THE ROLE OF AIRWAY CLOSURE IN POSTOPERATIVE HYPOXAEIA

J. I. ALEXANDER, A. A. SPENCE, R. K. PARIKH AND B. STUART

SUMMARY

Lung function studies were made on a total of 173 patients before and after elective surgery. Functional residual capacity was reduced postoperatively and this reduction was most severe in those patients who underwent an upper abdominal operation. In this group, the postoperative reduction in functional residual capacity was related to the concomitant increase in alveolar/arterial Po$_2$ difference. Studies of the distribution of ventilation showed that the alveolar/arterial Po$_2$ difference was related to the amount of closure of small airways. The increase in alveolar/arterial Po$_2$ difference following upper abdominal surgery was associated with an alteration in the relationship of functional residual capacity to the volume at which small airways close.

It is well established that patients undergoing abdominal surgery have arterial hypoxaemia for several days after operation (Knudsen, 1970). This is chiefly the result of misalignment of ventilation and perfusion in the lung but there is uncertainty as to whether it is caused by ventilation/perfusion inequality (George, Hornum and Mellemgaard, 1967), frank shunting past unventilated alveoli (Diamant and Palmer, 1967) or whether both of these lie in a spectrum of postoperative pulmonary disturbance.

A possible cause of maldistribution of ventilation is closure of small airways with gas trapping in dependent lung regions (Milic Emili et al., 1966). The extent of airway closure depends on the magnitude of the transpulmonary pressure. Bromage (1967) found that this pressure is raised in the presence of abdominal pain.

Alexander and associates (1972) have shown that the increased alveolar/arterial Po$_2$ difference following abdominal surgery is accompanied by an adverse shift in the relationship of the point of airway closure (CP) to end-tidal position (ETP). It has been postulated (Spence and Alexander, 1971) that, after abdominal surgery, the volume at which small airways close (closing volume (CV)) remains relatively constant and that the change in the relationship of CP to ETP is chiefly the result of a fall in FRC.

The purpose of this study was to investigate:

1. The effect of operation on FRC and the relationship of CV to FRC.
2. The relationship of lung volume changes to changes in arterial Po$_2$.

PATIENTS AND METHODS

Lung function was measured in a total of 173 surgical patients with normal cardiorespiratory function. The nature of the investigation was explained to the patients and consent obtained. Details of the patients are given in table I.

<table>
<thead>
<tr>
<th>Operation</th>
<th>No. of patients</th>
<th>Males</th>
<th>Females</th>
<th>Mean age (±s.e.m.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vagotomy and drainage</td>
<td>91</td>
<td>76</td>
<td>15</td>
<td>41.3 ± 1.2</td>
</tr>
<tr>
<td>Cholecystectomy</td>
<td>26</td>
<td>5</td>
<td>21</td>
<td>47.6 ± 2.5</td>
</tr>
<tr>
<td>Herniorrhaphy</td>
<td>25</td>
<td>24</td>
<td>1</td>
<td>46.0 ± 3.5</td>
</tr>
<tr>
<td>Stripping of varicose veins</td>
<td>21</td>
<td>9</td>
<td>12</td>
<td>42.2 ± 2.1</td>
</tr>
<tr>
<td>Other upper abdominal operations</td>
<td>10</td>
<td>6</td>
<td>4</td>
<td>49.8 ± 3.8</td>
</tr>
<tr>
<td></td>
<td>173</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The following measurements were made: arterial blood gases (Po$_2$, Pco$_2$, pH), lung volumes: FRC and CV, vital capacity (VC) and its subdivisions. The full range of measurements was not conducted in every patient.

As a rule, measurements were made on the day before operation and at 24 hours after operation. In
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patients having upper abdominal surgery, measurements were made on the second and fifth postoperative days also. Occasionally, a patient was unwilling to perform the tests on one day of the study. Values from these patients obtained at other appropriate times have been included in the results section.

Arterial gases.

Blood was taken from the radial artery. \( \text{Po}_2 \) and \( \text{Pco}_2 \) were measured with the appropriate Radiometer electrodes. A factor of 1.065 was applied to the \( \text{Po}_2 \) to correct the error caused by calibrating the electrode with air. This factor had been determined previously from tonometered whole blood. When appropriate, the values were corrected to the patient’s temperature using the Severinghaus slide rule (Severinghaus, 1966).

The alveolar/arterial \( \text{Po}_2 \) difference ((A-a)\( \text{Po}_2 \)diff) was calculated as follows:

\[
(A-a)\text{Po}_2\text{diff} = \text{PAo}_2 - \text{PaO}_2
\]

where

\[
\text{PAo}_2 = \text{P}1_02 - (\text{PaCO}_2/R)
\]

\[
\text{P}1_02 = \text{alveolar Po}_2
\]

\[
\text{PaCO}_2 = \text{arterial Pco}_2
\]

\[
R = \text{respiratory quotient}
\]

The respiratory quotient was assumed to be constant (Ellison et al., 1966) at 0.8. The patients breathed air during these measurements.

