

Effects of Alternating Lung Ventilation on Cardiopulmonary Functions in Dogs

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Differential ventilation of lungs has been employed in cases of respiratory failure. However, little is known regarding the basic physiologic effects of alternating lung ventilation. The authors therefore examined the changes which occur in cardiopulmonary functions when one lung is ventilated 180 degrees out of phase with the other.

Twenty-two dogs were studied. Changing from synchronous to alternating ventilation caused a marked decrease in airway pressure and a large increase in total (lung-thorax) compliance. Left mean airway pressure decreased from 6.3 to 4.2 mmHg (-33%) and the right from 5.1 to 2.8 mmHg (-45%). Left mean total compliance increased from 11 to 17 ml/cmH₂O (+55%) and the right from 13 to 27 ml/cmH₂O (+108%). By comparison to the large changes in the values for lung mechanics, only minor changes in circulatory function were observed.

It is conceivable that alternating lung ventilation would be beneficial in patients with marked unilateral lung damage in whom it may be desirable to reduce ventilation dependence on chest wall expansion and diaphragm movement. (Key words: Lung; compliance; intravascular pressures. Ventilation: alternating lung.)

DIFFERENTIAL VENTILATION of lungs has been employed during periods of lung lavage or in cases of respiratory failure.¹⁻³ Theoretically, its use would be advantageous when lung damage is predominantly unilateral, and the diseased lung has a markedly different time constant from the other. In this circumstance the diseased lung would require more pressure to receive a similar portion of the total ventilation. Recently, Hameroff *et al.*⁴ reported their ability to decrease PaCO₂ during alternating lung ventilation using high-frequency ventilation.

Little is known concerning the effects on the pulmonary circulation when the right and left lungs are ventilated alternately using a conventional respiratory rate. The purpose of this study was to examine the effects of such ventilation on respiratory and circulatory functions in dogs.

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Methods

Twenty-two mongrel dogs of either sex weighing 12.9 ± 0.5 (SE) kg were anesthetized with 32 ± 1 (SE) mg/kg sodium pentobarbital. They were paralyzed with 0.79 ± 0.03 (SE) mg/kg alcuronium, intubated with a standard endotracheal tube, and mechanically ventilated with a dual-cylinder Harvard® respirator (Type 618-D).

Tidal volume was adjusted to achieve a PaCO₂ of 35 to 40 mmHg with a constant respiratory rate of 20/min; thereafter, the volume [14.3 ± 0.3 (SE) ml/kg] and respiratory rate were not altered throughout the experiment.

A Swan-Ganz® catheter (Edwards Laboratories) was passed into the pulmonary artery by way of the left or right femoral vein. Body temperature was monitored using a thermistor located in the tip of the catheter. Pulmonary artery pressure (PAP) and pulmonary artery wedge pressure (PCWP) were measured from the catheter. Cardiac output was measured in duplicate by the thermodilution method (Edwards Lab. Cardiac output computer 9520A). A peripheral vein also was cannulated and lactated Ringer's solution was infused [36.9 ± 1.8 (SE) ml/kg] throughout the experiment. A femoral artery was cannulated for determination of blood pressure (BP) and blood gases (IL-213-05). A 10-cm esophageal balloon was positioned in the lower third of the esophagus to assess intrapleural pressure. All pressures were monitored continuously using standard Statham® strain gauges and Nihonkohden® RM-6000 eight-channel recorder.

A tracheostomy was then performed and a right-sided double-lumen endotracheal tube (Robertshaw) was passed and seated in the left main bronchus. Proper placement and complete division of both lungs were verified by observing the absence of air bubbles from one tube end placed under water while the opposite lung was inflated.

The tidal volume (V_T) was divided equally into the right and left components. The tidal volumes for each lung were 7.2 ± 0.2 (SE) ml/kg for the left and 7.1 ± 0.1 (SE) ml/kg for the right. The right and left airway pressures (P_{aw}) were measured at the end of inspiration when the flow to each lung was zero. Each lung was ventilated initially synchronously for about 20 min; when a near steady state was achieved, baseline mea-

surements (controls) were made of PAP, PCWP, CVP, CO, BP, P_{aw} , and blood-gas analyses (step 1).

After control determinations, the left cam on the common shaft driving the left and right cylinder pistons of the respirator was rotated 180 degrees, so that the inspiratory phase of one lung coincided with the expiratory phase of the other. After 20 min, the same measurements were performed (step 2). This was again followed by synchronous ventilation, as in step 1, and a third set of measurements was obtained after 20 min (step 3).

CALCULATIONS

Body surface area (S , m^2) was calculated by the following standard formula:

$$S = 0.11 \sqrt[3]{W^2}$$

where W is the weight in kg.

