

## Humidification of Base Flow Gas during Adult High-Frequency Oscillatory Ventilation: An Experimental Study Using a Lung Model

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In adult high-frequency oscillatory ventilation (HFOV) with an R100 artificial ventilator, exhaled gas from patient's lung may warm the temperature probe and thereby disturb the humidification of base flow (BF) gas. We measured the humidity of BF gas during HFOV with frequencies of 6, 8 and 10 Hz, maximum stroke volumes (SV) of 285, 205, and 160 ml at the respective frequencies, and, BF's of 20, 30, 40 l/min using an original lung model. The R100 device was equipped with a heated humidifier, Hummax II, consisting of a porous hollow fiber in circuit. A 50-cm length of circuit was added between temperature probe (located at 50 cm proximal from Y-piece) and the hollow fiber. The lung model was made of a plastic container and a circuit equipped with another Hummax II. The lung model temperature was controlled at 37°C. The Hummax II of the R100 was inactivated in study-1 and was set at 35°C or 37°C in study-2. The humidity was measured at the distal end of the added circuit in study-1 and at the proximal end in study-2. In study-1, humidity was detected at 6 Hz (SV 285 ml) and BF 20 l/min, indicating the direct reach of the exhaled gas from the lung model to the temperature probe. In study-2 the absolute humidity of the BF gas decreased by increasing SV and by increasing BF and it was low with setting of 35°C. In this study setting, increasing the SV induced significant reduction of humidification of the BF gas during HFOV with R100.

**Key words:** HFOV, humidification

High-frequency oscillatory ventilation (HFOV) is supposed to be one of the most effective lung-protective ventilatory modes for acute respiratory distress syndrome (ARDS). It has been widely used for neonatal respiratory failure, but is now becoming popular for adult respiratory failure because of recent development of the devices for HFOV [1-4]. Two

types of HFOV ventilators are available for adults in Japan: R100 (Metran Co. Ltd., Kawaguchi, Japan) and 3100B (CareFusion, Yorba Linda, CA, USA). Humidification during mechanical ventilation including HFOV is a critically important issue. Because the gas flow rate passing through the central airway of HFOV is much higher than that of conventional mechanical ventilation, inadequate humidification causes severe injury to the epithelial cells of the respiratory tract [5, 6].

R100 is equipped with a humidifier (Hummax

II; Metarn Co. Ltd.), which has a single airway temperature probe and single heating element. In HFOV ventilators for adults, oscillation is produced in the inspiratory circuit and then exhaled gas from the lung returns to the inspiratory circuit; some part of the gas may again return to the lung repeatedly. When the airway temperature probe controlling the heating element is placed at the Y-piece, the gas exhaled from the lung directly warms the temperature probe, which results in the heating element being no longer in control. To avoid this phenomenon, the airway temperature probe is placed at 50 cm from the Y-piece in the inspiratory circuit of R100 by the manufacturer. The partial volume of this compartment is approximately 190 ml. However there remains another possibility that the range of the stroke volume (SV) may influence the function of the humidifier.

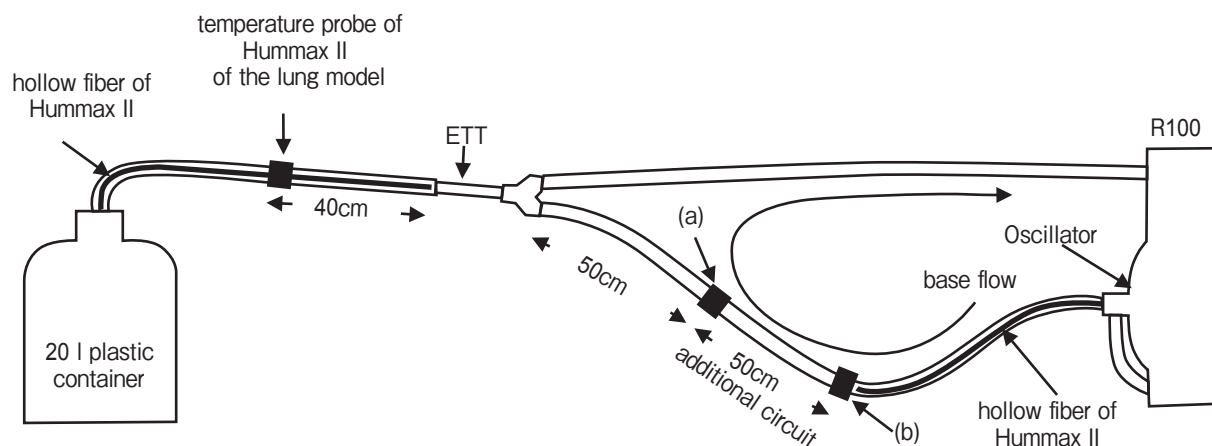
In this study, we investigated the effect of the SV setting of the R100 on the humidification of the base flow (BF) gas using an original lung model.

