Alveolar recruitment strategy improves arterial oxygenation after cardiopulmonary bypass

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Summary
Atelectasis occurs during general anaesthesia. This is partly responsible for the impairment of gas exchange that occurs peri-operatively. During cardiopulmonary bypass, this atelectasis is exacerbated by the physical collapse of the lungs. As a result, poor arterial oxygenation is often seen postoperatively. We tested the effect of an ‘alveolar recruitment strategy’ on arterial oxygenation in a prospective randomised study of 78 patients undergoing cardiopulmonary bypass. Patients were divided equally into three groups of 26. Group ‘no PEEP’ received a standard post bypass manual lung inflation, and no positive end-expiratory pressure was applied until arrival at intensive care unit. Group ‘5 PEEP’ received a standard post bypass manual inflation, and then 5 cmH2O of positive end-expiratory pressure was applied and maintained until extubation on intensive care. The third group, ‘recruitment group’, received a pressure-controlled stepwise increase in positive end-expiratory pressure up to 15 cmH2O and tidal volumes of up to 18 ml.kg⁻¹ until a peak inspiratory pressure of 40 cmH2O was reached. This was maintained for 10 cycles; the positive end-expiratory pressure of 5 cmH2O was maintained until extubation on intensive care. There was a significantly better oxygenation in the recruitment group at 30 min and 1 h post bypass when compared with the no PEEP and 5 PEEP groups. There was no significant difference in any of the groups beyond 1 h. Application of 5 cmH2O positive end-expiratory pressure alone had no significant effect on oxygenation. No complications due to the alveolar recruitment manoeuvre occurred. We conclude that the application of an alveolar recruitment strategy improves arterial oxygenation after cardiopulmonary bypass surgery.

Keywords  Atelectasis: cardiopulmonary bypass, lung recruitment.

Impaired gas exchange is a major complication after cardiac surgery involving the use of cardiopulmonary bypass [1]. The cause for this impairment is multifactorial. Alveolar inflammation due to cardiopulmonary bypass has been regarded as a principle cause; however, in 1979, Gale et al. [2] suggested that the most frequent complication was atelectasis. Cox et al. [3] showed that there is a similar degree of pulmonary dysfunction occurring with or without cardiopulmonary bypass, and concluded that the deterioration in gas exchange associated with cardiac surgery is not due to the use of cardiopulmonary bypass. Atelectasis occurs in all surgery involving the use of general anaesthesia, and is not limited to cardiac surgery. In 1992, Lindberg et al. [4] found an incidence of 90% of patients developing atelectasis during anaesthesia. He also showed that the resulting impairment of gas exchange and reduced $P_{a}$O₂ in the postoperative period correlated to the atelectasis formation.
In 1999, Tusman et al. [5] demonstrated that an ‘alveolar recruitment strategy’ improves arterial oxygenation during general surgery. The study concluded that the application of this strategy reversed anaesthesia-induced atelectasis and the ventilation/perfusion heterogeneity. Alveolar recruitment is not new. Lachmann et al. [6] suggested that atelectatic lungs could be re-opened using a combination of high inspiratory pressures to open them, and then sufficient positive end expiratory pressure (PEEP) to keep them open.

Tusman’s study population included patients considered to be at ‘low risk’ for the development of atelectasis, i.e. no upper gastrointestinal or thoracic surgery. Cardiac surgery using cardiopulmonary bypass involves the complete collapse of both lungs whilst on bypass. Prior to separation from the bypass circuit, the lungs are re-expanded. There is no standard technique for this re-expansion, and the application of PEEP afterwards is not standard practice.

We studied the effect of application of PEEP as an ‘alveolar recruitment strategy’ on our population, which would be considered at ‘high risk’ of developing atelectasis. Our primary objective was to show that by application of this alveolar recruitment strategy we might improve the arterial oxygenation following cardiopulmonary bypass. Secondary objectives were to observe whether this strategy altered the length of stay on cardiac intensive care, and whether the incidence of postoperative chest infections decreased. Also, any haemodynamic consequences of this manoeuvre and any other complications were noted.

