alveoli.[11,12] As a consequence, distal airway pressure increases, an effect sometimes referred to as "auto-PEEP."[13,14] We found the progressive increase of Paw and Pa_{O_2}/FI_{O_2} at higher respiratory rates, most notable at 240 b/min, to be significant, consistent with the current interpretation of the factors that generate and maintain auto-PEEP. The role of auto-PEEP was also confirmed by the observation that the improvement in oxygenation with higher respiratory rates was more obvious when the chest was open and the lungs were manipulated. It should, nonetheless, be emphasized that auto-PEEP is an uncontrolled development, potentially associated with deleterious consequences, and that more reliable methods to increase airway pressure during one-lung anesthesia are available.[2]

Finally, serious attention should be paid to the impressions of the two surgeons who participated in this study. Both reported technical difficulties related to over-distended lungs when gas exchange was optimal, at the higher respiratory rates. Although other surgeons, in similar subjective, uncontrolled studies, have stated that quiet, distended lungs facilitate identification of anatomical planes for pulmonary dissection[3,5] (although not for major airway surgery[3]), any real or perceived increase in technical difficulties may hamper the operation and unnecessarily place the patient at greater risk. It is certainly possible that the more frequent cancellation of planned surgery in patients randomized to higher respiratory rates reflected conscious or unconscious uneasiness on the part of the surgeon. In this respect, this investigation confirms a problem commonly reported during high-frequency ventilation studies.[3,5,7,15] Furthermore, this study did not prove any superiority of HFJV to conventional ventilation. Admittedly, the study protocol was not designed as a cross-over comparison, but paired observations obtained with the chest wall closed and open did not highlight any difference between the two techniques. While high-frequency ventilation can be used safely in a wide variety of clinical conditions, ranging from acute respiratory failure to thoracic surgery, very few positive indications exist. For HFJV, they are still restricted to management of patients with large bronchopleural fistula, and of individuals with injuries involving the upper airway, who may present special problems with respect to tracheal intubation.[16,17]

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REFERENCES

1. Hedenstierna G, Baehrendtz S, Klingstedt C, Santesson J, Soderborg B, Dahlborn M, Bindsley L: Ventilation and perfusion of each lung during differential ventilation with selective PEEP. ANESTHESIOLOGY 61:369–376, 1984
2. Rehder K, Wenthe FM, Sessler AD: Function of each lung during mechanical ventilation with ZEEP and with PEEP in man anesthetized with thiopental-meperidine. ANESTHESIOLOGY 39:597–606, 1973
3. Glenski JA, Crawford M, Rehder K: High-frequency, small-volume ventilation during thoracic surgery. ANESTHESIOLOGY 64:211–214, 1986
4. El-Baz N, El-Ganzouri A, Gottschalk W, Jensik R: One-lung high-frequency positive pressure ventilation for sleeve pneumonectomy: An alternative technique. Anesth Analg 60:683–686, 1981
5. Mutz N, Baum M, Benzer H, Koller W, Moritz E, Pauser G: Intraoperative application of high-frequency ventilation. Crit Care Med 12:800–802, 1984
6. Sjostrand UH, Eroksson IA: High rates and low volumes in mechanical ventilation—Not just a matter of ventilatory frequency. Anesth Analg 59:567–576, 1980
7. Carlon GC, Howland WS, Ray C, Miodownik S, Griffin JP, Groeger JS: High frequency jet ventilation. A prospective randomized evaluation. Chest 84:551–559, 1983
8. Schuster DP, Klain M, Snyder JV: Comparison of high frequency jet ventilation to conventional ventilation during severe acute respiratory failure in humans. Crit Care Med 10:625–630, 1982
9. Benumof JL: Physiology of the open chest and one-lung ventilation, Thoracic Anesthesia. Edited by Kaplan JB. New York, Churchill Livingstone, 1983, p 287–296
10. Nunn JF: The distribution of inspired gas during thoracic surgery. Ann R Coll Surg Eng 28:223–237, 1961
11. Rouby JS, Fusciardi J, Bourgain JL, Viars P: High frequency jet ventilation in postoperative respiratory failure. Determinants of oxygenation. ANESTHESIOLOGY 59:281–287, 1983
12. Benhamou D, Ecoffey C, Rouby JS, Fusciardi J, Viars P: Impact of changes in operating pressure during high frequency jet ventilation. Anesth Analg 63:19–24, 1984
13. Sutton JE, Glass DD: Airway pressure gradient during high-frequency ventilation. Crit Care Med 12:774–776, 1984
14. Beamer WC, Prough DS, Royster RL, Johnston WE, Johnson JC: High-frequency jet ventilation produces auto-PEEP. Crit Care Med 12:734–737, 1984
15. Malina JR, Nordstrom SG, Sjostrand UH, Wattwil LM: Clinical evaluation of high-frequency positive-pressure ventilation (HFPPV) in patients scheduled for open-chest surgery. Anesth Analg 60:324–330, 1981
16. Carlon GC, Ray C, Pierri MK, Groeger JS, Howland WS: High frequency jet ventilation. Theoretical considerations and clinical observations. Chest 81:350–354, 1982
17. Scheck PA, Mallios C: Peroral endoscopies using intravenous anesthesia and high-frequency ventilation. Crit Care Med 12:803–805, 1984