Mechanical Work on the Lungs and Work of Breathing with Positive End-Expiratory Pressure and Continuous Positive Airway Pressure*

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The mechanical work on the lung required during spontaneous breathing with positive end-expiratory pressure (PEEP) was compared with different methods of continuous positive airway pressure (CPAP) in nine young healthy athletes (surfers) at levels of 5, 10, 15, and 20 cm H2O. At the level of 20 cm H2O, PEEP increased the mean total work per minute by 116 percent and the total work per liter by 121 percent. The percent increase rose linearly with the level of PEEP. In contrast, with methods of CPAP that maintained the airway pressure (Paw) constant, the total work per minute decreased by 45 percent at a PEEP of 10 cm H2O and remained at this level with PEEP of 15 and 20 cm H2O. Use of PEEP did not increase the functional residual capacity (FRC) in these spontaneously breathing subjects. In contrast, CPAP resulted in a rise in FRC proportional to the level of CPAP. This suggests that CPAP must be applied in a manner that maintains Paw constant to provide optimal assistance to ventilation.

The use of continuous positive airway pressure (CPAP) and intermittent mandatory ventilation (IMV), developed for the treatment of infants with respiratory distress,¹ has become an accepted method of treating the adult acute respiratory distress syndrome.² ¹⁴ Spontaneous breathing with positive end-expiratory pressure (PEEP) will significantly increase the work of breathing. If it is applied effectively, CPAP should require less work than PEEP by assisting inspiratory effort, but it would be expected to increase work. Belenky et al⁵ have suggested that the elevation in the partial pressure of carbon dioxide in the arterial blood (PaCO₂) that is observed in infants receiving therapy with CPAP may be secondary to an inability to perform the increased respiratory work imposed by CPAP. Adult patients receiving high levels of CPAP develop evidence of distress, perhaps due either to a decrease in cardiac output as a result of excessive airway pressure (Paw) or to the increased work of breathing imposed by CPAP.

To minimize the work of breathing of a patient receiving CPAP, the Paw should be maintained at a constant level throughout the entire respiratory cycle. If the Paw falls below the set level during inspiration, added inspiratory work will be imposed; if it rises above the set level during expiration, added expiratory work is required. Since most systems delivering CPAP control the level of pressure with a high flow of gas through a fixed resistance, one would anticipate that during inspiration, when parallel flow occurs into the patient and flow through the fixed resistance decreases, the CPAP will fall. During expiration, when the flow of air from the patient is added to the constant high flow from the source of air, the flow through the fixed resistance is increased, and the Paw should rise. To avoid fluctuations in pressure, a capacitance or storage reservoir should be incorporated within the system. This will provide additional flow to maintain the Paw during inspiration and store volume during expiration, preventing a rise in Paw.

To assess the importance of the methods used to elevate end-expiratory pressure, a study was undertaken (1) to measure the changes in work done on the lungs by spontaneously breathing young athletes (surfers) when PEEP and various modes of administering CPAP were applied to the airway and (2) to measure the effectiveness of CPAP vs PEEP in increasing the functional residual capacity (FRC).

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MATERIALS AND METHODS

The protocol for this study and the safeguards taken were approved by the Committee on Investigations and Activities Involving Human Subjects. Informed consent was obtained from ten male paid volunteers between 21 and 34 years of age. All were in excellent condition, as evidenced by their active pursuit of the vigorous sport of surfing. Nine of the ten were certified scuba divers.

A history was taken, and a physical examination and screening studies of ventilatory function were done on all subjects prior to participation. The studies of ventilatory function included the forced vital capacity (FVC), the fraction of FVC expired in the first second, the maximum midexpiratory flow between 55 and 75 percent of the expired volume, and the flow-volume loop. In all subjects the history and physical examination confirmed that this was a group of well-conditioned athletes with no significant abnormalities. The results of all tests of respiratory function were within normal limits.

