OBSERVATIONS ON THE MECHANICAL WORK OF INTERMITTENT
POSITIVE PRESSURE RESPIRATION

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SUMMARY
The mechanical work of respiration imposed by intermittent positive pressure was investigated in five totally paralyzed subjects. The chest wall was found to have no demonstrable non-elastic component to its resistance. The effect of alteration of the duration of inspiration upon the lungs' elastic and non-elastic resistance and upon chest wall resistance was determined. The effect of altering the imposed tracheal positive pressure waveform at a constant duration of inspiration upon the lungs' elastic and non-elastic resistance was determined.

The work of breathing has been determined by two methods, which are almost independent. Metabolic work has been derived from measurement of oxygen consumption during forced overventilation (Liljestrand, 1917; Cournand et al., 1954; Campbell, Westlake and Cherniack, 1959), and is influenced not only by the mechanical work of moving the lungs and chest wall, but also by the biochemical and mechanical efficiency of the muscles of respiration. The mechanical work of moving the lungs has been determined by the analysis of dynamic pressure-volume loops (Wirz, 1923; v. Neergaard and Wirz, 1927; Mead and Whittenberger, 1953). To determine the work required to move the chest wall as well as the lungs the relaxed chest wall must be moved passively; a completely relaxed subject must be ventilated artificially. In this study the mechanical work of respiration was determined in totally paralyzed tracheotomized patients receiving intermittent positive pressure respiration (IPPR) with various imposed patterns of pulmonary inflation. The results obtained are expressed in this paper.

METHODS
Pressure-flow and pressure-volume loops representing the respiratory mechanical behaviour of the whole chest or chest wall were obtained by photographing an oscilloscope's trace when airflow or tidal volume was expressed on the Y axis against tracheal pressure or oesophageal pressure on the X axis.

Tracheal pressure was measured at the external end of the tracheotomy tube.

Oesophageal pressure was measured by the method of Dornhorst and Leathart (1952) and was used to represent intrapleural pressure.

Airflow between the respiration pump and patient was measured with a pneumotachygraph having a low deadspace (Opie, Spalding and Stott, 1959).

Tidal volume was expressed on the oscilloscope by electronic integration of a signal proportional to airflow, and was simultaneously measured with a Wright Anemometer. The integrator was linear under the conditions of use and had a time constant of 100 seconds.

The imposed tracheal positive pressure waveform and inspiratory airflow pattern were recorded with a four-channel pen writer using pens 16 cm long, working in an arc of 4 cm, with a peak-to-peak response time of 0.07 sec.

Analysis of pressure-volume and pressure-flow loops.
A typical pressure-flow loop obtained is shown in figure 1. At tracheal pressures A and B the trace crosses the X axis, demonstrating the tracheal pressures at which there is no gross airflow.
between the respiration pump and patient. The corresponding pressure-volume loop is shown in figure 2; tracheal pressures A and B are derived from figure 1. At points A and C on the pressure-volume loop there is no airflow and no change in tidal volume. As the chest usually exhibits an almost linear relationship between pressure and volume under static conditions within the normal range of tidal volumes, points on the line AC represent pressures at which there would be no airflow at the corresponding tidal volumes; these pressures are exerted against elastic resistance only. The pressure exerted against non-elastic resistance at any given tidal volume is the difference between the total tracheal pressure at that volume and the pressure exerted against elastic resistance. For example, at volume D (fig. 2) DE represents the pressure exerted against elastic resistance, DF the pressure exerted against total resistance and hence EF is the pressure opposing non-elastic resistance.

The mechanical work of breathing is measured as the product of the differential pressures across the system and the volume displaced. When no subatmospheric tracheal pressure is applied, expiration is achieved in the totally paralyzed patient by recoil of the inflated chest. The work exerted against elastic resistance in inspiration can be calculated geometrically as the area of the right-angled triangle ACG (fig. 2) of which hypotenuse AC is the line joining the points at which there is no airflow between the respiration pump and the patient. The work performed against non-elastic resistance in inspiration is the product of volume and the pressure exerted against non-elastic resistance, that is, irregular area ACFH (fig. 2).

