Tracheobronchial Dilating Effect of High Frequency Jet Ventilation

Hidenori TOYOOKA, Keisuke AMAHA and Kuninori YOKOYAMA

Effect of high frequency jet ventilation (HFJV) on tracheobronchial tone was examined in anesthetized dogs. Changes in intraluminal pressure of water-filled endotracheal cuff (Pcuff) were used as an indicator of tracheal smooth muscle tone. Animals were initially ventilated with conventional mechanical ventilation (CMV) to maintain normal Pa_{CO_2}. HFJV (2.0 Hz.) was then applied to each animal in such a way to maintain the same mean airway pressure and Pa_{CO_2} as in CMV.

Immediately after changing CMV to HFJV, Pcuff decreased significantly and remained decreased during the period of HFJV. After changing HFJV to CMV, Pcuff gradually returned to its previous level. Histamine-induced tracheobronchial constriction was partially released by HFJV as shown by a decrease in Pcuff and airway resistance (Raw) and by an increase in static lung-thorax compliance (Cst) measured immediately after the cessation of HFJV.

These results suggest that HFJV has a tracheobronchial dilating action, presumably mediated by pulmonary stretch reflex, and this may be one of the mechanisms of an increase in mucous secretion and of other reported favorable effects of HFJV in some types of respiratory failure. (Key words: high frequency jet ventilation (HFJV), tracheal cuff pressure, tracheobronchial dilation.)

(Toyooka H, Amaha K, Yokoyama K.: Tracheobronchial dilating effect of high frequency jet ventilation. J Anesth 4:206–212, 1990)

High frequency jet ventilation (HFJV), which delivers small tidal volume at a fast rate, is able to provide adequate ventilation and oxygenation at lower peak airway pressure and with less barotrauma and cardiovascular depression. HFJV is reportedly effective in both normal lungs and in lungs with various injuries, including oleic acid-induced pulmonary edema, bronchopleural fistula, and aspiration pneumonitis[1]. Gas exchange mechanisms of this and other types of high frequency ventilation have been studied extensively[2,3], however, up to now, no clinical or experimental study of the effect of high frequency ventilation on tracheobronchial tone has been reported.

Recently we have experienced several patients with severe asthmatic attack, who did not respond to conventional ventilator treatments, but were successfully treated with HFJV. This prompted us to examine the effect of HFJV on tracheobronchial tone.

In 1976, Himori and Taira[4] reported a simple method using cuff pressure of the endotracheal tube to measure tracheal tone. Accordingly we studied, by using this method, the effect of HFJV on tracheal tone in dogs in an attempt to clarify the effect of HFJV on airway smooth muscle tone.

Methods

Seven healthy mongrel dogs of either sex

Department of Anesthesiology and Critical Care Medicine, Faculty of Medicine, Tokyo Medical and Dental University, Tokyo, Japan

Address reprint requests to Dr. Toyooka: Department of Anesthesiology and Critical Care Medicine Faculty of Medicine, Tokyo Medical and Dental University 1-5-45 Yushima, Bunkyo-ku, Tokyo, 113 Japan

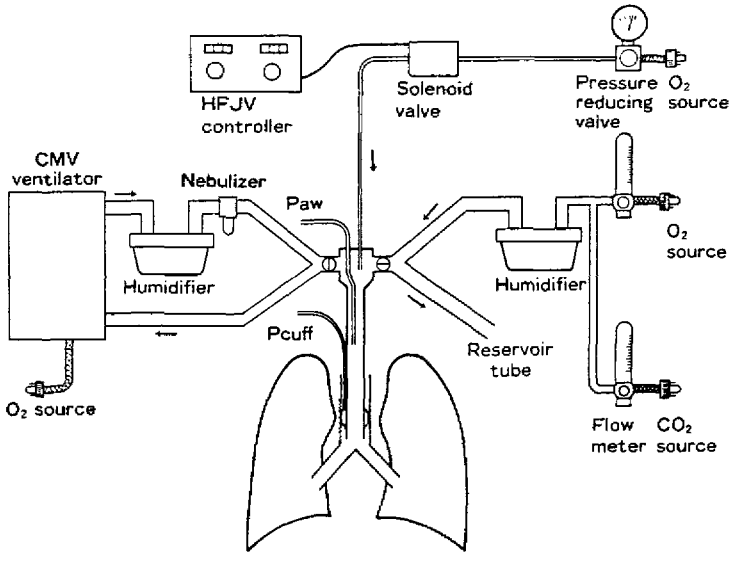

Fig. 1. Block diagram of the circuits for alternative application of conventional mechanical ventilation (CMV) and high frequency jet ventilation (HFJV).