To measure work done on the lungs, an oral mouthpiece was used, and the nares were occluded. A pneumotachograph (Hewlett-Packard No. 2) was attached to the mouthpiece to measure flow, and the various systems for PEEP and CPAP were then connected to the pneumotachograph. After anesthetizing the nares with 1 ml of a 2 percent solution of viscous lidocaine (Xylocaine), an esophageal balloon was introduced to measure the esophageal pressure. The balloon was inflated with 0.25 ml of air and was positioned 45 cm from the nares as described by Milic Emili et al.6 One port of a differential pressure transducer (Rosemount 8311 CH5) was attached to the esophageal catheter, and the other was exposed to atmospheric pressure; it was not connected to the airway. The flow and pressure transducers' signals were conditioned and amplified (Hewlett-Packard amplifiers 47304 [flow] and 47305A [pressure]).

The signals were fed to a computer system (Hewlett-Packard 5600 A), and each was digitized at the rate of 25 samples per second for periods of two minutes for each test run. Using a modification of the method described earlier, these signals were filtered and displayed on a screen for picking the start and end of each breath. The computer then calculated the respiratory rate, the tidal volume (TV), the minute ventilation, the total work per liter, and the total work per minute. The rationale for calculations is given subsequently.

The subjects breathed through a soft rubber mouthpiece, and nose clips were used to occlude the nasal passage. Two groups of studies were done, both with subjects seated upright in a chair. In the first set of studies (six subjects), no attempt was made to control respiratory rate, TV, or minute ventilation. The following three resistive devices were used to control the level of PEEP and CPAP: (1) an adjustable magnetic valve; (2) a manifold valve which uses a pressure-driven diaphragm over the expiratory port to maintain Paw; and (3) a column of water into which the large-bore expiratory tubing was inserted to the desired depth. For breathing with CPAP, a method similar to those described by Civetta et al2 and by Garg and Gill3 was used. To maintain Paw constant, a reservoir bag was inserted upstream from the patient and the pressure control valve. Since the available respiratory reservoir bags have very little elastic recoil and so are poor capacitors, a suggestion of S. R. Powers, Jr., M.D. (personal communication, August, 1977), was used. A 6-L bag was placed between two 10 × 12-inch boards that were hinged together at one end and had elastic bands strung between them at the other end. This gave a more uniform recoil over the volume range of the subject's TV. For CPAP, the air flow was set at 60 L/min, and the pressure control device was set to achieve the desired pressure. For studies of PEEP, the Paw during inspiration was atmospheric and rose to the desired PEEP during expiration.

End-tidal carbon dioxide pressure was monitored, and the study was stopped if this pressure fell below 20 mm Hg or rose above 40 mm Hg. The levels of CPAP and PEEP were applied in ascending order, rather than randomly, in order to be sure that the subject could tolerate the incremental step in Paw. Between each type of study, a control study with Paw equal to atmospheric pressure was done.

In these studies, subjects had a wide variance in respiratory rate, TV, and minute ventilation. Since the mechanical work is altered by changes in TV and respiratory rate, we could not separate the effects of PEEP and CPAP on work from those due to changes in respiratory rate and TV. Therefore, five of the six subjects in group 1 plus four other subjects were used in a second study.

In this second group of studies, the respiratory rate was controlled by having the subject follow the rhythm of a metronome set at 12 beats per minute. The subjects were able to maintain the rate well. The mean respiratory rate was 12 ± 1 respirations per minute. The TV was controlled by having the subjects watch an in-line Wright's respirator. The mean calculated TV was 0.860 ± 0.144 L. The first group of experiments showed that the type of resistive device did not alter the pattern of PEEP or work, so in group 2, only the magnetic valve was used.

All nine subjects in group 2 had respiratory mechanics and work measured at (1) levels of PEEP of 0, 5, 10, 15, and 20 cm H2O and (2) levels of CPAP of 0, 5, 10, 15, and 20 cm H2O with the "elastic bellows" reservoir bag in the breathing circuit and an air flow of 60 L/min. Six of the nine subjects were studied at levels of CPAP of 5, 10, 15, and 20 cm H2O with the following four additional forms of breathing apparatus: (1) an air flow of 60 L/min without the "elastic bellows"; (2) an air flow of 30 L/min with the "elastic bellows"; (3) an air flow of 30 L/min without the "elastic bellows"; and (4) a device for IMV and CPAP with a demand-flow valve (provided by the Bird Corp.). In all subjects the levels of PEEP and CPAP were applied in ascending order. The order in which the six types of apparatus were used was random.

