THE INTERRELATIONSHIPS OF PRESSURE, FLOW, AND VOLUME DURING VARIOUS RESPIRATORY MANEUVERS IN NORMAL AND EMPHYSEMATOUS SUBECTS[1,2]

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Introduction

Ventilatory mechanics are usually quantified in terms of pressure-flow, pressure-volume, or volume-time relationships. Recently, the importance of the flow-volume relationship has been recognized (1). It follows that the mechanics of ventilation could be characterized rather completely by recording the simultaneous interrelationships of pressure, flow, and volume. Heretofore there has been no systematic attempt to analyze these three variables simultaneously.

This report presents a method which permits the interrelationships between transpulmonary pressure, air flow, and volume, i.e., lung inflation, to be examined simultaneously. The method consists of plotting flow against volume, pressure against flow, and pressure against volume separately but simultaneously on three oscilloscopes. Any respiratory maneuver then appears as a path or loop on each of the respective planes, i.e., the flow-volume, pressure-flow, and pressure-volume planes. By comparing any two of the plots, the complex interrelationships among the three variables may be studied. This technique has been applied to a group of normal and emphysematous subjects. Certain clinical and physiologic phenomena particularly well visualized by this integrated approach to ventilatory mechanics are discussed. In addition, the simultaneous values of the three variables during certain important respiratory maneuvers have been established in these subjects. Such data are not available in the literature.

Methods

Transpulmonary pressure, the difference between intra-esophageal and lateral mouth pressure, was measured with the system described by Schilder and co-workers (2). Respiratory air flow was recorded with a concentric cylinder flowmeter and appropriate sensing element (3). Volume was recorded by measuring the displacement of a Krogh spirometer with a rotational transducer.[3] In addition to writing these variables on a multichannel recorder,[4] any two of the variables could be recorded simultaneously on the X and Y axes of an oscilloscope.

All subjects were studied in the sitting position. The elasticity of the lung was evaluated by two methods. The effective compliance of the lung during quiet breathing was measured by the method of von Neergaard and Wirz (4), the results being listed as compliance in table 1. The interrupted method (5) was used to measure the static transpulmonary pressure at various degrees of lung inflation. Special attention was paid to obtaining this measurement at resting end-expiration and at the maximal inspiratory point. These values are listed in table 1 as static transpulmonary pressure.

Airflow resistance was measured during quiet breathing by choosing isovolume pressure and flow points (6).

Following the above determinations, the subject performed a series of breaths of vital capacity volume, during which maximal effort was exerted throughout inspiration and expiration. The subject was asked to empty his lungs completely and then fill them as rapidly and completely as possible. He then immediately exhaled as hard and fast and completely as possible. This sequence was repeated several times for each determination. Such a maneuver has been defined elsewhere (7) as a maximal *effort* vital capacity breath. Next, the subject's tidal breathing was recorded followed by a brief series of breaths of the type employed in the maximal breathing capacity test. The volume reference for these various maneuvers was the maximal inspiratory point. During each of these maneuvers, plots of pressure versus flow, pressure versus volume, and flow versus volume were photographed from oscilloscopes.

In all subjects a maximal *flow* vital capacity breath was also recorded (7). This is obtained by having the subject first perform a maximally rapid inspiration of vital capacity volume followed by a series of expiratory vital capacity breaths of

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[3] Microsyn Type 1C-020J, Doelcam Corporation, Boston, Massachusetts.

[4] Sanborn Model 67-1200, Sanborn Company, Cambridge, Massachusetts.