weighing between 10 and 16 kg were anesthetized with 15–20 mg·kg^{-1} of thiopental i.v., and the trachea was intubated under 2 mg·kg^{-1} of succinylcholine chloride i.m. with a endotracheal tube (I.D. 8.0 mm) equipped with a rubber cuff of low compliance (Igarashi B type). Special care was taken to locate the whole cuff below the vocal cord and also at the extrathoracic portion of the trachea. Animals were then placed on a volume-cycled ventilator. Femoral artery was cannulated for obtaining blood samples and for monitoring blood pressure. Femoral vein was also cannulated for continuous fluid administration (Ringer's lactate solution, 6 ml·kg^{-1}·hr^{-1}). Anesthesia was maintained with intramuscular administration of 15 mg·kg^{-1} of pentobarbital. The cuff-inflating tube was cut at the proximal end of the pilot balloon and was connected to a pressure transducer (Model P50, Gould Inc.), an amplifier (Model 1236, San-Ei Inc.) and a recorder (Rectigraph-8K system, San-Ei Inc.). The cuff was then filled with water to maximize pressure swing corresponding to a given change in tracheal tone. The volume of water in the cuff system was adjusted initially to give resting intraluminal pressure of 15–35 mmHg, which was suitable for the observation of both dilation and constriction of trachea without causing ventilatory gas leak during the experiment. A 18 gauge polyethylene catheter was introduced into the trachea and advanced 5 cm below the outlet of the jet injector, and airway pressure (Paw) was continuously measured through this catheter connected to another channel of the same pressure recording system. The frequency response of the Paw monitoring system was in excess of 10 Hz.

Animals were initially ventilated with conventional mechanical ventilation (CMV) by a volume-cycled ventilator (Model 7200 A, Bennett Inc.) with humidified 100% oxygen, a tidal volume of 10–15 ml·kg^{-1} and a respiratory rate of 15·min^{-1} for maintaining Pa_{CO_2} between 35 and 40 torr. HFJV was delivered by following method (fig. 1). Oxygen were supplied under a pressure of 4 kg·cm^{-2}, lowered to a driving pressure of 0.7–1.0 kg·cm^{-2} with a pressure regulator valve, and pulsed by an electronically controlled solenoid valve through a noncompliant Teflon tube with a constant frequency of 120·min^{-1} and I/E ratio of 1:2. The Teflon tube was connected to an injector cannula with 1.5 mm in internal diameter and 5 cm in length, inserted into a three-way adaptor fixed to the endotracheal tube. Continuous flow (8 l·min^{-1}) of humidified 100% oxygen for possible entrainment was provided by an open anesthesia circuit. During HFJV,

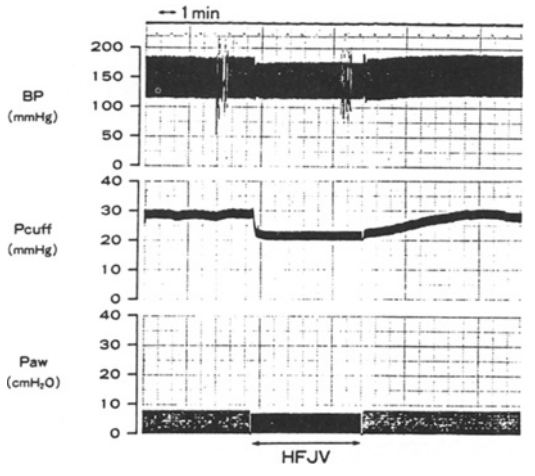

Fig. 2. Typical recordings of arterial blood pressure (BP), endotracheal cuff pressure (Pcuff) and airway pressure (Paw) before, during, and after high frequency jet ventilation (HFJV). The animal was placed on volume-cycled CMV except during the period shown by HFJV.