## Materials and Methods

**Lung model.** The lung model was made of a 20-liter, airtight rigid plastic container which was connected to a 130-cm respiratory circuit (ID 22 mm) internally equipped with a heated humidifier Hummax II. Hummax II is a unique system in that humidifica-

tion is performed through a porous hollow fiber surrounding a hose heater [7]. The lung model was connected via 8 mm ID endotracheal tube (ETT) to R100 as shown in Fig. 1. The temperature probe of the lung model was placed at 40 cm distal from the ETT so that the volume from the ETT was about 150 ml, approximately equal to anatomical dead space. This 130-cm respiratory circuit and distal half of the ETT were covered with insulating materials and also with a blanket during the study.

**Measurement of humidity and temperature.** A Moiscope (S.K.I. Net Inc. Tokyo, Japan) apparatus was used to measure humidity and temperature. Moiscope is equipped with a capacitive humidity sensor and a thermistor. These sensors measure the relative humidity (RH) and temperature of the ventilated gas, then calculate the absolute humidity (AH). During our study, the RH was less than 100%. We evaluated the humidity of the BF gas by the AH. The R100 was equipped with a Hummax II and the temperature probe was located 50 cm proximal from the Y-piece (at the just-distal end of the Hummax hollow fiber). A 50-cm length of respiratory circuit (ID 22 mm) covered with insulating materials was added between the temperature probe and the Hummax hollow fiber. The Moiscope was placed at the distal end of the added circuit (just proximal to the temperature probe) in study-1 and placed at the proximal end of the



**Fig. 1** This schema shows the lung model and the ventilation circuit. The lung model was connected via an 8-mm ID endotracheal tube (ETT) to the ventilation circuit. An additional circuit was added between (a) and (b). The circuit of the lung model and the extra circuit were covered with insulating materials. The temperature probe of the Hummax II of the R100 was placed at (a). In study-1, the Moiscope was also placed at (a). In study-2, the Moiscope was placed at (b). In this figure, the water supply circuit and the temperature control circuit were omitted.

added circuit (at the end of the Hummax hollow fiber) in study-2. Room temperature was kept between 23.5 and 24.5°C during all studies.

The preliminary study explored how the gas temperature at the fresh gas outlet of the R100 increased for 3 to 4 h after running and thereafter became constant. Therefore, we waited at least 4 h before initiating all studies under dry conditions with the following settings: frequency, 10 Hz; SV, maximum (160 ml); BF, 30 l/min; mean airway pressure (MAP), 30 cmH<sub>2</sub>O; and fraction of inspired oxygen (FIO<sub>2</sub>), 0.21.

**Study-1.** Hummax II of the lung model was activated and that of the R100 was inactivated. The indicated temperature of the lung model was controlled at 37°C. Temperature and AH were measured by the Moiscope just proximal of the temperature probe of R100 as described above. Measurements were repeated with different settings in a random order. The settings of R100 were as follows: frequency, 6, 8 and 10 Hz, SV indicated on the panel, (maximum 285 ml at 6 Hz, 205 ml at 8 Hz, and 160 ml at 10 Hz); BF, 20, 30 and 40 l/min; MAP, 30 cmH<sub>2</sub>O; and FIO<sub>2</sub>, 0.21.

