DISTRIBUTION OF VENTILATION IN THE SUPINE POSITION

BY

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SUMMARY

The relationship between lung volume and regional distribution of ventilation measured by the single breath oxygen test has been found to be similar in the upright and supine positions. When subjects breathe at progressively smaller lung volumes there is an increase in the slope of the alveolar plateau indicative of a redistribution of ventilation to the uppermost parts of the lung. On assuming the supine position the expiratory reserve volume falls and because of this change in volume there is a similar redistribution of inspired gas away from the well perfused base. The mechanics of these changes are discussed.

Impairment of pulmonary gas exchange is a frequent accompaniment of anaesthesia in the supine position, the underlying cause of this change being poorly understood. Recent studies have revealed a close relationship between pre-inspiratory lung volume and the topographical distribution of inspired gas (Milic-Emili et al., 1966; Dollfuss, Milic-Emili and Bates, 1967), so that gas inspired near residual volume (RV) enters preferentially the upper part of the lung. Nunn and co-workers (1965) have shown that gas exchange is impaired when breathing takes place at very low lung volumes, this effect being more noticeable in older subjects. On assuming the supine position there is a marked fall in expiratory reserve volume (ERV) and this change in volume may be sufficient in some subjects to result in a redistribution of ventilation away from the well perfused dependent parts of the lungs and impair gas exchange efficiency. Change in gas distribution may be inferred from analyses of the pattern of expired nitrogen after either a single breath of oxygen (Fowler, 1949), or after multiple breath nitrogen clearance with oxygen (Robertson, Siri and Jones, 1950). Extensive studies of the effect of posture on the result of the latter test have been reported, with conflicting results. Uneven distribution was found by Bouhuys and Van Lennep (1962), Hanson, Tabakin and Caldwell (1962), and also by Svanberg (1957) using one index of maldistribution (Becklake, 1952), but not with two other forms of analysis of the same data (Robertson, Siri and Jones, 1950; Fowler, Cornish and Kety, 1952). Jones (1967a) and Young, Martin and Hashimoto (1968) were unable to demonstrate a statistically significant change in distribution on the supine position using this test. No matter what mathematical treatment is applied to the data from multiple breath tests they give no information about topographical changes in distribution but are sensitive indices of lung gas mixing efficiency and, while overall mixing efficiency may be unchanged when posture is varied, there may be quite marked changes in regional distribution of inspired gas in relation to perfused lung tissue.

There have been few quantitative studies on the effect of the supine posture on the result of the single breath test. Greve (1960) failed to observe any changes in the appearance of the expired gas trace in the supine, prone, lateral and 30° head-down posture. Newman and Thomson (1960) found no change in the result of the single breath test on changing from the upright to the supine position in the two subjects studied. Young, Martin and Pace (1963) commented only on the similarity in the shape of the trace obtained in various positions. If the concentrations of oxygen, carbon dioxide and nitrogen are measured in single expirates, it can be calculated that the change in expired nitrogen concentration near residual volume coincides with the
emptying of regions with a high ventilation-perfusion ratio (Jones, 1967a, b) and that this is likely to be the uppermost part of the lung, no matter what posture the subject adopts (Clarke, Jones and Glaister, 1969). From this and other recent studies (Milic-Emili et al., 1966; Dollfuss, Milic-Emili and Bates, 1967) it appears that the single breath test affords a simple method of deriving information about topographical changes in ventilation which may be applied to anaesthetized patients. In the upright position the single breath test reveals a marked redistribution of inspired gas towards the uppermost parts of the lung when breathing at low lung volumes (Jones, 1967b). This observation is explained by the effect of gravitational force on the upright lung which is the principal determinant of regional ventilation. If gravity exerts a similar effect on regional ventilation from top to bottom of the supine lung (Kaneko et al., 1966; Clarke, Jones and Glaister, 1969), then the relationship between lung volume and regional distribution measured by the single breath test should be similar in the supine and upright positions. Because of the diminution in ERV on assuming the supine position the distribution of ventilation measured at FRC in this position should be less uniform than that observed at FRC in the upright position.

METHODS

A solenoid-operated valve was constructed to facilitate the introduction of the test breath of oxygen at predetermined lung volumes (Jones, 1967a). The general arrangement of this perspex valve is shown in figure 1. Its action was controlled by activation of a pair of phototransistors attached to a bag in a box spirometer. The volume of oxygen to be inspired (750 ml) was preset and the volume of air that preceded the oxygen could be varied from 500 ml to several litres. The concentration of expired nitrogen was measured with a mass spectrometer (MS4; AEI Ltd, Manchester), the 90 per cent response time being between 40 and 80 m.sec. The expired volume was recorded from a potentiometer attached to the spirometer, both nitrogen concentration and volume signals being registered on an ultraviolet recorder. The result of each test was expressed as nitrogen per cent difference between 750 ml and 1250 ml points in the expired gas volume (Fowler, 1949).