Cardiac index and stroke volume index (SVI) were calculated, and systemic vascular resistance (SVR), pulmonary vascular resistance (PVR), and left ventricular stroke work index (LVSWI) were derived using the following formulas:

$$SVR(\text{dyn} \cdot \text{s} \cdot \text{cm}^{-5}) = (\overline{BP} - \overline{RAP}) \cdot 80 / \text{CO}$$

assuming right atrial pressure (\overline{RAP}) equaled \overline{CVP}

$$PVR(\text{dyn} \cdot \text{s} \cdot \text{cm}^{-5}) = (\overline{PAP} - \overline{PCWP}) \cdot 80 / \text{CO}$$

$$LVSWI(\text{g} \cdot \text{m} / \text{m}^2) = (\overline{BP} - \overline{LAP}) \cdot \text{SVI} \times 0.0136$$

assuming \overline{LAP} equaled \overline{PCWP} .

Total (lung-thorax) compliance (TLC) was calculated by the following formula:

$$\text{TLC}(\text{ml} / \text{cmH}_2\text{O})$$

$$= V_T / (P_{aw} - \text{body surface pressure}),$$

assuming body surface pressure equaled atmospheric pressure.

Lung compliance (LC) was calculated by the following formula:

$$\text{LC}(\text{ml} / \text{cmH}_2\text{O}) = V_T / (P_{aw} - P_{cso})$$

Alveolar oxygen tension was estimated by applying the standard alveolar air equation:

$$P_{A_{O_2}} = P_{I_{O_2}} - P_{A_{CO_2}} \left[F_{I_{O_2}} + \frac{1 - F_{I_{O_2}}}{R} \right]$$

in which $F_{I_{O_2}} = 0.21$; R is assumed to be 0.8; and $P_{A_{CO_2}}$ is assumed to be equal to $P_{a_{CO_2}}$.

Hemoglobin was measured with an IL 282 CO-oximeter® with an adaptor for canine blood. Oxyhemo-

globin saturation (S_{O_2}) was calculated with a mathematical formula derived by Ruiz *et al.*,⁵ adjusting P_{O_2} for pH and P_{CO_2} by the following formula:

$$P_{O_2a} = P_{O_2i} \times 10^{0.48(pH_i - 7.4) + 0.06(\log 40 - \log P_{CO_2})}$$

where P_{O_2a} is adjusted P_{O_2} , and P_{O_2i} is the value from the blood-gas analyzer at 37° C.

Having a value for S_{O_2} , oxygen contents of arterial (Ca_{O_2}), mixed venous ($C\bar{v}_{O_2}$) and end-pulmonary capillary blood (C'_{CO_2}) were calculated by the following formula:

$$C_{O_2} = 1.34\text{Hb} \cdot S_{O_2} + 0.0031P_{O_2}$$

Then, the physiologic shunt was calculated by the following equation:

$$\dot{Q}_s / \dot{Q}_t = (C'_{CO_2} - Ca_{O_2}) / (C'_{CO_2} - C\bar{v}_{O_2})$$

Results were expressed as means \pm SE and were tested by one-way analysis of variance. When the F-ratio was significant at $P < 0.05$, multiple t tests were used to test for significance level of differences between step 1, step 2, and step 3.

Results

Mean values for circulatory variables in each step are presented in table 1. Changes in circulatory variables secondary to altering the ventilatory mode from synchronous (step 1) to alternating (step 2) were small and not significant both for the systemic circulation and the pulmonary circulation. When synchronous ventilation was reestablished (step 3), there were small but insignificant changes in CO, SVI, LVSWI, and SVR.

Mean values for lung mechanics are presented in table 2. Large changes in lung mechanics were seen between step 1 and step 2 as well as between step 2 and step 3. Airway pressure (P_{aw}) decreased 2.1 mmHg in the left lung and 2.3 mmHg in the right during alternating ventilation (step 2) and recovered to almost the same levels upon re-establishing synchronous ventilation. Esophageal pressure (P_{cso}) decreased 1.1 mmHg during step 2 and again increased 0.8 mmHg during step 3.

As a result of these changes, alternating ventilation of the lungs was associated with large increases in total lung compliance (TLC) from step 1 to step 2 (5.9 ml/cmH₂O in the left lung and 13.3 ml/cmH₂O in the right). At the same time, lung compliance of the right side increased 12 ml/cmH₂O and 8 ml/cmH₂O in the left side. These changes were all highly significant.