**Study-2.** Both the Hummax II device in the lung model and that of the R100 were activated. The indicated temperature of the lung model was controlled at 37°C and the setting temperature of R100 was fixed at 35°C or 37°C. Temperature and humidity were continuously measured by Moiscope and the data were collected every 5 sec for 30 min. Indicated temperatures of both Hummax II devices were recorded every 30 sec. The settings of the R100 were the same as in study-1 and additionally as follows: SV indicated on the panel, 205-160-80 ml at 8 Hz; BF, 40 l/min; MAP, 30 cmH<sub>2</sub>O; and FIO<sub>2</sub>, 0.21.

#### **Estimation of actual SV in the lung model.**

The pressure swing in the lung model (*i.e.* 20 l container) was measured by PF-300 (imtmedical, Buchs, Switzerland) under dry conditions with all settings, and the actual SV was estimated by calculation.

**Statistical analysis.** All values are expressed as means  $\pm$  standard deviations (m  $\pm$  SD). Statistical analysis was done using analysis of variance (ANOVA) followed by Bonferroni's correction. *P* values less than 0.05 were considered significant.

## **Results**

**Study-1.** Table 1 shows the temperature and

the AH without activating the humidifier of R100. Only with the setting of frequency 6 Hz, SV 285 ml, and BF 20 l/min was humidity detected. The temperature with the setting frequency of 6 Hz (SV 285 ml) was significantly higher than those with the setting frequency of 8 Hz (SV 205 ml) or 10 Hz (SV 160 ml).

**Study-2.** Fig. 2 shows the temperature and the AH of the BF gas. The setting temperature of the R100's humidifier was 35°C and 37°C, and other settings were the same as in study 1. As the frequency increased and the SV decreased, the temperature and the AH of the BF gas tended to increase. As the BF increased, the temperature and the AH of the BF gas decreased.