In this investigation, all estimations were made at a tidal volume of 600 ± 20 ml and at a ventilatory frequency of 13/min. Alternate respiratory cycles were investigated, and these were alternatively recorded as pressure-volume and as pressure-flow loops. Six respiratory cycles were analyzed, so that three results were obtained at each constant state of pulmonary ventilation. Each result presented is the arithmetical mean of these values.

The mechanical work performed against the chest wall by the imposed tracheal pressure was derived similarly from pressure-loops obtained by expressing tidal volume against oesophageal pressure on the oscilloscope screen. The work exerted against the lungs alone was derived by subtracting the work against the chest wall from the total work performed.

The work of respiration is expressed not as the work of each breath, but as the work done each minute. The units of the latter (kg.m/min) are really units of rate of doing work, or of power. The physiological convention of describing the
“work” of respiration, is, however, followed in this paper.

In the first part of this investigation, the duration of inspiration was varied within the limits 0.5 and 2.7 sec, using a “square” tracheal positive pressure waveform (waveform 1 in figures). The maximum pressure was reached within 0.1 sec of the start of inspiration and maintained for the remainder of the inspiratory phase of the respiratory cycle. When this tracheal pressure waveform was employed, the peak airflow occurred at the beginning of inspiration. As the ventilatory frequency was constant, prolongation of inspiration was at the expense of expiration.

In the second part of this investigation, the tracheal positive pressure waveform was varied at a constant duration of inspiration. Three different tracheal positive pressure waveforms were investigated, each at three durations of inspiration, 1 sec, 1.6 sec and 2.7 sec. With the first waveform, the peak airflow occurred at the beginning of inspiration: this airflow pattern was created by a “square” tracheal positive pressure waveform.

The second pressure waveform (waveform 2) gave a constant flow rate throughout the inspiratory phase of the respiratory cycle. The third airflow pattern reached a peak at the end of inspiration and was created by a “slowly rising” tracheal positive pressure waveform (waveform 3).

Subjects.

Five totally paralyzed patients were investigated. All had clinically and radiologically normal lungs at the time of investigation. Each patient was usually ventilated with a Radcliffe respiration pump (Russell et al., 1956) through a cuffed tracheotomy tube (Spalding and Smith, 1956) which provided an airtight seal in the trachea. During the course of this investigation each subject was ventilated with an experimental respiration pump which allowed the duration of inspiration and the imposed tracheal positive pressure waveform to be varied (Watson, Spalding and Smith, 1962). All subjects lay supine while measurements were made.

RESULTS

The mechanical work performed against the elastic resistance of the whole chest is expressed graphically against the duration of inspiration in figure 3. More work was done against elastic resistance when the duration of inspiration was 0.5 sec (mean 0.98 kg.m/min) than when the duration of inspiration was 1 sec (mean 0.66 kg.m/min) or longer. In figure 4 the work performed against the non-elastic resistance of the whole chest is expressed against the duration of inspiration. More work was exerted against the non-elastic resistance of the whole chest when the...
duration of inspiration was 0.5 sec (mean 0.90 kg.m/min) than when inspiration lasted 1 sec (mean 0.60 kg.m/min) or longer.

The work performed against the chest wall was exerted entirely against elastic resistance, as no hysteresis of the pressure-volume relationship of the chest wall was found in any patient. In all except one of the patients, more work was done against the chest wall resistance when the duration of inspiration was 0.5 sec (mean 0.27 kg.m/min) than when inspiration lasted 1 sec (mean 0.17 kg.m/min) or longer (fig. 5).

Figure 4 demonstrates the work done against non-elastic resistance of the lungs when waveform 1 was employed. The work performed against non-elastic resistance when waveforms 2 and 3 were used are shown in figures 7 and 8 respectively. The work required to overcome non-elastic resistance was greatest when waveform 1 was employed (fig. 4) and least when waveform 3 was used. Waveform 2 occupied an intermediate position.

