Pulmonary gas exchange and ventilation-perfusion relationships during hypocapnia and thoracotomy in anaesthetized dogs

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The effects of hypocapnia and thoracotomy, both individually and combined, on pulmonary gas exchange and distribution of ventilation-perfusion ratio ($\dot{V}_A/\dot{Q}$) were studied in anesthetized and paralyzed mongrel dogs by the six inert gas elimination technique. Normocapnia (PaCO_2 35 mmHg) and hypocapnia (PaCO_2 20 mmHg) were produced sequentially by varying the inspired CO_2 concentration. Thoracotomy was performed at the fourth intercostal space. When ventilation was changed from normocapnia to hypocapnia without thoracotomy, PaO_2 decreased from 160 ± 10 to 147 ± 11 mmHg and $\dot{Q}_s/\dot{Q}_t$ increased from 0.0 ± 0.0 to $0.6 \pm 0.7\%$. However, no change was observed in perfusion distribution following thoracotomy during normocapnia, PaO_2 decreased from 160 ± 10 to 113 ± 15 mmHg together with a shift of perfusion toward the low $\dot{V}_A/\dot{Q}$ region. However, no change was observed in $\dot{Q}_s/\dot{Q}_t$. When ventilation was changed from normocapnia to hypocapnia with thoracotomy, PaO_2 decreased from 113 ± 15 to 98 ± 12 mmHg and $\dot{Q}_s/\dot{Q}_t$ increased from 0.3 ± 0.8 to $3.4 \pm 2.0\%$. After thoracotomy, a shift of perfusion toward the low $\dot{V}_A/\dot{Q}$ region was observed, which was probably responsible for the decrease in PaO_2 . The decrease in PaO_2 during hypocapnia was due to an increase in the true shunt rather than the development of low $\dot{V}_A/\dot{Q}$ region. Hypocapnia combined with thoracotomy produced a further reduction of PaO_2 and a greater increase in $\dot{Q}_s/\dot{Q}_t$.

Les effets de l'hypocapnie et la thoracotomie individuellement ou combinés sur l'échange vasopulmonaire et la distribution de la ventilation perfusion ($\dot{V}_A/\dot{Q}$) furent étudiés par la technique de l'élimination des six gaz inertes chez des chiens bédards anesthésiés et paralysés. La normocapnie (PaCO_2 35 mmHg) et l'hypocapnie (PaCO_2 20 mmHg) furent produites d'une façon séquentielle en variant la concentration de CO_2 inspirée. La thoracotomie fut faite au quatrième espace intercostal. Lorsque la ventilation fut changée de la normocapnie à l'hypocapnie sans thoracotomie, la PaO_2 a diminué de 160 ± 10 à 147 ± 11 mmHg et le $\dot{Q}_s/\dot{Q}_t$ augmenta de 0.0 ± 0.0 à $0.6 \pm 0.7\%$. Cependant, aucun changement ne fut observé dans la distribution de la perfusion. Après thoracotomie lors de la normocapnie, la PaO_2 diminua de 160 ± 10 à 113 ± 15 mmHg avec un « shift » de la perfusion vers des régions avant un bas $\dot{V}_A/\dot{Q}$. Cependant, aucun changement ne fut observé dans le $\dot{Q}_s/\dot{Q}_t$. Lorsque la ventilation fut changée de la normocapnie à l'hypocapnie après thoracotomie, la PaO_2 diminua de 113 ± 15 à 98 ± 12 mmHg et le $\dot{Q}_s/\dot{Q}_t$ augmenta de 0.3 ± 0.8 à $3.4 \pm 2.0\%$. Après thoracotomie, un « shift » de la perfusion vers les régions à bas $\dot{V}_A/\dot{Q}$ fut observé, ce qui fut responsable de la diminution de la PaO_2 . La diminution de la PaO_2 durant l'hypocapnie était due à une augmentation du shunt vrai plutôt que la création de région de bas $\dot{V}_A/\dot{Q}$. L'hypocapnie combinée à la thoracotomie produit une plus grande diminution de la PaO_2 et une plus grande augmentation du $\dot{Q}_s/\dot{Q}_t$.