the mean airway pressure was maintained at the same level as in preceding CMV by adjusting driving pressure, as monitored by electrically smoothed Paw value. This ventilatory method usually resulted in a slightly lower peak airway pressure than that in CMV. Because Pa_{CO_2} usually showed a lower value during HFJV in our preparatory study, CO_2 gas (300–500 ml·min^{-1}) was added continuously to insufflation gas of HFJV to maintain the same Pa_{CO_2} level as in CMV. The temperature of the inspiratory gas was monitored in the endotracheal tube and was maintained at 30 ± 1°C during both CMV and HFJV by adjusting heated humidifiers.

After 30 min of stabilization of animals, CMV was changed to HFJV by actuating HFJV controller and manually switching swivel valves of both ventilatory circuits (fig. 1). Animals were kept on HFJV for 7 to 10 min, then were switched back on CMV. Trials were carried out three times consecutively on each animals. Thirty minutes were allowed to elapse between each trials.

Pcuff was measured at the following 6 points (A to F) in each trial, at the time before starting HFJV (A), 1 min (B) and 5 min (C) after the initiation of HFJV, 1 min (D), 5 min (E) and 10 min (F) after switching back to CMV. Arterial blood gas analysis (Model 1306A, Instrumentation Laboratories Inc.) were performed immediately before starting HFJV and 5 min after initiation of HFJV in each trial.

After these trials, an aqueous solution of histamine diphosphate (10 mg·ml^{-1}) was aerosolized to each animal by an ultrasonic nebulizer (Model 2101, De Vilbiss Inc.) during CMV to produce tracheobronchial constriction. The delivery of histamine aerosol was stopped when Pcuff doubled its initial value and Pcuff and Paw were further observed while CMV was continued. When both Pcuff and Paw were stabilized, CMV was temporarily switched to HFJV for two minutes and placed back on CMV again. Measurement of airway resistance (Raw) and static lung-thorax compliance (Cst) were performed immediately before and after the application of HFJV, and differences between these two values were considered as the effect of HFJV. Raw and Cst were measured during CMV with Bennett 7200 A ventilator which utilized the technique described by Don and Robson[5]. These histamine challenge and HFJV sequences were repeated up to three times in some animals if both Pcuff and Raw returned to their control values.

Data were analyzed by using analysis of variance, Duncan's multiple comparison test and paired t-test when appropriate. A P value of < 0.05 was considered to be significant.

Results

Effect of HFJV on tracheal tone

Immediately after changing ventilation from CMV to HFJV, Pcuff started to decrease rapidly and reached to its minimal value within 1 min. This decrease in Pcuff lasted during the whole period of HFJV, and gradually returned to its previous value after switching back on CMV (fig. 2). This decrease in Pcuff was consistently observed in any trial on all of the animals. The differences of mean Pcuff compared with the control value (at point A) were statistically significant at points B, C, D and E

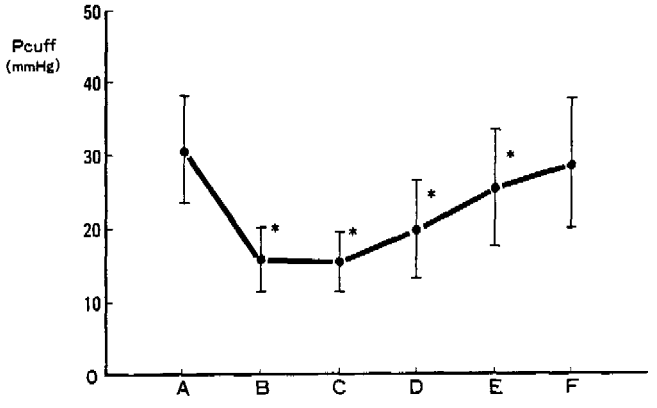

Fig. 3. Changes in Pcuff before, during and after HFJV
A: during initial CMV
B: 1 min after initiation of HFJV
C: 5 min after initiation of HFJV
D: 1 min after resumption of CMV
E: 5 min after resumption of CMV
F: 10 min after resumption of CMV
(mean ± 1 SD, n=21)
* Significantly different from control values (A) ($P < 0.01$)

