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Effects of Inspiratory Pressure Oscillation on Pulmonary Gas Exchange and Circulatory Functions in Anesthetized, Mechanically Ventilated Dogs

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Anesthetized, mechanically ventilated dogs were used to study the effects of inspiratory pressure oscillation on gas exchange. Respiratory failure was induced in dogs artificially, changing either tidal volume or ventilatory rate. Pressure oscillation of approximately 2 Hz with amplitudes of 2 to 7 cmH_2O was applied on the inspiratory phase of mechanical ventilation. PaO_2 and $PaCO_2$ were improved consistently by pressure oscillation while minute ventilation was kept fixed. No significant change was observed in AaD_{O_2}, cardiac output, heart rate, ECG and both systemic and pulmonary arterial pressures under oscillated ventilation. The oscillated ventilation could be continued for more than 60 minutes without causing any significant change in circulatory function. The ratio of alveolar ventilation to minute ventilation ($\dot{V}_A/\dot{V}_E$) increased and that of dead space to tidal volume (V_D/V_T) decreased significantly. The oscillated ventilation while breathing He-O_2 and SF_6-O_2 showed no consistent difference in the effects on gas exchange.

It can be concluded that simple pressure oscillation improves gas mixing in the lungs and may be applied to respiratory care. However the mechanism remains to be elucidated.

(Key Words: Pressure Oscillation, Gas Exchange, Respiratory Failure, High Frequency Ventilation).

INTRODUCTION

One of the cardinal principles of respiratory care is to maintain alveolar ventilation. Respiratory care with mechanical ventilators has shown marked progress, and an introduction of positive end-expiratory pressure (PEEP) has made a significant contribution to this field. The adverse and side effects of the positive pressure technique, however, have attracted much attention lately. The major complications of mechanical ventilation with PEEP are pulmonary barotrauma and depressions of cardiovascular functions. It is important to develop a new method which has an equivalent effect on gas exchange with lower pressure and lower oxygen concentration.

In 1967, high frequency positive pressure ventilation (HFPPV) was developed for this purpose by Jonzon *et al* (7). They reported that endotracheal insufflation of a tidal volume smaller than the dead space and with much higher frequency than spontaneous ventilation could provide

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adequate alveolar ventilation with lower airway pressure. Apart form HFPPV, it has been known that cardiogenic oscillation by cardiac thrust in the thorax enhances gas mixing in the airways. These results lead us to believe that simple pressure oscillation imposed on the inspiratory phase might improve pulmonary gas exchange. Here the effects of oscillated inspiration on gas exchange are reported in dogs with experimentally induced respiratory failure. Also, effects of external vibrations on either the abdomen or the sternum of dogs were observed on pulmonary gas exchange.

MATERIAL AND METHOD

Mongrel dogs weighing 10 to 20kg were anesthetized by intravenous administration of pentobarbital and tracheostomized to insert cannulae. The animals were paralyzed with succinylcholine chloride and were connected up to a volume-limited respirator. Ventilatory conditions were adjusted so that various control levels of hypoxemia and hypercapnia were obtained. In five dogs, right heart catheterizations were performed under fluoroscopy so as to obtain mixed venous blood samples and to measure pulmonary arterial pressures. Another catheter was introduced into the abdominal aorta through the femoral artery to sample arterial blood for gas analysis and to record arterial pressure. Figure 1 indicates the experimental arrangement in this study.