Method

The study was approved by the local ethics committee, and was conducted at the Yorkshire Heart Centre in Leeds, UK. Written informed consent was obtained from each patient. To determine the patient numbers required in the study, we performed a power calculation based on results from a previous study [5]. The sample size calculation was based on a statistical power of 80% and a significance level of 5%. In the original study, oxygenation remained at baseline or decreased in all control subjects, whereas the response was 30% in the treatment arm of the study. We performed the power calculations based on zero improvement in the treatment arm and a more modest 25% increase in the treatment arm. No patients were withdrawn from the published study as a result of hypotension. The mortality rate for routine cardiac surgery in Leeds is ≈ 1.5%. Therefore, we allowed an extra two patients per group to account for any unexpected withdrawals. On this basis, the sample size in each group was set at 26 patients (total number of 78 patients in the study).

Patients were all older than 50 years, classified ASA II–III and were randomly allocated to one of three groups by opening sealed envelopes. The patient was blinded to which group they were allocated. The three groups were labelled ‘no PEEP’, ‘5 PEEP’ and ‘recruitment group’. All patients were elective admissions for coronary artery bypass grafting and/or uncomplicated aortic valve surgery. Exclusion criteria included any patient with pre-existing lung disease, mitral valve disease, known pulmonary hypertension, chronic renal failure, morbid obesity or emergency surgery. Cardiopulmonary bypass was planned in all patients.

All patients received oxygen via facemask at 4 L.min⁻¹ after premedication until transfer to the anaesthetic room. Induction of anaesthesia varied among anaesthetists and individual patient requirements. Common practices involved high-dose opiates and paralysis. Maintenance of anaesthesia was with propofol infusion. All patients were intubated, and then ventilated with a fractional inspired oxygen concentration (FIO₂) of 0.4, using volume control setting at tidal volumes of 7–9 ml.kg⁻¹ and a ventilatory frequency of 12 breath.min⁻¹. Initially no PEEP was added. The respiratory cycle was divided into 33% inspiration with a constant flow and 67% expiration. All patients had arterial and central venous cannulation performed and arterial blood gases were taken after induction but prior to sternotomy.

The first arterial gas analysis was taken with an FIO₂ of 0.4. Surgery proceeded as routine; the lungs were not ventilated during cardiopulmonary bypass and the tracheal tube was open to air. During bypass, anaesthesia was maintained via a propofol infusion and/or isoflurane via the bypass circuit.

Once the surgeon indicated that it was time to ventilate the lungs, the patients’ management depended on their group allocation. Group ‘no PEEP’ received standard management, which included manual inflation of the lungs with 100% oxygen until the anaesthetist considered the lungs were adequately inflated. The patient was then reconnected to the ventilator as before bypass, with the same respiratory pattern. This was continued until the patient was admitted to intensive care, and then the standard postoperative therapy was started. This included volume-controlled ventilation using a Drager Evita 3 ventilator (Dräger Medical, Telford, PA) with tidal volumes of 7–9 ml.kg⁻¹ and PEEP of 5 cmH₂O. The second group or ‘5 PEEP’, received standard management but at the end of lung inflation 5 cmH₂O of PEEP was added via the ventilator, and continued on intensive care postoperatively until extubation. In the recruitment group, alveolar recruitment was achieved using a similar technique as described by Tusman et al. [6]:
1 The ventilator was changed to pressure control mode and pressure limited to 40 cmH2O.
2 PEEP was increased in steps of 5 cmH2O up to the target PEEP of 15 cmH2O.
3 Whilst PEEP was being increased, the inspiratory pressure was also being increased until either a tidal volume of 18 ml.kg\(^{-1}\) or a peak inspiratory pressure of 40 cmH2O was obtained.
4 Once the PEEP of 15 cmH2O and the required pressure limited tidal volume were reached, these settings were held for a total of 10 breaths at an inspiration/expiration (I:E) ratio of 1:2 and a rate of 12 breath.min\(^{-1}\). \(F_{\text{I}O_2}\) was 1.0.
5 The ventilator was then returned to volume control setting at the prebypass pattern but included 5 cmH2O PEEP. This was continued onto intensive care as the ‘5 PEEP’ group. During these manoeuvres the patients were all still on cardiopulmonary bypass.