TABLE 1

Physiologic Data of Subjects

Measurement	Normal		Emphysema	
	Mean	Standard Deviation	Mean	Standard Deviation
1. Vital Capacity (L)	4.6	0.5	3.1	0.7
2. Compliance (L/cm. H_2O)	0.242	0.1	0.207	0.07
3. Resistance (cm. H_2O/L/sec.)	1.98	0.8	9.41	6.5
4. MMF (L/sec.)	3.2	1.2	0.6	0.3
5. Static transpulmonary pressure (cm. H_2O)				
A. End-expiratory	−5.0	1.2	−3.3	1.6
B. MIP	−30.5	7.5	−13.0	3.8
6. Maximal expiratory flows (L/sec.)				
A. Maximal flow VC				
1. 75% VC	7.4	1.6	1.5	0.7
2. 50% VC	4.8	1.8	0.9	0.4
3. 25% VC	2.1	1.0	0.4	0.2
B. Maximal effort VC				
1. Peak flow	8.5	1.6	2.5	1.2
2. 75% VC	6.6	1.8	1.1	0.6
3. 50% VC	3.9	1.4	0.6	0.3
4. 25% VC	1.5	0.6	0.3	0.1
C. MBC	6.1	1.8	2.0	0.8
7. Maximal inspiratory flows (L/sec.)				
A. Maximal effort and maximal flow VC				
1. Peak flow	8.5	1.3	3.6	1.4
2. 75% VC	6.8	1.5	2.8	1.2
3. 50% VC	8.0	1.3	3.3	1.3
4. 25% VC	7.1	1.1	2.9	1.4
B. MBC)	6.5	1.5	2.4	1.1
8. Maximal expiratory pressures (cm. H_2O)				
A. Maximal effort VC				
1. Peak pressure	98	35	90	17
2. 75% VC	68	29.6	62	33
3. 50% VC	90	41	66	28
4. 25% VC	70	31	54	32
B. MBC	48	40	37	27
9. Maximal inspiratory pressures (cm. H_2O)				
A. Maximal effort VC				
1. Peak pressure	−35	10	−36	15
2. 75% VC	−30	9	−26	7
3. 50% VC	−29	9	−31	12
4. 25% VC	−26	9	−35	22
B. MBC	−26	9.7	−22	6

MMF = maximal midexpiratory flow
MIP = maximal inspiratory point
VC = vital capacity
MBC = maximal breathing capacity

varying effort. By plotting flow against volume it is possible to record the maximal inspiratory and expiratory flows that can be achieved at every degree of lung inflation. Additional aspects of this maneuver are discussed elsewhere (1, 7). By maintaining constant calibration factors in a given subject, it was possible to superimpose the figures obtained from the oscilloscope to provide composite graphs of the various maneuvers (figure 1).

It should be noted that the expiratory phase of the maximal effort vital capacity maneuver corresponds to a forced expiratory vital capacity breath. The inspiratory phase may be thought of as a forced inspiratory vital capacity breath.

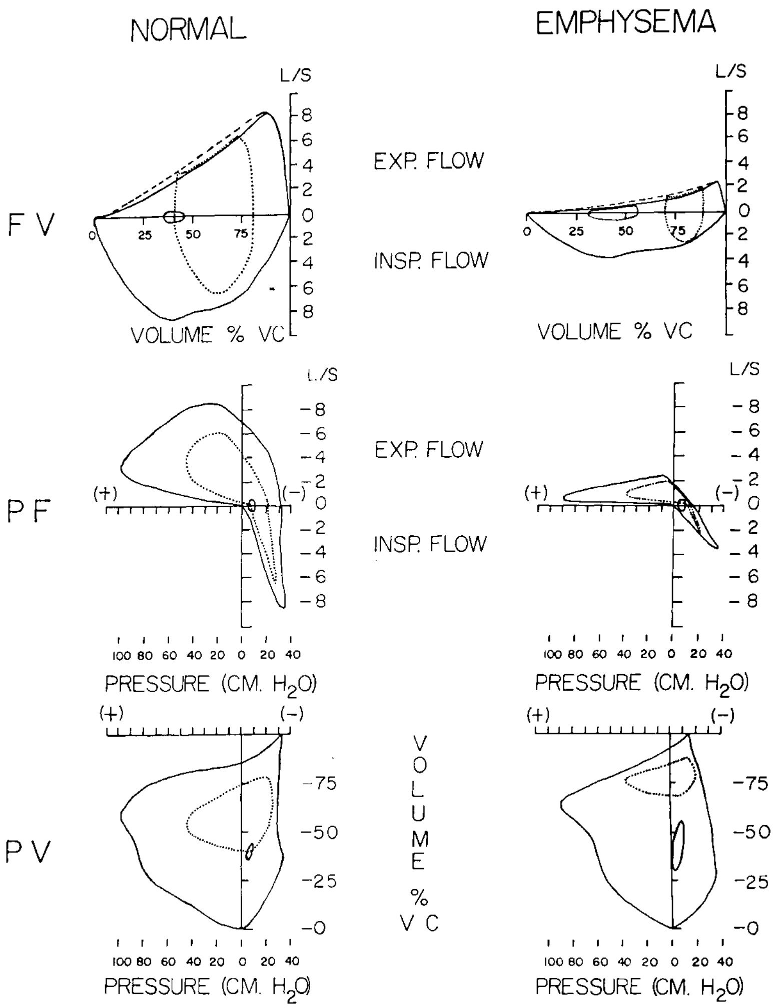

FIG. 1. Composite plots for normal and emphysematous groups. Composite flow-volume (FV), pressure-flow (PF), and pressure-volume (PV) plots for the normal and emphysematous groups. Volume is plotted as percentage of the observed vital capacity. Flow is given in liters per second. The solid line which forms the perimeter of all plots, except the expiratory portion of the FV plot, defines the maximal effort vital capacity (VC) maneuver. Its expiratory segment corresponds to a forced expiratory VC breath. The dashed lines on the expiratory portion of the FV plots depict the course of the maximal flow VC maneuver. The maximal breathing capacity (MBC) breathing is shown by the dotted loops. The small solid loops define resting tidal breathing. In the PV graph the maximal effort VC curve proceeds in a counterclockwise direction. The maximal flow VC maneuver is depicted on only the FV graph.