Alternating lung ventilation was associated with small decreases in $P_{a_{CO_2}}$ and in $P\bar{v}_{CO_2}$ and small increases in pH_a and in $pH\bar{v}$ (table 3). With return to step 3 the

TABLE 1. Values for HR, \overline{BP} , CO, SVI, LVSWI, SVR, \overline{PAP} , \overline{PCWP} , \overline{CVP} , and PVR in Step 1, Step 2, and Step 3

	HR (beat/min)	\overline{BP} (mmHg)	CO (l/min)	SVI (ml/m ²)	LVSWI (g·m/m ²)	SVR (dyn·s·cm ⁻⁵)	\overline{PAP} (mmHg)	\overline{PCWP} (mmHg)	\overline{CVP} (mmHg)	PVR (dyn·s·cm ⁻⁵)
Step 1: synchronous ventilation (mean ± SE)	154 ± 5	125 ± 4	2.59 ± 0.20	28 ± 1.5	44.5 ± 3.1	4162 ± 293	14.3 ± 1.5	6.3 ± 1.1	1.8 ± 0.4	268 ± 23
Step 2: alternating ventilation (mean ± SE)	156 ± 5	124 ± 5	2.57 ± 0.19	27 ± 1.3	43.5 ± 2.9	4126 ± 272	15.3 ± 2.0	6.2 ± 1.5	1.5 ± 0.4	287 ± 19
Step 3: synchronous ventilation (mean ± SE)	156 ± 5	124 ± 4	2.31 ± 0.13	24 ± 0.9	39.4 ± 1.9	4504 ± 265	14.2 ± 1.7	5.7 ± 1.6	1.5 ± 0.5	301 ± 19
Analysis of variance F ratio	0.04	0.01	0.80	1.75	1.04	0.57	0.13	0.04	0.12	0.68

HR = heart rate; \overline{BP} = mean systemic blood pressure; SVI = stroke volume index; LVSWI = left ventricular stroke work index; SVR = systemic vascular resistance; \overline{PAP} = mean pulmonary artery pres-

sure; \overline{PCWP} = mean pulmonary artery wedge pressure; and PVR = pulmonary vascular resistance.

changes were almost of the same magnitude and in opposite direction as those from step 1 to step 2. But these changes were not statistically significant.

No significant changes in \dot{Q}_s/\dot{Q}_t were observed in association with alternating ventilation of the lungs (table 3).

Discussion

The effective and complete separation of the canine right bronchus from the left with a double lumen endotracheal tube was an extremely difficult problem because, as has been pointed out by Benfield *et al.*,⁶ the distance between the carina and the left upper lobe orifice may be very short while the right upper lobe bronchus is even closer to the carina than the left. This pe-

culiar anatomy is different from that in humans and has made the design of a tracheal divider for dogs very difficult.⁶ We tried several different double-lumen tubes with poor results. In addition, the pressure gradient between the right and left bronchus during alternating ventilation made it more difficult to separate them completely without air leakage. After several trials, the insertion of a right-sided Robertshaw tube into the left bronchus proved to be the most satisfactory. To confirm complete separation in our dogs, after the final set of measurements they were killed and the trachea was opened. Dogs were accepted into the study only when the "Murphy eye" at the tip of the right-sided Robertshaw tube was fitted to the left upper lobe orifice and no obstruction of bronchi was observed. Forty dogs were studied and only 22 were accepted (55% of all).

TABLE 2. Values for Airway Pressure (P_{aw}), Esophageal Pressure (P_{eso}), Total Lung Compliance and Lung Compliance in Step 1, Step 2, and Step 3

	P_{aw} (mmHg)		P_{eso} (mmHg)	Total Lung Compliance (ml/cmH ₂ O)		Lung Compliance (ml/cmH ₂ O)	
	Left	Right		Left	Right	Left	Right
Step 1 (mean ± SE)	6.3 ± 0.3	5.1 ± 0.2	2.1 ± 0.1	11 ± 0.5	13 ± 0.5	16 ± 1.0	27 ± 4.1
Step 2 (mean ± SE)	4.2 ± 0.2	2.8 ± 0.2	1.0 ± 0.1	17 ± 1.0	27 ± 1.7	24 ± 2.5	39 ± 4.5
Step 3 (mean ± SE)	6.5 ± 0.1	5.2 ± 0.2	1.8 ± 0.1	11 ± 0.8	13 ± 0.6	16 ± 1.8	20 ± 1.4
Analysis of variance F ratio	18.2*	45.4*	18.7*	19.9*	49.4*	5.5*	7.4*
Multiple <i>t</i> test							
Step 1 vs. step 2	<i>P</i> < 0.001	<i>P</i> < 0.001	<i>P</i> < 0.001	<i>P</i> < 0.001	<i>P</i> < 0.001	<i>P</i> < 0.01	<i>P</i> < 0.05
Step 2 vs. step 3	<i>P</i> < 0.001	<i>P</i> < 0.001	<i>P</i> < 0.001	<i>P</i> < 0.001	<i>P</i> < 0.001	<i>P</i> < 0.01	<i>P</i> < 0.01
Step 1 vs. step 3	NS	NS	NS	NS	NS	NS	NS

* Significant F ratio (*P* < 0.01) using one-way analysis of variance.