With the subject breathing through the electromagnetic valve but not connected to the spirometer, he was instructed to expire to RV. Then a tap was turned manually connecting the subject to the spirometer circuit. The subject inspired at about 30 l./min, first the preset volume of air, and then 750 ml of oxygen. As soon as the oxygen had been inspired the electromagnetic valve closed and the subject immediately breathed out to RV at the same rate. A series of test breaths were made for different volumes of inspired air from about 500 ml above RV to several litres, the result being discarded if the total expired volume differed from the inspired volume by more than 150 ml. The subjects were first studied sitting in a chair and then lying flat on a tilt table, 3 minutes being allowed between each test breath and 10 minutes lying supine before beginning the study in that position.

The vital capacity and ERV were measured in the upright and supine positions while breathing.
on this circuit and the lung volumes were measured in the upright position by a closed circuit helium dilution method.

RESULTS

The age, height and lung volume of the nine subjects are shown in Table I. The fall in ERV on assuming the supine position is shown. After inspiring 750 ml of oxygen from FRC in the upright position, the expired nitrogen concentration is observed in Figure 2. The change in the slope of the plateau when breathing at low lung volume on assuming the supine position is also shown.

The plot of nitrogen per cent difference against the volume above RV for one subject in the upright and in the supine position is shown in Figure 3. The position of the ERV in each position is shown by the arrow. A similar curvilinear relationship was found in all subjects in both positions. A linear relationship was found in all subjects when nitrogen per cent difference was plotted against the reciprocal of the volume above RV.

There was no significant difference between the results obtained in the upright and supine positions for the pooled data of the group, although there were significant differences between regression lines in AS, NM, JS and SC. The equation for the regression line to each subject together with the significance of the difference is shown in Table II.

The pooled data from all the test breaths were analyzed to determine the statistical relationship between nitrogen concentration difference and the reciprocal of the pre-inspiratory volume above RV in the supine position.

The equation \( N\% = 0.22 + 2.51 \left( \frac{1}{\text{Vol. above RV}} \right) \) was found to fit the data \( (r=0.834, P<0.001) \).

It was observed that all subjects showed an increase in the slope of the nitrogen plateau with diminishing pre-inspiratory lung volume in the supine position.

In five of the subjects studied the slope produced at the normal ERV in the supine position was greater than that produced if the subject first expired to RV before inspiring to the same
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A linear relationship is found between nitrogen concentration difference and the reciprocal of volume above RV. The similarity between the curves in the supine and upright position is seen in most subjects. In some subjects in the supine position the nitrogen difference at the FRC in this position is shown by △.

FIG. 4

To show the correlation between the nitrogen per cent difference and the reciprocal of pre-inspiratory volume above RV in the sitting and supine positions and the significance of the difference between the regression lines in the two positions.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Sitting Correlation coefficient</th>
<th>Regression equation</th>
<th>Supine Correlation coefficient</th>
<th>Regression equation</th>
<th>Significance of difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>AS</td>
<td>0.946</td>
<td>y = 3.89x - 0.67</td>
<td>0.938</td>
<td>y = 2.78x - 0.13</td>
<td>0.01</td>
</tr>
<tr>
<td>GG</td>
<td>0.930</td>
<td>y = 1.87x - 0.48</td>
<td>0.929</td>
<td>y = 2.47x + 0.29</td>
<td>n.s.</td>
</tr>
<tr>
<td>ID</td>
<td>0.977</td>
<td>y = 1.16x + 0.95</td>
<td>0.959</td>
<td>y = 1.66x + 0.88</td>
<td>n.s.</td>
</tr>
<tr>
<td>NM</td>
<td>0.922</td>
<td>y = 1.37x - 0.18</td>
<td>0.854</td>
<td>y = 0.80x + 0.38</td>
<td>0.01</td>
</tr>
<tr>
<td>GJ</td>
<td>0.991</td>
<td>y = 3.77x - 0.32</td>
<td>0.987</td>
<td>y = 4.04x - 0.58</td>
<td>n.s.</td>
</tr>
<tr>
<td>JS</td>
<td>0.953</td>
<td>y = 2.87x + 0.50</td>
<td>0.988</td>
<td>y = 3.79x + 0.92</td>
<td>0.001</td>
</tr>
<tr>
<td>MM</td>
<td>0.904</td>
<td>y = 2.07x + 0.37</td>
<td>0.984</td>
<td>y = 2.46x - 0.04</td>
<td>n.s.</td>
</tr>
<tr>
<td>MR</td>
<td>0.936</td>
<td>y = 2.06x + 1.63</td>
<td>0.936</td>
<td>y = 2.48x + 1.57</td>
<td>n.s.</td>
</tr>
<tr>
<td>SC</td>
<td>0.954</td>
<td>y = 3.82x + 0.14</td>
<td>0.963</td>
<td>y = 2.47x + 0.11</td>
<td>0.001</td>
</tr>
</tbody>
</table>

