A New Method for Studying Mechanics of Breathing Using Cathode Ray Oscillograph.* (19135)

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It is the purpose of this paper to describe the use of the cathode ray oscillograph for the direct recording of pressure-volume or pressure-flow relationships. In addition, the use of a catheter for measuring alveolar pressure and the use of the oscilloscope for studying lag and phase shifts due to the inertia of the chest are described.

Apparatus. The equipment used is as follows: Two differential pressure gauges (Statham) with control unit (Hathaway); a cathode ray oscilloscope (Dumont 304-H); a recording spirometer equipped with a potentiometer geared to the pulley to act as a volume transducer; an Electrodyne Stimulator used as a time marker which interrupted the cathode ray beam at 0.1 sec. intervals; a pneumotachometer constructed of a porous bronze disc; a Drinker respirator for generation of cyclical pressures used in some experiments; and a 35 mm camera with bulb exposure and light shield for photographing the face of the oscilloscope. The arrangement of the apparatus was varied depending on the particular relationship studied, and will be described with each type of experiment.

Pressure-volume curve of the chest. The subject is connected by a tight-fitting mask to a rebreathing circuit including the recording spirometer. The subject may be inside the respirator with his head and the spirometer outside or, more conveniently, the spirometer may be inside communicating through tubes to the subject outside. In either case the subject endeavors to relax completely and permits the respirator to supply all the pressure required for the expansion and collapse of the chest. Alternating positive and negative pressures of varying magnitude and frequency are produced in the respirator. Pressure is recorded at the mouth by a strain gauge which produces a potential causing the beam of a cathode ray oscilloscope to move horizontally. Volume is recorded from the spirometer which produces a similar potential causing the spot to move vertically. With this arrangement a single respiratory cycle is represented by a loop on the oscilloscope. The record is interrupted at 0.1 sec. intervals by rhythmical potentials from the Electrodyne Stimulator applied to the Z axis of the oscilloscope. In Fig. 1A, 3 such loops at different pressure ranges were recorded on the same film by opening the camera shutter during 3 separate cycles. Inspiration is recorded upwards and positive mouth pressure, cm H_2O, to the left. A straight line, EL, drawn through the points of maximum and minimum volume on these loops represents the elastic component of the total pressure. Additional force, represented by a horizontal line from the elastic component line, EL, to the curve, is required to overcome resistance to the flow of gases through the tracheo-bronchial tree and tissue "viscance." This additional force is the *dynamic component* of the work of breathing and is a function of the rate of change of volume. In Fig. 1A the rate of change in volume is indicated by the vertical increment between the 0.1 second interval marks. The total dynamic work of breathing is represented by the area of the loop.

Resistance to flow is the ratio of the dynamic pressure (horizontal distance from EL to the curve) to the rate of change in volume, (vertical distance between successive spots). Tissue viscance is also included in this measurement. A rapid estimate of "conductance" (the reciprocal of resistance) during any time interval may be made by drawing a horizontal line from one point on the loop to the line EL

* This work was in part supported by contract with the Air Materiel Command, Wright Field, Dayton, O.

† Fellow of the Life Insurance Medical Research Fund.