The inspiratory phases of the maximal effort vital capacity and maximal flow vital capacity maneuvers are identical.

The notations of maximal effort vital capacity, maximal flow vital capacity, forced expiratory vital capacity, and forced inspiratory vital capacity refer to the specific respiratory maneuvers defined above. In this report these terms will also denote the graphic representations in figure 1 of the flow-volume, pressure-flow, and pressure-volume relationships during these maneuvers.

The maximal midexpiratory flow during a forced expiratory vital capacity breath was also measured (8). All volumes were expressed at ambient temperature and pressure saturated with water vapor (ATPS).

The subjects, all of whom were males, were divided into two groups. There were 12 subjects judged to have no significant complaints referable to the cardiopulmonary system. Mild chronic bronchitis was suspected in 4 subjects. Eight subjects were soft-coal miners and 5 of these had roentgenographic evidence of mild pneumoconiosis. The mean age was 48.6 years.

Fourteen subjects were considered to have significant degrees of pulmonary emphysema. The diagnosis of emphysema was based on the history, physical examination, routine pulmonary function studies (forced expiratory vital capacity and maximal breathing capacity), and objective evidence of restricted exercise tolerance. In all cases this diagnosis seemed consistent with the ventilatory mechanics data. All subjects in this group were miners and 5 had mild pneumoconiosis. The mean age was 56.5 years.

Results

Composite traces of the various maneuvers for both groups of subjects are presented in figure 1. These graphs were constructed from mean values for each group. Some of the values and standard deviations pertaining to figure 1 are listed in table 1. Values for maximal expiratory flow during the maximal flow vital capacity are given at 75, 50, and 25 per cent of the vital capacity (6A1-3). Values for maximal flows and pressures during the maximal effort vital capacity are given for the same volume points.

Much of the data in table 1 can be read directly from these traces. From the flow-volume plot the peak expiratory and inspiratory flows may be obtained during the maximal effort vital capacity, maximal flow vital capacity (6B1 and 7A1), and the maximal breathing capacity (6C and 7B). The flow at any volume during each of these maneuvers is also readily obtained (6A1-3, 6B2-4, 7A2-4). The pressure-flow plot also yields the peak flow values, as well as the peak expiratory and inspiratory pressures, during the maximal effort vital capacity (8A1 and 9A1) and maximal breathing capacity (8B and 9B). The static transpulmonary pressures at resting end-expiration and the maximal inspiratory point may be obtained from this plot (5A and 5B). The pressure-volume graph gives the peak expiratory and inspiratory pressures during the maximal effort vital capacity and maximal breathing capacity, the pressure at any volume during these maneuvers (8A2-4 and 9A2-4), and the static transpulmonary pressures at end-expiration and the maximal inspiratory point.

The emphysematous subjects in the study had smaller vital capacities than the normal subjects, but the effective compliance of the two groups was not significantly different (table 1). Striking differences did exist between the groups in terms of flow resistance, the maximal midexpiratory flow, and static transpulmonary pressure at the maximal inspiratory point. The static pressures at resting end-expiration showed little difference. In general, the subjects showed the expected inverse relationship between flow resistance and maximal midexpiratory flow. However, there were two individuals who showed definite reduction in maximal midexpiratory flow despite normal resistance. These subjects had values of 1.7 and 1.0 liters per second and corresponding resistances of 1.7 and 2.1 cm. of H_2O per liter per second.

In terms of pressure, flow, and volume,[5] the most striking difference between the two groups may be seen in the maximal flows developed during certain maneuvers, as indicated in figure 1. The normal subjects developed peak expiratory flows of 8.5 and 6.1 liters per second during the maximal effort vital capacity and maximal breathing capacity, respectively. The emphysematous subjects had corresponding flows of 2.5 and 2.0 liters per second. The flow-volume plots show that this degree of separation persisted throughout the entire expiratory flow-volume courses of these maneuvers.

