THE EFFECT OF POSTURE ON THE MECHANICS OF BREATHING DURING INTERMITTENT POSITIVE PRESSURE RESPIRATION*

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CHANGES IN POSTURE during anaesthesia are a well-recognized cause of ventilatory embarrassment to the patient^{1,2} Several authors have reported variations in vital capacity when conscious subjects have been placed in different surgical positions^{3,4,5} These variations bear a very indirect relationship to changes occurring in anaesthetized patients who are not breathing maximally¹ Similarly, the measurement of changes in tidal volume resulting from changes in position² indicate a change in work-load only very indirectly This study was designed to investigate the magnitude of the changes in the work of breathing required to maintain satisfactory ventilation in the anaesthetized subject when he is positioned for surgery, using the pressure-volume loop as a basis for measurement

METHOD

Thirty adult patients, clinically normal from the cardiopulmonary standpoint, were divided into three groups of ten The mechanics of respiration were measured in each group, in three different positions

Group I Supine, sitting, and right lateral positions

Group II Supine, lithotomy, and 45° Trendelenburg positions

Group III Prone on a Mackay frame⁶ well flexed, prone on a Mackay frame flattened but with abdomen clear of the table, and supine

Anaesthesia

All patients were premedicated with pantopon and hyoscine, anaesthesia was induced with sodium thiopentone and maintained with nitrous oxide oxygen in a proportion of 2:1 Sufficient *d*-tubocurarine was given to prevent spontaneous respiratory efforts, while ventilation was maintained at a tidal volume of 600 mL, twenty times per minute A 9.5 mm endotracheal tube was used in all except three patients in whom only a 9 mm tube could be passed A Morch piston respirator⁷ with the air intake converted to accept anaesthetic gases from a reservoir bag, and a Morch non-return valve, were employed in all cases

Instrumentation

Pressure gradients across the lung-thorax were detected by a Statham PR23 differential transducer, one side of which was connected to a point immediately proximal to the endotracheal tube. This transducer was calibrated by a water

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manometer before each measurement. Transpulmonary pressure gradients were obtained by connecting the other side of the transducer to a 15 cm oesophageal balloon, inserted in the lower third of the oesophagus. The pressure-volume characteristics of this balloon were such that no pressure changes were registered when it was filled with 0-4 mL of air. Maximum respiratory pressure fluctuations were obtained by inserting the balloon, open to atmospheric pressure, prior to connecting it to the transducer. Aspiration subsequently showed that negative intrathoracic pressure had drawn in 1-1.5 mL of air. Air flow was detected by a No. 2 Fleisch pneumotachograph, placed between the non-return valve and the endotracheal tube. The screen was heated by a 5 volt current. The pneumotachograph was calibrated with a continuous flow of air using Fisher-Porter flow meters, accurate to $\pm 1\%$. Flows of air were converted to values for 2:1 N₂O:O₂ mixtures on the basis of the difference in physical characteristics. Thus 100 L/min of air = 84.89 L/min N₂O:O₂, at 14.7 PSIA and 70° F. The pressure differential across the pneumotachograph screen was detected by a Statham PM5 transducer. Volumes were derived by electrical integration of flow, using a Grass U1-1 integrator.

Pressure differential, air flow, and volume were recorded continuously on a Grass Polygraph. Pressure and volume changes were displayed on a Tektronix dual beam oscilloscope, connected to the output of the Grass driver amplifiers and calibrated at the same time as the latter. A simple switching device permitted the output from the flow channel to be substituted for volume on the Y axis. Thus, either pressure-volume or pressure-flow loops could be displayed. Photographs of loops were made on Polaroid film for measurement purposes, the difference in screen and film calibration was constant, for a given camera lens and screen-to-film distance, and the appropriate conversion factor was applied to all photographic measurements.

Procedure

Each patient was measured only when the records of pressure, flow, and volume were steady. In each position, a pressure-volume loop was photographed, switching was performed on the next respiratory cycle and the film was then re-exposed, this time to the pressure-flow loop of the third cycle. Thus the pressure-volume and pressure-flow loops of two similar cycles were superimposed on the same film. The cycles from which the loops were recorded were marked automatically on the polygraph paper, by a switch synchronized with the shutter release cable. This provided the opportunity for subsequent checking of loop measurements from the polygraph trace and confirmation that the two loops were from comparable cycles. In each position, loops were obtained for lung-thorax and then for lung mechanics.

During intermittent positive pressure, lung compliance falls, and this may be increased by a single, large inflation⁸. Similarly, airway resistance may be reduced by a series of large breaths⁹. In the present series, every effort was made to carry out measurements during stable ventilatory circumstances and to avoid such large inflations. Once recordings were started, all measurements were made within as short a time interval as possible.