In the past, we have found it extremely difficult to achieve a collection of expired gas in the postoperative period without inducing hyperventilation and consequent disturbance of the “steady state”. Ellison and associates (1966) reported that there was no measurable change in R as a result of routine surgery. A similar conclusion could be drawn from the data of Spence and Smith (1971). Therefore, we have assumed that \( R=0.8 \) throughout. Under these circumstances, the more elaborate forms of the alveolar air equation are inappropriate.

Lung volumes.

Tidal and expiratory reserve volumes (ERV) and VC were measured with a Spirostest 1 spirometer. FRC was measured by the closed-circuit nitrogen equilibration technique (Herrald and McMichael, 1939) using a Godardt Nitrograph for measuring the nitrogen concentration in the circuit. Adjustment was made for the elimination of nitrogen from the tissues (Lundin, 1953) into the lungs. Total lung capacity (TLC) was calculated:

\[
\text{TLC} = (\text{VC} - \text{ERV}) + \text{FRC}
\]

All volumes were corrected to BTPS.

Airway closure.

CV was measured by the xenon-133 method described by Dollfuss, Milic-Emili and Bates (1967). The patient breathes through a 6-in. lead-shielded cuvette, into which is set a sodium iodide scintillation counter. The distal end of the tube is connected to a bell spirometer with a rotary transducer to allow recording of the bell excursion (volume expired) on the X axis of a Bryans 26000 X-Y recorder. The scintillation counter is connected through a pulse height analyser to an analogue ratemeter. The rate-meter output is taken to the Y input of the recorder. The patient breathes out to residual volume. Two ml (dose approximately 1 mCi) of xenon-133 gas is injected into the lead tube and the patient breathes in to total lung capacity (TLC). A slow expiration to residual volume is plotted on the recorder. Figure 1 shows a typical trace.

The trace can be divided into four phases. The first represents deadspace gas containing little or no xenon. There is a rise (phase II) to the alveolar plateau (phase III) which represents mixed gases from all parts of the lung. When the airways which were closed at the time of xenon distribution close again, their diluting effect is lost, causing a second rise (phase IV). The lung volume at the beginning of phase IV is the closing volume (CV). The precise point of closure is obtained by drawing a free line through the artefacts produced by cardiac oscillation. The “flat” part of phases III and IV are extrapolated to their point of intersection. This point denotes the closing volume. We have tried other methods such as computer assisted mathematical damping of the trace with differentiation of the mean line but the results are no better than from the method described.

At the time of measuring the arterial gases and lung volumes, the patients were semi recumbent in
bed in the laboratory. Lung volumes were measured in every patient but arterial gases were measured only in patients having upper abdominal surgery.

The experimental evaluation of the error in Po and Pco, measurements in this laboratory shows a coefficient of variation of less than 2%. The coefficient of variation for measurements of FRC and CV is less than 5%. However, these estimates are obtained under ideal conditions and we have no means of knowing what additional errors are incurred in comparing lung volumes before and after surgery. Every effort was made to eliminate the more obvious factors such as leaks around nasogastric tubes and variation in position of the subject. We attempted to ensure also that subjects performing the xenon-133 test breathed out at a slow, steady rate. Failure in these areas of the study accounted for most of the results which had to be excluded.

RESULTS

Arterial blood gases.

Table II shows blood-gas measurements from 101 patients before and after upper abdominal surgery. Po, fell from a mean value of 86.3 mm Hg before operation to 69.9 mm Hg on the first day (P<0.001) and 71.0 on the second day (P<0.001) after operation. By the fifth day, the mean value was 82.2 which was still significantly lower than before surgery (P<0.01). Alveolar/arterial Po, difference was significantly raised on the first (P<0.001), second (P<0.001) and fifth (P<0.01) postoperative days. There was no significant change in Pco,

<table>
<thead>
<tr>
<th>Operation</th>
<th>Number of patients</th>
<th>FRC post ×100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vagotomy</td>
<td>91</td>
<td>69.2±3.31</td>
</tr>
<tr>
<td>Cholecystectomy</td>
<td>26</td>
<td>70.5±2.56</td>
</tr>
<tr>
<td>Inguinal herniorrhaphy</td>
<td>25</td>
<td>85.5±2.78</td>
</tr>
<tr>
<td>Stripping varicose veins</td>
<td>21</td>
<td>96.8±3.20</td>
</tr>
</tbody>
</table>

In ninety-one patients undergoing vagotomy, FRC was measured up to the fifth postoperative day. The results are in table IV. Postoperative values are expressed as a percentage of the preoperative value. FRC is significantly reduced on the first (P<0.01) and second (P<0.01) postoperative days but not on the fifth.