Table 1. Arterial blood gas during initial CMV and 5 min after initiation of HFJV

	pH	Pa_{CO_2}	Pa_{O_2}
CMV	7.360 ± 0.038	38.8 ± 2.7	520.3 ± 56.9
HFJV	7.385 ± 0.069	37.7 ± 5.5	527.3 ± 59.4

(mean ± 1 SD, n=21)

($P < 0.01$) (fig. 3).

A slight decrease in systolic arterial blood pressure was observed during HFJV but mean arterial pressure did not show any change. Arterial blood gas analyses before and 5 min after the initiation of HFJV were shown in table 1. There was no significant difference either in pH, Pa_{CO_2} or Pa_{O_2}.

Effect of HFJV on histamine-induced tracheobronchial constriction

Histamine inhalation produced a marked transient rise in Paw and Pcuff. After the cessation of nebulization both of these pressures declined rapidly, and within 10 to 15 min stabilized at a sustained level higher than pre-histamine level. The short application of HFJV at this period dramatically decreased the elevated Pcuff and Raw, and increased Cst (fig. 4). These changes were also statistically significant (table 2).

Discussion

The present study has shown that HFJV significantly reduces the water-filled tracheal cuff pressure (Pcuff) in normal dogs, and that histamine-induced tracheobronchial constriction can also be partially released by HFJV as shown by a decrease in Pcuff and Raw.

Effects of various drugs and other factors on tracheobronchial tone has been studied by many investigators, but there has been no previous reports concerning the effect of HFJV on it.

Himori and Taira reported a simple method using endotracheal tube cuff pressure (Pcuff) to measure tracheal tone[4]. In the dog experiment, they demonstrated tracheal constriction by acetylcholine and the tracheal dilation by isoproterenol, epinephrine, and norepinephrine. They concluded that the increase and decrease of cuff pressures were caused by bronchial constriction and dilation, respectively.

Changes in arterial blood gas value such as Pa_{O_2} and Pa_{CO_2} can influence tracheobronchial tone[6]. Arterial blood pressure may also influence Pcuff by changing perfusion pressure of the tracheal mucosa. Since these variables as well as mean airway pressure and the temperature of the inspiratory gas were kept constant during HFJV, changes in Pcuff observed in our study are most probably due to the ventilatory mode itself.

The exact mechanism of tracheobronchial dilating effect of HFJV observed in our study is unknown. The rapid and profound decrease in Pcuff immediately after initiation of HFJV suggests that the response may be attributed to a reflex of

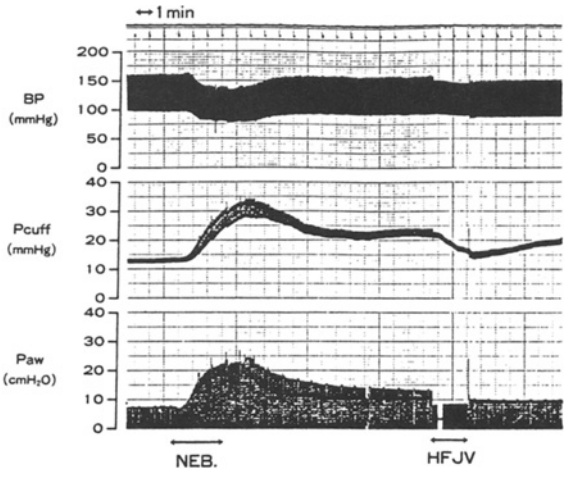

Fig. 4. Typical recordings of arterial blood pressure (BP), endotracheal cuff pressure (Pcuff) and airway pressure (Paw) in a histamine challenge study. Histamine was nebulized during the period shown by NEB. HFJV was applied during the period shown by HFJV, otherwise the animal was placed on volume-cycled CMV. Spikes observed every one minute in Paw during CMV are due to specific inspiratory waveforms for measurement of Raw.

