Use of a Vital Capacity Maneuver to Prevent Atelectasis after Cardiopulmonary Bypass

An Experimental Study

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Background: Respiratory failure secondary to cardiopulmonary bypass (CPB) remains a major complication after cardiac surgery. The authors previously found that the increase in intrapulmonary shunt was well correlated with the amount of atelectasis. They tested the hypothesis that post-CPB atelectasis can be prevented by a vital capacity maneuver (VCM) performed before termination of the bypass.

Methods: Eighteen pigs received standard hypothermic CPB (no ventilation during bypass). The VCM was performed in two groups and consisted of inflating the lungs during 15 s to 40 cmH₂O at the end of the bypass. In one group, the inspired oxygen fraction (FiO₂) was increased to 1.0. In the second group, the FiO₂ was left at 0.4. In the third group, no VCM was performed (control group). Ventilation-perfusion distribution was measured with the inert gas technique and atelectasis by computed tomographic scanning.

Results: Intrapulmonary shunt increased after bypass in the control group (from ± 4% to 20.8 ± 11.7%; P < 0.05) and was also increased in the vital capacity group ventilated with 100% oxygen (from 2.2 ± 1.3% to 6.9 ± 2.9%; P < 0.01) but was unaffected in the vital capacity group ventilated with 40% oxygen. The control pigs showed extensive atelectasis (21.3 ± 15.8% of total lung area), which was significantly larger (P < 0.01) than the proportion of atelectasis found in the two vital capacity groups (5.7 ± 5.7% for the vital capacity group ventilated with 100% oxygen and 2.3 ± 2.1% for the vital capacity group ventilated with 40% oxygen.

Conclusion: In this pig model, postcardiopulmonary bypass atelectasis was effectively prevented by a VCM. (Key words: Gas exchange; lung; measurements techniques; multiple inert gases elimination.)

IT is well known that cardiopulmonary bypass (CPB) impairs postoperative pulmonary gas exchange. A common finding is a postoperative increase in the intrapulmonary shunt to 20–25%. Hachenberg et al. found a shunt of 26% in 11 patients with respiratory dysfunction in the early postoperative period, and this was well correlated with atelectasis on computed tomography scanning. Recently, we have shown in a pig model that CPB generates a larger amount of atelectasis (35% of the total lung area) than a control group without CPB (2%) and that atelectasis is well correlated with PaO₂ and shunt.

Rothen et al. have shown that inflating the lungs to vital capacity (peak airway pressure = 40 cmH₂O) for 15 s reexpanded virtually all atelectatic lung tissue during general anesthesia in patients with healthy lungs. They have also shown that the composition of inspiratory gas plays an important role in the recurrence of collapse after reexpansion. With a moderate concentration of oxygen in nitrogen (inspired oxygen fraction [FiO₂] = 0.4) atelectasis reappeared very slowly. In contrast, when 100% oxygen was used, atelectasis recurred within 5 min.

The purpose of this study was to estimate, in a pig model, if a vital capacity maneuver (VCM) performed...
before termination of CPB could prevent the occurrence of atelectasis as well as the increase in intrapulmonary shunt and hypoxemia commonly seen after cardiac surgery. The aim of the study was also to determine if the VCM had a more long-lasting effect when 40% oxygen in nitrogen was used instead of 100% oxygen.

Materials and Methods

Animals
After approval by the Animal Research Ethical Committee of Uppsala University, 18 pigs (mixed breed of Hampshire, Yorkshire, and Swedish landrace) weighing 27-40 kg were used in the study. The pigs were assigned to one of three groups. In the vital capacity/40% oxygen group (n = 6), the pigs were ventilated before and after bypass with 40% oxygen in nitrogen and a VCM was performed at the end of the CPB. In the vital capacity/100% oxygen group (n = 6), a VCM was done in the same way as in the first group but the pigs were ventilated with 100% oxygen after CPB. In the control group (n = 6), the pigs were ventilated with 40% oxygen before and after bypass, and no VCM was performed.