\[ y = N_2 \% \text{ difference } 750 - 1250 \text{ ml.} \hspace{1cm} x = \frac{1}{\text{Vol. above RV}} \]

The significance of all the correlation coefficients was <0.001

level as the ERV and then taking the test breath. This difference was greater than would be expected from the observed change of lung volume in subjects, SC, ID, MM, AS, and for two out of three breaths in GJ (fig. 4).

DISCUSSION

There was a curvilinear relationship between nitrogen plateau slope and pre-inspiratory volume above RV in all the subjects studied. Over the upper 80 per cent of the vital capacity, alteration of lung volume had only a small effect on change in regional distribution of inspired gas, but over the lower 20 per cent of the vital capacity regional distribution was very sensitive to change in lung volume. Although the mechanics of the change in distribution away from the dependent parts of the lung are not fully understood, an attractive hypothesis based upon the effect of gravity on the lung has been proposed by Milic-Emili and associates (1966). It was suggested that a lung 30 cm in height with a density of about 0.25 g/ml would have a hydrostatic pressure difference of 7.5 cm H₂O between the apex and the base. At the normal end-expiratory point in the upright position the intrapleural pressure at the apex is about −10 cm H₂O and, because of the hydrostatic pressure
Diagrammatic representation of the distribution of lung units on the static compliance curve at FRC in the upright and supine positions. The supine lung lies on a lower part of the curve because of the smaller FRC in this position.

difference, the pressure at the base is about $-2.5$ cm H$_2$O (fig. 5). The transpulmonary pressure between the lumen of the airway and the intrapleural space at the apex is thus much greater than that at the base. On expiration the transpulmonary pressure at the base will diminish towards zero when the pressure at the apex is still about $-7.5$ cm H$_2$O. Airways with zero transpulmonary pressure are potentially collapsible, the only force resisting collapse being the elastic recoil of their walls. Elastic recoil is a function of lung volume, age and pulmonary disease. The lower the lung volume the lower is the elastic recoil and thus the resistance to airway closure. The younger the subject the higher the elastic recoil and the greater will be the resistance to airway closure (Clarke and Jones, 1969) so that young subjects will not tend to redistribute ventilation until they are breathing very near RV. The converse is found in old subjects (Holland et al., 1968). In the supine position the mechanism suggested by Milic-Emili and associates (1966) may also be applied and is compatible with the present results and those of Kaneko and associates (1966) in this position. Here the vertical height (front to back) is less than in the upright position and, assuming the same lung density, there is a hydrostatic pressure difference slightly less than the 7.5 cm H$_2$O postulated in the upright position. In spite of the smaller hydrostatic pressure difference between the top and bottom of the supine lung, the fall in lung volume on assuming the supine position may well be sufficient either to close dependent airways or to reduce the effective compliance of the dependent part of the lung so that gas is redistributed to the upper parts of the lung (fig. 5).

The functional consequences in terms of the single breath test can be seen from figure 5. If the test breath of oxygen is inspired near total lung capacity in either the upright or supine position the intrapleural pressure at the top of the lung is about $-28$ cm H$_2$O and at the bottom of the lung about $-20$ cm H$_2$O. The effective compliance of the whole lung is essentially the same and inspired gas is distributed evenly to different lung regions which contribute in the same proportion to the subsequent expiration. As the subject expires to a lower lung volume the dependent lung moves on to a more compliant part of the curve and empties more rapidly than does the upper part of the lung. In a series of single breath studies at progressively smaller lung volumes the end expiratory volume of the dependent lung will diminish disproportionately faster than the upper part of the lung and its contained nitrogen will be considerably more diluted after introduction of the 750 ml of oxygen. If the regional concentration of nitrogen is measured in two situations, first, when the test breath is taken near TLC and, second, when the breath is taken near RV, then at TLC the concentration will be almost uniform throughout the lung, but at RV there will be a considerably greater concentration of nitrogen in the uppermost parts of the lung. On expiration from TLC, no matter if all the lung regions empty either synchronously or asynchronously, the alveolar nitrogen plateau will be flat. On expiration from RV if all regions emptied synchronously, despite the large regional differences in nitrogen concentration there would still be a flat plateau. The steeply rising plateau is explained by sequential emptying, first of the dependent lung and then the upper lung.