Figure 5 expresses the work exerted against the elastic resistance of the lungs against the duration of inspiration. More work was done when inspiration lasted 0.5 sec (mean 0.72 kg.m/min) than when an inspiration of 1 sec (mean 0.48 kg.m/min) was used. The work performed against the non-elastic resistance of the lungs is the same as was exerted against the total chest (fig. 4), as the chest wall has no non-elastic resistance.

Tracheal positive pressure waveform.

The work done against the elastic resistance of the lungs was the same with all imposed tracheal pressure waveforms when measured in a given patient at a constant duration of inspiration and at a constant tidal volume. The values obtained did not differ significantly from those shown in figure 6.

Figure 6 expresses the work exerted against the elastic resistance of the lungs against the duration of inspiration. More work was done when inspiration lasted 0.5 sec (mean 0.72 kg.m/min) than when an inspiration of 1 sec (mean 0.48 kg.m/min) was used. The work performed against the non-elastic resistance of the lungs is the same as was exerted against the total chest (fig. 4), as the chest wall has no non-elastic resistance.

Waveform 2

Figure 7 expresses the work exerted against the non-elastic resistance of the lungs at different durations of inspiration using tracheal positive pressure waveform 2. Tidal volume 600±20 ml. Ventilatory frequency 13/min.
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Waveform 3

Work exerted against lungs' non-elastic resistance at different durations of inspiration using tracheal positive pressure waveform 3. Tidal volume 600 ± 20 ml. Ventilatory frequency 13/min.

DISCUSSION

A previous attempt has been made to measure the work of moving both the lungs and the chest wall by Otis, Fenn and Rahn (1950). These workers investigated normal subjects relaxing voluntarily within a tank respirator and found that the total work required was about 0.35 kg.m/min at a tidal volume of 500 ml with a ventilatory frequency of 16/min: 63 per cent of this work was exerted against elastic resistance. Nims, Connor and Comroe (1955) criticized the use of conscious normal subjects under these and similar circumstances, arguing that relaxation was almost certainly incomplete. McIlroy, Marshall and Christie (1954) found a mean value of 0.29 kg.m/min for the total work done against the lungs alone in subjects breathing spontaneously: 69 per cent of the work was exerted against elastic resistance. More work is required to ventilate the lungs of a patient by intermittent positive pressure, as both elastic resistance and non-elastic resistance are greater.

Elastic resistance of the lungs.

The elastic resistance of the lungs may also be expressed as its reciprocal, compliance. The variation of compliance found when different patterns of ventilation were imposed has been discussed in detail in a previous paper (Watson, 1962). Lung compliance decreased when the duration of inspiration was shortened to 0.5 sec but was not influenced by the imposed tracheal positive pressure waveform at a constant duration of inspiration. The values obtained for work done against the elastic resistance of the lungs are compatible with the derived values for compliance previously presented.

Non-elastic resistance of the lungs.

The work performed against non-elastic resistance is principally exerted against airway resistance (Marshall, McIlroy and Christie, 1954) which may oppose laminar or turbulent airflow. The resistance of the lung tissues to deformation, friction between visceral moving surfaces, the change in kinetic energy of the air, and acceleration and deceleration of the respiratory system also contribute to viscous resistance (Mead, 1956). No method has yet been evolved for the direct estimation of tissue viscous resistance and it is usually derived by subtracting airway resistance from total non-elastic resistance. The measurement of the resistance of the airway demands knowledge of simultaneous values for airflow and the pressure gradient across them. Alveolar pressures have been derived by a technique giving “instantaneous” interruption of airflow (v. Neergaard and Wirz, 1927; Otis and Bembower, 1949) but the validity of this is uncertain (Marshall and Dubois, 1956). Airway resistance has already been measured by causing the subject to breathe gases of differing densities and viscosities (Bayliss and Robertson, 1939; Dean and Visscher, 1941; McIlroy et al., 1955) or by using a body plethysmograph (Dubois, Botelho and Comroe, 1956; Marshall and Dubois, 1956).