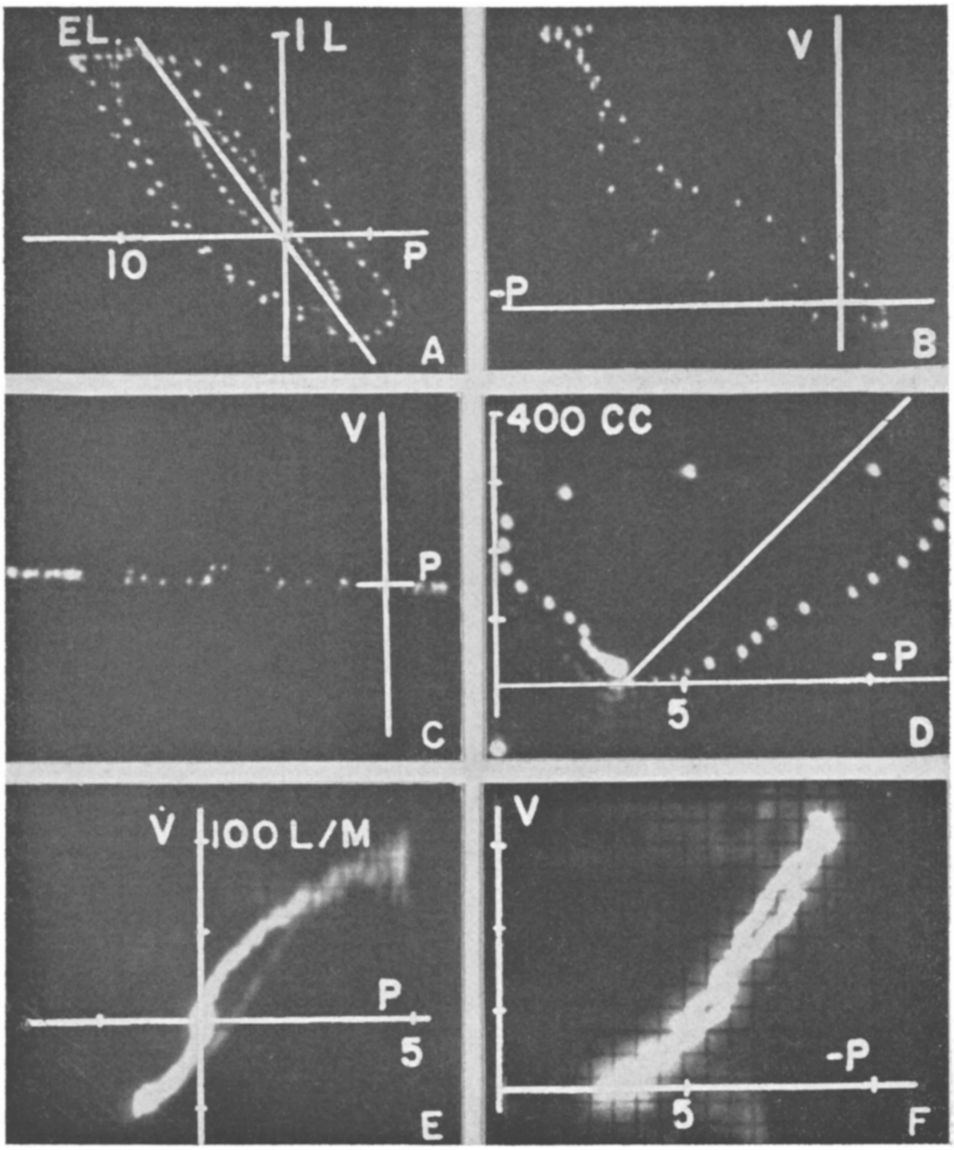

FIG. 1. Oscillographic records of breathing. A. Artificial respiration in the human subject—3 cycles at increasing pressures. Transthoracic pressures vs. volume. B. The same in a human poliomyelitis patient who is actively trying to assist the respirator. C. The same while the patient resists the respirator. D. Intrapleural pressure vs. volume in a dog. E. Alveolar pressure (P) vs. gas flow (liters per minute) in a dog. F. Lung tension (alveolar minus intra-pleural pressure) in cm H_2O vs. volume (V) in a dog. Marks on Y axis represent 100 cc increments.

and connecting the point of intersection to the next point on the loop. The angle thus subtended by two adjacent points is (nearly) proportional to the conductance. This method of analysis is useful in comparing different loops or different parts of the same loop.

Deviations from the normal pressure-volume curve occur when there is a change in tone of the chest muscles, or a change in resistance to gas flow or tissue movement. With respect to these possible deviations there is a double advantage in using the cathode ray oscilloscope. One may ascertain immediately whether the subject is relaxed and is following the respirator merely by observing the curve as it is generated. On the other hand, chest function may be tested by asking the subject to aid or resist the action of the respirator deliberately. In either case, part of the dynamic work of breathing will not appear because it has been replaced by muscular force which cannot be measured in terms of pressure. This is illustrated in Fig. 1B which was obtained by asking a poliomyelitis patient with an indwelling tracheotomy tube to aid the respirator as much as possible. The patient followed the action of the respirator until a point near maximum inspired volume was reached, whereupon a rapid inspiratory effort was made. The patient then relaxed, again following the respirator during expiration.

Fig. 1C shows the result obtained when the same patient was asked to resist the respirator. Only a small volume change was brought about, indicating that the patient had retained some control of his respiratory muscles.

Intrapleural pressure-volume curve. Transpulmonary pressure (between mouth and pleural space) is measured by a differential strain gauge and transmitted to the X axis of the oscilloscope. Volume is recorded as in the previous method. The 0.1 sec. intervals are brought about as before through the Z axis of the oscilloscope. This approach is illustrated in Fig. 1D, obtained from an anesthetized dog. In this case, the curve is plotted counterclockwise, originating at the abscissa at the point of negative pressure normally existing in the pleural space during the respiratory pause. Pressure is noted in terms of cm H_2O and lung volume in 100 cc units. The line of elastic force (lung tension) is drawn through the points of maximum and minimum volume. This is difficult to do precisely in Fig. 1D because of the rapid change in pressure without apparent change in volume at the height of inspiration. This seems to be a characteristic of the respiratory pattern of the dog. In this case the selection of the proper point was facilitated by simultaneous time records of changes in pressure and volume taken for another purpose. This permitted the selection of the pressure simultaneous with the point of maximum volume.