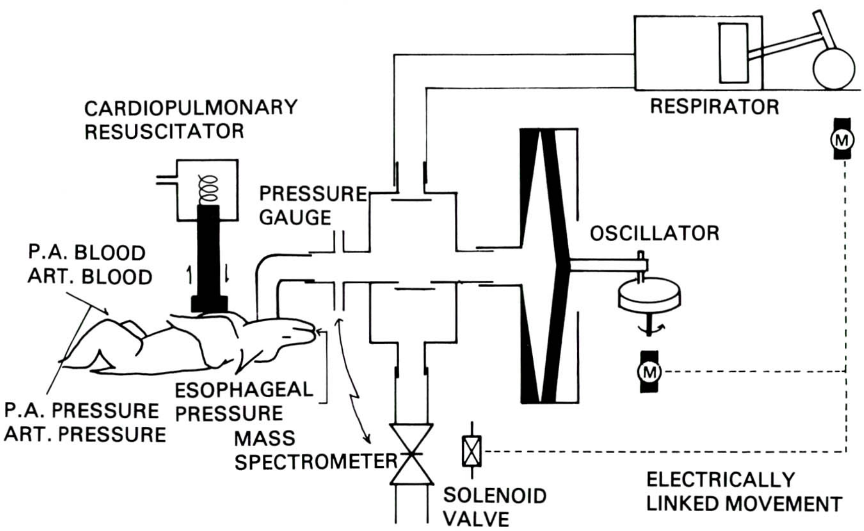

Fig. 1 The experimental arrangement used in this study.

Body temperature was measured by a thermistor located in the esophagus and esophageal pressure was measured by means of a catheter with a balloon. ECG and airway pressure were also recorded. pH and blood gases were analyzed by IL Meter (Model 113-04), and O_2 and CO_2 contents of both arterial and mixed venous blood were analyzed by Van Slyke-Neill manometric apparatus. Cardiac output was obtained by the direct Fick method. Expired gases were collected in a Douglas bag for five minutes and expired minute volume was determined by a dry gasometer. O_2 and

CO_2 concentrations in the expirates were analyzed by a Scholander micro-gas analyzer, and continuous monitoring of expired gas concentrations were made by a mass spectrometer (Varian MAT M-3).

The pressure oscillation was produced by a hard rubber diaphragm, the center of which was driven by an electric motor with various frequencies and strokes. The amplitude of oscillation could be changed by the stroke of the diaphragm and the frequency was varied within the range 0 to 5 Hz. Pressure oscillation was imposed only on the inspiratory phase of mechanical ventilation. During oscillated inspiration, the expiratory site of a one-way valve was closed by an electromagnetic valve, which was operated by a phase trigger of the respirator.

After basal measurements were completed under conditions of artificially induced hypoxemia and hypercapnia, oscillated ventilation was started maintaining the same ventilatory volume as the control, and was continued for at least 20 minutes before the next measurements were performed.

A cardiopulmonary resuscitator (Nihon Kohden Co., Ltd.) was employed to vibrate externally either the thoracic cage or the abdomen so as to compare the effects with those of oscillated inspiration. In some part of the experiments, the animals were ventilated with 20% O_2 in helium or in sulfur hexafluoride (SF_6).

RESULTS

The experimental results of oscillated ventilation of approximately two Hz with two different strokes are summarized in Table 1. $\dot{V}_E$ during oscillated ventilation was adjusted to remain unchanged as compared to the control. PaO_2 increased and $PaCO_2$ decreased significantly, while O_2 consumption ($\dot{V}_{O_2}$) and AaD_{O_2} showed no significant change under oscillation.

Table 1 The experimental results of mechanical ventilation (control) and 2 Hz oscillation with two different strokes. The left column indicates the stroke of 3 mm and the right indicates the stroke 1 mm. Values are means ± SE. * $p < 0.001$, ** $p < 0.05$ compared to control.

	CONTROL n=6	OSCILL. (STROKE 3 mm)	CONTROL n=24	OSCILL. (STROKE 1 mm)
PaO_2 (torr)	72.1±6.3	102.3±2.0**	71.0±2.7	79.7±2.7*
$PaCO_2$ (torr)	43.8±4.3	25.4±0.9**	49.5±1.9	45.3±1.7*
pH	7.300±0.036	7.426±0.024**	7.279±0.015	7.302±0.013
AaD_{O_2} (torr)	17.9±2.3	17.1±2.1	14.6±2.1	15.4±2.3
$\dot{V}_A/\dot{V}_E$ (%)	34±2	73±3*	38±2	47±2*
V_D/V_T (%)	66±2	27±3*	62±2	53±2*
$\dot{V}_{O_2}$ (ml/min)	54±4	62±3	72±6	74±5
R	0.72±0.03	0.87±0.03**	0.75±0.03	0.81±0.03*
$\dot{V}_E$ (l/min)	2.35±0.26	2.66±0.18	2.49±0.16	2.45±0.16

The ratio of dead space to tidal volume (V_D/V_T) decreased and that of alveolar ventilation to minute ventilation ($\dot{V}_A/\dot{V}_E$) increased significantly ($P < 0.001$). The larger the stroke volume, the more significant the effects of oscillation on arterial blood gases and pulmonary gas exchange.

