VARIATIONS IN LUNG VOLUME AND COMPLIANCE DURING PULMONARY SURGERY

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Many factors affect pulmonary function during surgery on the lung. The consequences on lung volume, ventilatory mechanics and the distribution of ventilation between the lungs when turning the patient to his side are well documented. Thus, the FRC of the upper lung increases markedly, while that of the dependent lung decreases somewhat. If intermittent positive pressure ventilation is used, the greater fraction of tidal volume is directed to the upper side, the compliance of which is greater than that of the dependent side (Rehder et al., 1972). Less is known about the changes in lung volume which occur during the operative procedure—those brought about by opening the pleura or by one-lung ventilation. As regards postoperative changes, Lambert, Willauer and Dasch (1955) obtained chest x-rays shortly after lung surgery and found marked signs of impaired aeration in the dependent lung, suggesting a reduction in volume. However, to our knowledge, lung volume has not been measured directly at this stage. We measured functional residual capacity (FRC), compliance of the ventilatory system and the distribution of ventilation between the lungs during various phases before, during and after thoracic surgery. Interest was focused primarily on the dependent lung, that is, the lung not undergoing surgery.

PATIENTS AND METHODS

Ten patients undergoing elective pulmonary surgery were studied (table I). Any patient with marked impairment of lung function or cardiac decompensation was not included. Patients gave informed consent and the project was approved by the Local Human Studies Committee. Patients were premedicated with morphine and hyoscine. Anaesthesia was induced with thiopentone. Suxamethonium was given and the trachea was intubated with a Carlens’ double lumen tube (Rüschi), size 39 (n = 6), 37 (n = 3) or 35 (n = 1). During one-lung ventilation (OLV) the lumen of the non-ventilated side was left open to the

SUMMARY

Functional residual capacity (FRC) and breath-by-breath compliance of the ventilatory system (Crs) were measured in 10 mechanically ventilated patients during anaesthesia for lung surgery (pneumonectomy, lobectomy, lung or pleural resections or exploratory thoracotomy). In eight patients not requiring pneumonectomy, FRC of the lower lung decreased by 8 ± 9% (mean ± 1 SD) (P < 0.05) while that of the upper lung increased by 75 ± 24% (P < 0.001) when the patient was turned to the lateral position. When the pleura was opened, FRC of the lower lung decreased by a further 10 ± 10% (P < 0.01). One-lung ventilation (OLV), however, increased FRC of the lower lung back to the value found in the supine position before surgery. When two-lung ventilation was re-established, FRC of the lower lung was about the same as during corresponding stages before OLV. In the two patients who underwent pneumonectomy, FRC of the remaining lung was about 30% greater after OLV than at corresponding stages before surgery. In the patients not requiring pneumonectomy, Crs decreased from 29 ± 6 ml/cmH2O to 23 ± 6 ml/cmH2O (P < 0.05) on the lower side when the patient was turned on his side. The corresponding figures on the upper side were 24 ± 8 ml/cmH2O and 30 ± 5 ml/cmH2O respectively (P < 0.05). There was no further significant change when the pleura was opened. After surgery when the patient was turned to the supine position, Crs of the lung not operated on was almost the same as before surgery.
A single dose of alcuronium 10–15 mg was given shortly after tracheal intubation. Anaesthesia was maintained with 50–65% nitrous oxide in oxygen plus intermittent pethidine i.v. The lungs were ventilated by a Servo ventilator 900 C (Siemens–Elema Company). The rate of ventilation was 10–15 b.p.m. and the inspired minute ventilation (ATPD) was 9.0±1.3 litre min⁻¹. This was adjusted at the start of anaesthesia so that end-tidal Pco₂ of the lung not operated on was between 4.0 and 4.5 kPa. Subsequently, it was held constant. However, the rate of ventilation was temporarily increased from 10 to 15 b.p.m. during OLV in three of the patients. Insufflation time was 25–33% and end-inspiratory pause time was 10% of the breathing cycle. A breathing pattern with a constant insufflation flow was used. End-expiratory pressure was zero.