Vital Capacity Maneuver
The first four vital capacity pigs were also used to determine which peak airway pressure should be applied to obtain the same inflation of the lungs with an open thorax as achieved with a peak airway pressure of 40 cmH2O with a closed chest before sternotomy. For this purpose, the lungs of these four pigs were inflated with 40% oxygen in nitrogen to a peak airway pressure of 40 cmH2O while their thoraxes were still intact. This was thought to correspond to a maximum inflation, and the inflation volume was measured. At the end of CPB, when the thorax was open, the same volume was used to inflate the collapsed lung. A peak airway pressure of 37-42 cmH2O was required in all four pigs. For the remaining pigs, the VCM was performed at the end of CPB by inflating the lungs to 40 cmH2O and holding this pressure for 15 s. With this technique, the mean volume used for the hyperinflation was 45.1 ± 5.9 ml/kg; that is, nearly five times the tidal volume.

The similar airway pressure measured with inflation of a constant volume of gas in closed and open chest conditions, despite the absence of a chest wall elastance with an open chest, probably reflects the decrease in the functional residual capacity and respiratory compliance that might occur during CPB with the airway open to air.

Anesthesia
Before the transport from the farm, the pigs were sedated with a neuroleptic (40 mg azaperone [Stresnil]; Janssen, Beerse, Belgium) given intramuscularly. Induction was done with 0.04 mg/kg atropine given intramuscularly, 6 mg/kg tiletamine/zolazepam (Zoletil; Reading Laboratories, Carros, France), and 2.2 mg/kg zylazine (Rompun; Bayer AG, Leverkusen, Germany). A cannula was inserted in an ear vein and 5 µg/kg fentanyl was injected. A tracheostomy was performed and a cuffed endotracheal tube (6-mm inner diameter) was inserted. Muscle relaxation was provided with 0.2 mg/kg pancuronium and artificial ventilation was instituted with a Servo ventilator in volume-cycled mode (Servo 900C; Siemens-Elema AB, Solna, Sweden). The tidal volume was 10 ml/kg and the frequency adjusted to maintain an end-tidal carbon dioxide tension between 5.2 and 5.6 kPa (39-42 mmHg) using a Capnomac Ultima analyzer (Datex, Helsinki, Finland). Thereafter the frequency was not changed. The inspiratory time was 25% and the inspiratory pause was 10% of the inspiratory cycle with a positive end-expiratory pressure of 4 cmH2O. The ventilator settings were kept constant throughout the procedure. The FiO2 was 0.4, balance nitrogen. Anesthesia was maintained with a constant infusion of a hypnotic (clomethiazole at 400 mg/h), pancuronium (2 mg/h), and fentanyl (150 µg/h).

Catheterization
A catheter (18 gauge) was inserted in the carotid artery via a cut-down for pressure measurements and blood sampling. A fiberoptic catheter (Pulsioath 4F FT PV 2024; Pulsion Medical System, Munich, Germany) was inserted in the same artery and advanced into the aorta for lung water measurements. A Swan-Ganz thermodilution catheter was introduced in the external jugular vein via the same incision.

Cardiopulmonary Bypass
A median sternotomy was performed and the pericardium opened. Heparin sodium (porcine type; 400 IU/kg) was administered and the activated clotting time was kept above 400 s (Hemochron 400; International Technidyne Corp., Edison, NJ). A single 28-French venous return cannula was inserted through the right atrial appendage and a 16-French cannula was inserted into the ascending aorta. The extracorporeal circuit consisted of a membrane oxygenator (Univox Membrane Oxygenation Module, Bentley; Baxter, Irvine, CA), a cardiomyotomy reservoir with filter (BCR-2500, Bent-
ley; Baxter), and polyvinyl chloride tubing. Ringer’s acetate solution (600 ml) and mannitol 15% (200 ml) were used to prime the circuit. Perfusion was conducted using a nonpulsatile pump (type PMO 10–220; Gambro, Lund, Sweden). After the beginning of the CPB, ventilation was stopped, the respirator disconnected, and the airway opened to the atmosphere. The aorta was clamped and cardioplegic solution (St. Thomas type I) with procaine (0.27 mg/l) was injected in the root of the aorta until cardiac arrest. A minimum of 15 ml/kg was always given and it was repeated every time cardiac activity was restarted (total, 19.2 ± 2.8 ml/kg). Hypothermia to 30°C was induced.

