Improved P_{CO_2} Monitoring during High Frequency Jet Ventilation

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During high frequency jet ventilation (HFJV), it has been shown that P_{aCO_2} can be predicted by capnography when the frequency was temporarily reduced to obtain a steady expiratory CO_2 tension (PET_{CO_2}). The influence of the sampling site of expiratory gas in the airway and the driving pressure of the ventilator on the difference between P_{aCO_2} and PET_{CO_2} was investigated in ten adult patients who underwent general anesthesia. During HFJV (frequency; 100 bpm, inspiratory duty cycle; 30%), its frequency was temporarily reduced to 10 bpm in twelve different condition; i.e., 3 different driving pressures (Pd; 20, 30, and 40 psi) at 4 different sampling sites (d; 0, 2, 5, and 10 cm in the endotracheal tube). Both PET_{CO_2} and P_{aCO_2} were measured simultaneously, and their difference was evaluated by using Student's t-test. The difference between P_{aCO_2} and P_{maxCO_2} (the maximum P_{CO_2} value in the airway during exhalation) was minimal, when Pd was greater than 30 psi, and d was greater than 5 cm. The present study suggests that better prediction of P_{aCO_2} can be done by PET_{CO_2} during HFJV, when d and Pd were set as large as possible to obtain stable expiratory P_{CO_2} curve. (Key words: ventilation, high frequency jet ventilation, end-tidal P_{CO_2})

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High frequency jet ventilation (HFJV) has been widely accepted as an alternate way of ventilation during anesthesia and intensive care, however it is difficult to evaluate CO_2 elimination without frequent arterial blood gas analysis. Although end-tidal CO_2 tension (PET_{CO_2}) represents arterial CO_2 tension (P_{aCO_2}) during conventional mechanical ventilation, it is shown not to correlate well with P_{aCO_2} during HFJV^{1,2}. One of the major rea-

son is that during HFJV expiratory time is not long enough to equilibrate the end-tidal CO_2 concentration to alveolar CO_2 .

In our previous study³, we introduced a technique to predict P_{aCO_2} during HFJV by using capnograph while ventilatory frequency was temporally reduced. Although PET_{CO_2} by this technique correlated well with P_{aCO_2} in that study, a number of factors were found to influence its correlation; i.e., when the cardiogenic oscillation affects the plateau of the expired CO_2 concentration curve, and when the expired gas was diluted by the fresh gas flow during expiration at the sampling site of a capnograph.

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Fig. 1. Diagram of jet ventilation circuit. The letter d indicates the distance from jet outlet to the distal end of the sampling catheter of capnograph. The sampling catheter was able to be moved into the trachea.

Fig. 2. The measurement of plateau time (T_p).

The purpose of the present study is to elucidate whether and how the sampling site of expiratory gas in the airway, and the driving pressure of the ventilator can influence the relation between $PETCO_2$ and $Paco_2$ by our technique.

Subjects and Methods

Ten adult patients (40–55 kg, and ASA I), who underwent elective surgery, were involved in this study. The anesthesia was induced with the intravenous administration of thiopental sodium and succinylcholine chloride. After the endotracheal intubation, anesthesia was maintained with N_2O , O_2 , and enflurane. Pancuronium bromide was given to obtain muscle relaxation.

An elbow-connector which was in-

corporated with a jet nozzle and a sampling catheter were inserted between an endotracheal tube and a T-connector (fig. 1). The T-connector has a reservoir tube containing fresh gas from anesthesia circuit, and its distal end is open to the atmosphere. The sampling catheter was inserted into the endotracheal tube to change the sampling site. The sampling site was defined as the distance (d) between the tip of the sampling catheter and the jet nozzle; i.e., 0, 2, 5, or 10 cm. The CO_2 tension in the airway (Pco_2) was measured by using a capnograph (Oscar, DATEX Co. Ltd., Sweden), whose sampling rate was $200 \text{ ml} \cdot \text{min}^{-1}$. The capnograph was calibrated by using 5% CO_2 in nitrogen at body temperature and pressure saturated (BTPS) prior to the study. The air flow at the proximal end of the endotracheal tube was also measured by a hot-wire flow meter at two sampling sites ($d=0$ and 2 cm).