TABLE 3. Values for PaO₂, PaCO₂, pH_a, P \bar{V} O₂, P \bar{V} CO₂, pH \bar{V} , and \dot{Q}_s/\dot{Q}_t in Step 1, Step 2, and Step 3

	PaO ₂ (mmHg)	PaCO ₂ (mmHg)	pH _a	P \bar{V} O ₂ (mmHg)	P \bar{V} CO ₂ (mmHg)	pH \bar{V}	\dot{Q}_s/\dot{Q}_t (%)
Step 1 (mean \pm SE)	94 \pm 2.7	36.5 \pm 0.8	7.401 \pm 0.01	45 \pm 1.2	40.5 \pm 1.1	7.372 \pm 0.01	6.0 \pm 1.2
Step 2 (mean \pm SE)	96 \pm 2.8	34.0 \pm 1.0	7.419 \pm 0.01	45 \pm 1.3	37.6 \pm 1.0	7.393 \pm 0.01	5.9 \pm 1.3
Step 3 (mean \pm SE)	94 \pm 2.7	35.7 \pm 1.1	7.403 \pm 0.01	45 \pm 1.2	39.0 \pm 1.2	7.378 \pm 0.01	6.0 \pm 1.4
Analysis of variance F ratio	0.13	1.82	0.85	0.02	1.76	0.86	0.06

pH_a and pH \bar{V} = pH in arterial blood and in mixed venous blood, respectively.

In surveying the data obtained, the magnitude of changes in circulatory variables from step 1 to step 2 seemed surprisingly small not only for the systemic but also the pulmonary circulation (table 1). By contrast, striking changes occurred in lung mechanics (table 2). Airway pressure (P_{aw}) and esophageal pressure (P_{eso}) decreased with alternating ventilation reflecting the increase in lung compliance since tidal volumes for both lungs remained constant. These results might be explained by less dependence on chest wall expansion. The two lungs need not compete for volume since when one lung is in a phase of inspiration the other is in a phase of expiration. The data also indicate that the right lung expands with greater ease than the left (table 2).

In addition, considering the higher P_{aw} of the left side than the right in every step (table 2), the division of the tidal volume for both lungs might have been inappropriate. Perhaps the volume for the left lung should be smaller.

It is well-known that intrapulmonary mean pressure has an important relation to pulmonary blood flow. However, the decreases in P_{aw} and P_{eso} we observed were not reflected by changes in circulatory variables. Although central venous pressure decreased slightly, CO did not increase during step 2 (table 1). These results might indicate that the advantages of alternating lung ventilation on lung mechanics may be offset by negative effects on circulatory functions.

The small insignificant decrease in PaCO₂ and increase in pH might suggest that the alternating expanding lung movement deflates the opposite lung augmenting exhalation and CO₂ removal as has been pointed out by Hameroff *et al.*⁴ though these changes are not significant. It is well-known also that, when one lung is put under PEEP, pulmonary blood flow is diverted from that lung to the other exaggerating ventilation-perfusion inequality.⁷ But maldistribution of ventilation and blood flow following alternating lung ventilation seems unlikely considering the lack of changes in PaO₂ and \dot{Q}_s/\dot{Q}_t during step 2 (table 3).

In calculating the oxyhemoglobin saturation, we used the formula derived by Ruiz *et al.*⁵ assuming that the oxyhemoglobin dissociation curve for dogs did not differ greatly from that for humans.⁸ Alternatively, we could obtain directly the values for oxyhemoglobin saturation and oxygen contents in arterial and mixed venous blood from the IL 282 CO-oximeter. The values in end-pulmonary capillary blood still must be calculated from the calculated PA_{O₂}. We did re-calculate the intrapulmonary shunt (\dot{Q}_s/\dot{Q}_t) using directly measured CaO₂ and C \bar{v} O₂ and C \dot{c} O₂ calculated from the normal oxygen-dissociation curve. The results (\dot{Q}_s/\dot{Q}_t) obtained by this method were 5.7 \pm 0.9% (SE) in step 1, 6.1 \pm 1.2% (SE) in step 2, and 5.9 \pm 1.1% (SE) in step 3, essentially the same as those obtained by the former method (table 3).

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