Changes in lung volume with change in posture have been known since the work of Hutchinson in 1846, and Whitfield, Waterhouse and Arnott (1950) have tabulated the mean findings of several
authors who compared the results obtained in the supine and sitting positions. While little change occurs in the size of the residual volume on changing from the sitting to the supine position, most authors agree that the pre-inspiratory volume is considerably reduced by a fall in ERV. Blair and Hickam (1955) found a diminution exceeding 50 per cent in the size of the ERV in the supine position, a similar finding having been reported by Sjostrand (1951). The present study, confirming the fall in ERV in the supine position, has demonstrated that the relationship between nitrogen plateau slope and the volume above RV in the supine position is similar to that found in the upright position and, because of the diminution in ERV, inspired gas is less uniformly distributed in the supine than in the upright position. The similarity of the filling pattern in the sitting and supine positions has been reported by several workers (Milic-Emili et al., 1966; Kaneko et al., 1966; Clarke, Jones and Glaister, 1969). They observed that, on inspir- ing from RV, the first few millilitres of gas enter only the topmost parts of the lung, little enter- ing the most dependent zones of the lung. As the subject continues to inspire, the proportion of gas passing to the dependent zones of the lung increases until at about 1 litre above RV inspired gas is passing in equal amounts to upper and lower zones. Above this point the flow rate into the lower zones exceeds that into the upper. These observations were explained on the basis of the regional differences in transpulmonary pressure brought about by gravity, resulting in different lung regions functioning on different parts of the compliance curve. This hypothesis assumed a uniform lung compliance, the distribution of ventilation being determined solely by the effect of gravity on the lung. In a later paper Bake and associates (1967), while supporting the gravitational theory of distribution of ventilation, pointed out that there may be a regional dif- ference in lung compliance, the lower lobe being more compliant than the upper lobe. Further studies have shown that the magnitude (Bryan, Milic-Emili and Pengelly, 1966; Jones, Clarke and Glaister, 1969) and direction (Clarke, Jones and Glaister, 1969) of gravitational force is the most important determinant of distribution in all positions of the lung, so that even when the lung is inverted gas inspired near residual volume flows predominantly to the uppermost part, now the lung base.

From the present data it appears that there is little difference in the relationship between lung volume and plateau slope in the upright and supine positions. One subject (JS) showed a significantly greater degree of maldistribution of ventilation in the supine position while two others (SC and AS) showed a significantly smaller degree of maldistribution. The evidence suggests that there may be greater regional differences in lung compliance and thus of ventilation in some subjects which may to some extent exceed the effects of changing the direction of gravitational force on the lung.

The degree of slope of the alveolar plateau can be explained on the basis both of regional inhomogeneity of intrapulmonary gas where lung regions having differing ventilation per unit volume fill and empty asynchronously, the time-constant theory (Otis et al., 1956) and by stratifi- cation of gas tensions in the terminal airway units (Georg et al., 1965; Cumming et al., 1968), so that incomplete mixing of gas occurs in the terminal airways even after many seconds. It has been shown that in both upright and supine posi- tions the uppermost part of the lung fills and empties preferentially near residual volume (Milic-Emili et al., 1966; Kaneko et al., 1966), but the terminal airway units in the upper parts of the lung are several times larger in size than those in dependent parts of the lung (Glazier et al., 1967), and also have smaller ventilation per unit volume (West, 1962), a situation leading to a slower gas- mixing equilibrium time by accentuating the stratified gas-tension difference. Thus as expira- tion approaches residual volume the slope of the alveolar plateau steepens not only due to the in- creasing proportion of gas from the upper zone, which has a relatively high nitrogen concentra- tion, but also because there is a large stratified nitrogen tension difference due to incomplete dif-fusion equilibrium within the terminal airways in this region. Experiments to investigate differences in gas stratification at different lung volumes, using an inspired mixture of neon and sulphur hexafluoride, support the hypothesis of impaired gas mixing on breathing near residual volume (Cumming et al., 1968). This effect may be some-
what less in the supine position where the differences in size of alveoli between the top and the bottom of the lung are less marked than that observed in the upright lung (Glazier et al., 1967).

