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Cross-talk between the lungs in piglets

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Abstract *Hypothesis:* During alternating ventilation (AV) (i.e. differential ventilation (DV) of both lungs with a phase difference of half a ventilatory cycle) volume expansion of the inflated lung will occur partly by compression of the opposite lung.
Objective: We studied whether and how large an undulating flow would occur out of and into the non-ventilated lung during unilateral ventilation.
Design: In 20 anaesthetized, paralysed piglets (11.0±1.0 kg) DV was applied at a rate of 10 breaths per minute (bpm). In 6 animals, 15 and 20 bpm were also applied with the tidal volume adapted no normocapnia. As the measure of interaction (cross-talk) served the volume change in the non-ventilated lung, found by integration of the low signal, in percentage of the tidal volume to the other lung.
Results: In all pigs, tidal volume to the left lung ($V_{T,l} = 7.33 \pm 1.06$ ml kg^{-1}) caused a volume change in the right lung of about 21% of $V_{T,l}$ at 10 bpm. The right-to-left cross-talk was significantly lower and about 15% of $V_{T,r}$ (9.07 ± 1.21 ml kg^{-1}). At higher ventilatory rates, the l-to-r and the r-to-l cross-talk did not change.
Conclusion: During unilateral ventilation, volume expansion of the inflated lung occurs partly by compression of the opposite lung. The lower mean lung volume during AV compared to synchronous differential ventilation can be explained by such compression. The mechanism of compression is similar at different ventilatory rates.

Key words Alternating · Cross-talk · Differential · Interaction · Lung · Mechanical · Ventilation

Introduction

Differential ventilation (DV) is separate ventilation of both lungs [1, 2]. It does not change cardiac output when compared to conventional, common ventilation of both lungs [3, 4]. Recently, we observed a lower central venous pressure and higher cardiac output during alternating differential ventilation (AV) of both lungs compared to synchronous differential ventilation (SV) [5]. During AV, the start of inflation of one lung is half a ventilatory cycle out of phase with that of the other lung, i.e. the start of inflation of one lung coincides with the start of expiration of the other lung. The higher cardiac output during AV compared to SV could be attributed to the lower central venous pressure. This lower pressure was explained by a lower intrathoracic pressure due to a smaller mean lung volume during AV, which we verified in a second series of experiments [6].

We hypothesized that the lower mean lung volume and intrathoracic (oesophageal and pericardial) pressure during AV compared to SV were caused by volume expansion of the inflated lung at the expense of the opposite lung, which is in the expiration phase. To test this hypothesis,

we analysed the interaction between the lungs during unilateral ventilation, i.e. ventilation of one lung with open airways in the other. Because our previous study was performed at a ventilatory rate of 10 breaths per minute (bpm), we performed our experiments at the same ventilatory rate. We extended the study to 15 and 20 bpm in part of the experiments to verify whether the interaction is also present at higher ventilatory rates.

Materials and methods

Surgery

We obtained the approval of the committee for Animal Research of our university for this study. The details of the surgery have been described previously [5, 6]. Twenty young female pigs of 11.0±1.0 kg (mean±sd) body weight (BW) were anaesthetized with an intraperitoneal injection of 30 mg pentobarbital sodium (Abbott/Sanofi, Maassluis, The Netherlands) per kg BW. The animals were studied in the supine position. Body temperature was about 38 °C. Pentobarbital sodium was infused intravenously (8.5 mg·h^{-1}·kg^{-1} BW via an ear vein) during surgery.

Electrocardiographic (ECG) electrodes were placed subcutaneously on the sternum at the manubrium and on the left foreleg. A Y-shaped cannula was inserted into the trachea. The two limbs of the cannula were connected to the two pistons of our computer-controlled ventilator [7]. In this modified device the pistons could be controlled independently of each other. Initially, only one piston delivered the tidal volume to both lungs during common ventilation (CV). Tidal volume was adjusted to an arterial partial pressure of carbon dioxide ($PaCO_2$) close to 5.6 kPa. Ventilation was performed at a rate of 10 bpm, with a time ratio of inflation to inspiratory pause to expiration of 4 : 1 : 5. To avoid atelectasis, a positive end-expiratory pressure (PEEP) of 2 cmH_2O was applied throughout the first 6 experiments and 5 cmH_2O during the remaining 14 experiments. The inspired gas was ambient air. All ventilatory settings were maintained constant throughout the experiments. In the first 6 experiments ventilatory rates of 15 and 20 bpm were also applied. We adapted tidal volume to the same normocapnic condition ($PaCO_2$ was about 5.8 kPa) as at 10 bpm (Table 1).