After these studies were performed, the FRC was determined at levels of PEEP of 0, 5, 10, 15, and 20 cm H2O and at levels of CPAP of 5, 10, 15 and 20 cm H2O using the "elastic bellows" and an air flow of 60 L/min. The FRC was measured with a method using helium dilution that was developed in our laboratory by Heldt and Peters.7 In this method a special two-way valve allows the subject to be connected either to the CPAP or PEEP or to a 1-L bag enclosed in a box. When the subject is connected to the bag, the system for CPAP or PEEP is connected to the box surrounding the bag. By simply switching a valve, this apparatus allows the same Paw to be maintained while the subject rebreathes from the bag as when he is breathing directly from the breathing apparatus. The bag is prefilled at fixed pressure with a measured volume of a mixture of 15 percent helium and 85 percent oxygen. The gas volumes before and after the test are measured with a large syringe, and the concentrations of helium are measured with a mass spectrometer (Perkin-Elmer). The PaCO2 is monitored, and the test is discontinued if the PaCO2 rises above 45 mm Hg before helium equilibrium is reached.
Rationale for Computations

The computer calculated the respiratory rate, the TV, and the minute ventilation as previously described. The calculations of work were modified for this experiment. We were interested in the work done on the lung by the subject’s effort. The work done by the subject and the system for CPAP equals:

\[ W = \int (P_{aw} - P_{r}) \, dv \]

where \( P_{aw} \) is the pressure at the airway opening, \( P_{r} \) is the pleural pressure, and \( dv \) is the flow into and out of the patient. The work done by the system for CPAP is:

\[ W_{sys} = \int (P_{aw} - P_{a}) \, dv \]

where \( P_{a} \) is the atmospheric pressure. The work done by the subject’s effort on the lung is the difference between these two equations or

\[ W_{sys} = \int (P_{aw} - P_{a}) \, dv - \int (P_{aw} - P_{r}) \, dv \]

The direction and so the sign of flow changes from inspiration to expiration, and unless the sign of pressure changes at the same moment, this integral will be negative for part of the period. During the periods when the sign is negative, the change in pulmonary volume is not the result of the subject’s effort but rather is done by the force of the system for CPAP or by stored elastic energy in the lungs. To determine the work done by the subject, the algorithm should calculate the positive work without subtracting the negative work. In our algorithm, we make the electrical signal for inspiratory flow negative and that for expiratory flow positive. The electrical signal for subatmospheric esophageal pressure is negative and for pressure above atmospheric is positive. During inspiration, when pleural pressure is subatmospheric \( P_{aw} - P_{r} < 0 \), the subject’s effort brings air into the lungs. When \( P_{aw} - P_{r} > 0 \), CPAP is providing the inspiratory force. During expiration, when pleural pressure is above atmospheric, the patient’s effort provides the force to push air out of the chest. When \( P_{aw} - P_{r} < 0 \) during expiration, pulmonary recoil is providing the force to push air out. Using an algorithm which sums the products of \( (P_{aw} - P_{r}) \Delta V \), work is calculated only when the sign of the product is positive \( (\Delta V \) is change in volume). The positive work was measured over the cycle of each breath to give the total work per breath. The values for each breath were summed for a two-minute period to calculate work per minute and were divided by minute ventilation to get work per liter.

Results

Group 1: Unconditioned Response

In group 1, in which no attempt was made to control the respiratory rate or TV, the subjects responded in two different ways to PEEP and CPAP with an air flow of 60 L/min with the “elastic bellows.” Four of the subjects maintained their respiratory rate, TV, and minute ventilation fairly constant while receiving PEEP and CPAP. Two of the subjects increased their respiratory rate, TV, and minute ventilation with increasing levels of CPAP. Studies on these two subjects were discontinued at levels of CPAP of 15 and 20 cm H₂O because of a marked fall in end-tidal carbon dioxide pressure with the induced hyperventilation.