The surgery was completed and the patients transferred to the intensive care unit, where they were extubated at varying times depending on individual circumstances. Transfer from operating theatre to intensive care used an Oxylog 2000 portable ventilator (Dräger Medical) set at the same tidal volumes as the operating theatre ventilator and, where appropriate to the study protocol, 5 cmH2O PEEP.

Once on the intensive care unit, the patients from all three groups were managed according to the standard postoperative protocols used in this institution. All patients were ventilated with synchronised intermittent mandatory ventilation at rate of 12 breath.min\(^{-1}\). Tidal volumes continued at 7–9 ml.kg\(^{-1}\) depending on \(P_{\text{CO}_2}\) measurements. PEEP of 5 cmH2O was added to all patients. Once the patient was rewarmed adequately, and cardiovascular stability was achieved, sedation was stopped and the patients was allowed to waken. Extubation was performed when the patient was awake and breathing adequately on continuous positive airway pressure (CPAP) of 5 cmH2O and pressure support of 10 cmH2O.

**Monitoring**

Blood samples were obtained from the radial or femoral arterial line. Arterial blood analysis was taken prebypass at 30 min post induction at a set \(F_{\text{I}O_2}\) of 0.4. This repeated at 30 min after bypass. To obtain a comparable oxygenation index between patients receiving different inspired oxygen fractions, the \(P_{\text{I}O_2}/F_{\text{I}O_2}\) ratio was used in comparisons.

Results of \(F_{\text{I}O_2}, P_{\text{I}O_2}, P_{\text{CO}_2}\), respiratory rate, tidal volumes and peak airway pressures were recorded at 1, 2 and 6 h postoperatively on the intensive care unit. The length of time to the nearest hour spent on intensive care was recorded. The length of stay in hospital to the nearest day was recorded. All patients were followed up until discharge from hospital for occurrence of respiratory tract infections or other complications.

**Blood-gas analysis**

Intra-operative samples were analysed using a Ciba-Corning 288 blood gas system (Bayer Diagnostics, Newbury, UK). Post-operative samples were analysed using a Chiron-Diagnostics 865 blood gas analyser (Bayer Diagnostics). Samples were processed within 5 min and were not corrected for body temperature.

**Statistical analysis**

Values are expressed as means and standard deviations. Ratios of \(P_{\text{I}O_2}/F_{\text{I}O_2}\) were calculated for all data, and the differences between pre- and post-recruitment ratios at 30 min, 1, 2 and 6 h were analysed using analysis of variance (ANOVA). Normality of these differences was confirmed using Kolmogorov–Smirnov tests. Age, sex, height, weight and body mass index (BMI) data were analysed using ANOVA. Where there are significant differences between the groups as found by the ANOVA, a multiple \(t\)-test with downward adjustment of the \(p\)-value was performed (Bonferroni test).

**Results**

**Patient characteristics**

Between February 2000 and February 2001, 80 patients were allocated randomly to one of three groups. Demographic data are presented in Table 1. One patient in the 5 PEEP group was not studied because a cervical epidural was sited and it was felt that this may influence the postoperative results. A second asymptomatic patient in the recruitment group was not studied because on sternotomy the surgeons noted large emphysematous bullae. All other patients completed the study and were followed until discharge. There were no significant differences in age, sex, height, weight and BMI. All recruitment manoeuvres were performed just before separating from the bypass circuit, and thus no cardiovascular changes were noted that would have required

<table>
<thead>
<tr>
<th>Group n</th>
<th>No PEEP 26</th>
<th>5 PEEP 26</th>
<th>Recruitment 26</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age; years</td>
<td>65 (8)</td>
<td>63 (7)</td>
<td>60 (8)</td>
</tr>
<tr>
<td>[49–78]</td>
<td>[52–78]</td>
<td>[41–74]</td>
<td></td>
</tr>
<tr>
<td>BMI; kg.m(^{-2})</td>
<td>26.9 (5.5)</td>
<td>27.9 (4.1)</td>
<td>26.8 (3.6)</td>
</tr>
<tr>
<td>[20.3–33.6]</td>
<td>[19.1–38.2]</td>
<td>[20.2–33.9]</td>
<td></td>
</tr>
<tr>
<td>Gender (F/M); n</td>
<td>6/20</td>
<td>5/21</td>
<td>9/17</td>
</tr>
</tbody>
</table>

Table 1 Demographic data presented as means (SD) [ranges]. Body mass index (BMI) = weight/(height)\(^2\).
stopping the manoeuvre. Table 2 shows the mean difference in oxygenation compared with baseline oxygenation for the three groups at 30 min, 1, 2 and 6 h.