An arterial catheter was inserted via the right common carotid artery into the aortic arch to measure aortic pressure and to sample arterial blood. We inserted two catheters via the right external jugular vein: (1) a pulmonary arterial catheter to sample mixed venous blood in all experiments and measure pressure in the last 6 experiments (in the preceding experiments we used the sampling channel for computer analysis of pulmonary arterial pressure for other reasons), and (2) a four-lumen catheter to measure central venous pressure, infuse pentobarbital sodium (again 8.5 mg h^{-1} kg^{-1}) and pancuronium bromide (0.2 mg h^{-1} kg^{-1}, Pavulon, Organon Teknika, Boxtel, The Netherlands; after surgery). Urine flow was measured with the use of a catheter through the urethra. It was inserted transabdominally. The bladder and abdominal wall were tightly sutured after insertion.

Measurements and calculated variables

ECG and aortic, central venous and airway pressures (pressure transducers type Uniflow, Baxter) were recorded continuously on a chart recorder (Gould, RS 3800) with the use of amplifiers for ECG (HP 8811 B) and pressures (HP 8805 B). Two probes for measuring airflow into and out of the right and left lungs (Pneumotachograph, Godart, Bilthoven, The Netherlands) were positioned on the two limbs of the tracheal cannula. Data sampling was done by computer (PC-AT) at a rate of 250 Hz. Samples were stored on disk for off-line analysis. Arterial blood gases were analysed with a blood gas analyser (type ABL 510, Radiometer). Inspiratory and expiratory gas concentrations were determined with a mass spectrometer (Perkin Elmer, type 1200, modified to a fast recording system). Values for blood gases, gas concentrations and ventilation were used to calculate cardiac output according to the Fick method. We fixed a mercury cord around the thorax and calibrated it to changes in lung volume, as previously reported [6].

The zero-level of blood pressures was taken at the tip of the four-lumen catheter near the right atrium, located by transversal radiographic examination. For calibration of the blood pressure transducers, a known pressure was applied. The pressure transducers for airway pressures were balanced against ambient air pressure and calibrated by a water manometer.

Ventilation of left and right lungs

After surgery, during CV at 10 bpm via the right limb of the tracheal cannula, a period of 30 min was used to adapt tidal volume (V_T) to normocapnic conditions and to stabilize gas exchange and haemodynamic variables. Then, a flexible tube (CF cuffed tracheal tube, Murphy eye, i.d. 4.5 mm, o.d. 6.2 mm; Sheridan, Argyle, N.Y.)

Table 1 Haemodynamic and gas exchange data (Q' cardiac output determined with the Fick method, Pa arterial pressure, P_{cv}* central venous pressure, P_{pa}, PaO_2 and SaO_2 arterial oxygen pressure and saturation, $PaCO_2$ arterial CO_2 pressure)

	Experiments							
	10 bpm (n = 20)		10 bpm (n = 6)[a]		15 bpm (n = 6)[a]		20 bpm (n = 6)[a]	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Q' (ml·s^{-1}·kg^{-1})	1.89	0.32	1.66	0.14	1.56	0.15	1.61	0.20
Pa (mmHg)	94	8	95	7	94	9	93	7
P_{cv} (mmHg)	4.0	1.4	2.6	0.8	2.5	1.0	2.1*	1.0
P_{pa}[b] (mmHg)	18.7	1.7						
PaO_2 (kPa)	11.7	1.8	10.9	2.1	10.7	2.1	10.9	0.8
SaO_2 (%)	95	3	93	3	92	5	93	4
$PaCO_2$ (kPa)	5.4	0.4	5.9	0.3	5.7	0.3	5.7	0.3

