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Effect of high-frequency jet ventilation on oxygenation during one-lung ventilation in patients undergoing thoracic aneurysm surgery

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Abstract
Purpose. To evaluate the effect of high-frequency jet ventilation (HFJV) and continuous positive airway pressure (CPAP) on oxygenation and the shunt fraction (Qs/Qt) during one-lung ventilation (OLV).
Methods. Twenty-five patients who were undergoing resection of a descending aortic aneurysm were studied. Arterial oxygenation, Qs/Qt, and hemodynamics were evaluated just before the initiation of OLV (T_1), 15 min after OLV (T_2), and 15 min (T_3) and 30 min (T_4) after the application of HFJV or CPAP to the nondependent lung.
Results. There were no significant changes in the mean arterial blood pressure (MAP), heart rate (HR), central venous pressure (CVP), or mixed venous partial pressure of oxygen throughout this study. The arterial partial pressure of oxygen (Pa_{O_2}) values after the application of HFJV or CPAP increased significantly, from 173.8 ± 39.6 mmHg (T_2) to 344.1 ± 87.9 mmHg (T_3) and 359.9 ± 82.4 mmHg (T_4) in the HFJV group ($P < 0.05$), and from 153 ± 38.5 mmHg (T_2) to 243 ± 48.5 mmHg (T_3) and 249.7 ± 55.0 mmHg (T_4) in the CPAP group ($P < 0.05$). The shunt fraction decreased significantly after the initiation of HFJV or CPAP, from 38.7% ± 8.9% (T_2) to 27.0% ± 8.0% (T_3) and 25.9% ± 8.7% (T_4) in the HFJV group ($P < 0.05$), and from 44.6% ± 8.6% (T_2) to 34.3% ± 10.2% (T_3) and 32.6% ± 8.5% (T_4) in the CPAP group ($P < 0.05$). The arterial saturation of oxygen (Sa_{O_2}) increased significantly after the application of either HFJV or CPAP ($P < 0.05$).
Conclusions. Both HFJV and CPAP can improve oxygenation during OLV.

Key words One-lung ventilation · HFJV · CPAP · Oxygenation · Shunt fraction

Introduction

The surgical resection of a descending aortic aneurysm requires an anterolateral incision. Therefore, the left lung must be collapsed to facilitate surgical access to the aneurysm. This procedure requires one-lung ventilation (OLV) using a double-lumen endobronchial tube. However, severe hypoxia can be induced during OLV because it creates a right–left transpulmonary shunt through the nondependent lung [1]. The current methods for preventing arterial oxygen desaturation during OLV are the use of a high fraction of inspired oxygen, the application of continuous positive airway pressure (CPAP) to the nondependent lung, and repeated inflation of the nondependent lung. Previously, we compared the effects of propofol, isoflurane, and sevoflurane on oxygenation and the shunt fraction during OLV and concluded that Pa_{O_2} increased and shunt fraction decreased significantly during propofol anesthesia [2]. The application of positive end-expiratory pressure (PEEP) to the dependent lung improves oxygenation [3,4] but may reduce arterial oxygenation [5]. High-frequency jet ventilation (HFJV) has been reported to have better oxygenation effects than CPAP in patients undergoing resection of thoracoabdominal aortic aneurysm [6]. It is well known that the application of CPAP to the nonventilated lung is useful for maintaining arterial oxygenation during OLV. To study the usefulness of HFJV, we investigated the effects of HFJV or CPAP application to the nondependent lung on arterial oxygenation, hemodynamics, and shunt fraction during OLV in patients undergoing resection of descending aortic aneurysm under propofol anesthesia.