In some subjects it was observed that the gradient of the alveolar plateau in the supine position was greater if the subject took the test breath at the true FRC (supine) instead of first expiring to RV, then inspiriring to the position of the FRC (supine) before taking the test breath. No such difference was observed in the upright lung. That prolonged closure of dependent airways may occur in the supine position in some subjects after expiring to RV is suggested by this observation that the volume history of the lung affects the slope of the alveolar plateau. When the breath of oxygen is taken at about a litre above RV it is likely that it is distributed equally between the upper and lower zones but, because of the smaller amount of gas in the lower zone at this lung volume, the absolute concentration of nitrogen will be less than that in the upper zone. On subsequent expiration the first point measured on the alveolar plateau occurs where the contribution from the lower zone is suddenly diminishing, the remainder of the expire coming from the upper and middle zones. The result is a steeply sloping plateau. If the subject first expires to RV the airways in the lower zone may close and because the pressure required to re-open them may be large (Mead, Whittenberger and Radford, 1957; Levine and Johnson, 1965) they may remain closed when the test breath is taken and on subsequent expiration. With a smaller volume of untrapped gas in the lower zone, the 750-ml sampling point will occur after the lower zone has emptied and the 750–1250 ml nitrogen per cent difference now represents the gas tension difference between middle and upper zones.

Other workers have studied the effect of posture on distribution of ventilation. Svanberg (1957), in an extensive study of the effect of change in posture on pulmonary function found, using an open circuit nitrogen washout method, that there was no significant effect either on the size of the deadspace or on the distribution of ventilation using the analytical techniques of Robertson, Siri and Jones (1950) or of Fowler, Cornish and Kety (1952) although, using the Becklake index, he found gas mixing impaired in the supine position. Fowler (1950), Wilson and associates (1956) and Larson and Severinghaus (1962) have demonstrated a diminution of anatomical deadspace in the supine position. The Becklake index may be sensitive to this change whereas the other indices correct for deadspace effects. Bouhuys and van Lennep (1962) using the lung clearance index found evidence of impaired gas mixing in the supine position which they considered to be a consequence of the diminution in lung volume in this position. A similar result was reported by Hanson, Tabakin and Caldwell (1962) and by Bouhuys (1964) who found that the effect of histamine in impairing gas mixing in the lung was enhanced by change to the supine position. Bouhuys and van Lennep (1962) considered that the impairment of gas mixing was consequent upon changes in surface tension (Clements, Brown and Johnson, 1958), passive narrowing of bronchioles at small lung volumes, and viscous cohesive forces in the mucus lining of the small bronchioles (Troelstra and Heemstra, 1960). Recently Jones (1967a) and Young, Martin and Hashimoto (1968) could find little significant change in the distribution of ventilation in the supine position compared with the upright position. They concluded that while change in distribution of ventilation produced by a variety of manoeuvres other than change in posture could be detected with their techniques, if any change in distribution of ventilation occurred in the supine position, it produced no statistically significant effect on the results of their multiple breath tests.

The present study showed that on assuming the supine position there was a change in regional distribution of gas in the lung which was readily detected by the single breath technique. From these results one might expect that there would be an overall impairment of gas mixing as suggested by Bouhuys and van Lennep (1962) and might be surprised at the absence of effect, as suggested by Young, Martin and Hashimoto (1968). It seems likely that the answer lies somewhere between the two studies. The results of Bouhuys and van Lennep (1962) probably overestimate the mixing defect because they neglected to allow for the effect of the dilution ratio of tidal volume (VT) to alveolar volume (Vl) on the result. In multiple breath studies where correction for changes in dilution ratio has been made (Cuming and
The solenoid-operated valve was constructed by Mr. Bryan, A.C., Milic-Emili, J., and Pengelly, G. (1966). Bake, B., Bjure, J., Grimby, G., Milic-Emili, J., and Prys-Roberts and co-workers (1967) who found evidence of basal airway closure leading to arteriovenous shunting in normal subjects at low lung volume. It is suggested that these effects are more likely to be important in older subjects because they tend to lose their lung elastic recoil and are more susceptible to basal airway closure at higher lung volume.

ACKNOWLEDGEMENTS

The solenoid-operated valve was constructed by Mr. Colin Williams in the Medical Unit Workshop following discussion at the MRC Pneumoconiosis Research Unit, Llandough, South Wales. Miss Susan Pepper carried out the statistical analysis. This work was supported by the Endowment Fund of the United Birmingham Hospitals.

REFERENCES