[a] Obtained from the first 6 experiments in Table 2
[b] n = 6, obtained from the last 6 experiments in Table 2
*p = 0.03 tested against P_{cv} at 10 bpm (n = 6)

was inserted through the left limb of the tracheal cannula [5] into the trachea (Fig. 1) with the opening about 1 cm cranial from the carina. We called this tube the endobronchial tube. Next, V_T was divided 50:50 between both pistons and was inflated through the right limb of the tracheal cannula and the endobronchial tube. Both lungs were still ventilated in common. Airway pressures monitored in the tracheal cannula and endobronchial tube were equal to airway pressure during CV before insertion of the tube. Next, the cuff part of the endobronchial tube was advanced into the left main bronchus between carina and the first side branch to the left cranial lobe. From the moment the cuff was positioned in the left main bronchus, each lung received half of the V_T. Consequently, left airway peak pressure ($P_{aw,l}$) became higher and right airway pressure ($P_{aw,r}$) lower than during CV. We inflated the balloon at the tip of the endobronchial tube to a pressure of 150–200 mmHg to ensure an airtight fit in the left main bronchus. Next, we increased V_T to the right lung ($V_{T,r}$) and decreased $V_{T,l}$ by the same amount until both airway pressures ($P_{aw,l}$ and $P_{aw,r}$) at the end of the inspiratory pause were equal. $P_{aw,l}$ and $P_{aw,r}$ were measured in the endobronchial tube and the tracheal cannula, respectively. We checked for an airtight fit by unilateral ventilation at the closed airway of the opposite lung [5]. Inspection after all of the experiments revealed the location of the opening of the endobronchial tube between the carina and the first bronchial branch to the left cranial lobe. This lobe was normally expanded in all cases.

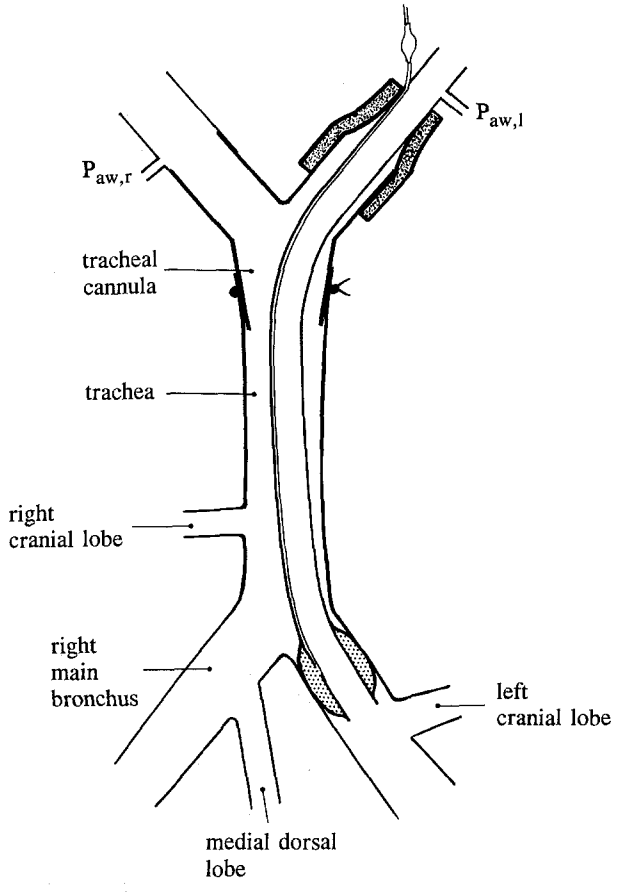

Fig. 1 Scheme of the endobronchial tube in situ. The right side in the scheme represents the left side in the pig. The endobronchial tube is inserted via the left limb of the Y-shaped tracheal cannula, while the animal is fully ventilated via the right limb. Initially, the tip is positioned about 1 cm above the carina. Next, the tidal volume is divided fifty-fifty between the right limb of the tracheal cannula and the endobronchial tube. Then, the tip of the endobronchial tube is advanced into the left main bronchus, causing a difference between the two peak airway pressures: $P_{aw,l} > P_{aw,r}$. Gradually the tube is advanced until a further rise in $P_{aw,l}$ occurs (with no change in $P_{aw,r}$), because then half the tidal volume is inflated into the left lung minus its cranial lobe. Next, the tube is withdrawn about half a centimetre and the balloon is inflated to high pressure. This inflation appeared to be more to avoid leakage than a necessity, because the tip of the tube fitted well in the left main bronchus. Note the side bronchus to the right cranial lobe, which is about 2 cm proximal of the carina. The distance between the carina and the branch to the left cranial lobe is slightly more than 1 cm