Key words

CARBON DIOXIDE: hypocarbia;
LUNG: gas exchange;
SURGERY: thoracotomy;
VENTILATION: ventilation-perfusion.

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It is well known that a decrease in PaO_2 may be observed frequently during chest surgery. In such a situation, deliberate hyperventilation during anaesthesia will further decrease PaO_2 . Despite several studies the cause of this is not known. Thoracotomy in anaesthetized and paralysed humans decreases PaO_2 as a result of ventilation-perfusion maldistribution and pulmonary shunt.¹ Similarly, hypocapnia also decreases PaO_2 in humans.^{2,3} These investigations suggest that changes in cardiac output may play some role. Several authors have speculated that the

decrease in PaO_2 during hypocapnia may be induced by attenuation of the hypoxic pulmonary vasoconstriction (HPV) response as a result of the respiratory alkalosis.^{4,5} However, whether the decrease in PaO_2 , during thoracotomy or hypocapnia, is due to increased true shunt ($\dot{Q}_s/\dot{Q}_t$), to increased unevenness of the distribution of ventilation and perfusion, or both, is not known. Furthermore, there are few investigations about the combined effect of hypocapnia and thoracotomy on ventilation-perfusion relationships.

The purpose of this study was to determine the mechanism of the decrease in PaO_2 during thoracotomy, hypocapnia, and during hypocapnia combined with thoracotomy. Changes in the distribution of the intrapulmonary ventilation-perfusion ratio ($\dot{V}_A/\dot{Q}$) were measured using the six inert gas elimination techniques developed by Wagner *et al.*⁶

Methods

Six adult mongrel dogs weighing 9.5–11.5 kg were used in this study. After *iv* administration of 25 $\text{mg} \cdot \text{kg}^{-1}$ pentobarbital sodium, the trachea was intubated with a Hi-Lo jet tube (8.0 I.D. Mallinckrodt, Inc.). Anaesthesia was maintained by *iv* administration of 15 mg of pentazocine and 10 mg of diazepam for every two hours. Pancuronium was administered *iv* for muscle relaxation and the lungs were ventilated by a non-rebreathing, piston type ventilator (R50-S Aika Co.).

A 6Fr polyethylene catheter was inserted into the right carotid artery for continuous measurement of arterial pressure and arterial blood sampling. Another 6Fr catheter was inserted into the right atrium via the right jugular vein to measure right atrial pressure and a 5Fr thermodilution catheter (SP5105 Spectramed Co.) was inserted into the pulmonary artery via the same vein to measure pulmonary arterial pressure, pulmonary arterial wedge pressure, and cardiac output. Then an 8Fr polyethylene catheter was inserted into the left femoral vein for continuous administration of the six inert gas solution. After these procedures, the animals were placed in the left side decubitus position simulating the clinical situation.

The FiO_2 was set at 0.3, tidal volume at 20 $\text{ml} \cdot \text{kg}^{-1}$, and the frequency at 20 cycles $\cdot \text{min}^{-1}$. These ventilatory conditions were maintained throughout the experiment. In pilot experiments, it had been recognized that this would maintain PaCO_2 at approximately 20 mmHg (hypocapnia). To produce normocapnia, CO_2 was added to the inspired gas and the animal's PaCO_2 was maintained at 35 mmHg. Initially the lungs were ventilated to produce normocapnia or hypocapnia without thoracotomy in a random fashion. Thereafter, a right thoracotomy was performed at the fourth intercostal space and normocapnia or hypocapnia was produced in the animals in a