Table 2. Endotracheal cuff pressure (Pcuff), airway resistance (Raw) and static lung-thorax compliance (Cst) during initial CMV, after histamine nebulization, and immediately after HFJV

	Pcuff (mmHg)	Raw ($cmH_2O \cdot l^{-1} \cdot sec^{-1}$)	Cst ($ml \cdot cmH_2O^{-1}$)
initial CMV	18.0 ± 5.7	7.5 ± 1.4	25.0 ± 5.5
after histamine	28.5 ± 8.8*	20.6 ± 10.4*	16.2 ± 2.7*
after HFJV	16.7 ± 4.3*+	13.1 ± 4.0*+	19.1 ± 3.3*+

(mean ± 1 SD, n=20)

* significantly different from corresponding values on initial CMV; $P < 0.01$

\+ significantly different from corresponding values after histamine; $P < 0.01$

the bronchopulmonary nervous system, and pulmonary stretch or the speed of stretching induced by HFJV may be the main factor to initiate the reflex mechanism. Loofbourrow et al.[7] reported that, by using manual inflation, stretch of the lungs produced a surprisingly prompt relaxation of hypercapnia-induced tracheal constriction. They concluded that it seems probable that lung stretch initiates the relaxation by reflex inhibition and that the relaxed state persists if ventilation is adequate to avoid hypercapnia. Stein and Widdicombe[8] and Widdicombe[9] also reported that increasing ventilation caused reflex airway dilation even if endtidal P_{CO_2} was held constant, and they suggested that the reflex dilation was mediated by pulmonary stretch receptors situated in the airway. They also suggested that the stretch of the lung caused reflex airway dilation via afferent and efferent pathways in the vagus nerve. Hida et al.[10] reported that in healthy subjects with bronchoconstriction induced by methacholine, a rapid deep inspiration reduced respiratory resistance (Rrs) more strongly than a slow deep inspiration did.

Thus, the tracheobronchial dilating effect observed in HFJV is most probably due to some physical characteristics of this type of ventilation. More abrupt and frequent changes in direction of flow, or larger inspiratory flow rate of shorter duration in HFJV may stimulate pulmonary stretch receptors

and overall tracheobronchial dilating reflex more effectively than in CMV.

The clinical implications of our observations have still to be clarified. The tracheobronchial dilating effects of HFJV may explain, at least in part, the favorable effects of loosening the airway secretion[11], which play a great role in respiratory care of a variety of patients. HFJV is generally considered contraindicated to asthmatic patients or patients with chronic obstructive pulmonary disease either because of possible difficulty in maintaining adequate alveolar ventilation in the presence of high airway resistance or because of possible hyperinflation of slow emptying units by augmenting auto-PEEP[12]. On the other hands, some reports suggest that HFJV may be a good indication to broncho-constricted states. Kuwasako[13] examined the effect of HFJV on four different experimentally induced animal models of respiratory failure, i.e., 1) oleic acid-induced pulmonary edema, 2) pneumothorax, 3) methacholine-induced bronchoconstriction, and 4) surfactant-depleted IRDS model. He demonstrated, on the basis of blood gas criteria, that among these, only the methacholine-induced bronchoconstriction was a good candidate of HFJV. Yoshinari et al.[14] reported three cases of severe asthmatic patients who were deteriorating on CMV but dramatically improved after starting HFJV superimposed on CMV. In these patients, HFJV for 12 to 24 hr resulted in marked improvement in both lung mechanics and pulmonary gas exchange, and the authors suggested that this technique might be a choice for mechanical ventilation of patients with severe status asthmatics.

Although our results show that HFJV has a tracheobronchial dilating effects in normal as well as in histamine-challenged healthy animals, these results do not necessarily imply that HFJV may have the same effects on asthmatic patients.