Cross-talk unilateral ventilation

We studied cross-talk during 30-s periods (i.e. five ventilatory cycles) of unilateral ventilation of one lung and open airways in the non-ventilated lung. The effect of ventilation of one lung on the volume displacement of the other, non-ventilated, lung was quantified by recording the inspiratory flow into the non-ventilated lung during expiration of the ventilated lung (Fig. 2). This inspiratory flow signal into the non-ventilated lung was integrated. Each integration period was started at expiration of the ventilated lung and ended at the start of inflation.

The calibration factor of this flow signal was determined during the first inflation of that lung immediately after the period of non-ventilation. This flow signal during inflation was sampled and integrated, giving area units (AU). After dividing the integrated value by the applied V_T, the calibration factor in AU/ml was obtained. Thus, if an integrated area in AUs is divided by the calibration factor, a value in ml will result.

The zero-line of the flow signal during calibration, as well as during the period of unilateral ventilation, was defined by the virtual horizontal line through the zero flow signal of the inflation pause of the first ventilatory cycle after the period of unilateral ventilation. During that phase, all valves were closed, and thus flow was zero. The value of this zero flow signal was obtained from the last 200 ms of the inflation pause of 0.6 s, i.e. the averaged value of 50 samples at 250 Hz.

The amount of cross-talk was calculated as the mean of the five integrated flow curves into the non-ventilated lung during expiration of the ventilated lung. This amount was expressed as the volume displacement of the non-ventilated lung in ml as well as in percentage of V_T of the ventilated lung.

Upper airway pressure in the non-ventilated lung was equal to the applied PEEP, due to a common final expiratory tube for both lungs in the water seal.

Protocol

After the stabilization period during CV, observations of cardiac output, blood pressures, gas concentrations, end-expiratory lung volume and calibration of the mercury cord [5] were made. Next, the endobronchial tube was inserted and ventilation was changed to DV, as mentioned above. Both lungs were synchronously ventilated with the same pattern as mentioned above. At intervals of 3 to 5 min we applied four periods of unilateral ventilation, each with a duration of five ventilatory cycles, i.e. 30 s. Data were sampled for 39 s from 3 s before until 6 s after the period of unilateral ventilation. Firstly, a period of unilateral ventilation of the right lung and one of the left lung was introduced, each with closed airways in the opposite lung to check for air leaks from the endobronchial tube.