Alveolar pressure and gas flow. A Cournand cardiac catheter connected to a strain gauge is introduced into the bronchial tree of an anesthetized dog and advanced until it becomes occluded in a small bronchus. The small segment of lung thus occluded presumably derives its pressures from the surrounding lung, yielding a satisfactory approximation of alveolar pressure. This pressure is transmitted to the X axis of the oscilloscope and gas flow is applied to the Y axis by means of a pneumotachometer (Fig. 1E). During inspiration the curve starts at the origin, moves down and to the left and then returns to the origin along the same curve. During expiration it moves up and to the right in the opposite quadrant, again returning to the origin. These two curves are represented by the equation $P = K\dot{V} + K'\dot{V}^2$(1). The constants K and K′ are easily derived by plotting points obtained from the curves according to the equation $P/\dot{V} = K + K'\dot{V}$. In the figure shown, these constants are $K = 0.3$ and $K' = 0.5$ (when $P =$ cm H_2O and $\dot{V} =$ l/min.). The inspiratory and expiratory curve are identical when superimposed and indicate that in this animal there is no appreciable change in the constants K and K′ with respect to the phase of the respiratory cycle. Loops are sometimes observed which are due to mechanical factors such as intermittent occlusion of the catheter or leakage around the tip of the catheter when the bronchi are fully dilated by inspiration. These are easily eliminated by repositioning the catheter.

Lung tension curve. A differential strain gauge is connected to an intrapleural needle and an alveolar catheter in a dog and led to the X axis of the oscilloscope. This arrangement effectively subtracts the air flow component of intrapleural tension from the total, leaving only the elastic component of lung tension. Volume at the mouth is recorded on the Y axis by means of a spirometer. The resulting curve is shown in Fig. 1F. During inspiration the curve moves up and to the

1. Otis, A. B., Fenn, W. O., and Rahn, H., *J. App. Physiol.*, 1950, v2, 592.

right. During expiration it returns toward the starting point. The slope of this line represents the extensibility of the lung, or change in volume per unit pressure. This is the inverse of the elastic constant (more strictly, the volume modulus). Deviations from this line occur when there is partial obstruction of the needle or catheter. These are cleared with an air syringe. Theoretically, there should be a small loop representing work in overcoming tissue viscance. The figure presented shows a very slight deviation but this is obscured by other irregularities which are presumably due to heart action. The slope of this curve is nearly the same as the one drawn in Fig. 1D.

Lag between pressure around chest and at mouth. For the purposes of ordinary testing of pressure-volume and pressure-flow relationships, it is convenient to assume that the inertia of the chest and gases is negligible. To test this assumption a subject was placed in the respirator, and a sudden pressure was released into it from a 3-liter can containing air compressed to 7 lb per square inch above atmospheric pressure. This triggered a single sweep on the oscilloscope, and pressure at the occluded mouth of the subject was recorded on the Y axis. The pressure in the respirator reached maximum in about a sixtieth of a second, and the pressure at the mouth of the subject reached maximum within two-sixtieths of a second. This closed chest-mouth system thus showed a small but finite lag due presumably in large part to inertia of the chest. A small transmission time from alveoli to mouth is included.

Natural frequency of the chest. The lag due to inertia of the chest could be expected to cause a shift in phase between a rapidly oscillating transthoracic pressure and the resultant flow at the mouth. A cylinder and piston whose shaft was eccentrically placed on a wheel were connected to the respirator. Pressure fluctuations which are sinusoidal in nature were produced up to a frequency of 20 per second. Transthoracic pressure was measured by a strain gauge and transmitted to the X axis, and flow at the mouth by a pneumotachometer which drove the Y axis of the oscilloscope. As the frequency of the piston was increased to 15 cps the resulting curve widened out toward an elliptical form. The presence of inertia of the chest was thus demonstrated. Vibration of the apparatus became excessive at frequencies above 20 cps. The inertia of the chest is of an order of magnitude which makes it unnecessary to consider it in an ordinary analysis of the mechanics of breathing. However, it may be of significance in unusual situations such as explosive decompression. It is suggested that the cathode ray oscilloscope provides a convenient means of visualizing this factor.

Summary. (1) Pressure-volume curves of the chest and lungs may be portrayed directly on the cathode ray oscilloscope to show the elastic and viscous properties described by previous authors(1,2). Alterations of muscle tone of the thorax affect the pressure-volume curve in such a way as to aid or resist artificial respiration and are immediately detectable by this method. (2) Pressure-flow curves may be recorded in a similar manner. This method permits the easy evaluation of the constants involved in the equation $P = K\dot{V} + K'\dot{V}^2$ which are determined by the physical characteristics of the lung tree. (3) Inertia of the thorax causes a small lag between pressure around the chest and flow at the mouth. This time lag is of the order of one-sixtieth of a second.

The authors wish to gratefully acknowledge the advice and help of Dr. W. O. Fenn and Dr. H. Rahn throughout the experiments.

2. Fenn, W. O., *Am. J. Med.*, 1951, v10, 77.

Received October 4, 1951. P.S.E.B.M., 1951, v78.