In both the no PEEP and 5 PEEP groups there was a decrease in the arterial oxygenation index at 30 min after bypass (mean decrease of 15.5 and 15.0 kPa, respectively); however, in the recruitment group there was an increase in oxygenation compared to baseline at 30 min (mean increase of 1.9 kPa) (Fig. 1). Table 3 shows the inferential statistical differences among the groups. The difference between the recruitment group and the other two groups was significant at 30 min (p < 0.001). At 1 h after bypass the difference was less marked but still significant for the no PEEP group comparison (p = 0.002) and for the 5 PEEP group (p = 0.04) (Fig. 2). No significant difference was found between the two control groups (no PEEP and 5 PEEP). At 2 and 6 h post bypass there was no significant difference between the three groups (Figs 3 and 4).

**Monitoring**
Heart rate, systolic and diastolic arterial pressures, end-tidal carbon dioxide concentration and oxygen saturations were within the normal range during the study. No complications as a result of the recruitment manoeuvre occurred in any patient.

**Discussion**
Atelectasis occurs during general anaesthesia [7–12] and has been demonstrated using computerised tomography scanning as well as multiple inert gas elimination techniques [13]. Clarke et al. [14] tried several methods to reverse peri-operative atelectasis in non-cardiac patients, and although they showed that intra-operative reversal of pulmonary dysfunction could be achieved, no method had any effect on postoperative pulmonary function. A previous study by Marvel et al. [15] showed that application of PEEP would improve intra-operative pulmonary dysfunction; however, once discontinued,

<table>
<thead>
<tr>
<th>Group</th>
<th>No PEEP</th>
<th>5 PEEP</th>
<th>Recruitment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxygenation index difference 30 min; kPa</td>
<td>15.4 (17.5)</td>
<td>15.0 (13.2)</td>
<td>−1.9 (16.8)</td>
</tr>
<tr>
<td>Oxygenation index difference 1 h; kPa</td>
<td>20.6 (15.7)</td>
<td>16.2 (13.1)</td>
<td>5.9 (15.3)</td>
</tr>
<tr>
<td>Oxygenation index difference 2 h; kPa</td>
<td>18.2 (15.4)</td>
<td>13.6 (13.0)</td>
<td>9.1 (16.2)</td>
</tr>
<tr>
<td>Oxygenation index difference 6 h; kPa</td>
<td>18.1 (13.2)</td>
<td>13.1 (14.6)</td>
<td>9.9 (15.7)</td>
</tr>
</tbody>
</table>

**Table 3 Inferential statistics.**

<table>
<thead>
<tr>
<th>Dependant variable</th>
<th>A</th>
<th>B</th>
<th>Mean difference (A – B)</th>
<th>Standard error</th>
<th>Significance (p-value)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pao2/Fio2 30 min difference</td>
<td>No PEEP</td>
<td>5 PEEP recruitment</td>
<td>0.4</td>
<td>4.4</td>
<td>1.00</td>
</tr>
<tr>
<td>1 h difference</td>
<td>5 PEEP recruitment</td>
<td>17.4*</td>
<td>4.4</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>2 h difference</td>
<td>No PEEP</td>
<td>5 PEEP recruitment</td>
<td>4.4</td>
<td>4.1</td>
<td>0.84</td>
</tr>
<tr>
<td>6 h difference</td>
<td>5 PEEP recruitment</td>
<td>4.6</td>
<td>4.1</td>
<td>0.80</td>
<td></td>
</tr>
</tbody>
</table>