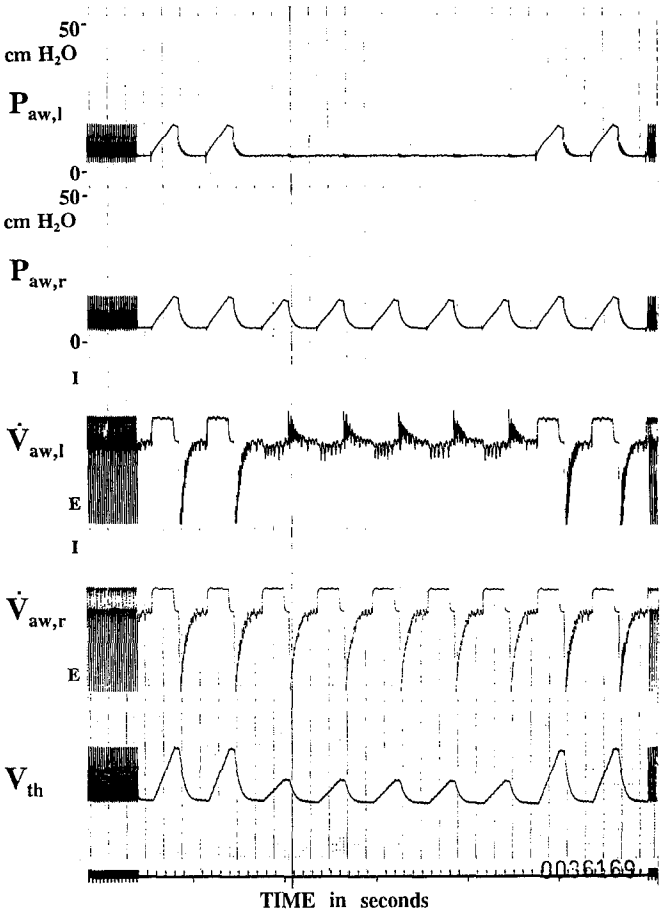

Fig. 2 Individual example of cross-talk between the two lungs. $P_{aw,l}$, $P_{aw,r}$ left and right airway pressures, respectively, measured in the endobronchial tube and the tracheal cannula, respectively, $V'_{aw,l}$, $V'_{aw,r}$ volume flow of left and right lung, respectively, *I* inspiratory flow, *E* expiratory flow, *Vth* recording of the mercury cord signal in arbitrary units, where the upward waves represent thoracic expansion. Inflation of the right lung coincided with an expiratory flow from the left lung and expiration of the right lung with an inspiratory flow into the left lung

Then, again, two such periods were introduced but with open airways in the opposite lung, which allowed us to study cross-talk. We called the volume effect of the left lung on the right lung "l-to-r cross-talk" and the opposite interaction "r-to-l cross-talk". These observations were followed by two determinations of cardiac output with the use of the Fick method. Haemodynamic data were also sampled and averaged per ventilatory cycle. The periods of unilateral ventilation and the observations were performed at intervals of about 5 min.

In the first 6 animals, after the observations at 10 bpm, we repeated the same observations at 15 and 20 bpm in alternating order every other experiment. The division of total V_T was adapted to equal airway pressures in both lungs as for 10 bpm. In the remaining 14 animals, the observations for analysing cross-talk were followed by observations for another aim.

Statistical analysis

R-to-l and l-to-r cross-talk were compared by Student's *t*-test for paired values to determine the *p*-value of differences. The same was done for the other ventilatory rates. In the last 6 experiments we also compared pulmonary arterial pressure during the first ventilatory cycle with that during the fifth ventilatory cycle of the 30-s periods of unilateral ventilation. The r-to-l and l-to-r cross-talk was also compared between the first and fifth cycle.

Results

Baseline conditions and changes during unilateral ventilation

The haemodynamic and gas exchange data during the steady-state mechanical ventilation are given in Table 1. Cardiac output, blood pressures and blood gases showed normal conditions. In the 6 experiments with the three ventilatory rates, only one significant difference was found: central venous pressure at a ventilatory rate of 20 bpm was slightly lower than that at 10 bpm. Pulmonary arterial pressure, averaged per ventilatory cycle during SV, was normal (Table 1) but increased by 2.1 ± 0.7 mmHg ($p < 0.001$, $n = 12$) from 19.7 ± 1.6 mmHg in the first cycle to 21.8 ± 2.1 mmHg in the fifth cycle of unilateral ventilation of the right and left lung, respectively.

Cross-talk

During inflation of the right lung with open airways in the left, we observed an expiratory flow from the left lung, and during expiration of the right lung we observed an inspiratory flow into the left lung (Fig. 2). The same occurred on the right side during unilateral ventilation of the left lung.

There was no significant difference in the l-to-r or in the r-to-l cross-talk between the first and the fifth cycles of unilateral ventilation ($p = 0.073$ for the difference in l-to-r and $p = 0.36$ for the r-to-l cross-talk, $n = 20$). In fact, there were no differences between cross-talks in the five cycles. Therefore, we averaged the five intraindividual values for each period of unilateral ventilation as shown in Fig. 2.

The data for cross-talk during ventilation at a rate of 10 bpm are presented in Table 2. In all experiments, $V_{T,r}$ was larger than $V_{T,l}$, as shown also by the ratios between them. The volume displacement of the right lung (ΔV_r in ml/kg) during ventilation of the left lung was larger than the volume displacement of the left lung (ΔV_l) during ventilation of the right lung ($p = 0.004$). As a consequence, ΔV_r as a percentage of $V_{T,l}$ was even larger than ΔV_l as a percentage of $V_{T,r}$ ($p < 0.00001$).