A jet ventilator (VS 600, Instrument Development Corp., USA) was used for ventilation. The HFJV was set at a frequency of 100 bpm and an inspiratory duty-cycle of 30%. First, HFJV was applied to the patient for five minutes, and arterial blood gas was measured by blood gas analyzer (288 blood gas system, CIBA-Corning Diagnostics Corp., USA). Thereafter, the frequency was reduced to 10 bpm (low frequency jet ventilation, LFJV) for

Fig. 3. Typical recording of capnograph during conventional ventilation (CV, left), high frequency jet ventilation at the rate of 100 bpm (HFJV), middle), and jet ventilation at the rate of 10 (JV, right).

Fig. 4. Typical recording of capnograph when the expiratory CO₂ tension did not represent PaCO₂. The plateau of CO₂ tension was influenced by the cardiogenic oscillation, suggesting the dilution of expiratory gas by the fresh gas.

one minute at the same driving pressure and inspiratory duty cycle. P_{CO_2} was continuously measured throughout the study. The measurements were made in twelve conditions, i.e., 3 different driving pressures (P_d ; 20, 30, and 40 psi) at four different sampling sites ($d=0, 2, 5$, and 10 cm).

P_{CO_2} and flow rate at the airway were recorded by a data recorder and were processed by an AD converter (MacLab, Analog Digital Instruments Pty Ltd., Australia) and analyzed by using a computer system (Macintosh IICx, Apple Co. Ltd., USA). The plateau time (T_p), which is the duration between the beginning of the ascending limb and the end of the plateau in the P_{CO_2} curve, was measured (fig. 2,4). The maximum value of P_{CO_2} during T_p (P_{maxCO_2}) were also analyzed. The first three waveforms of the P_{CO_2} curve were used for analysis.

The difference between P_{aCO_2} and P_{maxCO_2} was analyzed by Student's t-test. The linear correlation between P_{aCO_2} and P_{maxCO_2} , as well as between P_d and T_p were analyzed by using a least-squares method. Probability less than 5% was considered as statistically significant.

Results

Figure 3 shows one of the recordings of P_{CO_2} curve during conventional ventilation (CV, left), jet ventilation at a rate of 100 bpm (HFJV, middle), and 10 bpm (LFJV, right). During exhalation, P_{CO_2} showed steady plateau during CV at a rate of 10 bpm. During CV at a rate of 10 bpm. During HFJV, no plateau was found and inspiratory CO₂ tension did not reach to 0 mmHg. On the other hand, during LFJV, P_{CO_2} showed steady plateau during exhalation.

Figure 4 shows the typical recording

Table 1. Difference between PaCO_2 and PmaxCO_2 at various distance (d) and driving pressure (Pd)

		d (cm)			
		0	2	5	10
Pd (psi)	20	$10.54 \pm 9.41^*$	$7.36 \pm 12.12^*$	$4.21 \pm 7.74^*$	0.19 ± 8.38
	30	$1.72 \pm 3.24^*$	$3.04 \pm 3.63^*$	$1.46 \pm 4.65^*$	0.30 ± 3.39
	40	$5.18 \pm 2.47^*$	$4.11 \pm 2.17^*$	$3.01 \pm 3.00^*$	$1.98 \pm 4.17^*$

n=10, Mean $\pm$ SD (mmHg) * $P < 0.05$

The numbers in this table represent the difference between PaCO_2 and PmaxCO_2 (mmHg).