The volume courses of maximal inspiratory flow for the two groups do not show as marked a separation. Moreover, in emphysema there is a greater reduction in maximal expiratory flow than in maximal inspiratory flow during the maximal effort and maximal flow vital capacity maneuvers. This is best seen at the mid-vital capacity, i.e., 50 per cent of the vital capacity. At this volume in the normal subjects the ratio of maximal expiratory to maximal inspiratory flow during the maximal effort vital capacity was 0.49. This ratio was reduced to 0.18 in the emphysematous group. Comparison of peak flow values (table 1) does not reveal this disproportionate reduction in expiratory flow as strikingly.

From the pressure-flow and pressure-volume plots it is apparent that both groups developed approximately the same transpulmonary pressures during the maximal effort vital capacity

[5] In the study of some respiratory maneuvers, it would be preferable to plot volume as per cent observed or predicted total lung capacity rather than as per cent of observed vital capacity.

and maximal breathing capacity. The volume courses of pressure (pressure-volume graph) were very similar for both groups during the maximal effort vital capacity. Marked variability in absolute pressures among subjects in both groups did occur, however, as evidenced by the large standard deviations (8, 9; table 1).

The volume course of maximal expiratory flow (flow-volume plot) differed from that of maximal inspiratory flow in both groups. During the expiratory phase of the maximal effort vital capacity breath, once peak flow had been attained, a semi-exponential fall in flow occurred with decreasing lung inflation. On the other hand, during the inspiratory phase, flow reached maximal values after inspiration of approximately 35 per cent of the vital capacity, and tended to stay near this level until about 80 per cent of the vital capacity had been inspired. The curve representing the maximal flow vital capacity (dashed line) followed the same course as that of the maximal effort vital capacity throughout inspiration and during early expiration until peak expiratory flow had been attained. Past this point, the maximal flow vital capacity exceeded the maximal effort vital capacity. As is also seen from the flow-volume plots, the expiratory portion of the maximal breathing capacity curves tended to lie between the maximal effort and maximal flow vital capacity curves.

An interesting relationship was seen in the flow-volume plots between the expiratory portion of the tidal breathing curve, on the one hand, and the corresponding segments of the maximal effort and maximal flow vital capacity curves, on the other. In normal subjects, the tidal breathing curve was widely separated from the other traces. In emphysematous subjects, the tidal breath almost coincided with the maximal effort vital capacity curve. In several patients the tidal breath exceeded the maximal effort vital capacity and, in 2 individuals, much of the tidal breathing curve followed the same course as the maximal flow vital capacity.

Discussion

The study of ventilatory mechanics from simultaneously obtained determinations of flow-volume, pressure-flow, and pressure-volume plots has been rewarding. Relating the three variables during various breathing maneuvers allows the characterization of most aspects of the mechanics of breathing. By combining any two sets of plotted data (figure 1), any breathing maneuver may be quantified in terms of all three variables. For example, the interrelationships of pressure, flow, and volume can be determined throughout the entire forced expiratory vital capacity maneuver by relating the flow-volume plot to the pressure-flow graph in terms of corresponding flow values. Thus, in normal subjects, the peak expiratory flow of 8.5 liters per second occurs at 88 per cent of the vital capacity and at a transpulmonary pressure of +23 cm. of H_2O.

Certain plots are particularly valuable in studying specific aspects of ventilatory mechanics. The relationship between tidal breathing and maximal expiratory flow is best visualized from the flow-volume plots which demonstrate in dramatic fashion the limited expiratory flow reserve available to the emphysematous subject. Since the maximal flow vital capacity curve defines the highest expiratory flow that can be obtained at any lung inflation, the emphysematous subject, unlike the normal subject, must in part meet any significant demand for increased ventilation by breathing at a greater degree of lung inflation. Indeed, it has been suggested that the relationship between tidal breathing and the maximal flow vital capacity as obtained from flow-volume plots might serve as an index of severity and disability in emphysema (9).