random manner. Mean arterial pressure (MAP), mean pulmonary arterial pressure (MPAP), pulmonary arterial wedge pressure (PAWP), and mean right atrial pressure (MRAP) were measured by strain gauge transducers (TP-200T Nihonkohden Co.), monitored continuously on a four-channel polygraph (Multipurpose Polygraph RM-45, Nihonkohden Co.), and recorded simultaneously. Cardiac output was measured by a thermodilution technique using a cardiac output computer (Hemopro-1, Spectramed Co. Ltd.). The cardiac index ($\dot{Q}$) was determined by dividing cardiac output by the body surface area of the subject according to Dubois's formula.⁷ The systemic vascular resistance index (SVRI) and the pulmonary vascular resistance index (PVRI) were calculated by the following formulas:

$$\text{SVRI} = (\text{MAP} - \text{MRAP}) \times 80/\dot{Q}$$

$$\text{PVRI} = (\text{MPAP} - \text{PAWP}) \times 80/\dot{Q}$$

Mean airway pressure (MPaw) was measured by a strain gauge transducer (P-50, Gould Inc.) connected to a catheter built into the Hi-Lo jet tube (Mallinckrodt, Inc.), which terminated near the distal end of the tube, and was recorded continuously on another four-channel polygraph (Multipurpose Polygraph RM-45, Nihonkohden Co.).

Arterial blood gas tensions and pH values were measured by a blood gas analyzer (BHS3-Mk2 PHM73, Radiometer Inc.).

Arterial blood noradrenaline and adrenaline were separated by high performance liquid chromatograph (L-6000, Hitachi Corp.), and then the concentrations were measured by the fluorimetric trihydroxyindole method.⁸

The method employed for measuring $\dot{V}_A/\dot{Q}$ distribution has been described in detail elsewhere⁹ but is summarized briefly below. The solution in which six inert gases had been dissolved was injected continuously through the catheter in the left femoral vein. The expired gas was collected continuously in a fluorinated resin bag for five minutes from 15 min after injection of the solution and an arterial blood sample of 30 ml was drawn simultaneously into a heparinized syringe. Then the concentrations of the six inert gases in each sample were measured by gas chromatography. In this study, however, a new method of air equilibration¹⁰ was employed for the collection of these gases in the blood sample. Namely, 3.5 ml of blood was pipetted into a 7 ml screw cap glass vial with a silicon septum. After stirring for 15 min at 37° C, the gas in the vial was aspirated into a gas-tight syringe of 2 ml capacity (Pressure Lok® Precision Sampling Corp.) and then was injected into a gas chromatograph. From the concentrations of the six inert gases in each sample obtained by gas chromatography, the distribution of $\dot{V}_A/\dot{Q}$ was calculated by Wagner's formula⁶ using a computer (Facom 340 Fujitsu Co.). We modified their computer

program except the basal theoretical formula to fit our computer. The distributions of ventilation and perfusion obtained were analyzed with respect to their mean values ($\dot{V}_{\text{mean}}$, $\dot{Q}_{\text{mean}}$) extent ($\dot{V}_{\text{SD}}$, $\dot{Q}_{\text{SD}}$), dead space (V_D/V_T), and true shunt ($\dot{Q}_s/\dot{Q}_t$). The PaO_2 value was also estimated from the $\dot{V}_A/\dot{Q}$ distribution curve.⁶

A perfusion distribution curve was created by determining the perfusion occurring for each fraction of the $\dot{V}_A/\dot{Q}$ ratio as a percentage of the cardiac index and then averaging the curves to obtain a single distribution curve in each group.

All of these measurements were made during four ventilatory conditions; i.e., during both normocapnia (CN) and hypocapnia (CH) without thoracotomy and during both normocapnia (ON) and hypocapnia (OH) with thoracotomy. At intervals, at least 30 min after a new condition had been established, the six inert gas solutions were infused continuously, and then an expired gas and an arterial blood sample were collected continuously for five minutes 15 min after infusion of the solution to measure $\dot{V}_A/\dot{Q}$ distribution and arterial blood gas variables. After these sample circulatory variables were measured immediately.

All data are expressed as the mean $\pm$ SD. Statistical analysis was performed by using analysis of variance and a paired *t* test, and $P < 0.05$ was considered significant.