Table 2. Correlation between PaCO_2 and PmaxCO_2 at various distance (d) and driving pressure (Pd)

		d (cm)			
		0	2	5	10
Pd (psi)	20	0.408	0.012	0.365	0.185
	30	0.843	0.927	0.838	0.876
	40	0.917	0.935	0.915	0.808

The numbers in this table represent correlation coefficient.

Fig. 5. Relationship between PmaxCO_2 and PaCO_2 at the driving pressure of 40 psi. ($R=0.89$)

of Pco_2 , and the airflow at the airway, where PETCO_2 did not represent PaCO_2 . The airflow recording was ad-

Fig. 6. Changes in plateau time (T_p) with different driving pressure (Pd) and the sampling site (d).

justed to the time delay of the capnograph. It is evident that expiratory gas was diluted by the inward airflow during exhalation, resulted in the unstable expiratory plateau, i.e., short T_p . The unstable Pco_2 may be due to the cardiogenic oscillation, since the reciprocal airflow was coincident with heart beat. When the expiratory flow became less than the sampling flow rate, the plateau concentration was reduced by the dilution.

The difference between PaCO_2 and PmaxCO_2 was calculated at 12 different settings (table 1). There were significant differences among them except 10 cm of d at 20 and 30 psi of Pd.

The correlation between $P_{\max\text{CO}_2}$ and P_{aCO_2} was shown in table 2. They correlated well at 30 and 40 psi of Pd. Figure 5 shows a good correlation between $P_{\max\text{CO}_2}$ and P_{aCO_2} at 40 psi of Pd.

The relation between Tp and d was shown in figure 6. When Pd was higher, the longer Tp was obtained ($P < 0.05$).

Discussion

P_{ETCO_2} is known to represent P_{aCO_2} during conventional ventilation in the normal lungs¹. During HFJV, P_{ETCO_2} has been demonstrated not to correlate well with P_{aCO_2} , because the expiratory time is not long enough to obtain expiratory plateau to predict alveolar CO_2 concentration during exhalation. In our previous study, the double-barrel jet nozzle was introduced for either ventilation or gas sampling, and it was shown that the temporary large tidal volume with longer expiratory time during HFJV enables P_{ETCO_2} to represent P_{aCO_2} during airway reconstruction³. In that study, the difference between P_{ETCO_2} in LFJV and P_{aCO_2} was relatively large, although they were well correlated. It should be answered whether the sampling site and driving pressure can influence the relation between P_{ETCO_2} in LFJV and P_{aCO_2} .

The present study clearly demonstrated that higher driving pressure and deeper sampling site are needed to obtain better prediction of P_{aCO_2} by P_{ETCO_2} during jet ventilation. In this study, driving pressure plays an important role for the measurement, since the correlation coefficient between $P_{\max\text{CO}_2}$ (or P_{ETCO_2}) and P_{aCO_2} was greater than 0.8 only when the driving pressure was 30 psi or greater.

The sampling site and the driving pressure can influence the difference

and the relation between $P_{\max\text{CO}_2}$ and P_{aCO_2} during LFJV. The greater were the distance and the driving pressure, the less was the difference between $P_{\max\text{CO}_2}$ and P_{aCO_2} . When the driving pressure was low and expiratory volume was small, the expiratory flow rate in the airway may become less than the sampling rate in the middle of expiratory time, resulted in the dilution of expiratory gas by the fresh gas at the sampling site which is proximal to the circuit. The degree of such dilution was also dependent on the sampling site. When the expiratory flow becomes slower than the sampling speed, and the sampling site is close to the circuit with fresh gas, the dilution starts earlier. On the other hand, when the sampling site is far from fresh gas, such dilution is less likely. These findings suggest that P_{CO_2} curve should be displayed during monitoring. If cardiogenic oscillation has any influence on P_{CO_2} plateau, it indicates that the expiratory gas is diluted by the fresh gas at the sampling site. In such situation, the sampling site should be placed far away from the circuit, or driving pressure should be increased to obtain higher expiratory flow.

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