Table 2 Cross-talk between the lungs during unilateral inflation at a ventilatory rate of 10 bpm in 20 experiments[a]

Expt.	Weight (kg)	Left-to-right			Right-to-left			
		$V_{T,l}$	ΔV_r	ΔV_r (% of $V_{T,l}$)	$V_{T,r}$	ΔV_l	ΔV_l (% of $V_{T,r}$)	$V_{T,r}/V_{T,l}$
		(ml kg^{-1})			(ml kg^{-1})			
1	12.1	5.95	1.12	19	8.93	1.09	12	1.50
2	11.6	6.72	1.36	20	8.36	1.43	17	1.24
3	11.4	6.10	1.62	27	7.06	0.97	14	1.16
4	13.1	5.88	0.72	12	7.86	0.98	12	1.34
5	11.6	5.73	0.91	16	6.34	0.90	14	1.11
6	10.5	5.52	0.81	15	7.33	0.87	12	1.33
7	8.3	7.23	1.74	24	9.04	1.51	17	1.25
8	10.9	7.71	1.13	15	9.72	1.08	11	1.26
9	9.2	8.15	2.37	29	10.33	2.00	19	1.27
10	11.2	8.75	1.50	17	10.89	0.72	7	1.24
11	11.0	8.18	1.76	22	9.09	1.18	13	1.11
12	10.2	9.12	2.04	22	10.00	2.21	22	1.10
13	10.8	7.41	1.76	24	9.63	1.53	16	1.30
14	11.9	6.81	1.66	25	8.32	1.62	19	1.22
15	11.3	7.96	1.74	22	8.85	1.63	18	1.11
16	10.7	7.48	2.12	28	10.28	1.92	19	1.38
17	10.8	7.69	1.49	19	9.91	1.18	12	1.29
18	11.0	7.82	1.61	21	9.91	1.35	14	1.27
19	10.9	8.07	1.84	23	9.36	1.64	17	1.16
20	10.7	8.41	1.65	20	10.28	0.93	9	1.22
mean	11.0	7.33	1.55	21	9.07	1.34	15	1.24
SD	1.0	1.06	0.43	4.5	1.21	0.41	3.9	0.10

[a] The mean of the intraindividual coefficients of variation of ΔV_l was 6.4±3.2% and of ΔV_r, 6.2±4.4%

Table 3 Cross-talk between the lungs at different ventilatory rates in six experiments ($n = 6$)

Ventilatory rate (bpm)	Left-to-right			Right-to-left			
	$V_{T,l}$	ΔV_r	ΔV_r (% of $V_{T,l}$)	$V_{T,r}$	ΔV_l	ΔV_l (% of $V_{T,r}$)	$V_{T,r}/V_{T,l}$
	(ml kg^{-1})			(ml kg^{-1})			
10							
Mean	5.98	1.09	18.2	7.65	1.04	13.6	1.28
SD	0.41	0.35	5.08	0.93	0.21	1.94	0.14
15							
Mean	4.42	0.86	19.6	5.98	0.87	14.7	1.37
SD	0.48	0.25	5.71	0.60	0.25	4.56	0.25
20							
Mean	3.81	0.76	20.0	5.08	0.80	15.7	1.36
SD	0.50	0.19	4.82	0.62	0.21	4.45	0.32

The interindividual variation coefficient of $V_{T,l}$ was 14% and that of $V_{T,r}$ 13%. Those of mean ΔV_l and ΔV_r were 31 and 28%, respectively.

The results of the 6 experiments (experiments 1–6 in Table 1) at the three ventilatory rates are given in Table 3. The ratios between the right and left tidal volumes ($V_{T,r}$ and $V_{T,l}$, respectively) were not significantly different between the three ventilatory rates. L-to-r cross-talk in ml/kg at 10 bpm was not significantly different from r-to-l cross-talk ($p = 0.72$). The percentage values of about 18 and 14% were close to those for all 20 experiments, but the difference was not significant ($p = 0.065$). At 15 and 20 bpm, V_T to both lungs was significantly smaller, and also ΔV_l and ΔV_r in ml/kg BW decreased. Although we found similar percentages for the volume displacements as we found at 10 bpm, these differences were not significant, in contrast to those in all 20 experiments.