Lung volumes.

Table III shows the effect of surgery on the FRC in 163 patients. The FRC at 24 hours after operation is expressed as a percentage of the preoperative value. The results are divided according to operation. The fall in FRC after vagotomy is greater than after herniorrhaphy (P<0.01) or stripping of varicose veins (P<0.01) but not significantly greater than after cholecystectomy. FRC was reduced more after herniorrhaphy than after stripping of varicose veins (P<0.01).

<table>
<thead>
<tr>
<th>Operation</th>
<th>Number of patients</th>
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<tbody>
<tr>
<td>Vagotomy</td>
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</tr>
<tr>
<td>Stripping varicose veins</td>
<td>21</td>
<td>96.8±3.20</td>
</tr>
</tbody>
</table>

Figure 2 shows the change in alveolar/arterial oxy- gen tension difference after upper abdominal surgery plotted against the concomitant percentage reduction in FRC. The correlation is highly significant r=0.503; P<0.001. The regression equation is:

\[ \triangle(A-a)P_{O_2} \text{diff} = 35.7 - 29 \times (\text{FRC postop}/\text{FRC preop}). \]

Some of the patients showed an increase in FRC after operation. This figure represents pooled data up to the fifth postoperative day, and these improvements in lung volumes occurred at that time. The improved FRC was associated with an improvement in alveolar/arterial Po, difference in nearly every case.

Airway closure.

Airway closure was measured in 67 patients before and after upper abdominal operation. CV and its relationship to FRC (FRC–CV) and the changes in
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37

Chang* in A-aDO2

\[ +40 \]

\[ +20 \]

\[ 0 \]

\[ -20 \]

\[ -40 \]

\[ -60 \]

FIG. 2. The change in alveolar/arterial Po2 difference as a result of operation plotted against the concomitant percentage change in FRC. Upper abdominal surgery.

these volumes following operation are recorded in table V.

Figure 3 shows (A-a)Po2.diff plotted against (FRC-CV). The correlation \( r = -0.61 \) is statistically significant \( (P<0.001) \). A positive value of (FRC-CV) indicates that airways close in the expiratory reserve volume. When they close within the tidal volume, or the inspiratory reserve volume, (FRC-CV) has a negative sign. The regression equation is:

\[
(A-a)Po_2\text{diff} = 28.5 - 14.6 \text{ (FRC-CV)}
\]

In figure 4 (A-a)Po2.diff is plotted against CV/FRC:

\[
(A-a)Po_2\text{diff} = 42.5 \text{ (CV/FRC)} - 15.6
\]

The correlation \( r = 0.57 \) is statistically significant \( (P<0.001) \).

In figure 5 (A-a)Po2.diff is plotted against the concomitant value of CV/TLC:

\[
(A-a)Po_2\text{diff} = 58.1 \text{ (CV/TLC)} - 8.1
\]

The correlation \( r = 0.62 \) is statistically significant \( (P<0.001) \). Figures 2-4 show pooled preoperative and postoperative data.

The correlation coefficient for the nett increase in alveolar/arterial Po2 difference after upper abdominal surgery plotted against the nett change in (FRC-CV) is statistically significant \( (r = -0.418; P<0.001) \).

DISCUSSION

The study confirms previous reports of arterial hypoxaemia persisting up to five days after upper abdominal surgery (Knudsen, 1970; Spence and Smith, 1971). We also confirm that there is a fall in FRC following various types of surgery (Beecher, 1933). The extent of the reduction depends on the site of operation, being most severe after upper abdominal surgery and least following surgery on the extremities. The changes after upper abdominal surgery persist for at least five days and parallel the changes in arterial Po2. We have found a significant correlation between the changes in FRC and the changes in alveolar/arterial Po2 difference.

TABLE V. Pre- and postoperative measurements of closing volume (CV) and (FRC-CV) in 67 patients undergoing upper abdominal surgery. Mean values (\( \pm \text{s.e.m.} \)).

<table>
<thead>
<tr>
<th>Preoperative day</th>
<th>Postoperative days</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Number of patients measured</td>
<td>67</td>
</tr>
<tr>
<td>CV (L)</td>
<td>2.97</td>
</tr>
<tr>
<td>( \pm 0.12 )</td>
<td>±0.13</td>
</tr>
<tr>
<td>Reduction in CV (L)</td>
<td>-</td>
</tr>
<tr>
<td>( \pm 0.10 )</td>
<td>±0.10</td>
</tr>
<tr>
<td>FRC-CV (L)</td>
<td>0.38</td>
</tr>
<tr>
<td>( \pm 0.07 )</td>
<td>±0.05</td>
</tr>
<tr>
<td>Change in FRC-CV</td>
<td>-</td>
</tr>
<tr>
<td>(L)</td>
<td>( \pm 0.07 )</td>
</tr>
</tbody>
</table>
Fig. 3. (A-a)PO₂ diff plotted against (FRC-CV).