Circulatory funtions including cardiac output, heart rate, ECG, and both systemic and pulmonary arterial blood pressures did not differ significantly from those of the control (Table 2). Continue oscillated ventilation could be carried out for more than 60 minutes without changes in cardiac output, blood pressures and ECG. Figure 2 and Figure 3 show illustrative experimental records of blood pressures, airway and esophageal pressures and ECG.

The external vibration on either the sternum or the abdomen of the animal could produce similar pressure oscillation in the airways. Although a tendency to increase PaO_2 and to decrease $PaCO_2$ was observed, these changes were not significant. A combination of external vibration of 2.5 Hz and oscillated inspiration of 4.5 Hz, however, seemed to enhance the changes in PaO_2 and $PaCO_2$.

Table 3 indicates the results of $He\text{-}O_2$ and $SF_6\text{-}O_2$ breathings under oscillation. The effects of oscillated inspiration of both $He\text{-}O_2$ and $SF_6\text{-}O_2$

Table 2 Changes in circulatory functions. Values are mean ± SE.

		CONTROL	OSCILL.
$P_{art.}$ (torr)	systolic	157 ± 4	153 ± 3
n = 9	diastolic	122 ± 5	118 ± 4
P_{PA} (torr)	systolic	25 ± 3	23 ± 1
n = 6	diastolic	11 ± 2	11 ± 1
HR (bt/min) n = 10		160 ± 7	164 ± 8
CO (l/min) n = 10		2.35 ± 0.17	2.11 ± 0.12

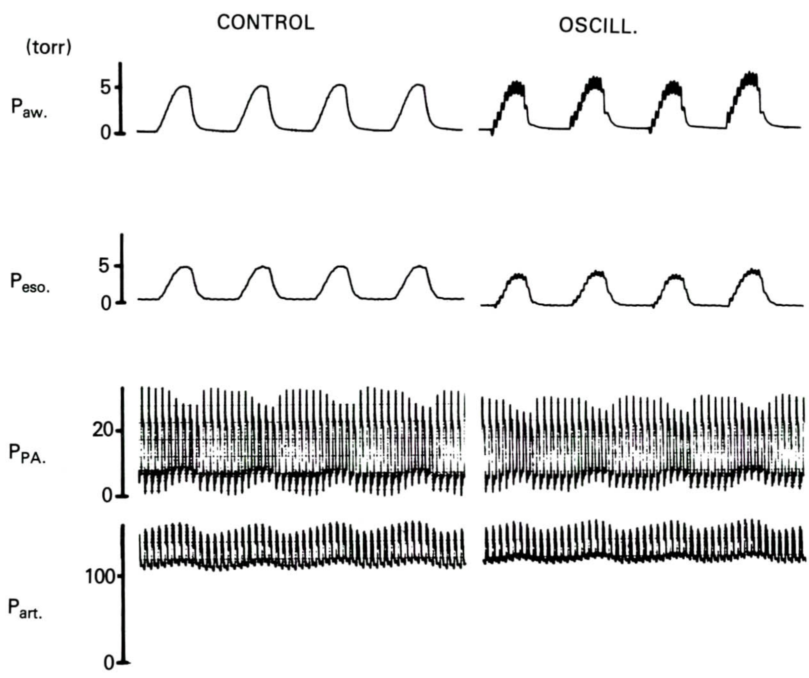

Fig. 2 Experimental records. The records from the bottom panel indicate arterial pressure, pulmonary arterial pressure, esophageal pressure and airway-pressure, respectively.

mixtures on arterial blood gases and on pulmonary gas exchange were similar to those under air breathing, whereas there was no significant difference between He-O_2 and SF_6-O_2 breathings.