Discussion

Baseline conditions

The haemodynamic and gas exchange conditions were at normal levels in these animals (Table 1). In the first six animals, where the observations were repeated at higher ventilatory rates, the conditions were the same. We regard the

slight, but significant, difference between the central venous pressure at 10 and 20 pbm as not physiologically significant for the amount of interaction.

In all experiments, the endobronchial tube was airtight and in the right place in the left main bronchus, whereas the left cranial lobe showed normal expansion. In all cases, these observations indicated separate ventilation in the two lungs. Therefore, the gas flow from the non-ventilated lung during inflation of the ventilated lung was not caused by a leakage of the cuff. It has to be attributed to a volume decrease in the non-ventilated lung by compression. The inflow into the non-ventilated lung during expiration of the ventilated lung was regarded as the volume recovery after compression.

In spite of a slight but significant rise in pulmonary arterial pressure throughout the period of unilateral ventilation, which we studied in the last six animals, no change was found in the amount of cross-talk during the period of unilateral ventilation. Therefore, we regarded a shift in pulmonary blood flow between the lungs of little importance for the amount of cross-talk.

Tidal volume to each lung

In our two previous studies we found a ratio between right and left V_T at a ventilatory rate of 10 pbm of 1.30 ± 0.11 [5] and 1.21 ± 0.07 [6], which together give a value of 1.25 ± 0.10, which is equal to the value in the present study of 1.24 ± 0.10. In our previous paper we regarded the ratio between the two lung volumes as the same as the ratio between both tidal volumes. These ratios were determined at an early stage of our experiments, after we changed from CV to DV. They were kept constant throughout the experiments at 10 bpm. Giving a double V_T to both lungs during a ventilatory cycle of 12 s (comparable to a sigh) always increased lung volume a little and decreased peak airway pressures in both lungs. Small changes in lung volume over time are inherent in the experimental situation, e.g. a low PEEP of 2 cmH_2O, and are hard to control during an experiment let alone to standardizing between experiments. The slight instability in lung volume during the first 6 experiments was the reason that we applied a PEEP of 5 cmH_2O in the other experiments. Although there were then less obvious changes in lung volume throughout the experiments, they were not eliminated completely.

Although the ratios between right and left V_T at 15 and 20 bpm showed larger values, they were not significantly different from the ratio at 10 bpm. The standard deviations of these ratios at 15 and 20 bpm also showed larger values. These differences might be due to effects over time on the volumes of both lungs, which decreased about 10 to 20 ml, probably causing a larger variation between the experiments. We had no information on the decrease in volume in each lung separately.

Hypothesis

The hypothesis that the higher cardiac output during AV compared to SV in both lungs is due to a lower mean central venous pressure as a consequence of a lower intrathoracic pressure, caused by a lower mean thoracic volume, has been challenged and verified previously [5, 6]. To explain the lower mean thoracic volume during AV compared to SV, we hypothesized that, during AV, the inflated lung will expand partly by compression of the opposite lung and the remainder by expansion of the thorax. To test this hypothesis, we considered that as a consequence during unilateral ventilation a volume change should occur in the opposite, non-ventilated lung if its airways were open to ambient air. Our results clearly revealed that, during inflation and expiration of the ventilated lung, an expiration and inspiration occurred from and into the non-ventilated lung, respectively (Fig. 2), indicating a volume decrease and recovery, respectively, of the non-ventilated lung.

We reasoned also that during AV, inflation of one lung will result in a lower volume in the other lung at end-expiration if compared to its end-expiratory volume during SV. Thus, during AV, each lung will be inflated from a lower end-expiratory volume. Consequently, mean lung volume will be lower compared to SV, as we demonstrated previously [6]. Our data strongly support the hypothesis that the lower mean lung volume during AV compared to that during SV is due to compression of the non-inflated lung. We regard this lower mean lung volume as the main reason for the lower intrathoracic pressure and higher cardiac output during alternating ventilation compared to synchronous ventilation of both lungs.

