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High-frequency Alternating Lung Ventilation

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A new mode, high-frequency alternating lung ventilation (HFALV) is described and demonstrated in which the lungs are alternately pulsed. A fluidic oscillator may be used to deliver two pulsed gas streams, 180 degrees out of phase, to bronchial catheters placed via a double lumen endobronchial tube. Inspiratory phase of one lung thus coincides with expiratory phase in the other, and characteristic lateral rocking chest movement is observed.

In six dogs, HFALV was compared to simultaneous pulsing of both lungs with comparable flow (18.5 l/min), frequency (144 min^{-1}), and pulse wave shape. Arterial P_{CO_2} was significantly lower ($P < 0.001$) with HFALV. Arterial P_{CO_2} was also found to increase linearly ($r = -0.862$, $P < 0.001$) with distance of the catheters' distal tips from the dogs' carinae. Theoretical mechanisms and possible applications of HFALV are discussed. (Key words: Equipment: ventilators. Ventilation: alternating lung; high-frequency.)

VENTILATION at high rates has been described in varying modes and frequency ranges.[1–4] One type of high-frequency ventilation is high-frequency jet ventilation (HFJV) which delivers pulsed gas streams via small bore plastic catheters.[5] A bistable fluidic amplifier[6] can be adjusted to oscillate and produce two pulsed streams which are 180 degrees out of phase (fig. 1). If such streams are connected to two bronchial catheters placed via a double lumen endobronchial tube, the lungs may be ventilated alternately (180 degrees out of phase) at frequencies from 60–300 min^{-1}. Inspiratory phase of one lung thus coincides with the expiratory phase of the other. To investigate HFALV, we performed the following studies.

Methods

Six mongrel dogs (10–15 kg) were anesthetized in the dorsal recumbent position with pentobarbital (35 mg/kg), paralyzed with pancuronium (0.1 mg/kg), and their tracheas intubated with right-sided double lumen endobronchial tubes. Polyethylene catheters (3 mm internal diameter) were passed into both endobronchial lumens and placed so the distal tips were at the orifices (average 1 cm past the carina). Proper endobronchial placement was verified by auscultation and by observing absences of air bubbles from the proximal catheter ends when only the opposite lung was ventilated. The proximal catheter ends were then connected to the outputs of the fluidic oscillator driven by 100 per cent oxygen (20 lbs/in^2). Lateral rocking chest movements further verified proper endobronchial tube placement. Electrocardiogram and temperature were monitored and a femoral vein and artery cannulated for administration of maintenance crystalloid (5 ml/kg/hr), continuous blood pressure monitoring, and determination of arterial blood gases (ABG). Preliminary studies showed that at total flow of 18.5 l/min (measured by a rotameter proximal to the oscillator), pressures within the system ranged from 3–5 cm H_2O, and adequate ventilation ($Pa_{CO_2} < 45$ torr, $Pa_{O_2} > 300$ torr) could be obtained regardless of frequency (60–300 min^{-1}), inflation of the endobronchial tube cuffs, or PEEP (0–20 cm H_2O) delivered via a circle system connected to the endobronchial tube.

To determine if HFALV significantly differs from HFJV, each dog was ventilated in random alternating 45-min sequences in the two modes and ABG measured at 15-min intervals. HFJV was made comparable to HFALV by using one output from the fluidic oscillator through a "Y" connector to both bronchial catheters and adjusting flow rate (18.5 l/min to each lung during inspiration), frequency (144 min^{-1}), and pressure wave shape (oscilloscopically). Thus each lung received the same apparent flow, rate, and pressure pulse characteristics (I:E = 1:1) during the two modes. With HFJV, the lungs were pulsed simultaneously while with HFALV, the two lungs were pulsed alternately.

Effects of catheter tip placement (at 144 min^{-1}) were studied by randomly changing position of both catheters in tandem and measuring ABG at 15-min intervals.