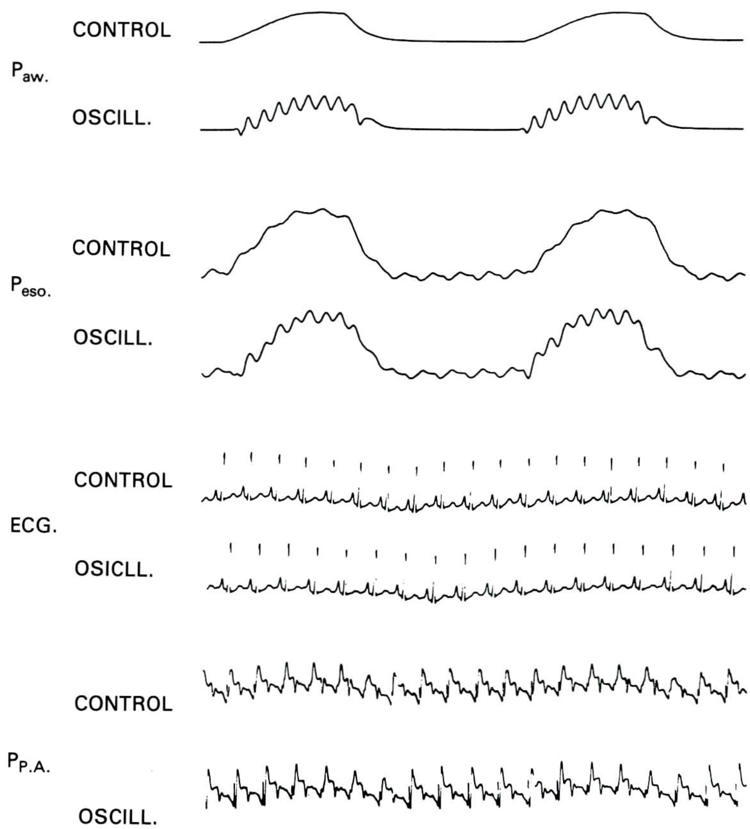

Fig. 3 Experimental records. The records from the bottom panel indicate pulmonary arterial pressure, ECG, esophageal pressure and airway pressure, respectively.

Table 3 Experimental results of He-O_2 and SF_6-O_2 breathings. The left column of the table indicates He-O_2 breathing, and the right column indicates SF_6-O_2 breathing.

	He-O_2		SF_6-O_2	
mean ±S.E.	CONTROL n=8	OSCILL. n=8	CONTROL n=7	OSCILL. n=7
F_IO_2	0.2086±0.017		0.2078±0.014	
$\dot{V}_E$ (l/min)	1.80±0.12	2.03±0.21	2.08±0.14	2.15±0.19
INSP.PRESS. (cmH_2O)	10.3±0.7	12.0±0.7	10.6±0.7	14.8±0.7
PaO_2 (torr)	62.8±4.3	73.7±4.5	50.8±7.2	59.0±7.9
$PaCO_2$ (torr)	48.5±4.6	41.4±4.2	50.8±5.9	42.3±4.4
pH	7.303±0.037	7.352±0.029	7.293±0.034	7.340±0.035
AaD_{O2} (torr)	18.7±9.7	25.4±5.9	26.3±5.7	33.2±2.7
$\dot{V}_A/\dot{V}_E$ (%)	36±4	51±5	36±5	46±6
V_D/V_T (%)	64±4	50±5	64±5	54±6
R	0.74±0.07	0.91±0.10	0.71±0.05	0.75±0.06
$\dot{V}_{O2}$ (ml/min)	51±4	53±5	59±4	61±4
$TEMP_{BODY}$ (°C)	37.8±0.2	37.8±0.2	37.9±0.2	37.7±0.2

DISCUSSION

It was convincingly shown in this study that significant improvement of gas exchange in dogs could be achieved by applying pressure oscillation on the inspiratory phase of mechanical ventilation. The method of oscillated ventilation is the same as the conventional mechanical ventilation except that pressure oscillation of 2 to 7 cmH_2O (used here) was applied to the inspiratory phase. More visible effects on gas exchange could have been expected by increasing the stroke volume which also raises the airway pressure, while adverse effects on circulatory functions and/or hazards such as barotrauma may have resulted. Within our experimental conditions, however, no significant adverse effect was observed. Since expiration is done passively by relaxation as spontaneous breathing and the end-expiratory pressure in the airways is atomospheric, adverse effects of oscillated ventilation may be reduced in the method used here.