If the mean arterial pressure during CPB (49.2 ± 5.3 mmHg) decreased to less than 40 mmHg for a period longer than 5 min, a bolus of 50 μg epinephrine was given (this was only necessary in four pigs). The pump flow rate (56 ± 9.4 ml·kg⁻¹·min⁻¹) was limited by the venous return. To limit the hemodilution, no further crystalloid or allogenic blood were given.

A second dose (100 ml) of the cardioplegic solution was given 10 min before the aortic clamp was released (total duration of the cardiac ischemia, 45 min). Rewarming was then initiated. Cardiopulmonary bypass lasted 90 min. Fifteen minutes before termination of bypass, ventilation was reinstalled at one half the tidal volume. Just before termination of the bypass, the VCM was done for the two vital capacity groups. The lungs were then ventilated as before bypass, and the control group and vital capacity/100% O₂ group had their FiO₂ maintained at 0.4 and the vital capacity/100% O₂ group had an FiO₂ of 1.0. At the end of the bypass, all the pump prime was returned to the animals through the aortic cannula. The heparin effect was reversed with protamine (1 mg for each 100 IU used).

Measurements and Study Protocol

Baseline and Postbypass Measurements. A delay of 30 min was allowed after the surgical preparation before baseline measurements were made.

The infusion of inert gases was restarted after the end of the bypass; because of the time necessary to obtain a new steady state, the postbypass measurements of circulatory and ventilatory variables were not taken until 45 min after the bypass. During this waiting time, the CPB cannulas were removed and the chest closed.

Parameters measured included arterial and mixed venous blood gases (ABL 300 and OSM 3 Hemoximeter; Radiometer, Copenhagen, Denmark), heart rate, systemic and pulmonary arterial pressures (Tran series 7010 monitor; Marquette Electronics Inc., Milwaukee, WI), cardiac output measured by thermodilution, extravascular lung water and intrathoracic blood volume measured with the double-indicator dilution method, respiratory mechanics, and ventilation–perfusion relations.

Measurements of Thoracic Intra- and Extravascular Fluid Volumes. The same indicator bolus was used to determine cardiac output and lung fluid volumes and consisted of indocyanine green (an intravascular marker) mixed in 5 ml ice-cold 5% glucose (a thermal intra- and extravascular indicator). The bolus was injected in the right atrium. The dilution curves for dye and temperature were recorded simultaneously in the aorta with the thermistor-tipped fiberoptic catheter. A lung water computer (Pulsion COL1 Z021; Pulsion Medical Systems, Münchén, Germany) determined the mean transit time for the thermal indicator and for the dye indicator and calculated cardiac output, total thermal volume, intrathoracic blood volume, and extravascular lung water. All measurements were made in triplicate, and the mean was calculated and used for statistical evaluation (for further details, see Hachenberg et al.⁶)

Ventilatory Parameters. Compliance and resistance of the total respiratory system were measured using the technique of rapid airway occlusion during constant-flow inflation.¹⁰ Resistance was calculated as the difference between peak airway pressure and the pressure after 2 s of end-inspiratory pause, divided by the flow.¹¹ Compliance was calculated as V, divided by the end-inspiratory pressure minus the end-expiratory pressure. Pressure and flow were measured in the ventilator on the inspiratory side and fed into a computer for on-line signal processing (Lab-VIEW 3.1 software; C-O Sjöberg Engineering, National Instruments, Austin, TX). Gas compression in the ventilator tubings was corrected for when gas volume and flow were calculated. The mean value of two “inspiratory hold” maneuvers was used for statistical analysis.

Measurements of Ventilation–Perfusion Distribution. The multiple inert gas elimination technique is based on the steady-state elimination (obtained after a 40-min equilibration period) of six inert gases with different solubility in the blood (sulfur hexafluoride, ethane, cyclopropane, enflurane, dichlorylther, and acetone), as described by Wagner et al.¹²-¹⁴ This mixture is dissolved in isotonic saline and infused at a constant rate (2-3 ml/min, depending on the minute ventilation) in a peripheral vein. After 40 min of infusion, under steady-state conditions, arterial and mixed venous blood was collected together with an expired gas sample and analyzed by gas chromatography (model 5690, series II, Hewlett-Packard, Little

Anesthesiology, V 88, No 1, Jan 1998
PREVENTION OF POST-CARDIOPULMONARY BYPASS ATELECTASIS

Table 1. Ventilatory Parameters (Six Pigs in Each Group)