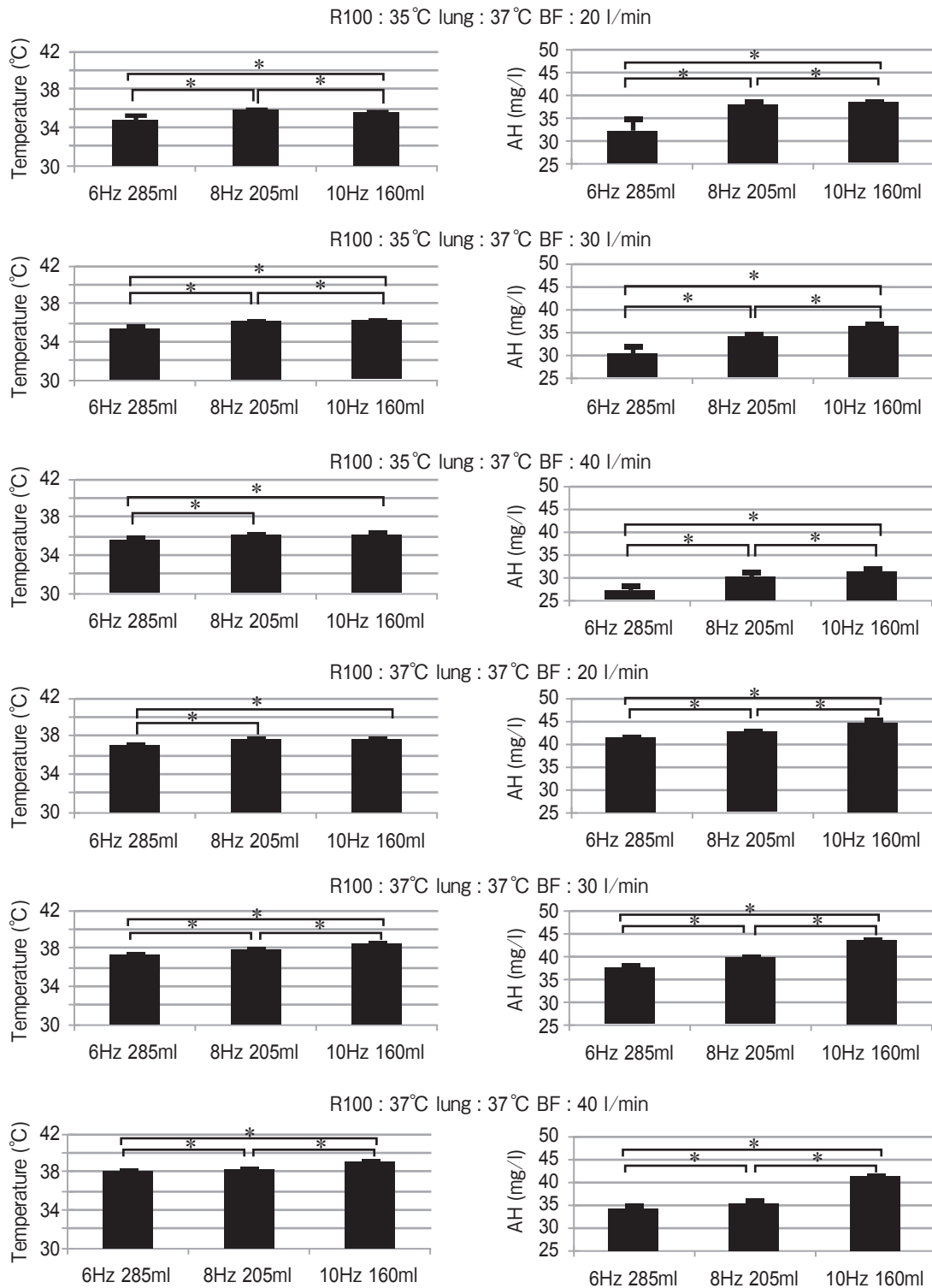
Fig. 3 shows the temperature and the AH of the BF gas. The settings of R100 were a frequency of 8 Hz and BF of 40 l/min, and the setting temperature of the R100's humidifier was 37°C. As the SV increased, the AH and the temperature of the BF gas tended to decrease.

**Actual SV estimation.** Estimated actual SV is shown in Table 2. Estimated actual SV was different from the SV that was indicated on the panel. The estimated actual SV changed as the BF and/or frequency changed.

**Table 1** Temperature and absolute humidity of BF gas without the R100 humidifier

| (A)       |                   |                 |                 |
|-----------|-------------------|-----------------|-----------------|
| frequency | Base flow (l/min) |                 |                 |
|           | 20                | 30              | 40              |
| 6 Hz      | 35.6 $\pm$ 0.3    | 35.4 $\pm$ 0.2  | 35.5 $\pm$ 0.1  |
| 8 Hz      | 34.4 $\pm$ 0.6    | 34.1 $\pm$ 0.8  | 34.3 $\pm$ 1.3  |
| 10 Hz     | 34.2 $\pm$ 0.5    | 34.4 $\pm$ 0.5  | 34.1 $\pm$ 0.5  |
| (B)       |                   |                 |                 |
| frequency | Base flow (l/min) |                 |                 |
|           | 20                | 30              | 40              |
| 6 Hz      | 2.56 $\pm$ 0.05   | 0.25 $\pm$ 0.05 | 0.10 $\pm$ 0.00 |
| 8 Hz      | 0.10 $\pm$ 0.00   | 0.12 $\pm$ 0.04 | 0.12 $\pm$ 0.04 |
| 10 Hz     | 0.12 $\pm$ 0.04   | 0.10 $\pm$ 0.00 | 0.10 $\pm$ 0.00 |

(A) shows the temperature (mean  $\pm$  S.D.) (°C) of the BF gas. (n = 5) (B) shows the absolute humidity (mean  $\pm$  S.D.) (mg/l) of the BF gas. (n = 5) The humidifier of R100 was turned off while the humidifier of the lung model was controlled to be 37°C. Only at 6 Hz, SV 285 ml and BF 20 l/min was humidity detected.