Results

Effect of hypocapnia

The PaCO_2 was 35 ± 3 mmHg during normocapnia and 19 ± 2 mmHg during hypocapnia. The PaO_2 decreased from 160 ± 10 to 147 ± 11 mmHg ($P < 0.01$). Arterial pH increased from 7.34 ± 0.05 to 7.53 ± 0.06 ($P < 0.01$) (Table).

The $\dot{Q}_s/\dot{Q}_t$ increased from 0.0 ± 0.0 to $0.6 \pm 0.7\%$ ($P < 0.05$), but the $\dot{Q}_{\text{mean}}$ and the $\dot{Q}_{\text{SD}}$ were unaffected by hypocapnia (Table).

The perfusion-distribution curves during normocapnia and hypocapnia without thoracotomy are shown in Figure 1. When ventilation was changed from normocapnia to hypocapnia, $\dot{Q}_s/\dot{Q}_t$ increased slightly but significantly ($P < 0.05$). A shift in perfusion toward the low $\dot{V}_A/\dot{Q}$ region, however, did not occur.

The $\dot{V}_D/\dot{V}_T$, the $\dot{V}_{\text{mean}}$ and the $\dot{V}_{\text{SD}}$ remained unaltered by hypocapnia (Table).

The MPaw , MAP , HR , $\dot{Q}$, SVRI , MPAP , and PVRI remained unaltered (Table). No change was noted in the blood noradrenaline and adrenaline concentration.

Effect of thoracotomy

The PaCO_2 was 35 ± 3 mmHg before thoracotomy and 38 ± 4 mmHg after thoracotomy. The PaO_2 decreased from

FIGURE 1 The perfusion distribution curve during normocapnia and hypocapnia without thoracotomy. Each curve was described by averaging the distribution curves of six dogs in the same ventilatory condition. O—O: during normocapnia ($n = 6$), ●—●: during hypocapnia ($n = 6$).

160 ± 10 to 113 ± 15 mmHg after thoracotomy ($P < 0.01$). Arterial pH decreased from 7.34 ± 0.05 to 7.30 ± 0.06 after thoracotomy ($P < 0.05$) (Table).

The $\dot{Q}_s/\dot{Q}_t$ was unaffected by thoracotomy. However, the $\dot{Q}_{\text{mean}}$ shifted toward a low $\dot{V}_A/\dot{Q}$ region; i.e., from 1.96 ± 0.65 to 1.21 ± 0.54 ($P < 0.05$), and the $\dot{Q}_{\text{SD}}$ increased from 0.35 ± 0.25 to 1.45 ± 0.39 after thoracotomy ($P < 0.01$) (Table).

The perfusion-distribution curves before and after thoracotomy during normocapnia are shown in Figure 2. No change was observed in the $\dot{Q}_s/\dot{Q}_t$, but a shift in perfusion toward the low $\dot{V}_A/\dot{Q}$ region was noted.

The $\dot{V}_D/\dot{V}_T$, the $\dot{V}_{\text{mean}}$ and the $\dot{V}_{\text{SD}}$ remained unaltered by thoracotomy (Table).

After thoracotomy, the MPaw increased from 4.5 ± 0.7 to 5.2 ± 0.5 cmH₂O during normocapnia ($P < 0.05$) (Table).

The MAP , HR , $\dot{Q}$, and SVRI remained unaltered by thoracotomy. The MPAP increased from 23 ± 7 to 28 ± 9 mmHg ($P < 0.05$) and PVRI increased from 212 ± 56 to 291 ± 122 dynes $\cdot$ sec $\cdot$ cm⁻⁵ $\cdot$ m² after thoracotomy ($P < 0.01$) (Table). No change was noted in the blood noradrenaline and adrenaline concentration.

Combined effect of hypocapnia with thoracotomy

The PaCO_2 was 19 ± 2 mmHg before thoracotomy and 20 ± 3 mmHg after thoracotomy. The PaO_2 decreased

FIGURE 2 The perfusion distribution curve before and after thoracotomy during normocapnia. $\circ-\circ$: without thoracotomy ($n = 6$), $\bullet-\bullet$: with thoracotomy ($n = 6$).

from 147 ± 11 to 98 ± 12 mmHg after thoracotomy ($P < 0.01$). The values during hypocapnia with thoracotomy were also lower than during normocapnia and thoracotomy ($P < 0.01$). Arterial pH decreased from 7.53 ± 0.06 to 7.46 ± 0.07 after thoracotomy ($P < 0.01$) (Table).