Fig. 4. (A-a)PO₂ diff plotted against CV/FRC.
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Our results support the view that closure of small airways, with maldistribution of ventilation, is a factor causing intrapulmonary shunting as evidenced by the alveolar/arterial $P_{O_2}$ difference. The relationship of the closing volume to the FRC appears to be important in this connection. We have explored the relationship of the closing volume to total lung capacity in view of the suggested relevance of the vital capacity or "sigh" capacity to postoperative hypoxæmia (Bendixen, Hedley-Whye and Laver, 1963). This relationship does not appear to be more important than that of closing volume to FRC. A significant correlation between the changes in (FRC−CV) and alveolar/arterial $P_{O_2}$ difference as a result of surgery confirms our previous observation (Alexander et al., 1972) that the closing point approaches, or exceeds, the end-tidal position after upper abdominal surgery. However, there is a greater reduction in FRC than in closing volume. Thus, closing volume may be regarded as the more constant of the two volumes.

There are several possible reasons for the reduction in FRC following surgery. These include distension of bowel, distension of the abdominal cavity as a result of pneumoperitoneum, spasm of abdominal muscles as a result of abdominal wound pain, and collapse of lung tissue. We consider collapse of lung tissue to be the least likely since that would produce compensatory distension of the remaining healthy tissue, tending to prevent airway collapse and reduce CV. Thus, one would anticipate a greater reduction in CV than in FRC, which is precisely the opposite of our findings. We regard our measurements as signifying the compression of the lung by external forces which cause a rise in transpulmonary pressure at resting lung volume (end-tidal position or FRC). In that position, the lung volume is smaller than before operation, with a greater degree of narrowing of small airways. This is responsible, in part, for hypoxæmia after abdominal surgery.

We believe that the concept of airway closure helps to reconcile differing explanations on the nature of the increased shunt in the postoperative period (i.e., ventilation/perfusion inequality and frank intrapulmonary shunting). If airways are narrowed or closed in only a part of the respiratory cycle, reduction in the ventilation/perfusion ratio of affected lung regions will result. However, closure of airways throughout all of the respiratory cycle will completely prevent ventilation of the affected alveoli causing a frank shunt. Many patients can be expected to exhibit a spectrum of these changes.

ACKNOWLEDGEMENTS

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REFERENCES


ROLE JOUE PAR L'OCCLUSION DES VOIES RESPIRATOIRES DANS L'HYP oxEMIE POST-OPERATOIRE

SOMMAIRE
Des études de la fonction pulmonaire ont été effectuées sur un total de cent soixante-treize malades, avant et après des interventions chirurgicales électives. La capacité fonctionnelle résiduelle a été réduite après l'intervention et cette réduction a été le plus souvent sévère chez les malades ayant fait l'objet d'une opération au niveau de la partie haute de l'abdomen. Dans cette série, la réduction post-opératoire de la capacité fonctionnelle résiduelle était associée à une augmentation concomitante de la différence Po2 alvéolaire/Po2 artérielle. Des études de la distribution de la ventilation ont montré que la différence Po2 alvéolaire/Po2 artérielle était en rapport avec le degré d'occlusion des voies respiratoires de petit calibre. L'augmentation de la différence Po2 alvéolaire/Po2 artérielle, consécutive à des interventions chirurgicales ayant porté sur la partie haute de l'abdomen, a été associée à une perturbation de la relation existante entre la capacité fonctionnelle résiduelle et le débit d'air pour lequel les voies respiratoires de petit calibre sont en état d'occlusion.

ÜBER DIE BEDEUTUNG DES VERSCHLUSSES DER ATEMWEGE BEI DER POSTOPERATIVEN HYPOXÄMIE

ZUSAMMENFASSUNG

EL PAPEL DEL CIERRE DE LA VIA AEREA EN LA HIPOXEMIA POSTOPERATORIA

RESUMEN
Fueron efectuados estudios de la función pulmonar de ciento setenta y tres pacientes antes y después de operaciones electivas. La capacidad residual funcional estaba reducida postoperatoriamente y esta reducción era más intensa en pacientes sometidos a una operación abdominal superior. La reducción postoperatoria de la capacidad residual funcional en este grupo estaba relacionada con el incremento concomitante de la diferencia de Po2 alveolar-arterial. Estudios de la distribución de la ventilación mostraron que la diferencia de Po2 alveolar-arterial estaba relacionada con la magnitud del cierre de las vías aéreas pequeñas. El incremento de la diferencia de Po2 alveolar-arterial después de operaciones abdominales superiores estaba asociado con una alteración de la relación entre la capacidad residual funcional y el volumen al cual quedan cerradas las vías aéreas pequeñas.