The breathing system is depicted schematically in figure 1. A valve system in the ventilator tubing ensured that expired gas from one lung was directed back to the expiratory port of the ventilator which performed the insufflation. The expired gas from the other lung was directed to the expiratory port of a second Servo ventilator electronically synchronized with the first. Thus, the expired volume from each lung could be measured separately. Since only one ventilator performed the insufflation, the insufflation pressure on both sides was equal. Thus the distribution of the tidal volume between the lungs depended on the resistance and compliance of the two sides. Airway pressure was measured on each side close to the expiratory valve with the standard manometer on the ventilators. Signals representing airway pressure and expired tidal volume were recorded on an ink-jet recorder (Mingograph–81, Siemens–Elema Company). After surgery, there was frequently leakage of gas from the upper lung into the pleural cavity. As a result, the tidal volume of this lung could not be measured directly during these stages. Instead, it was calculated from total inspired tidal volume and measured expired tidal volume of the other lung. Since at least 90 min of anaesthesia had elapsed, we assumed that there was negligible net transport of nitrous oxide into or from the body.

On each side, breath-by-breath compliance of the ventilatory system (Crs) was obtained as

\[ C_{rs} = \frac{\dot{V}t}{P_{pause}} \]

where \( \dot{V}t \) = inspired tidal volume and \( P_{pause} \) = pressure at the end of the end-inspiratory pause. The duration of this zero
Functional residual capacity (FRC) was measured by a multiple breath washout technique using sulphur hexafluoride ($\text{SF}_6$) as tracer gas (Jonmarker, Castor et al., 1985; Jonmarker, Jansson et al., 1985). $\text{SF}_6$ was washed in through a catheter until the alveolar concentration of $\text{SF}_6$ was about 0.5%. This was measured with an $\text{SF}_6$ analyser, the transducer of which was placed over a cuvette in the airway. Signals representing expired flow and $\text{SF}_6$ concentration were fed into a computer (PDP-11, Digital Equipment Corp.) which calculated the FRC. The value was corrected for apparatus deadspace. Duplicate FRC measurements were obtained on each occasion. Figure 1 shows that two $\text{SF}_6$ analysers were used. However, only one was connected to the computer and when it was desired to measure FRC in both lungs, this was done sequentially. The $\text{SF}_6$ analysers had a slightly different design. One was sensitive to carbon dioxide and a $\text{CO}_2$-Analyzer 930 (Siemens-Elema Company) was incorporated to the circuit in order to permit electrical compensation for this. The other $\text{SF}_6$ analyser, a newly delivered prototype, was used only to test the seal between the lungs. This was done by observing the $\text{SF}_6$ signal on one side, while supplying $\text{SF}_6$ to the other side. In addition, the seal was tested by auscultation. As the $\text{SF}_6$ delivery system used at present is able to give only a constant flow of $\text{SF}_6$ during inspiration, it is essential that inspiratory flow is also constant to prevent variations in the inspiratory $\text{SF}_6$ concentration. Although we used a breathing mode with constant insufflation flow the possibility remained that, since the inspiratory gas was distributed freely between the two lungs, flow into each lung could vary during inspiration. To assess this, a flow meter (Siemens-Elema 6395 420) was placed close to the Y-piece on the side on which FRC was measured (fig. 1). Signals from the flow meter were recorded on the Mingograph and the
maximum deviation between instantaneous inspiratory flow velocity and the mean inspiratory flow velocity was calculated from the curve during the various phases. The deviation was 6 ± 6% of mean flow velocity (mean ± 1 SD). This was considered acceptable.

The resistance to flow in the Carlens' tube and its connections up to the Y-piece was tested in vitro. The decrease in pressure over the left lumen at a flow of 0.5 litre s⁻¹ was 1.58, 1.05 and 0.96 kPa for tube sizes 35, 37 and 39, respectively. The corresponding figures for the right lumen were 1.40, 0.98 and 0.94 kPa. The compliance of the whole tubing system was 10.5 ml kPa⁻¹. Apparatus deadspace, including the heat/moisture exchanger, was about 45 ml on each side. The flow meters of the ventilators were calibrated daily with 50% nitrous oxide in oxygen using a wet gas meter (Flonic, Schlumberger). It was confirmed separately that the changes in inspired oxygen concentration that took place during anaesthesia (between 35 and 50%) did not appreciably alter the measurement of volume. The ventilator manometer was calibrated with a mercury manometer. A factor of 1.09 was used to convert expired volume and FRC from ATPS to BTPS.

The measurements were made at seven stages: (1) before surgery, supine position; (2) before surgery, lateral position, 90°; (3) after opening the pleura; (4) during OLV; (5) after OLV, before closing the pleural cavity; (6) after surgery, lateral position; (7) after surgery, supine position.

During stages 1 and 2, FRC and compliance were measured on both sides. During the remaining stages, time permitted FRC measurements only on the dependent side. It would in any case have been difficult to obtain meaningful measurements from the operated lung after OLV because leaks into the pleural cavity were usually present. Surgery was discontinued during the measurements.