*Significant difference using Bonferroni adjustment.*
there was no sustained beneficial effect upon oxygen transfer or radiological evidence of atelectasis following coronary artery bypass grafting. Rothen et al. [7–10] conducted further studies of alveolar recruitment and showed that the atelectasis, as found during general anaesthesia in patients with healthy lungs, may be expanded by deep inflations. They were also able to demonstrate that most of the re-expanded lung tissue remained inflated for at least 40 min after the recruitment manoeuvre. Tusman et al. [5] showed significant improvement in oxygenation up to 40 min after the manoeuvre and a trend towards improvement for up to 2 h. This increase in arterial oxygenation after the recruitment manoeuvre suggested a reversal of the anaesthesia-induced atelectasis and the ventilation/perfusion mismatch. These authors appear to be the first to apply an active re-expansion manoeuvre combined with stabilisation of the newly recruited alveoli by PEEP. They concluded that ventilation by a pressure-limited mode might have opened alveoli more effectively and that the improvement in oxygenation could have been greater if the recruitment pressure had been > 40 cmH₂O as suggested by Rothen et al. [7]. For this reason we decided to use pressure-controlled ventilation for the recruitment manoeuvre.

The development of atelectasis is proposed as the major contributing factor in the development of impaired gas exchange following cardiopulmonary bypass. Hatchenberg et al. [1] utilised multiple inert gas techniques with recordings of haemodynamics to analyse the separate effects of intrapulmonary shunt and ventilation–perfusion mismatch. Intrapulmonary shunt, probably as a result of atelectasis, is the major component of impaired gas exchange during and after cardiac surgery. This study also suggested that after cardiopulmonary bypass, extravascular lung water increases and/or further collapse of lung tissue might aggravate this shunt. Certainly, studies using radiology to determine the possible aetiology of postoperative respiratory complications, have shown that atelectasis is the most frequent pulmonary complication, occurring in 64% of patients after cardiac surgery with cardiopulmonary bypass [2]. It has been established from previous studies, that patients undergoing cardiopulmonary bypass have a marked deterioration in oxygenation postoperatively [1–3, 16]. Cox et al. [3] randomly allocated patients to undergo coronary revascularisation with or without normothermic cardiopulmonary bypass and showed that there were no significant differences between the two groups of patients in regards to the alveolar–arterial oxygen gradients. They concluded that the deterioration in pulmonary gas exchange associated with cardiac surgery is due to factors other than the use of cardiopulmonary bypass.

Figure 2 Boxplot of the oxygen index differences among groups at 1 h post bypass. The box represents the middle 50% (interquartile range) of the data and the lines extending to either side the extent of the data. The central horizontal line represents the median value.

Figure 3 Boxplot of the oxygen index differences among groups at 2 h post bypass. The box represents the middle 50% (interquartile range) of the data and the lines extending to either side the extent of the data. The central horizontal line represents the median value.

Figure 4 Boxplot representation of the oxygen index differences among groups at 6 h post bypass. The box represents the middle 50% (interquartile range) of the data and the lines extending to either side the extent of the data. The central horizontal line represents the median value.
We have attempted to demonstrate that a manoeuvre similar to that described by Tusman et al. [5] could improve oxygenation postoperatively. We had hoped to show improved oxygenation exceeding the 40 min achieved by Tusman. We have attained significant improvements at 30 min post manoeuvre, and significant improvements at 1 h but were unable to show any improvements after this. Application of our results to clinical practice could suggest that the early deterioration in oxygenation occurring postoperatively is initially reversible. This has several implications. First, we could use this recruitment manoeuvre to improve oxygenation quickly after surgery and allow early extubation. The follow-on effect of early extubation would be reduced intensive care stay, and possibly increased patient throughput.

Second, our study supports previous studies [5, 7, 9, 10]. Oxygenation can only be improved for a limited time after a single recruitment manoeuvre. Repetition of the manoeuvre may allow prolongation of the beneficial effect. Alternatively, preventing recurrence of atelectasis may be achieved in the intensive care unit by using closed suction devices with high-flow ventilator compensation, or changes to nursing practice that would prevent unnecessary disconnections from the continuous PEEP [18–20].

In summary, ‘alveolar recruitment strategy’ is an easy and safe method to reduce the expected early deterioration in arterial oxygenation after surgery utilising cardiopulmonary bypass. This recruitment manoeuvre has no complications in this group of patients. Further studies are needed to determine if the benefit of this recruitment could be further prolonged and able to produce a more lasting clinical benefit.

Acknowledgments

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References