<table>
<thead>
<tr>
<th></th>
<th>Control</th>
<th>Vital Capacity/40% O₂</th>
<th>Vital Capacity/100% O₂</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Baseline</td>
<td>Post-CPB</td>
<td>Baseline</td>
</tr>
<tr>
<td>Tidal volume (ml/kg)</td>
<td>10.1 ± 0.6</td>
<td>10.3 ± 0.4</td>
<td>10.0 ± 0.2</td>
</tr>
<tr>
<td>Minute volume (ml⁻¹·kg⁻¹·min⁻¹)</td>
<td>237.3 ± 31.1</td>
<td>232.3 ± 34.7</td>
<td>238.0 ± 24.4</td>
</tr>
<tr>
<td>Paw (cmH₂O)</td>
<td>20.4 ± 3.9</td>
<td>25.7 ± 4.3*</td>
<td>22.2 ± 3.7</td>
</tr>
<tr>
<td>Pₐaw (cmH₂O)</td>
<td>16.8 ± 4.0</td>
<td>21.4 ± 3.3*</td>
<td>17.6 ± 3.0</td>
</tr>
<tr>
<td>Compliance (ml/cmH₂O)</td>
<td>26.7 ± 5.9</td>
<td>18.5 ± 4.9*</td>
<td>28.4 ± 6.0</td>
</tr>
<tr>
<td>Resistance (cmH₂O⁻¹·s⁻¹)</td>
<td>16.9 ± 1.5</td>
<td>19.9 ± 6.5</td>
<td>14.6 ± 1.8</td>
</tr>
</tbody>
</table>

CPB = cardiopulmonary bypass; Paw = peak airway pressure; Pₐaw = end-inspiratory pressure.
* P < 0.01 versus baseline.
† P < 0.05 versus baseline.

Falls, DE). These data enable the construction of a virtually continuous distribution of blood flow or ventilation against ventilation-perfusion ratios (Vₐ/Q), with separation of shunt (Vₐ/Q < 0.005) from regions with low Vₐ/Q ratios (0.005 < Vₐ/Q < 0.1 = poorly ventilated lung units in relation to their perfusion) as well as the calculation of a normal Vₐ/Q region, units with high Vₐ/Q ratios (10 < Vₐ/Q < 100), and dead space (Vₐ/Q > 100). The dispersion of (Vₐ/Q) ratios is expressed as the logarithmic standard deviation of perfusion distribution. It describes the degree of Vₐ/Q mismatch.

Computed Tomography. At the end of the study, the pigs were moved to the computed tomography scan laboratory (Somaton Plus 4; Siemens, München, Germany). At approximately 1 h after the end of the bypass, an anteroposterior topogram covering the chest was obtained at end-expiration to define the limits of the lungs. One computed tomography scan was performed at end-expiration, 0–1 cm above the diaphragm (146 mA, 140 kV; slice thickness, 5 mm). The scans were analyzed for distribution of lung tissue density, and the total lung area was delineated manually. Nonaerated (atelectatic) lung tissues were defined as regions with attenuation values between −100 and +100 Hounsfield Units (HU), and poorly aerated lung tissues were defined as regions presenting values between −500 and −100 HU. The extent of atelectasis and poorly aerated lung tissue was expressed as a percentage of the total lung area (excluding the mediastinum).

At the end of the experiment, the animals were killed.

Table 2. Hemodynamic and Lung Water Parameters (Six Pigs in Each Group)