Statistics

The two-sided Student's test for paired observations was used. Probability values less than 0.05 were considered to indicate statistical significance.

RESULTS

Morphometric data, preoperative lung function, initial FRC during anaesthesia, diagnoses and extent of surgery are shown in table I. Forced vital capacity was 81 ± 15% of predicted and FEV₁₀ was 80 ± 15% of predicted (Berglund et al., 1963; Birath, Kjellmer and Sandquist, 1963). Consequently, FEV₁₀/FVC was close to the expected value (99 ± 16%). One-lung ventilation was performed in eight of the patients. Surgery lasted 1.9 ± 1.2 h and anaesthesia 4.7 ± 1.2 h. The measurements prolonged anaesthesia by about 1 h.

Patients who did not undergo pneumonectomy (n = 8) (fig. 2)

FRC. In the lung not to be operated on, FRC decreased 8 ± 9% (mean ± 1 SD) (P < 0.05) when the patient was turned from the supine to the lateral position. In the other (upper) lung, FRC increased by 75 ± 24% (P < 0.001). In the dependent lung, FRC decreased further when the pleura was opened, but when OLV was established (n = 6), FRC increased again. At this stage FRC was 3 ± 12% greater (ns) than in the supine position before surgery. When bilateral lung ventilation was re instituted, FRC in the dependent lung decreased to about the same value as before OLV. Likewise, after closing the pleural cavity, the values were similar to those observed before the pleura was opened. In the supine position after surgery, FRC of the lung not operated on was 10 ± 15% greater (ns) than in the supine position before surgery.

Compliance of the ventilatory system (Crs). When the patient's position was changed from supine to lateral, Crs of the dependent side decreased from 29 ± 6 ml/cm H₂O to 23 ± 6 ml/cm H₂O while Crs of the upper side increased from 24 ± 8 ml/cm H₂O to 30 ± 5 ml/cm H₂O. Opening the pleural cavity caused no significant change in Crs of the dependent side, but closing the chest resulted in a significant decrease in Crs to 20 ± 4ml/cm H₂O. When the patient was turned back to the supine position, Crs of the side not operated on increased to 27 ± 6ml/cmH₂O; that is, it was nearly the same as in the supine position before surgery.

Distribution of the tidal volume between the lungs.

The fraction of the tidal volume going to the lower lung decreased from 53 ± 6 to 44 ± 6% when the patient was turned from the supine to the lateral position. No further change appeared when the pleural cavity was opened. After OLV, when the pleural cavity had been closed and the operation was finished, there was a slight increase in the fraction of ventilation to the lower lung. During the final measurement (supine position), the lower lung received 63 ± 11% of the minute ventilation,
PULMONARY FUNCTION DURING LUNG SURGERY

FIG. 2. FRC, compliance of the ventilatory system and fraction of ventilation to the lower lung in patients who did not undergo pneumonectomy. Eight patients, except during OLV (n = 6). Mean values and 1 SEM. *P < 0.05; **P < 0.01; ***P < 0.001. O = Lung operated on; • = other (lower) lung.

which was not significantly different from the value obtained before surgery.

Patients who underwent pneumonectomy (n = 2) (fig. 3)

The findings in respect of FRC and $C_{rs}$ were similar to those in the other patients, except that FRC of the remaining lung was greater after pneumonectomy than at corresponding stages before surgery.

DISCUSSION

The method for measuring FRC was chosen specifically because it is convenient to use in the operating room during nitrous oxide in oxygen anaesthesia. The accuracy and reproducibility of the method have been discussed previously (Jonmarker, Castor et al., 1985; Jonmarker, Jansson et al., 1985).