The amount of cross-talk

Zero-level and calibration

Two main conditions had to be fulfilled for an accurate measure of the inflow into the non-ventilated lung during expiration of the inflated lung. Firstly, a correct zero-level of the flow signal was needed, and secondly, the flow signal had to be accurately calibrated. As indicated in Materials and methods, the flow signal during the non-flow condition of the inspiratory pause of the first normal ventilatory cycle after the period of unilateral ventilation was taken as the zero-level. The period of 200 ms was regarded as satisfactory to level out random variations and variations due to the 50 Hz of the electrical system. All samples necessary for the integration to estimate the inflow into the non-ventilated lung were corrected for this zero-level. Such a mathematical procedure avoided an off-set in the integrated values, because the zero-level was obtained during each observation period of 39 s, which implied an automatic compensation for zero drift.

We integrated the inflow into the non-ventilated lung, because the flow transducer was calibrated with the inflow during the first inflation after the period of unilateral ventilation of the other lung. In each period of unilateral ventilation the flow signal was recalibrated automatically. Thus, eventual changes by droplets of water were automatically taken into account. We calibrated with ambient air, whereas the inflow signal during unilateral ventilation was mainly caused by mixed expiratory air. We ignored the effect of this slight difference in air composition, because it caused only a minor change in the numerical data with no consequence for our conclusions.

The measure and amount

We presented the amount of cross-talk in two measures: (1) in volume units, i.e. ml/kg BW, and (2) as a percentage of V_T into the ventilated lung. We regarded the percentage measure the most useful for two reasons. It indicated the part of the inflated V_T that was not expanding the thoracic cage but compressing the other lung, and it eliminated to some extent interindividual differences in V_T between animals. The latter point is illustrated by the variation coefficients. The variation coefficients of ΔV_l and ΔV_r in ml/kg (SD in % of the mean value, 31 and 28%, respectively) imply the variation of the tidal volumes and are larger than the corresponding coefficients of variation of the percentages (26 and 21%, respectively). These values are almost twice the interindividual coefficients of variation of $V_{T,l}$ and $V_{T,r}$ (14 and 13%, respectively). Only a minor part (about 1/5) of the large interindividual variation in ΔV_l and ΔV_r could be attributed to the intraindividual variation in the ΔV_l and ΔV_r (6.4 and 6.2%, respectively). The intraindividual variation was obtained from the five measurements in each period of unilateral ventilation. These intraindividual coefficients of variation are given at the bottom of Table 2.

We found a significantly higher l-to-r than r-to-l cross-talk, 21 versus 15%. Thus, about 21% of the volume expansion of the left lung occurred by compression of the right lung and about 15% of the volume expansion of the right lung by compression of the left lung. We failed to find a satisfactory explanation for the larger l-to-r than r-to-l cross-talk.

Similar results were also found at the higher ventilatory rate and, consequently, lower tidal volumes. Thus, cross-talk is not a phenomenon restricted to a low ventilatory rate. Although the significant difference between r-to-l and l-to-r effects disappeared in the 6 experiments, probably due to the low number of experiments, we regard these mutual effects to be different by attributing greater importance to the 20 experiments.

Mechanisms of cross-talk

It was not an aim of the study to analyse the mechanism(s) of cross-talk. We assume that two routes of interaction could be possible: (1) a direct r-to-l and l-to-r effect through the mediastinum, or (2) a r-to-l and l-to-r effect via an increase in pressure in the abdomen. Although we regarded a shift of blood volume of little importance in explaining (at least partly) the amount of cross-talk, our results do not definitely exclude a third route through the pulmonary circulation. A combination of the mechanisms might be a possibility as well. Furthermore, an answer to the question of which route predominates will not give per se an answer to the question why a quantitative difference exists between the two opposite directions of cross-talk. In this respect, we could speculate on an asymmetrical location of heart and liver. However, without any evidence, we have no basis on which to draw a logical and reasonable conclusion.

Clinical relevance

It is important to know that mean lung volume will decrease if AV is applied instead of SV. That phenomenon might be on the negative side in the decision to apply AV because of the possible development of atelectasis. But in combination with a PEEP larger than the critical opening pressure of the alveoli, it will oppose cardiac output less than SV.

Conclusion

During unilateral ventilation, volume expansion of the inflated lung occurs partly by compression of the opposite lung. The lower mean lung volume during AV compared to SV can be explained by such compression.

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