In group 1, no attempt was made to analyze statistical differences in total work per liter or total work per minute at different levels of PEEP or CPAP because of the wide range in respiratory rate, TV, and minute ventilation among subjects. In all six subjects the total work per liter and total work per minute were not affected by the type of resistive device used to obtain the different levels of PEEP and CPAP.

Group 2: Conditioned Response

Figures 1 and 2 show the computerized plots of the mean percentage of change in total work per liter and total work per minute at different levels of PEEP and CPAP in the ten subjects when respiratory rate and TV were controlled. Note that the plots of the percent change in total work per liter (Fig 1) and total work per minute (Fig 2) are almost identical, which is evidence of the excellent control of respiratory rate and TV achieved in this second group of studies.

At zero PEEP and CPAP (baseline), the mean of

![Figure 1](http://journal.publications.chestnet.org/pdffile.asmx?url=/data/journals/chest/21064/ on 06/25/2017)
The absolute value for total work per liter was 0.071 kg·m/L and for total work per minute was 0.725 kg·m/min. For PEEP the absolute value of total work per minute rose by 116 percent to 1.57 kg·m/min, and the total work per liter rose 121 percent to 0.157 kg·m/L at 20 cm H₂O. Work increased significantly over the value at zero PEEP for all levels of PEEP. The mean percentage of increase in work rose linearly with the level of PEEP applied. At a level of PEEP of 20 cm H₂O, all of these well-conditioned athletes stated that they could not maintain this form of breathing for much longer than the testing period.

The levels of work for the various types of CPAP were dependent on their efficiency in maintaining Paw constant at the set level of CPAP; however, there was significant subject-to-subject variation. Using analysis of variance, the differences are shown in Table 1.

Figures 1 and 2 illustrate that in general, as the levels of PEEP and CPAP increased, the difference between the total work per liter and the total work per minute with PEEP and CPAP increased to a maximum and then began slowly to decrease. If the mean values for the percentage of increase or decrease in total work per liter and total work per minute with PEEP and CPAP at an air flow of 60 L/min with the “elastic bellows” are compared, it is evident that at levels of 5, 10, 15, and 20 cm H₂O, PEEP requires the subject to do 279, 265, 317, and 441 percent more work on the lungs per liter of air and 258, 255, 316, and 452 percent more work on the lungs per minute, respectively, than CPAP at an air flow of 60 L/min with the “elastic bellows” at each level of pressure.

Table 1—Significance of Different Methods of CPAP and PEEP*

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*Note: Method at top of column required more work than method at far left; †, method at top of column required less work than method at far left; and NS, not significant.

†Use of CPAP at air flow of 30 L/min required significantly more work than at least two other forms of CPAP.

Figure 3 shows the change in FRC with PEEP and with CPAP at an air flow of 60 L/min with the “elastic bellows.” Analysis of variance demonstrated that the mean value for FRC with PEEP was not significantly different from the mean resting FRC of 3,139 ml. At each level of PEEP, the FRC varied a great deal among subjects, while at some levels of PEEP, the FRC was significantly increased. Analysis of variance showed that the mean value for the group was not significantly different from the mean resting value.

With CPAP, the increase from resting FRC was not uniform at each level of CPAP, but the mean FRC with CPAP was significantly different from the resting FRC and from the FRC with PEEP. The mean increases above the resting FRC at levels of CPAP of 5, 10, 15, and 20 cm H₂O with the bellows were 485, 974, 1,354, and 1,530 ml, respectively. These represent increases of 16, 31, 43, and 49 percent.
sum of the forces applied by the many muscles of respiration. The elastic work on the wall of the chest can be estimated from its compliance, but in the complex system of CPAP, one cannot readily separate the portion of elastic work done by the system for CPAP and that done by the subject. Since we were interested in the relationship between the mechanical method used to raise the Paw and the mechanical response of the subject, we elected to measure changes in mechanical work.