Fish et al.[15] demonstrated that a single lung inflation transiently reduced airway resistance in methacholine-challenged hay-fever subjects, but such a reduction in airway resistance was not observed in methacholine-challenged asthmatic subjects. Liu et al.[16] reported that immediately after deep inspiration, respiratory resistance (Rrs) decreased in normal subjects, whereas, in asthmatic subjects a significant increase in Rrs was observed. These reports suggest that regulation of bronchomotor tone by lung stretch is different between asthmatic and nonasthmatic patients. Further investigation may be needed to determine whether or not the effect of HFJV on the tracheobronchial tone in the asthmatic patients is similar to our observation in healthy and pharmacologically-induced bronchoconstriction animal models.

In conclusion, a significant decrease of tracheobronchial tone was observed during HFJV both in normal and histamine-challenged healthy dogs. The exact mechanism is unknown, but certain types of pulmonary stretch-reflex mechanisms may be involved. This may be one of the mechanisms of reported favorable effects of HFJV in some types of respiratory failure.

(Received Feb. 8, 1990, accepted for publication Feb. 21, 1990)

References

1. Rouby JJ, Viars P: Clinical use of high frequency ventilation. Acta Anaesth. Scand. 90:134–139, 1989
2. Permutt S, Mitzner W, Weinmann G: Model of gas transport during high frequency ventilation. J Appl Physiol 58:1956–1970, 1985
3. Scherer PW, Muller WJ, Raub JB, Haselton FR: Convective mixing mechanisms in high frequency intermittent jet ventilation. Acta Anaesth Scand 90:58–64, 1989
4. Himori N, Taira N: A method for recording smooth muscle and vascular responses of the blood-perfused dog trachea in situ. Br J Pharmacol 56:298–306, 1976
5. Don HF, Robson JG: The mechanisms of the respiratory system during anesthesia. Effects of atropine and carbon dioxide. Anesthesiology 26:168–175, 1965
6. Green M, Widdicombe JG: The effects of ventilation of dogs with different gas mixtures on airway calibre and lung mechanics. J Physiol (Lond) 186:363–381, 1966
7. Loofbourrow GN, Wood WB, Baird IL: Tracheal constriction in the dog. Am J

Physiol 191:411–420, 1957
8. Stein JF, Widdicombe JG: The interaction of chemo- and mechanoreceptor signals in the control of airway calibre. Resp Physiol 25:363–370, 1975
9. Widdicombe JG: The activity of pulmonary stretch receptors during bronchoconstriction, pulmonary edema, atelectasis and breathing against a resistance. J Physiol (Lond) 159:436–442, 1961
10. Hida W, Arai M, Shindou C, Liu YN, Sasaki H, Takishima T: Effect of inspiratory flow rate on bronchomotor tone in normal and asthmatic subjects. Thorax 39:86–92, 1984
11. Freitag L, Long WM, Eldridge M, Kim CS, Wanner A: Clearance of excessive mucous in the sheep trachea by asymmetric high frequency ventilation. Am Rev Respir Dis 135:A364, 1987
12. Simon BA, Weinmann GG, Mitzner W: Mean airway pressure and alveolar pressure during high-frequency ventilation. J Appl Physiol 57:1069–1077, 1984
13. Kuwasako Y: The effects of high frequency jet ventilation on four injured lungs in dogs. Jap J Anesth (Masui) 34:1085–1094, 1985
14. Yoshinari M, Nakazawa K, Ogawa S, Matsukawa S: Application of HFJV to patients with status asthmaticus. J Intens Care Med (ICU & CCU) 10:1053–1056, 1986 (in Japanese)
15. Fish JE, Ankin MG, Kelly JF, Peterman VI: Regulation of bronchomotor tone by lung inflation in asthmatic and nonasthmatic subjects. J Appl Physiol 50:1079–1086, 1981
16. Liu YN, Sasaki H, Ishii M, Sekizawa K, Hida W, Ichinose M, Takishima T: Effect of circadian rhythm on bronchomotor tone after deep inspiration in normal and in asthmatic subjects. Am Rev Respir Dis 132:278–282, 1985