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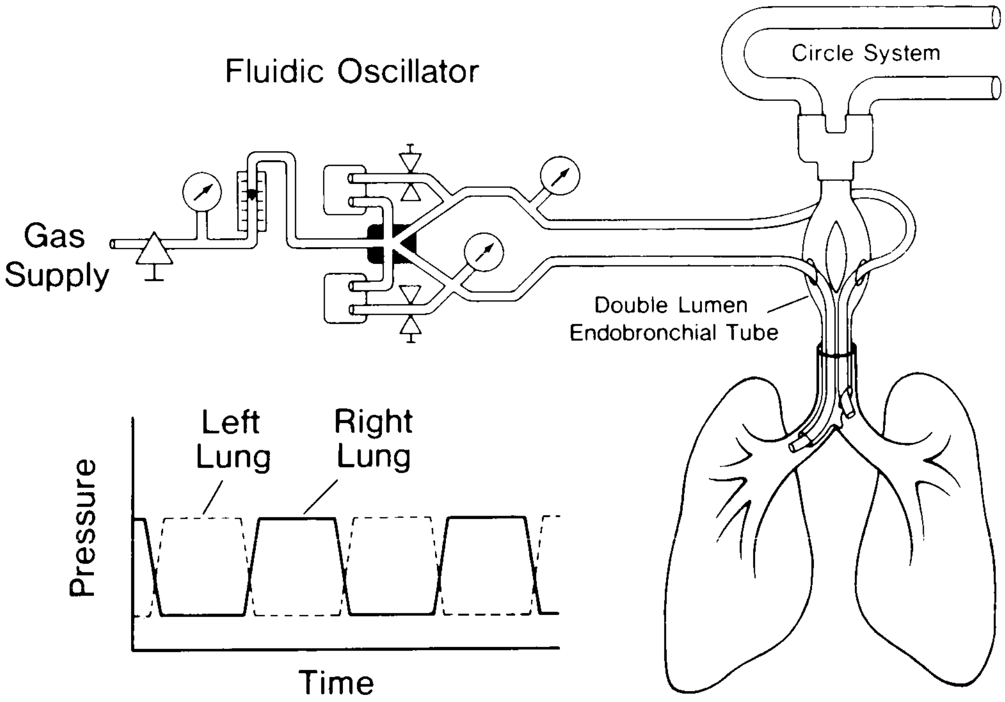

FIG. 1. Schematic representation of high-frequency alternating lung ventilation (HFALV). A bistable fluidic oscillator, driven by a 20 psi gas source, produces two pulsed gas streams which are 180 degrees out of phase (insert). These pulsed streams are delivered to the bronchi by polyethylene catheters (3 mm diameter) via a double lumen endobronchial tube.

Data were analyzed using Student's *t* test for grouped data and linear regression analysis. Significance was defined as $P < 0.05$ and linearity as $r > |0.8|$.

Results

Compared to HFJV, HFALV resulted in lower arterial P_{CO_2} ($P < 0.001$, table 1). HFALV arterial P_{O_2} was significantly higher than HFJV P_{O_2} ($P < 0.05$), however, calculated alveolar arterial oxygen differences ($A\text{-}aD_{O_2}$, respiratory quotient = 1) did not differ significantly between the two groups. We observed no differences in blood pressure, heart rate, or rhythm.

In the HFALV mode, arterial P_{CO_2} correlated linearly ($r = -0.862$, $P < 0.001$, fig. 2) with catheter tip distance from the carina. In one dog, pushing the catheters 5 cm past the carina resulted in fatal barotrauma. Arterial P_{O_2} was not significantly altered by the catheters' tip position.

TABLE 1. Arterial Blood Gases (torr) with High-frequency Alternating Lung Ventilation (HFALV) Compared to High-frequency Jet Ventilation (HFJV)

	HFALV	HFJV
P_{CO_2}	36.8 ± 1.5*	49.2 ± 2.5
P_{O_2}	446.1 ± 6.2†	417.6 ± 10.8
$A\text{-}aD_{O_2}$	169.8 ± 7.1	186.1 ± 12.4

Values are group means ± standard error of the mean.

Significantly different from HFJV by Student's t test for grouped data at $*P < 0.001$, $\dagger P < 0.05$.

Alveolar arterial oxygen differences ($A\text{-}aD_{O_2}$) were calculated assuming respiratory quotient = 1. Both HFALV and HFJV at 18.5 l/min, 144 min^{-1}, with similar pulse wave shapes to each lung.