Since with PEEP the FRC was not significantly increased, the subjects apparently elect to maintain their inspiratory work nearly constant and do extra work during expiration. With CPAP, the subjects increase FRC. Figure 4 shows a plot of one subject's

![Graph showing FRC and work changes with CPAP and PEEP](image)

**Discussion**

The effects of the alteration in methods of ventilation on work can be measured in two ways, i.e., (1) by measuring the change in oxygen consumption, and (2) by calculating mechanical work. In this study, we were interested in changes in mechanical work done on the lungs by the subject, not by the breathing apparatus used to assist ventilation. As discussed under the rationale, we ignored the force provided by systems for CPAP. In addition to providing the force to do work on the lung, the subjects must provide force to overcome the elastic and resistive properties of the thoracic cage. The lung has no intrinsic muscles to provide force for expansion or compression. The force for movement of both the lungs and chest is provided by the muscles of the thoracic cage. The force to change pulmonary volume is the difference between mouth pressure and $P_{pl}$.

As pointed out in the rationale, the portion of the force provided by the subject's effort is the difference between body surface or atmospheric pressure $P_{pl}$ when it is in phase with the direction of flow. Mechanical force on the wall of the chest and diaphragm cannot be directly measured; it is the
change in FRC and end-expiratory and inspiratory pressures and work as CPAP with an air flow of 60 L/min with the bellows is increased from 0 to 20 cm H₂O. The dynamic compliance falls progressively from 200 ml/cm H₂O at zero CPAP to 114 ml/cm H₂O at CPAP of 15 cm H₂O and 89 ml/cm H₂O at CPAP of 20 cm H₂O. The FRC progressively rises from 3,400 ml at zero CPAP to 5,200 ml at CPAP of 20 cm H₂O.

The work of inspiration likewise falls progressively, as depicted in Figure 4, until it is very small at CPAP of 20 cm H₂O. The subject elects to allow the system for CPAP to do the work of inspiration. The diagram suggests that the subject ceases doing inspiratory work and exchanges this for expiratory work.

Figure 5 shows another and probably more precise interpretation of mechanical work. In this diagram, we have assumed that the compliance of the wall of the chest is the same as the pulmonary compliance. At a pulmonary volume of 4,500 ml, the thoracic cage is expanded to its relaxed volume. Any further increase in the volume of the thoracic cage will require either application of muscular force or elevation of pleural pressure. At a volume of 6,000 ml with CPAP of 20 cm H₂O, the pleural pressure would have to be raised to 8 cm H₂O if all muscles were relaxed. As the pulmonary volume increases, the inspiratory work done on the lungs of these subjects decreased; however, an increasing amount of elastic work had to be done on the thoracic cage during inspiration. The elastic energy stored by hyperexpanding the thoracic cage then provides part of the force for expiration. This portion of work is depicted in the shaded areas in Figure 5. The subjects in fact use CPAP for inflating the lungs and muscular effort to expand the thoracic cage. For expiration against CPAP, the elastic recoil of the lungs and thoracic cage do most of the work. Active expiratory work is equal to the unshaded area within the work loops when pleural pressure is positive (Fig 5). This diagram suggests that the subject distributes effort between inspiration and expiration with increasing levels of CPAP.

If a patient had stiff lungs, an increase in volume would provide greater recoil force than was the case in these normal subjects. One would then expect that the same distribution between work done by the system for CPAP and that done by the patient would result in lower pulmonary volume for any level of CPAP.

The pattern of ventilation chosen by these subjects and their likening it to breathing off scuba tanks suggests that divers may likewise elect to change their FRC and use the elastic recoil of the wall of the chest and of the lungs for part of the expiratory force. It was interesting that the subjects without training for scuba diving did not use the CPAP as effectively for pulmonary inflation as the others.

This study demonstrates the importance of maintaining a constant Paw when CPAP is used. The CPAP will then provide optimal assistance to ventilation.

REFERENCES