Materials and methods

This investigation was approved by our ethical committee on human studies (Sakurabashi Watanabe Hospital

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and Nagoya Tokushukai General Hospital), and written, informed consent was obtained from each patient. Subjects were scheduled for procedures that required OLV for descending aortic aneurysm. Forty patients were enrolled in this study from February 2000 to November 2004 in Sakurabashi Watanabe Hospital and Nagoya Tokushukai General Hospital. The application of HFJV to the nondependent lung was done in 22 patients. We also compared the usefulness of HFJV application to the nondependent lung with CPAP, which was performed subsequent to the HFJV study for 18 patients. A thoracic epidural catheter was placed (T7–T8) for postoperative pain relief and tested with 5 ml 2% lidocaine 1 day before surgery. Epidural medications were not given until the end of the procedure, after all the data were collected. On admission to the operating room, patients were placed on a water-circulating heating mattress and an IV cannula was inserted under local anesthesia. A radial artery cannula was inserted under local anesthesia and arterial pressure was monitored continuously. Anesthesia was induced with 2 mg·kg^{-1} propofol IV and 0.2 mg fentanyl IV supplemented with sevoflurane 1%. Vecuronium 0.1 mg·kg^{-1} was given to facilitate tracheal intubation.

A left-sided double-lumen endobronchial tube (Broncho-cath; Mallinckrodt Laboratories, Athlone, Ireland) was placed and initially positioned by auscultation. After turning the patient to the lateral decubitus position, the position of the double-lumen endobronchial tube was confirmed by fiberoptic bronchoscopy just before the initiation of OLV. The dependent lung was ventilated with 100% oxygen and a tidal volume of 10 ml·kg^{-1} with the rate adjusted to maintain $\mathrm{PET_{CO_2}}$ at 35–45 mmHg, throughout the procedure. After the tracheal intubation, patients were given an infusion of vecuronium bromide 0.1 mg·kg^{-1}·h^{-1} and propofol 4 mg·kg^{-1}·h^{-1}, which was reduced to 2.5 mg·kg^{-1}·h^{-1} and maintained throughout the procedure. A flow-directed pulmonary artery catheter and triple-lumen catheter were inserted via the right internal jugular vein and zeroed in the horizontal plane of the vertebral column in the lateral position.

We took samples and collected other data at four time points. Arterial blood gas and mixed venous blood gas sampling and hemodynamic measurements were performed just before the start of OLV (T_1), 15 min after the start of OLV (T_2), and 15 min (T_3) and 30 min (T_4) after the application of HFJV or CPAP to the nondependent lung. All blood gas samples were placed on ice and analyzed within 5 min. Conventional ventilation, with a tidal volume of 10 ml/kg and a frequency of 10/min, was applied to both lungs when the chest was open and the left lung was collapsed and retracted by the surgeon. PEEP was not used during this study.

HFJV was provided with a driving gas pressure of 0.5 kg/cm^2 at a rate of 180 jet pulses per minute with an inspiratory/expiratory ratio of 0.3 and an inspiratory gas of 100% oxygen, using an MD-705XL anesthesia machine with an Acutronic MK800 ventilator (Senko Ika Kogyo, Tokyo, Japan). CPAP was provided using a Bain circuit apparatus connected to the nondependent lung at an oxygen flow rate of 5 l/min and a positive pressure of 10 cm H_2O. Airway pressure was maintained at about 10 cm H_2O throughout the HFJV.

Cardiac output (CO) was measured using the thermodilutional technique, by forcibly injecting, twice, 10 ml 5% glucose at room temperature through the proximal port of the pulmonary artery catheter that was connected to an OptiQ continuous cardiac computer (Abbott Laboratories, Abbott Park, IL, USA). The following variables were measured: mean arterial blood pressure (MAP), heart rate (HR), central venous pressure (CVP), pulmonary artery pressure (PAP), CO, arterial partial pressure of oxygen ($\mathrm{Pa_{O_2}}$), arterial partial pressure of carbon dioxide ($\mathrm{Pa_{CO_2}}$), arterial saturation of oxygen ($\mathrm{Sa_{O_2}}$), oxygen saturation of venous admixtures ($\mathrm{Sv_{O_2}}$), and shunt fraction (Qs/Qt). The Qs/Qt calculation was performed with the formula: venous admixture = Qs/Qt = ($\mathrm{Cc_{O_2}}$ − $\mathrm{Ca_{O_2}}$)/($\mathrm{Cc_{O_2}}$ − $\mathrm{C_{O_2}}$) where $\mathrm{Cc_{O_2}}$, $\mathrm{Cv_{O_2}}$, and $\mathrm{Cv_{O_2}}$ are the oxygen content in the pulmonary capillary, systemic arterial, and mixed venous blood, respectively.