Measurements

Each loop was traced on millimeter squared graph paper. The dynamic compliance line was drawn between points of minimum and maximum volume. Where the shape of the loop was such that there was a pressure change with no volume change at end-inspiration or at end-expiration, the exact points of zero flow were determined by reference to the Grass recording and to the superimposed pressure-flow loop, as described by Watson¹⁰ (see Discussion). Elastic work

FIGURE 1 Idealized pressure-volume loop $AXBY$. AB represents the dynamic compliance line.

was calculated by measuring the area of the triangle ABV' (see Fig. 1). Non-elastic work was measured from the area of the half loop ABX . When any part of the expiratory half of the loop crossed the Y axis, this area was added to the non-elastic work. This occurred in a few instances in the prone position. In keeping with the standard form for spontaneous respiration, all work values were multiplied by the respiratory rate and quoted in kg M/min . Dynamic compliance was obtained by dividing the volume V' by the pressure differential P' .

RESULTS

The arithmetic means of the results obtained are shown in Tables I, II, and III. Other authors^{11,12} have shown the lack of validity of oesophageal balloon values obtained in the supine position. Consequently, only the results obtained in the sitting, right lateral, and prone positions have been used in calculations separating lung and thoracic wall components from total lung-thorax values.

Statistical Analysis

Since the resistances to lung and chest wall expansion vary markedly with body size,¹³ each group of ten values showed a large variation from the mean. While

TABLE I
LUNG-THORAX MEASUREMENTS
(Each figure represents the arithmetic mean of values for ten patients)

Group	Positions	Total work, kg M/min	Non-elastic work, kg M/min	Elastic work, kg M/min	Dynamic compliance, L/cm H ₂ O
I (10 patients)	Supine	0.97	0.46	0.51	0.077
	Sitting	0.92	0.38	0.53	0.073
	Right lateral	0.91	0.41	0.50	0.076
II (10 patients)	Supine	0.92	0.44	0.47	0.079
	Lithotomy	0.96	0.47	0.49	0.078
	45° Trendelenburg	1.0	0.49	0.52	0.074
III (10 patients)	Prone flexed	0.99	0.39	0.59	0.086
	Prone flat	0.93	0.39	0.54	0.071
	Supine	0.82	0.43	0.39	0.089

Significant differences
 Group I Non-elastic work R lateral < supine > sitting
 Group II Elastic work } Trendelenburg > supine
 Non-elastic work }
 Total work }
 Group III Dynamic compliance Trendelenburg < supine
 Elastic work Prone flexed > prone flat > supine
 Total work Prone flexed > supine < prone flat
 Dynamic compliance Prone flexed < supine > prone flat

TABLE II
LUNG MEASUREMENTS
(Each figure represents the arithmetic mean of values for ten patients)

Group	Positions	Total work, kg M/min	Non-elastic work, kg M/min	Elastic work, kg M/min	Dynamic compliance, L/cm H ₂ O
I (10 patients)	Sitting	0.66	0.33	0.32	0.126
	Right lateral	0.63	0.35	0.28	0.150
III (10 patients)	Prone flexed	0.52	0.31	0.20	0.199
	Prone flat	0.59	0.36	0.23	0.175

No significant differences

TABLE III
THORACIC WALL MEASUREMENTS
(Each figure represents the arithmetic mean of values for ten patients)

Group	Positions	Total work, kg M/min	Non-elastic work, kg M/min	Elastic work, kg M/min	Dynamic compliance, L/cm H ₂ O
I (10 patients)	Sitting	0.26	0.06	0.21	0.213
	Right lateral	0.29	0.06	0.22	0.210
III (10 patients)	Prone flexed	0.47	0.08	0.39	0.189
	Prone flat	0.36	0.05	0.31	0.171

Significant differences, Group III, elastic work Prone flexed > prone flat

FIGURE 2 Comparison of arithmetic means of total elastic and non elastic work in supine, sitting and right lateral positions

FIGURE 3 Comparison of arithmetic means of total, elastic and non elastic work in supine lithotomy and 45° Trendelenburg positions

FIGURE 4 Comparison of arithmetic means of total elastic and non-elastic work in prone flexed prone flat, and supine positions

this could have been reduced by relating each value to body weight this was considered less useful than letting each patient serve as his own control

Lung thorax values (Table I Figs 2 3 and 4) The total raw data were submitted to an analysis of variance from which it was found that the following means were significantly different at the 5 per cent level

Group I Non elastic work was greater in the supine position than in either the sitting or right lateral positions

Group II Elastic non elastic and total work were greater and the dynamic compliance lower in the Trendelenburg than in the supine position

Group III Elastic and total work were greater in both prone positions than in the supine position Elastic work was greater when the Mackay frame was flexed than when flat Dynamic compliance was lower in both prone positions than in the supine position

Lung values (Table II) The total raw data were submitted to an analysis of variance and none of the means were found to be significantly different

Thoracic wall values (Table III) Standard deviations and the standard error of the means were calculated for the differences between values for each pair of positions These figures were submitted to a *t* test and only one pair of values were found to be significantly different at the 5 per cent level Thus the thoracic wall elastic work was greater when the Mackay frame was flexed than when it was flattened

DISCUSSION

During spontaneous respiration, in conscious subjects, ventilation is adjusted to maintain the arterial carbon dioxide tension within very narrow limits. Tidal volumes and respiratory rate combine to strike a compromise between the need to overcome dead space—largely a matter of elastic work—and variations in non-elastic resistance, overcome by changes in respiratory frequency.¹⁴ Consequently, values for work are quoted per minute in order to encompass both factors.