<table>
<thead>
<tr>
<th></th>
<th>Control</th>
<th>Vital Capacity/40% O₂</th>
<th>Vital Capacity/100% O₂</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Baseline</td>
<td>Post-CPB</td>
<td>Baseline</td>
</tr>
<tr>
<td>Heart rate (beats/min)</td>
<td>107.8 ± 11.1</td>
<td>119.8 ± 21.6</td>
<td>98.2 ± 9.1</td>
</tr>
<tr>
<td>MAP (mmHg)</td>
<td>83.0 ± 7.6</td>
<td>59.3 ± 11.5*</td>
<td>75.7 ± 2.3</td>
</tr>
<tr>
<td>MPAP (mmHg)</td>
<td>16.2 ± 3.3</td>
<td>22.5 ± 3.7*</td>
<td>16.3 ± 2.5</td>
</tr>
<tr>
<td>CVP (mmHg)</td>
<td>3.5 ± 1.8</td>
<td>4.8 ± 1.3</td>
<td>5.3 ± 0.8</td>
</tr>
<tr>
<td>PCWP (mmHg)</td>
<td>5.2 ± 1.7</td>
<td>5.7 ± 1.2</td>
<td>7.2 ± 1.3</td>
</tr>
<tr>
<td>CO (ml/min)</td>
<td>4.3 ± 0.7</td>
<td>3.8 ± 0.9</td>
<td>3.7 ± 0.6</td>
</tr>
<tr>
<td>EVLWl (ml/kg)</td>
<td>5.1 ± 0.9</td>
<td>6.6 ± 5.0</td>
<td>4.7 ± 1.1</td>
</tr>
<tr>
<td>ITBVI (ml/kg)</td>
<td>20.8 ± 2.3</td>
<td>17.8 ± 5.3</td>
<td>18.0 ± 1.3</td>
</tr>
</tbody>
</table>

CPB = cardiopulmonary bypass; MAP = mean arterial pressure; MPAP = mean pulmonary arterial pressure; CVP = central venous pressure; PCWP = pulmonary capillary wedge pressure; CO = cardiac output; EVLWl = extravascular lung water indexed for the weight; ITBVI = intrathoracic blood volume indexed for the weight.
* P < 0.001 versus baseline.
† P < 0.01 versus baseline.
‡ P < 0.05 versus baseline.
§ P < 0.05 versus control group.

Anesthesiology, V 88, No 1, Jan 1998
Table 3. Ventilation–Perfusion Relationship, Gas Exchange, and Acid–Base Status Parameters (Six Pigs in Each Group)

<table>
<thead>
<tr>
<th></th>
<th>Control</th>
<th>Vital Capacity/40% O₂</th>
<th>Vital Capacity/100% O₂</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Baseline Post-CPB</td>
<td>Baseline Post-CPB</td>
<td>Baseline Post-CPB</td>
</tr>
<tr>
<td>Shunt (%)</td>
<td>4.9 ± 4.0</td>
<td>20.8 ± 11.7*</td>
<td>3.3 ± 2.1</td>
</tr>
<tr>
<td>Log SDo</td>
<td>0.60 ± 0.10</td>
<td>0.66 ± 0.12</td>
<td>0.61 ± 0.13</td>
</tr>
<tr>
<td>PaO₂/FI O₂ (mmHg)</td>
<td>433.2 ± 67.4</td>
<td>267.5 ± 100.5*</td>
<td>471.0 ± 67.6</td>
</tr>
<tr>
<td>PaCO₂ (mmHg)</td>
<td>43.5 ± 3.5</td>
<td>51.9 ± 8.0†</td>
<td>42.3 ± 3.4</td>
</tr>
<tr>
<td>Atelectasis (%)</td>
<td>21.3 ± 15.8</td>
<td>21.3 ± 15.8</td>
<td>2.3 ± 2.1§</td>
</tr>
<tr>
<td>Poorly aerated (%)</td>
<td>31.8 ± 6.4</td>
<td>31.8 ± 6.4</td>
<td>21.0 ± 7.6†</td>
</tr>
<tr>
<td>Base excess (mM)</td>
<td>5.8 ± 1.0</td>
<td>-4.9 ± 4.3†</td>
<td>6.5 ± 3.4</td>
</tr>
<tr>
<td>pH</td>
<td>7.45 ± 0.05</td>
<td>7.24 ± 0.08‡</td>
<td>7.47 ± 0.05</td>
</tr>
</tbody>
</table>

CBP = cardiopulmonary bypass; shunt = intrapulmonary shunt as measured with the inert gases technique; Log SDo = logarithmic standard deviation of perfusion distribution; Atelectasis, Poorly aerated lung tissues = measured with CT scanning and calculated in % of the total lung area.

* P < 0.05 versus baseline.
† P < 0.01 versus baseline.
‡ P < 0.001 versus baseline.
§ P < 0.01 versus control group.
¶ P < 0.05 versus control group.
** P < 0.001 versus control group.