The $\dot{Q}_s/\dot{Q}_t$ increased from 0.6 ± 0.7 to $3.4 \pm 2.0\%$ ($P < 0.01$). It also showed higher values during hypocapnia than during normocapnia with thoracotomy ($P < 0.05$). No change was observed in the $\dot{Q}_{\text{mean}}$, however, the $\dot{Q}_{\text{SD}}$ increased from 0.37 ± 0.08 to 0.87 ± 0.68 ($P < 0.05$) (Table).

The perfusion-distribution curves before and after thoracotomy under hypocapnia are shown in Figure 3. After thoracotomy, $\dot{Q}_s/\dot{Q}_t$ increased significantly ($P < 0.01$), and a perfusion to the low $\dot{V}_A/\dot{Q}$ region also slightly appeared.

The $\dot{V}_D/\dot{V}_T$, the $\dot{V}_{\text{mean}}$ and the $\dot{V}_{\text{SD}}$ remained unaltered by thoracotomy during hypocapnia (Table).

After thoracotomy, the MPaW increased from 5.0 ± 0.7 to 5.4 ± 0.0 cmH₂O during hypocapnia ($P < 0.05$) (Table).

The MAP, HR, $\dot{Q}$, and SVRI were unaltered by thoracotomy. The MPaW increased from 19 ± 6 to 27 ± 9 mmHg ($P < 0.05$) and PVRI increased from 183 ± 77 to 344 ± 94 dynes $\cdot$ sec $\cdot$ cm⁻⁵ $\cdot$ m² after thoracotomy ($P < 0.01$) (Table). No change was noted in the blood noradrenaline concentrations. The blood adrenaline concentration increased from 3 ± 3 to 70 ± 70 pg $\cdot$ ml⁻¹ after thoracotomy ($P < 0.01$).

FIGURE 3 The perfusion distribution curve before and after thoracotomy during hypocapnia. $\circ-\circ$: without thoracotomy ($n = 6$), $\bullet-\bullet$: with thoracotomy ($n = 6$).

Throughout the experiment, the PaO_2 values estimated from the $\dot{V}_A/\dot{Q}$ distribution curves correlated with the PaO_2 measured polarographically ($r = 0.74$, $P < 0.01$), although the former values were about 19 mmHg higher than the latter (Table).

Discussion

In this study, PaO_2 was decreased by two factors: thoracotomy and hypocapnia. Following thoracotomy, PaO_2 decreased from 160 ± 10 to 113 ± 15 mmHg during normocapnia and from 147 ± 11 to 98 ± 12 mmHg during hypocapnia. We suspected that both a limited expansion of the non-dependent lung with a decrease in FRC and a decrease in the lung volume on the dependent side due to a shift of the mediastinum, particularly the heart, occurred after thoracotomy in the lateral decubitus position. These decreases in the ventilatory capacity resulted in the development of the low $\dot{V}_A/\dot{Q}$ region and a decrease in PaO_2 . In fact, the shift of perfusion toward the low $\dot{V}_A/\dot{Q}$ region was magnified and the perfusion distribution was broader after thoracotomy during both normocapnia and hypocapnia.