**Fig. 2** The temperature and the absolute Humidity (AH) of the Base Flow (BF) gas. The settings are indicated on each graph. Other settings of R100 were MAP: 30cmH<sub>2</sub>O and FIO<sub>2</sub>: 0.21. The histogram represents the mean ± S.D. of the temperature and the AH of the BF gas. As the frequency became higher and the SV became smaller, the temperature and the AH of the BF gas tended to become higher. (\*p < 0.05) As the BF increased, the temperature and the AH of the BF gas tended to decrease.

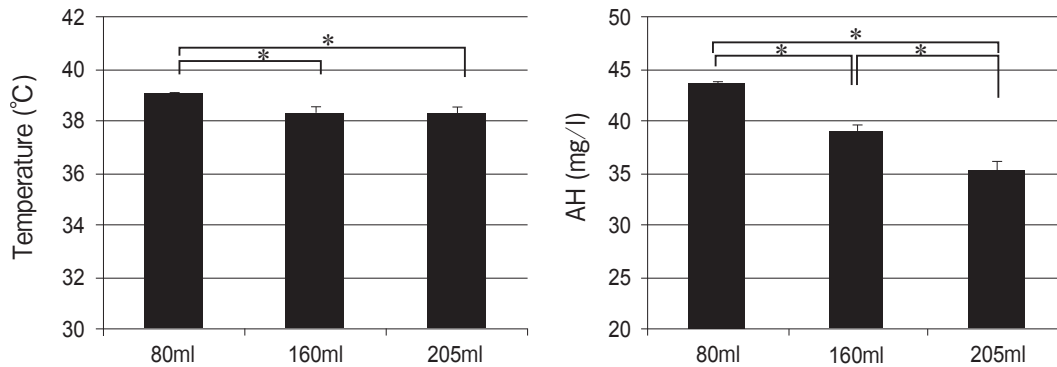


Fig. 3 The effect of SV change. The temperature and the absolute humidity of BF gas at the settings of BF 40l/min and frequency 8Hz. The temperature of the R100's humidifier was set at 37°C; the temperature of the lung model's humidifier was also controlled at 37°C. The histogram represents the mean ± S.D. of the temperature and the AH of BF gas. As the SV increased, the AH and the temperature of BF gas tended to decrease (\**p* < 0.05).

Table 2 Estimated actual SV

| SV (ml)         | 285         | 205         | 160         | 160         | 80         |
|-----------------|-------------|-------------|-------------|-------------|------------|
| frequency (Hz)  | 6           | 8           | 8           | 10          | 8          |
| BF = 20 (l/min) | 269.7 ± 1.1 | 198.6 ± 1.5 | —           | 152.8 ± 1.1 | —          |
| BF = 30 (l/min) | 260.6 ± 1.7 | 190.1 ± 1.8 | —           | 147.9 ± 1.9 | —          |
| BF = 40 (l/min) | 252.6 ± 1.2 | 183.6 ± 0.8 | 138.5 ± 0.7 | 142.5 ± 1.1 | 72.0 ± 0.5 |

Estimated actual SV (mean ± S.D.) (ml) (n = 5) is different from SV which is indicated on the panel. Estimated SV changes as BF and/or frequency change.

### Discussion

Although humidification during HFOV is an important issue, there have been few studies investigating the HFOV ventilator for adults [8]. We measured the humidity of BF gas with various settings during HFOV with R100 to investigate the effect of the SV, using an original lung model to simulate an adult human.

In our lung model, the temperature probe was placed 40cm distal from the ETT so that the volume from the ETT was approximately equal to the anatomical dead space. Therefore, the lung model temperature was considered as simulating the alveolar temperature, and it was controlled at 37°C throughout the study. This system is considered to be more suitable to controlling the lung model temperature than the system with a lung model placed in an incubator. The reason why we added a 50-cm length of cir-

cuit between the temperature probe and the Hummax hollow fiber was to evaluate the humidity of the BF gas itself by excluding the influence of exhaled gas coming back to the inspiratory circuit. In study-2 we collected data for 30min because the temperature indicated on the Hummax II of R100 was not always stable with a fixed temperature setting. On the other hand, in study-1 we recorded rough data because the main purpose was whether warmed and humidified gas exhaled from the lung model could be detected or not.