Changes in hemodynamic data, the arterial and mixed venous blood sampling data, and the Qs/Qt were compared using repeated measures analysis of variance with Fisher's least significance differences test for multiple comparisons, and paired and unpaired *t* tests when appropriate. All data are expressed as the mean ± SD. Changes were considered significant at the 5% level ($P < 0.05$).

Results

Forty patients were enrolled in this study, but 15 were dropped because of severe hypoxemia (3 patients in HFJV group and 3 in the CPAP group), because a cardiopulmonary bypass was unexpectedly required during the procedure (3 HFJV patients and 2 in the CPAP group), or because the surgical procedure was disrupted by the ventilation method (4 CPAP patients). Therefore, a total of 25 patients completed the study. In the final study group, application of HFJV to the nondependent lung was done in 16 patients and CPAP in 9.

Table 1 shows the patient profiles. There were no significant differences between the groups in age, height, sex, body weight, OLV time, or anesthesia time. There was no evidence of congestive heart failure or lung edema before the surgery. There were no significant changes in MAP, HR, CVP, or CO at any time point in either group. The mean PAP values increased significantly after the initiation of OLV compared with two-lung ventilation in both groups but returned to the baseline value after the initiation of HFJV or CPAP (Table 2). There were no significant changes in the Pa_{CO_2} or the Sv_{O_2}, but arterial oxygen saturation increased after the application of HFJV and CPAP (Table 3). As shown in Fig. 1, after the initiation of OLV, Pa_{O_2} decreased significantly in both groups (from 399.6 ± 79.5 to 173.8 ± 39.6 mmHg in the HFJV group and from 370.5 ± 57.1 to 153.0 ± 38.5 mmHg in the CPAP group).

After the initiation of HFJV to the nonventilated lung during OLV, the Pa_{O_2} values increased significantly, from 173.8 ± 39.6 mmHg (T_2) to 344.1 ± 87.9 mmHg (T_3) and 359.9 ± 82.4 mmHg (T_4) ($P < 0.05$). After the initiation of CPAP, the Pa_{O_2} values increased significantly, from 153.0 ± 38.5 to 243.0 ± 48.5 mmHg (T_3) and 269.7 ± 55.0 mmHg (T_4) ($P < 0.05$). In the HFJV group, the Pa_{O_2} values were significantly higher at T_3 and T_4 compared with those of the CPAP group. As shown in Fig. 2, the shunt fraction (Qs/Qt) increased significantly after the initiation of OLV in both groups (from 21.3% ± 4.0% to 38.7% ± 8.9% in the HFJV group and from 22.5% ± 5.6% to 44.6% ± 8.6% in the CPAP group). After the initiation of HFJV, the Qs/Qt decreased significantly, from 38.7% ± 8.9% (T_2) to

Table 1. Demographic data of patients

	HFJV	CPAP
Sex (male/female)	13/3	6/3
Age (years)	64.4 ± 7.4	61.4 ± 7.6
Body weight (kg)	59.0 ± 8.1	55.4 ± 9.2
Height (cm)	160.2 ± 5.9	161.4 ± 7.6
OLV time (min)	95.6 ± 19.4	101.1 ± 27.9
Anesthesia time (min)	282.7 ± 34.2	328.2 ± 51.1

Data are mean ± SD
HFJV, high-frequency jet ventilation; CPAP, continuous positive airway pressure; OLV, one-lung ventilation