Discussion

Decreased P_{CO_2} with HFALV compared to HFJV may result from less dependence on chest wall expansion and compliance when only one lung is ventilated, assuming that lung expansion may be transmitted across the mediastinum. In one dog, a thoracotomy was performed during HFALV and the lungs and mediastinum were observed to "rock" back and forth with each gas pulse. Thus, the two lungs need not compete for volume within the chest and the expanding pulsed lung may deflate the opposite lung, augmenting exhalation and CO_2 removal. An alternative explanation for lower P_{CO_2} with HFALV may be increased cardiac output, not measured in this study. Correlation of P_{CO_2} with HFALV catheter tip placement may be due to pulse dampening, increased dead space[2] and/or obstruction of expired gas flow by the ventilating pulse streams.

We have demonstrated a new high-frequency mode of ventilation, HFALV, in dogs. Disadvantages include the need for a double lumen endobronchial tube and therefore lack of pediatric application, uncertainty over mediastinal compliance in human adults, and the potential for barotrauma if the catheter tips extend too far into smaller airways. Several potential HFALV advantages may warrant further study. These include lower mean lung volumes (above functional residual capacity) which might reduce pulmonary vascular resistance and dead space in some lung areas.[2] Mediastinal displacement by unilateral lung expansion could reduce ventilation dependence

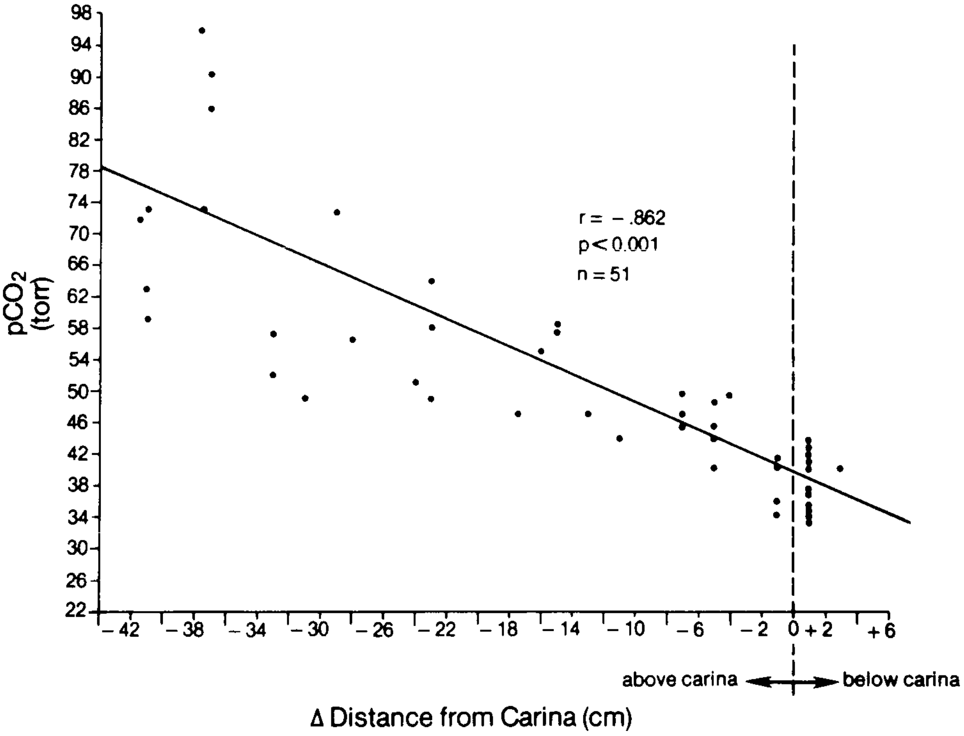

FIG. 2. Arterial P_{CO_2} as a function of distance of distal catheter tips from the carina during HFALV. The catheters were moved randomly, in tandem, and P_{CO_2} rose as the distance above the carina increased. By linear regression analysis, r = −0.862, $P < 0.001$.

on chest wall and diaphragm movement, thus improving overall compliance. Cardiovascular effects of pulsed mediastinal displacement may depend on relative timing of the pulse to the cardiac cycle. High-frequency ventilation electronically coupled to the EKG reportedly can augment cardiac output.[7] A final potential HFALV advantage is that at a given frequency, the inspiratory time, flow rate, tidal volume, PEEP, and pulse wave shape may be customized for differing lung pathologies[8,9] including "one lung" anesthesia for lateral thoracotomy.

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