The reasons why pressure oscillation was not applied throughout the respiratory cycle were as follows; (1) simplification of the experimental arrangement, (2) to keep a natural pattern of spontaneous breathing, and (3) to avoid any adverse effect on circulatory function.

It is reasonable to expect that oscillated ventilation with PEEP will be more effective for respiratory care of severe respiratory failure. An alternative to enhance the effect of the present method is to increase inspired O_2 concentration, whereas we aimed at reducing a hazardous O_2 concentration by applying oscillated ventilation.

The optimum frequency of oscillation for gas exchange is one of the unsolved problems. In the cardiogenic oscillation, the frequency is around 1 Hz. In case of high frequency jet ventilation (HFJV), the frequency of insufflation is usually adjusted at 60 to 110 cycles per minute (10). Other groups however, employ oscillation frequencies of 10 to 20 Hz in their high frequency oscillation (HFO), using a piston or other oscillator. Lunkenheimer *et al* (9) reported that a wide range of oscillation frequencies were effective and the frequency did not influence O_2 absorption, whereas CO_2 elimination was affected by the frequency. Bohn *et al.* (2) once reported that the optimum frequency for CO_2 elimination was around 15 Hz, but later, it was found to be a resonant frequency of their apparatus. The optimum frequency is closely connected with the mechanism of gas exchange in both oscillated ventilation and high frequency ventilation. Changes in V_D/V_T and in $\dot{V}_A/\dot{V}_E$ observed here indicated an increment of alveolar ventilation. However, to increase alveolar ventilation a number of fundamental mechanisms have to be considered.

Gas mixing by cardiogenic oscillation has lead us to the idea of oscillated ventilation. Engel *et al* (3) suggested that the important mechanisms of cardiogenic gas mixing were convective diffusion such as Taylor dispersion and convective mixing by secondary flows, which were caused by cardiac thrust motion. Although the convective mixing in the airways is hard to assess, an attempt was made to observe fluctuations of O_2 and CO_2 concentrations in the main bronchus during oscillated inspiration by introducing a catheter connected to a mass spectrometer whose response time was 120 msec. In the airway no visible fluctuation in FO_2 and FCO_2 was observed in this order. However, the interface of inspired bulk flow with the stale gas should be located further upstream, that is, around the terminal bronchioles, and, a to-and-fro movement of the front due to pressure oscillation may be expected, this would enhance convective mixing of the tidal gas and the stale gas in the lungs.

When convective diffusion in the airways was considered, a heavier gas (SF_6) was thought to be more appropriate than a lighter gas (He) according to the theory of Aris (1), in contrast to diffusive mixing in the static gas phase. The results of He-O_2 and SF-$_6O_2$ breathing in Table 3 may be said to show essentially the same tendency, regardless of different breathing media. It may be assumed that convective diffusion was augmented in SF_6-O_2 breathing, making good the disadvantage of diffusive mixing in the static gas phase, while convective mixing in the airways was increased in both He and SF_6 breathings. Wood *et al* (12) reported that SF_2 breathing reduced the intraregional parallel inhomogeneity and AaD_{O_2}. This was not the case in the present study.

Fredberg (4) and Slutsky *et al* (11) stressed the importance of augmented diffusion as a gas exchange mechanism of high frequency oscillation. This will also work favorably in oscillated ventilation here. As suggested by Haselton *et al.* (6), the branching of the airways will enhance the gas transport through bulk exchange mechanism, and the secondary flows at bifurcations and so-called DISCO lung mechanism by Lehr (8) will reduce inter- and intra-regional inhomogeneity. All these new concepts concerning gas exchange mechanisms during HFPPV, HFJV and HFO will work in the oscillated inspiration described here.

We conclude that this method of oscillated inspiration may be satisfactorily applicable to respiratory care, although the mechanism has yet to be explained.

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