Table 2. Time course changes of hemodynamics

	T_1	T_2	T_3	T_4
MAP (mmHg)				
HFJV	81.8 ± 12.6	90.5 ± 12.0	81.5 ± 13.7	77.4 ± 11.5
CPAP	91.4 ± 8.0	94.0 ± 8.0	88.6 ± 13.8	91.4 ± 16.5
HR (/min)				
HFJV	68.6 ± 9.7	77.0 ± 11.2	79.9 ± 11.3	78.1 ± 12.2
CPAP	69.5 ± 10.8	74.7 ± 8.2	74.9 ± 8.1	74.4 ± 5.2
CVP (mmHg)				
HFJV	6.9 ± 1.7	7.8 ± 1.9	8.4 ± 2.5	8.3 ± 2.0
CPAP	7.5 ± 2.6	7.0 ± 2.2	8.3 ± 1.8	8.4 ± 2.2
PAP (mmHg)				
HFJV	17.4 ± 5.4	23.0 ± 9.2*	19.9 ± 9.2	19.3 ± 5.9
CPAP	19.6 ± 2.3	24.1 ± 2.7*	22.8 ± 1.8	21.6 ± 2.8
CO (l/min)				
HFJV	4.0 ± 0.5	4.1 ± 0.7	4.3 ± 0.6	4.4 ± 0.9
CPAP	4.3 ± 0.7	4.5 ± 0.8	4.4 ± 0.9	4.5 ± 0.9

MAP, mean arterial blood pressure; HR, heart rate; CVP, central venous pressure; PAP, mean pulmonary artery pressure; CO, cardiac output
*$P < 0.05$ compared with T_1

Table 3. Time course changes in respiratory parameters

	T_1	T_2	T_3	T_4
Pc_{O_2} (mmHg)				
HFJV	35.5 ± 3.4	36.1 ± 4.3	35.1 ± 3.4	34.7 ± 3.2
CPAP	38.1 ± 5.8	42.7 ± 5.4	41.8 ± 6.7	40.3 ± 6.3
Sv_{O_2} (%)				
HFJV	79.1 ± 2.9	76.7 ± 5.6	80.6 ± 4.2	81.6 ± 3.6
CPAP	80.5 ± 8.3	74.4 ± 6.6	76.2 ± 7.3	78.5 ± 6.8
Sa_{O_2} (%)				
HFJV	99.8 ± 0.1	97.5 ± 1.0	99.4 ± 0.6*	99.6 ± 0.4*
CPAP	99.9 ± 0.9	96.2 ± 2.8	99.0 ± 2.9*	99.0 ± 2.4*

T_1, two-lung ventilation; T_2, 15 min after the start of one-lung ventilation (OLV); T_3, 15 min after the start of high-frequency jet ventilation (HFJV) or continuous positive airway pressure (CPAP); T_4, 30 min after the start of HFJV or CPAP
*$P < 0.05$ compared with T_2

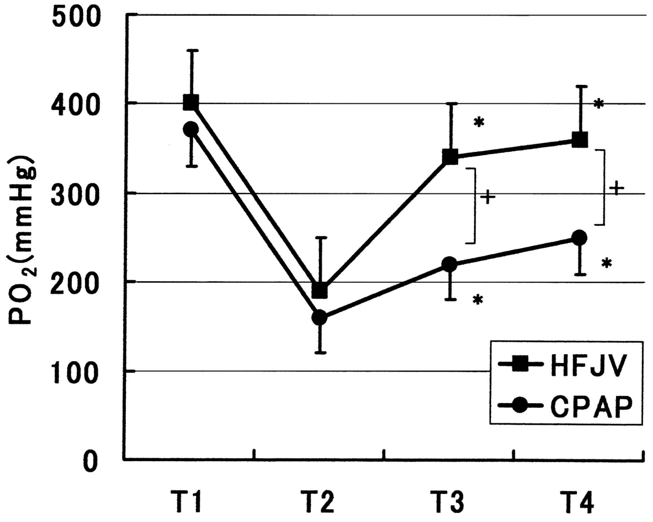

Fig. 1. Time course of changes in the arterial partial pressure of oxygen during one-lung ventilation. *T*$_1$, two-lung ventilation; *T*$_2$, 15 min after the start of one-lung ventilation (OLV); *T*$_3$, 15 min after the start of high-frequency jet ventilation (*HFJV*) or continuous positive airway pressure (*CPAP*); *T*$_4$, 30 min after the start of HFJV or CPAP. *$P < 0.05$ compared with T$_2$; +$P < 0.05$ compared with CPAP (mean ± SD)