Statistics

Data in the text, tables, and figures are presented as means ± SD. Analysis of variance with the Bonferroni/Dunn post hoc test was used for baseline comparisons of normally distributed parameters, and the remaining parameters (mean arterial pressure, pulmonary capillary wedge pressure, and the hematocrit concentration) were compared using the Mann-Whitney U test. For the comparison of the three groups, analysis of variance for repeated measurements was used. Probability values < 0.05 were considered significant.

Results

Baseline

The pigs were of the same size in all groups (vital capacity/40% O₂ group: 33.2 kg ± 3.9; vital capacity/100% O₂ group: 30.2 kg ± 2.1; control group: 30.8 kg ± 2.4). There were no significant pre-bypass differences between the three groups in any measured variable (see tables 1-3).

After Cardiopulmonary Bypass

Ventilation and Respiratory Mechanics. Small increases in airway pressures were seen in all groups after CPB. These changes were only significant in the control and vital capacity/40% O₂ groups. In the control group, a significant increase was also seen in compliance (table 1).

Hemodynamics and Lung Fluids. There were no significant changes after CPB in heart rate or cardiac output compared with baseline (table 2). In all groups the mean systemic arterial pressure decreased and the mean pulmonary arterial pressure increased. The central venous pressure tended to increase in all groups, but this was only significant in the vital capacity/40% O₂ group.

No changes in the extravascular lung water were seen in any group. The intrathoracic blood volume tended to decrease, but this change was significant only in the group ventilated with 100% oxygen (table 2).

Ventilation–Perfusion Relations and Gas Exchange. In the vital capacity/40% O₂ group there were no changes after the CPB, compared with baseline, regarding intrapulmonary shunt, partial pressure of oxygen (PaO₂), or the partial pressure of carbon dioxide (PaCO₂). Shunt increased in the vital capacity/100% O₂ group and even more in the control group (fig. 1). The PaO₂ decreased and PaCO₂ increased in the control group (table 3 and fig. 2). Thus, in the control group, shunt and PaCO₂ were significantly higher while PaO₂ was significantly lower compared with the two vital capacity groups.

There were no “low VA/Q” regions either before or after CPB. The logarithmic standard deviation of perfusion...
distribution tended to increase in all groups, but this was significant only in the vital capacity/40% O₂ group.

After bypass, arterial pH decreased and base excess became more negative in all groups (table 3).

**Atelectasis and Aeration of the Lung.** Little or no atelectasis was seen in the vital capacity/40% O₂ group (mean, 2.3%; fig. 2A). Despite the fact that the proportion of atelectatic area (mean, 5.7%; fig. 2B) in the vital capacity/100% O₂ group was twice as large as in the vital capacity/40% O₂ group, this difference was not statistically significant. The control group showed large atelectasis that accounted for more than 20% of the total lung area (mean, 21.3%; fig. 3C), and the atelectasis was significantly larger than in the two vital capacity groups (table 3). There was also a significant correlation between the magnitude of shunt and the size of the atelectasis when the three groups were pooled (according to the equation, shunt = 6.8 + 0.41 × atelectasis, R = 0.52, P < 0.05; where shunt is expressed as a percentage of cardiac output and atelectasis as a percentage of the total lung area). Areas with poor aeration amounted to approximately 20-30% of the lung area but with large variation within the groups.

**Discussion**

**Effect of the Vital Capacity Maneuver**

Our results show that a VCM is helpful in preventing the impairment in gas exchange that was seen after CPB.
in pigs. Thus the control pigs showed extensive atelectasis after the CPB, accounting for more than 20% of the total lung area (fig. 3C). There was also a marked increase in the intrapulmonary shunt and a decrease in PaO₂. In contrast, the two groups treated before termination of CPB with a VCM showed only minor or moderate atelectasis (table 3, figs. 3A, 3B). When a VCM was performed before termination of bypass and the lungs were ventilated throughout the procedure with 40% oxygen in nitrogen, no abnormal changes in the intrapulmonary shunt or in the PaO₂ could be detected after CPB. These results confirm our previous results that showed that atelectasis is one of the major causes of post-CPB gas exchange impairment. Furthermore, the nearly complete absence of atelectasis and only minor shunt in the vital capacity/40% O₂ group are similar to what we have seen in pigs during anesthesia without any sternotomy or CPB. This suggests that a VCM reverses all adverse effects of sternotomy and CPB. Thus it is likely that the previously seen moderate increase in shunt and gas exchange impairment after sternotomy can be explained by a factor that is opposed by a VCM. This factor could possibly be microatelectasis that is not visible on the computed tomography scan because of partial volume effects and may be located in areas that we have defined to have poor aeration.