Non-elastic resistance increased markedly when the duration of inspiration was shortened to 0.5 sec. Although the rate of lung tissue deformation, the acceleration of the respiratory system, the rate of movement of visceral surfaces and the kinetic energy of the air all increased under these circumstances, it is probable that the greatest increase occurred in airway resistance. The mean inspiratory flow rate increased to introduce a given tidal volume in a shorter time and it is possible that in some air passages laminar airflow became turbulent.

The non-elastic resistance changed when the imposed inspiratory airflow pattern was altered. The radius of a conducting vessel is of great importance in determining the resistance of fluid.
flow (Poiseuille, 1830). The minimum non-elastic resistance was found when the peak inspiratory airflow occurred at the end of inspiration. This was probably a result of enlargement of the terminal conducting passages by the time that the peak inspiratory airflow was conducted. The greatest non-elastic resistance was found when the peak inspiratory airflow occurred at the beginning of inspiration when very little enlargement of the smaller conducting airways had taken place.

It is probable that transient maldistribution of the inspired air was greatest when the total non-elastic resistance was maximum. A large total non-elastic resistance would result in preferential inflation of those lung units having relatively low individual airway resistance. The importance of transient intrapulmonary pressure gradients resulting from such maldistribution is uncertain. Traumatic emphysema has been described in dogs transient intrapulmonary pressure gradients and tissue deformation must be very low.

Chest wall resistance.

The absence of a non-elastic component to chest wall resistance means that chest wall inertia and the viscous resistance resulting from joint movement and tissue deformation must be very low.

The elastic resistance of the chest wall was greater when inspiration was short. This is compatible with the observed decrease in chest wall compliance found under these circumstances (Watson, personal data). The cause of this increased elastic resistance is uncertain. It may be a consequence of using oesophageal pressure as representing intrapleural pressure (Ferris, Mead and Frank, 1959; Knowles, Hong and Rahn, 1959; Mead and Gaensler, 1959). It is probable that maldistribution of air occurs when the duration of inspiration is only 0.5 sec, and that those lung units having the lowest individual airway resistance are preferentially inflated (Watson, 1962). If these lung units were paramediastinal, lateral compression of the oesophagus might have occurred during inspiration. Increased respiratory pressure swings within the oesophagus would have resulted in an apparent increase in chest wall elastic resistance and an apparent decrease in chest wall compliance. An alternative explanation of the increase in elastic resistance of the chest wall is that the pattern of chest wall movement changed under these circumstances and that relatively more movement occurred within a limited area. Simple inspection of movements of the chest and abdomen during inspiration did not confirm this.

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REFERENCES

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SOMMAIRE
Le travail "mecanique" de respiration imposé par pression positive intermittente a été étudié chez cinq sujets totalement paralysés. Il constata que la paroi thoracique n'a pas de composante non-élastique provable dans sa résistance.

L'auteur étudia l'effet de l'altération de durée de l'inspiration sur la résistance élastique et non-élastique des poumons et sur la résistance de la paroi thoracique.

L'auteur étudia (et détermina) également l'effet provoqué par modification du rythme onduleur de la pression trachéale positive imposée à durée constante de l'inspiration sur la résistance élastique et non-élastique pulmonaire.

ZUSAMMENFASSUNG
Der mechanische Atemvorgang, der mit intermittierendem positivem Druck erzielt wird, wurde an fünf vollständig gelähmten Versuchspersonen untersucht.

Es zeigte sich, dass die Thoraxwand keine nachweisbare unelastische Komponente aufweist, die ihr Widerstand leistet.

Der Effekt einer Änderung der Inspirationsdauer auf den elastischen und den unelastischen Widerstand der Lungen und auf den Widerstand der Thoraxwand wurde bestimmt.

Der Effekt einer Änderung des eingestellten positiven trachealen Drucks in Bezug auf seine Wellenform wurde bei konstanter Inspirationsdauer in seiner Wirkung auf den elastischen und den unelastischen Widerstand der Lungen bestimmt.