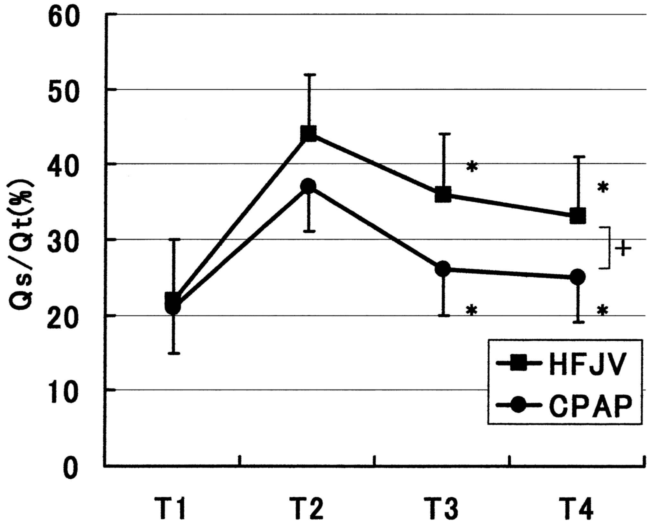

Fig. 2. Time course of changes in the shunt fraction (*Qs/Qt*) during one-lung ventilation. *T*$_1$, two-lung ventilation; *T*$_2$, 15 min after the start of one-lung ventilation (OLV); *T*$_3$, 15 min after the start of high-frequency jet ventilation (*HFJV*) or continuous positive airway pressure (*CPAP*); *T*$_4$, 30 min after the start of HFJV or CPAP. *$P < 0.05$ compared with T$_2$; +$P < 0.05$ compared with CPAP (mean ± SD)

27.0% ± 8.0% (T$_3$) and 25.9% ± 8.7% (T$_4$) ($P < 0.05$). After the initiation of CPAP, Qs/Qt decreased significantly from 44.6% ± 8.6% (T$_2$) to 34.3% ± 10.2% (T$_3$) and 32.6% ± 8.5% (T$_4$) ($P < 0.05$). In the HFJV group, the shunt fraction was significantly lower at T$_4$ than in the CPAP group.

Discussion

The purpose of this study was to determine the usefulness of HFJV for the maintenance of arterial oxygenation and hemodynamics during OLV. For this assessment, we compared the usefulness of HFJV with that of CPAP application to the nondependent lung.

There were two important limitations to this study. First, the patients who participated in it were not divided randomly into groups. Originally, we studied the effect of HFJV application to the nondependent lung on arterial oxygenation and hemodynamics during OLV in 16 patients. However, to discuss the usefulness of HFJV for improving arterial oxygenation during OLV, it was necessary to compare HFJV with CPAP, so we assessed the effect of CPAP application to the nondependent lung as a second study. Second, although it is possible to measure and monitor the airway pressure during high-frequency oscillation, it is difficult to measure it during HFJV. In the CPAP study, we maintained airway pressure at about 10 cm H_2O.

Our data show that the application of either HFJV or CPAP to the nondependent lung improved the arterial oxygenation and shunt fraction during OLV. This study also shows that beginning the surgical resection of descending aortic aneurysm in the lateral decubitus position induced a dramatic deterioration in arterial oxygenation and a significant increase in shunt fraction in both groups. Various methods have been proposed to reduce the risk of hypoxemia during OLV, including the application of PEEP to the dependent lung, the application of CPAP to the nondependent lung, and repeated ventilation of the nondependent lung. However, the surgical procedure used here would be disturbed by the repeated ventilation of the nondependent lung, making this method undesirable.

The application of PEEP to the dependent lung during OLV may reduce arterial oxygenation [3]. In general, CPAP application to the nondependent lung is useful for preventing arterial desaturation during OLV. On the other hand, HFJV has been shown to recruit alveoli through the PEEP effect it generates [7], and this method could reopen some lung areas and reduce the risk of arterial hypoxemia during OLV. Crimi et al. [8] reported a dramatic improvement in arterial oxygenation and unchanged hemodynamics with the application of HFJV to the nondependent lung and ventilation of the dependent lung with intermittent positive pressure, in patients with one-lung injury. In addition, the rate of carbon dioxide elimination can be regulated with HFJV by changing the driving gas pressure and the respiratory rate.