During intermittent positive pressure respiration, the size of the tidal volume is determined by the respirator. When the latter is patient-triggered, the patient may determine his own respiratory frequency but, during controlled respiration, this too is determined mechanically. Thus, values for work obtained under these circumstances bear little comparison with those quoted for spontaneous respiration. In this study, most patients were hyperventilated (12 L/min), even allowing for mechanical dead space. This accounts in part for the relatively high work values.

During spontaneous respiration, the shape of the pressure-volume loop is determined by the characteristics of the lungs and airway. To some extent, the shape of one patient's loop is comparable with that of another. However, when the respiratory pattern is determined by a mechanical ventilator, the shape of the loop also depends on the characteristics of the respirator—particularly with regard to its inspiratory air flow pattern. Expiration will usually be passive, unless the respirator assists in this phase, but may be modified slightly by the

FIGURE 5 Typical pressure-volume loop, obtained with Morch piston respirator (The horizontal portion at the start of inspiration is related to the transient "surge" of air when the Morch valve opens)

expiratory valve resistance Both inspiratory and expiratory non-elastic resistance will be contributed to by endotracheal intubation Thus, loops obtained from patients on respirators will only be comparable when identical respirator circumstances have been employed and when ventilation has been delivered through airways of identical resistance These requirements were met, in this series, by ventilating all patients identically and letting each patient serve as his own control

Watson has described the relatively square loop produced by the Radcliffe respirator¹⁰ and his method of determining the points of no flow has been used in this series The Morsch respirator produces a more sinusoidal air flow pattern and consequently a more "classical" pressure-volume loop, as shown in Figure 5

Changes in body position can be expected to influence the mechanics of respiration in a variety of ways, such as by alterations in lung volume (particularly FRC),^{9,15,16} changes in intrapulmonary blood volume, and interference with thoracic wall movements and with diaphragmatic descent Unfortunately, the measurement technique used can only separate the lung contribution in certain positions and, in these, any changes produced were too small to be statistically significant However, the nature of changes in work-load can be detected in many instances Thus, in the prone position on bolsters, the additional load is primarily elastic resistance to chest wall expansion, whereas, in the Trendelenburg position, both elastic and non-elastic work are increased

The magnitude of changes in work of breathing necessary to maintain constant ventilation, despite changes in body position, can be calculated from Tables I-III For example, the largest percentage change produced was in moving from the prone flexed to the supine position, when the total lung-thorax elastic work fell by 34 per cent, although the total work changed by only 17 per cent Tilting patients from supine to a 45° Trendelenburg position only imposed an additional 9 per cent on the total lung-thorax work (Table I)

Presumably, these percentage changes would be greater with pathological states, such as obesity, ascites, hydrothorax, pneumothorax, pneumonia, pulmonary congestion

In a study on a series of supine paralysed patients, Watson was unable to demonstrate any thoracic wall non-elastic resistance¹⁰ During intermittent positive pressure in the paralysed patient, the proportion of the chest wall contribution to total resistance probably depends on the size of the tidal volume and the extent to which this passes the neutral chest wall position In this series, chest wall non-elastic resistance accounted for 6 per cent of the total work in the sitting position, 7 per cent in the right lateral, 8 per cent in the prone flexed, and 3 per cent in the flat prone position

One unexpected finding was the unusually low elastic work in patients turned from the prone to the supine position The reason for this is not apparent, from the available data, but it may be related to the relatively high inflation pressures necessary in the prone position, a resulting low intrapulmonary blood volume and an improved air distribution might account for the subsequent low elastic work when patients were turned to the supine position

The reason that the lung-thorax non-elastic resistance is higher in the supine

than in the sitting and right lateral positions is not apparent. Again, lung and chest wall components cannot be separated, but probably the "falling away" of the abdominal contents, in the last two positions, plays a significant role. Changes in lung volume may be an important factor.

From the practical standpoint, one must conclude that certain changes in position do influence the respiratory work load significantly in the paralysed anaesthetized patient. Under such circumstances inflation pressure must be adjusted appropriately, if constant ventilation is to be maintained.

SUMMARY

Mechanics of breathing have been measured in thirty curarized anaesthetized normal adults, ventilated by intermittent positive pressure. The magnitude and nature of the changes in work of breathing required to maintain constant ventilation despite changes in body position have been assessed. Possible reasons for these changes are suggested.

RÉSUMÉ

Chez 30 malades adultes sous anesthésie, nous avons mesuré les composantes mécaniques de la respiration en employant les courbes pression-volume obtenues au cours de la respiration avec pression positive intermittente. Nous avons mesuré le travail total de la respiration, le travail élastique, le travail non élastique et la compliance dynamique pour l'ensemble poumon-thorax et, cela, dans les positions suivantes: assise, latérale droite, lithotomie, Trendelenburg 45° et ventrale. La part du poumon et de la paroi thoracique dans ces données est notée pour les positions assise, latérale droite et ventrale. Une analyse statistique des résultats obtenus a été faite et nous avons souligné l'importance des différences appréciables du travail-poids respiratoire.

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