Several studies have described changes in ventilation and perfusion following postural changes. Previous studies reported that the FRC decreased on the dependent compared with the non-dependent side in the lateral decubitus position in man.^{11,12} After thoracotomy, these changes would become more serious.¹

TABLE Blood gas analyses, distribution of $\dot{V}_A/\dot{Q}$, and haemodynamic data

	CN	CH	ON	OH
mPaO ₂ (mmHg)	160 ± 10	147 ± 11†	113 ± 15†	98 ± 12§
cPaO ₂ (mmHg)	178 ± 14	158 ± 9*	143 ± 22*	115 ± 20‡¶
PaCO ₂ (mmHg)	35 ± 3	19 ± 2†	38 ± 4	20 ± 3§
pH	7.34 ± 0.05	7.53 ± 0.06†	7.30 ± 0.06*	7.46 ± 0.07§
Qs/Qt (%)	0.0 ± 0.0	0.6 ± 0.7*	0.3 ± 0.8	3.4 ± 2.0‡
Q _{mean} ($\dot{V}_A/\dot{Q}$)	1.96 ± 0.65	1.51 ± 0.24	1.21 ± 0.54*	1.51 ± 0.49
QSD (log SD)	0.35 ± 0.25	0.37 ± 0.08	1.45 ± 0.39†	0.87 ± 0.68¶
$\dot{V}_D/\dot{V}_T$ (%)	22.2 ± 7.8	30.0 ± 11.6	24.3 ± 10.6	28.5 ± 15.4
$\dot{V}_{mean}$ ($\dot{V}_A/\dot{Q}$)	2.10 ± 0.12	1.70 ± 0.08	2.25 ± 0.07	2.53 ± 0.21
$\dot{V}_{SD}$ (log SD)	0.36 ± 0.22	0.35 ± 0.05	0.72 ± 0.52	0.45 ± 0.15
MPAW (cmH ₂ O)	4.5 ± 0.7	5.0 ± 0.7	5.2 ± 0.5*	5.4 ± 0.0¶
MAP (mmHg)	138 ± 31	145 ± 17	142 ± 35	148 ± 24
HR (bpm)	147 ± 45	157 ± 36	153 ± 37	175 ± 33
Q (L · min ⁻¹ · m ⁻²)	3.8 ± 0.9	3.4 ± 0.7	3.5 ± 0.7	3.1 ± 0.8‡
SVRI (dyns · sec · cm ⁻⁵ · m ²)	2907 ± 597	3391 ± 522	3336 ± 1259	3961 ± 1162
MPAP (mmHg)	23 ± 7	19 ± 6	28 ± 9*	27 ± 9¶
PVRI (dyns · sec · cm ⁻⁵ · m ²)	212 ± 56	183 ± 77	291 ± 122*	344 ± 94¶

Values are means ± SD (*n* = 6). CN: normocapnia without thoracotomy. CH: hypocapnia without thoracotomy. ON: normocapnia with thoracotomy. OH: hypocapnia with thoracotomy. *0.01 < *P* < 0.05, †*P* < 0.01 (different from CN), ‡0.01 < *P* < 0.05, §*P* < 0.01 (different from ON), ¶0.01 < *P* < 0.05, ||*P* < 0.01 (different from CH). mPaO₂: actually measured PaO₂ values. cPaO₂: calculated PaO₂ values by $\dot{V}_A/\dot{Q}$ distribution. Qs/Qt: true shunt. Q_{mean}: the mean value of the perfusion distribution. QSD: the extent of the perfusion distribution. $\dot{V}_D/\dot{V}_T$: dead space/tidal volume fraction. MPAW: mean airway pressure. MAP: mean arterial pressure. HR: heart rate. Q: cardiac index. SVRI: systemic vascular resistance index. MPAP: mean pulmonary arterial pressure. PVRI: pulmonary vascular resistance index.

Increases in the mean pulmonary arterial pressure and the pulmonary vascular resistance index were observed after thoracotomy in the lateral decubitus position. It was supposed that these changes were induced by limited expansion of the lung after thoracotomy and gravitational compression of the dependent lung by the mediastinum. This same mechanism was also considered to have caused an increase in the mean airway pressure after thoracotomy in spite of no change in the PaCO₂ levels.

When PaCO₂ was decreased, PaO₂ decreased from 160 ± 10 to 147 ± 11 mmHg before thoracotomy and from 113 ± 15 to 98 ± 12 mmHg after thoracotomy. The Qs/Qt increased from 0.0 to 0.6% before thoracotomy and from 0.3 to 3.4% after thoracotomy.