Recently, there has been increasing interest in using HFJV for thoracic operations. During general anesthesia for thoracic surgery, OLV is indicated to facilitate exposure of the surgical site and/or prevent contamination by bleeding into the ventilated lung. Dynamic lung hyperinflation often occurs during OLV when a double-lumen endobronchial tube is used to separate the two lungs [9]. Several methods can prevent arterial oxygen desaturation during OLV: PEEP causes an increase in functional residual capacity (FRC), which contributes to the prevention of airway and alveolar closure at end-expiration and to the recruitment of airways and alveoli during inspiration. The increase in lung volume and in airway and alveolar opening results in improved lung compliance, ventilation, and an increased ratio of ventilation to perfusion. However, the application of PEEP to the nonventilated lung may reduce arterial oxygenation [5], as already mentioned.

Godet et al. [6] studied the effectiveness of HFJV and CPAP on respiratory parameters in 20 patients undergoing resection of thoracoabdominal aortic aneurysm and reported that differential ventilation with CPAP did not improve any of the respiratory parameters. In contrast, they found that differential ventilation with HFJV improved respiratory parameters and concluded that because HFJV improved gas exchange without affecting surgical comfort, differential ventilation with HFJV is superior to differential ventilation with CPAP. In our study, however, both HFJV and CPAP application to the nonventilated lung improved arterial oxygenation and shunt fraction. Differential lung ventilation using HFJV was significantly superior to CPAP for the Pa_{O_2} and shunt fraction, but in terms of clinical benefit, the effectiveness of HFJV and CPAP in maintaining the arterial oxygenation and shunt fraction during OLV was the same. The Godet et al. study did not use a cardiopulmonary bypass or a bypass shunt in any of the cases. In our study, a cardiopulmonary bypass or a bypass shunt was required in all but 3 cases in the CPAP group. In addition, Godet reported that the application of CPAP to the nonventilated lung during surgery for thoracoabdominal aortic aneurysm markedly interferes with the surgical procedure, as it does not allow the surgeon to rapidly control the upper part of the thoracic aneurysm in some patients. In our study, 4 of the total 18 patients in the CPAP group were dropped from this study because of a marked change required in the surgical procedure after the application of CPAP to the nonventilated lung.

We conclude that it is possible to improve arterial oxygenation and decrease the shunt fraction during OLV with the application of HFJV or CPAP to the nonventilated lung.

References

1. Benumof JL (1985) One-lung ventilation and hypoxic pulmonary vasoconstriction; implication for anesthetic management. Anesth Analg 64:821–833
2. Abe K, Shimizu T, Takashina M, Shiozaki H, Yoshiya I (1987) The effects of propofol, isoflurane, and sevoflurane on oxygenation and shunt fraction during one-lung ventilation. Anesth Analg 87:1164–1169
3. Benumof J (1982) One-lung ventilation: which lung should be PEEPed? Anesthesiology 56:161–163
4. Abe K, Mashimo T, Yoshiya I (1998) Arterial oxygenation and shunt fraction during one-lung ventilation: a comparison of isoflurane and sevoflurane. Anesth Analg 86:1266–1270
5. Benumof JL, Rogers SN, Moyce PR (1979) Hypoxia-induced vasoconstriction and regional and whole lung PEEP in the dogs. Anesthesiology 51:503–507
6. Godet G, Bertrand M, Rouby JJ, Coriat P, Hag B, Kieffer E, Viars P (1994) High-frequency jet ventilation vs continuous positive airway pressure for differential lung ventilation in patients undergoing resection of thoracoabdominal aortic aneurysm. Acta Anaesth Scand 38:562–568
7. Rouby JJ, Simonneau G, Benhamou D (1985) Factors influencing pulmonary volumes and CO_2 elimination during high-frequency jet ventilation. Anestehsiology 63:473–482
8. Crimi G, Gandiari A, Conti G (1986) Clinical applications of independent lung ventilation with unilateral high-frequency jet ventilation (ILV-UHFJV). Intens Care Med 12:90–94
9. Larsson A, Malmkvist G, Werner O (1987) Variation in lung volume and compliance during pulmonary surgery. Br J Anaesth 59:585–591