A limitation of the FRC measuring system currently in use is that it requires a constant insufflation flow. This is because, at present, the system is able to deliver only a constant flow of SF$_6$ through the thin catheter (fig. 1) during insufflation. If inspired flow varies, the SF$_6$ concentration of the inspired gas will also fluctuate and not yield a uniform alveolar concentration of SF$_6$. Fortunately, the inspiratory flow to each lung was almost constant in the present study.
Regional variations in the uptake of nitrous oxide constitute another source of error, since this will cause alveolar SF₆ concentration to be non-uniform, even with constant inspired SF₆ concentration. The problem is probably of minor importance since about 200 ml min⁻¹ of nitrous oxide, that is only 3–4 % of the alveolar minute ventilation, is taken up after 15 min of breathing a 75 % nitrous oxide mixture (Beatty, Kay and Healy, 1984). Longer exposure reduces the uptake but, on the other hand, uptake may possibly have been accentuated by opening of the pleural cavity (Weatherill et al., 1984). One factor which may have limited the impact of nitrous oxide uptake as a source of error is that alveolar concentration of SF₆ at the end of wash-in was obtained as the mean value over a large fraction of the expiration, viz. the final half of the volume (Jonmarker, Jansson et al., 1985). Furthermore, uptake of nitrous oxide ceases when alveolar nitrous oxide tension approaches mixed venous tension. The latter tension increases rapidly after the patient starts to inhale nitrous oxide and this sets a lower limit below which local nitrous oxide tension cannot decrease. This will in turn reduce the scope for variations in alveolar SF₆ concentration. In contrast, mixed venous oxygen tension is always much less than inspired oxygen tension, which should allow for greater regional variation in alveolar oxygen tension. Possibly, therefore, differential oxygen uptake with consequent variation in alveolar SF₆ concentration may have constituted a problem at least as important as nitrous oxide uptake. Differential oxygen uptake is, of course, a general problem which occurs also during oxygen–air breathing and with tracer gases other than SF₆.

When the patient was turned from the supine to the lateral position, FRC, Crs and the fraction of total ventilation decreased slightly on the lower side while, on the upper side, the same indices (particularly FRC) increased (75 ± 24 %). This is in agreement with other studies in mechanically ventilated subjects (Rehder et al., 1972; Baehrendtz and Klingstedt, 1984; Hedenstierna et al., 1984). The probable cause of these changes is that the lower lung is compressed by the weight of the mediastinum and by the elevation of the diaphragm (Froese and Bryan, 1974). In the present study, FRC of the lower lung decreased further when the pleural cavity was opened, presumably because of a shift downwards of the unsupported mediastinum. We did not measure FRC in the upper lung at this stage, but both theory and direct observation in the wound tell us that FRC decreased also in this lung. The decrease in lung volume when the pleura is opened is consistent with the study by Kerr and co-workers (1974) who found an increase in venous admixture at this point. However, both in their study and in a study from our hospital (Werner et al., 1984), the impairment in arterial oxygenation appeared to be clinically unimportant. Zero end-expiratory pressure was used in both these studies, as in the present one.

During OLV, mean FRC of the non-operated lung increased to about the same value as in the supine position before surgery. An explanation for the increase is that the lung did not have enough time to deflate during expiration, despite the fact that it lasted about 3 s. The explanation is supported by the finding of an appreciable airway flow at the end of expiration (12 ± 9 % of early expiratory flow). The high resistance to gas flow in the Carlen's tube and the fact that the whole of the minute volume was directed to the lower lung during OLV probably contributed to the delayed emptying. Many studies (Khanam and Branthwaite, 1973; Aalto-Setälä, Heinonen and Salorinne, 1975; Capan et al., 1980; Katz et al., 1982) have shown that PEEP during OLV has either a harmful or no effect on arterial oxygenation. We suggest that this is because the dependent lung is adequately expanded already without PEEP. Thus, the harmful effects of selective PEEP to the dependent lung—diversion of blood flow from the ventilated lung to the collapsed upper lung—dominate over the beneficial effects.

In the patients undergoing pneumonectomy, FRC of the dependent lung increased markedly after the pneumonectomy. This is partly explained by the same mechanism as outlined above for the FRC increase during OLV. Another factor is that −5 to −8 cm H₂O of pressure was applied to the empty pleural cavity via the pleural drains. This is less than pressures normally prevailing in the pleura at end-expiration during controlled ventilation (about −3 cm H₂O (Nunn, 1977)).

Despite the fact that most of the effect of the single dose of neuromuscular blocking drug (alcuronium) must have worn off, we found that FRC and compliance of the non-operated side had not decreased after surgery in comparison with corresponding measurements made before surgery. This result is consistent with findings by Kerr and colleagues (1974) and by Katz and...
co-workers (1982), neither of whom found any impairment of arterial oxygenation after lung surgery. Superficially, the present finding that FRC of the non-operated lung was maintained after surgery, is contradicted by x-ray studies in which pictures taken in the lateral decubitus position shortly after surgery showed marked changes in the dependent lung. However, both Lambert, Willauer and Dasch (1955) and Potgieter (1959) found that these changes resolved shortly after the patient was placed supine. Craig, Bromley and Williams (1962) found areas of increased opacity in the lung fields in patients undergoing closed mitral commissurotomy, but in only four out of 49 patients who had undergone lung or pleural surgery.

We conclude that FRC and compliance of the non-operated side vary markedly during lung surgery, but that the changes are reversible.

REFERENCES