Influence of the Inspired Oxygen Fraction
Rothen et al. have shown that after a VCM, in anesthetized healthy humans ventilated with 100% oxygen, atelectasis occurred within 5 min, whereas in patients ventilated with 40% oxygen in nitrogen, a VCM eliminated atelectasis for at least 40 min. The reexpansion of the lungs by one VCM before termination of CPB in the present study was effective and significantly reduced the amount of atelectasis 60 min after CPB in the two treatment groups, especially the one ventilated with FIO₂ 0.4. Our study does not permit us to estimate how long lasting this effect might be. It is possible, perhaps even likely, that recurrence of collapse of the reexpanded atelectatic lung tissue will occur. The vital capacity group ventilated with 100% oxygen showed a significant increase in shunt that is reasonably explained by the appearance of atelectasis (significant correlation between shunt and atelectasis). This is again similar to what has been demonstrated in anesthetized humans ventilated with 100% oxygen after a VCM, although there seems to be quantitative differences that may be related to species differences.

The control group in our previous study was ventilated with 100% oxygen after bypass and showed atelectasis accounting for 52% of the lung area, whereas in this study the control group was ventilated with 40% oxygen after bypass and showed atelectasis accounting for 21% of the lung area. Thus the FIO₂ may have an effect on the atelectasis formation, as shown during routine anesthesia.

Previous Studies
Many efforts have been made to prevent postbypass lung function impairment. In particular, lung management during CPB has been studied for this purpose. Continuous positive airway pressure with varying levels of airway pressure has given different results. Some studies have shown a decrease in lung function with no difference compared with lungs that were left to collapse during CPB.

Anesthesiology, V 88, No 1, Jan 1998
Fig. 3. Thoracic computed tomography scans of one pig of each group (A) VCM 40% pig with 0.7% of atelectasis (percentage of total lung area). (B) VCM 100% pig with 4.2% of atelectasis, and (C) control pig with 27.2% of atelectasis. Ventilation–perfusion data for the same pigs with the inert gas technique are shown in figure 1.

ers have shown better lung function after CPB when continuous positive airway pressure was used, but the improvement had disappeared 5 h after CPB. Only Boldt et al. concluded that moderate continuous positive airway pressure seemed to optimize postbypass pulmonary function. Maintaining standard ventilation has also been studied with varying results: no difference with the preoperative values, decrease in the lung function identical to the decrease found if the lungs were left to collapse, or even with worse results when compared with no ventilation.

These conflicting results may be due to varying study protocols, the use of different species, different CPB techniques, different gas mixtures (air, pure oxygen, helium), different respiratory rates when the lungs were ventilated, and different PEEP levels. The length of bypass has also varied and there may have been different fluid balance regimens. Finally, the methods for assessing pulmonary function have also varied among studies (Paw, shunt, Pc–A–O2, extravascular lung water, compliance) as have the postoperative period until measurements were made.

Fluid Balance and Lung Tissue Edema
We used a large amount of mannitol (approximately 1 g/kg) in the priming fluid of the heart-lung machine.
to increase the oncotic pressure and to force the diuresis. This could explain why we observed no increase in extravascular lung water after CPB. Similarly, to counteract hemodilution and avoid blood transfusion, we decided to limit as much as possible the priming volume and not to add Ringer’s solution during CPB. This may explain why the blood flow during CPB was low and why the pigs were acidic at the end of CPB. Acidosis may have some deleterious effect on post-CPB myocardial function, but we found no difference in the cardiac output between the groups.

Conclusions

In a pig model, a VCM before termination of CPB, followed by ventilation with 40% oxygen in nitrogen, nearly completely eliminated atelectasis, reduced intrapulmonary shunt, and improved \( P_{\text{aO}_2} \) compared with a control group. Ventilation with 100% oxygen after bypass tended to cause larger atelectasis and significantly increased shunt at the recording, 60 min after bypass. Before extrapolating these findings to humans, however, they should be tested in patients having cardiac surgery.

References