In study-1, some humidity was detected with a frequency of 6Hz, SV of 285ml, BF of 20l/min (estimated actual SV: 270ml). This showed that exhaled gas from the patient lung with a large SV could directly reach the temperature probe. Because the volume from ETT to the Moiscope including ETT was about 220ml in study-1, the exact reason why no humidity was detected at a frequency of 6Hz, SV of 285ml, and BF of 30 or 40l/min (estimated actual

SVs: 261ml and 253ml) was unclear. However, the volume difference of the estimated actual SV and the BF gas per half cycle of oscillation (242ml for 20l/min BF, 219ml for 30l/min BF and 197ml for 40l/min BF with the setting frequency of 6Hz) might be related.

Another important finding in study-1 was that Moiscope recorded higher temperature at the 6-Hz setting than at 8 or 10Hz (Table 1). It could be speculated that different SVs made some kind of different temperature gradient from the temperature probe of the lung model along the distal part of inspiratory circuit, and that increasing the SV possibly influenced the temperature probe by changing this temperature gradient even without the direct reach of the exhaled gas to the temperature probe. This might be another mechanism of "interference" with the humidifier by increasing the SV.

Study-2 provided fairly clear evidence that the absolute humidity (AH) of BF gas in R100 decreased as the SV became larger. This indicates that the so-called "interference" might always happen with higher SVs, and the above-mentioned possible mechanism explains this well. One should note that the spontaneous breath during HFOV might have the same effect as increasing the SV. The reason why the first experiment used settings of different frequencies and different SVs (maximum SVs) was that in clinical situations the frequency is decreased with the maximum SV if the ventilation from increasing the SV to the maximum is not sufficient. The reason why higher BF (> 30L/min) decreased the humidity is supposed to be the overcapacity of the humidifier. We additionally studied the effects of different SV settings with a constant frequency of 8Hz. The results showed that the level of the SV might be an important issue (Fig. 3). The reason why we did not investigate the effect of the frequency on the humidity of BF gas was that the frequency was not expected to affect the humidity of the BF gas when the actual SV was constant.

Study-2 was done with 2 temperature settings of Hummax II, 35°C and 37°C. The humidity with the temperature set at 35°C was significantly lower than that at 37°C. We have experienced one inadequately humidified case with the temperature setting of 35°C and with a frequency of 10Hz, SV of 160ml, BF of 40l/min. The AH of the BF gas was only about 31.3mg/l with this setting in study-2. Therefore, the

temperature setting of 35°C might not be recommended clinically. Furthermore, study-2 showed that the AH of the BF gas tended to decrease by increasing the BF. This might indicate that the humidification capacity of the Hummax II decreased with increasing BF and was not enough for a BF of 40l/min with the temperature setting of 37°C.

We investigated the humidification of the BF gas, not the inspired gas, which was made of exhaled gas from the lung and fresh BF gas. However, the humidity of the inspired gas is important clinically. Chikata *et al.* measured AH at the proximal end of the ETT with SVs of 100, 150 and 200ml using a lung model placed in an incubator and reported that both the AH and temperature were the highest with an SV of 200ml in R100 [8]. They measured the average humidity of the inspired gas and the exhaled gas. Higher AH might be related to higher temperature in their study. Although their lung model was placed in an incubator, they did not report the lung model temperature. We could control the lung model temperature actively using the Hummax II. On the other hand, the humidity of the inspired gas might be less influenced by the humidity of the BF gas as the SV increases. Therefore, further studies for evaluating the humidity of inspired gas with our lung model are needed.

In summary, the AH of the BF gas from a R100 decreased as the SV increased in the setting of our study. The SV is supposed to influence the effect of humidification during HFOV with an R100.

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