Many studies have reported upon the effect of hypocapnia on the pulmonary circulation, especially on the HPV response. Lloid⁴ noted that the HPV response was diminished by alkalization of the perfusate in isolated dog lungs. Marshall *et al.*¹³ showed that both acidosis and alkalosis reduced the HPV response of isolated rat lungs. Raffestin *et al.*,¹⁴ however, showed that intracellular alkalosis and acidosis, respectively, potentiated and blunted the HPV response in isolated rat lungs. They proposed that intracellular alkalosis increased the contractility of smooth muscle in the pulmonary arteries induced by the Ca⁺⁺ or by the release of vasoactive mediators from some of the lung cells.

In general, when the HPV response is diminished, an increase in perfusion toward the low $\dot{V}_A/\dot{Q}$ region is usually observed rather than an increase in the true shunt. If PaO₂ decreases as the result of a diminished HPV response due to hypocapnia, the distribution of perfusion should not increase in the true shunt but should shift toward the low $\dot{V}_A/\dot{Q}$ region. In the present study, a slight increase in true shunt was noted but no shift in perfusion toward the low $\dot{V}_A/\dot{Q}$ region was observed. These results suggested that the decrease in PaO₂ during hypocapnia might be caused by an increase in true shunt rather than a diminished HPV response. Furthermore, no changes were noted in circulatory variables when the ventilatory condition was altered from normocapnia to hypocapnia before thoracotomy. After thoracotomy, a decrease was noted only in cardiac output. If the HPV response was attenuated, a decrease in pulmonary arterial pressure should have been observed but it was not.

Recently, Hirano¹⁵ reported that a decrease in cardiac output may amplify the decrease in PaO₂ due to the unevenness of the $\dot{V}_A/\dot{Q}$ particularly due to the shift of perfusion toward the low $\dot{V}_A/\dot{Q}$ region. In this study, cardiac output tended to decrease during hypocapnia without thoracotomy and decreased significantly with thoracotomy. In general, hypocapnia decreases cardiac output^{16,17} and thoracotomy also decreases it, but not markedly.¹⁸ Therefore the decrease in PaO₂ during hypo-

capnia, particularly with thoracotomy, may be caused in part by the decrease in cardiac output.

Several effects of hypocapnia on the pulmonary circulation have been reported, mainly, attenuation of the HPV response due to a change in the blood acid-base balance toward alkalosis^{4,5} and a decrease in the blood catecholamine level, particularly due to depression of sympathetic nervous activity. The blood catecholamines, such as adrenaline and noradrenaline, are some of the chemical mediators for increasing the HPV response.¹⁹ We had assumed that the $\dot{V}_A/\dot{Q}$ distribution would be attenuated by a decrease in the blood catecholamine level following hypocapnia. Unexpectedly, the blood catecholamine level increased during hypocapnia, and particularly after thoracotomy. It is unlikely that this increase is associated with the changes in blood gases and acid-base balance but it is likely that it is associated with sympathetic nerve excitation, probably via the baroreceptor response to the decrease in cardiac output. In this study, every individual in a certain group was maintained in as similar a controlled condition as possible but the blood catecholamine concentrations varied widely. The reason for such variation is not clear.

In practice, when a decrease in PaO_2 is found in a patient, one is tempted to increase lung ventilation. However, hyperventilation will induce a more profound decrease in PaCO_2 due to the above mechanisms. Therefore, to improve the hypoxoemia, it is preferable to increase the inspiratory oxygen concentration or apply hyperventilation using a breathing circuit with an additional dead space device.

In conclusion, the decrease in PaO_2 after thoracotomy in the lateral decubitus position is thought to be due to a shift of pulmonary perfusion toward the low $\dot{V}_A/\dot{Q}$ region and the decrease in PaO_2 during hypocapnia to be due to the increase in the true shunt. Hypocapnia combined with thoracotomy produced a further reduction of PaCO_2 caused by a greater increase in $\dot{Q}_s/\dot{Q}_t$.

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