Several factors that influence the volume ventilated during the maximal breathing capacity test have been studied in detail. These include the rate of breathing, maximal expiratory and inspiratory flow rates (10), and the magnitude of transpulmonary pressure swings (11). However, there has been no evaluation of this test by considering the pressure, flow, and volume variables simultaneously. It is evident (figure 1 and table 1) that normal and emphysematous subjects develop similar pressure swings during this maneuver; hence, an inability to develop normal pressure does not explain the reduced maximal breathing capacity characteristic of emphysema. Although the emphysematous subject tended to perform the maximal breathing capacity test at near-maximal lung inflation, considerable variation was noted in the degree of lung inflation at which subjects in each group performed the test. This fact suggests that prediction of the maximal breathing capacity from some fixed segment of the forced expiratory vital capacity maneuver is of limited value. It is also apparent that the degree of lung inflation at which the test is performed may be a major determinant of the volume ventilated, a consideration generally neglected in previous studies. The flow-volume plot of the emphysematous group may be considered as an example. If the volume per breath of the maximal breathing capacity test is held constant, performing the test at a lesser degree of inflation would reduce the volume ventilated due to the reduced expiratory flow available. Conversely, limitation of maximal inspiratory flow would reduce the volume ventilated if the test were performed at a greater lung inflation. In a given individual, knowing the flow-volume plot of the maximal flow vital capacity, the volume of the maximal breathing capacity breath, and the degree of lung inflation at which the test is performed, the greatest volume that can be ventilated and the rate that must be utilized can be calculated. Thus, the important ventilatory determinants of the maximal breathing capacity test may be studied rather simply and completely from the flow-volume plot. It should be stressed, however, that the physiologic factors determining the rate of breathing, the breath volume, and the degree of lung inflation at which a subject performs the test have not been elucidated.

The relations of volume to flow (flow-volume plot) and to pressure (pressure-volume plot) during a forced expiratory vital capacity breath indicate that the level of expiratory flow during this maneuver is not directly related to the force applied to the lung. The emphysematous group, for example, attained maximal expiratory flow at a transpulmonary pressure of only 8.4 cm. of H_2O. The experimental design of this study did not permit an absolute measurement of the pressures associated with the expiratory phase of the maximal flow vital capacity maneuver. However, preliminary data from related investigations indicate that over the lower 60 per cent of the vital capacity the transpulmonary pressures associated with maximal expiratory flow (maximal flow vital capacity) were approximately only one-fourth of those developed during the forced expiratory vital capacity. Therefore, during this latter maneuver all subjects easily developed pressures in excess of those necessary to produce truly maximal expiratory flow over this volume range. Since the ordinate values of flow for the maximal effort and maximal flow vital capacity are not too different, the forced expiratory vital capacity test should be quite reproducible over this general volume range. This agrees with reported clinical experience (8).

The subjects who developed the greatest inspiratory pressure during a forced inspiratory vital capacity test did not necessarily achieve the highest flow. However, in a given subject at a given lung inflation, the magnitude of inspiratory flow was directly related to the force applied to the lung. This finding had been predicted on the basis of the relative linearity of the pressure-flow relationships during inspiration (7).

In emphysema, attention has been focused primarily on the reduction in maximal expiratory flow characteristic of this condition. However, few data are available on the volume course of this retarded expiratory flow. It is evident from figure 1 and table 1 that comparison of maximal expiratory flows at the mid-vital capacity provides a better separation between normal and emphysematous subjects than does comparison of peak flow values. Thus, during a forced expiratory vital capacity, peak expiratory flow in the patients was 29 per cent of normal, while at 50 per cent of the vital capacity it was only 15 per cent of normal.

It has been known that maximal inspiratory flow is also reduced in emphysema. However, the volume course of this reduced inspiratory flow has not previously been measured. Furthermore, the disproportionate reduction in expiratory flow in emphysema has received little attention. McNeill and associates (12) did compare peak expiratory and inspiratory flows from volume-time curves. As in the present study, they found expiratory flow to be disproportionately reduced in emphysema. However, as noted above and as is evident from the flow-volume plots, the excessive expiratory flow reduction in emphysema is better studied at the mid-vital capacity. The implications of this predominant reduction in expiratory flow in emphysema are apparent from the emphysema flow-volume plot. To increase ventilation significantly above resting levels, these subjects must not only breathe at higher levels of lung inflation but also must make full use of the greater inspiratory flow reserve that is available. In general, the patient must achieve high flows very quickly during inspiration since expiration will proceed at lower flows and consequently occupy more time.

Normal and emphysematous subjects showed little difference in effective lung compliance. A significant reduction in lung elasticity in this disease is revealed, however, when static transpulmonary pressures at maximal lung inflation (maximal inspiratory point) are compared. This important feature of emphysema has received only limited attention (6, 13).

Reductions in maximal expiratory flow are generally attributed to an increase in flow resistance and a decrease in lung elasticity, defects which permit marked narrowing of the bronchial tree at relatively low flow velocities and transpulmonary pressures. The majority of the present subjects fit this concept, but two interesting exceptions were encountered who had decreased maximal midexpiratory flow but normal resistance. The static transpulmonary pressure at the maximal inspiratory point was reduced in one but normal in the other. Thus, it would appear that factors other than elevated flow resistance and reduced lung retractive force were responsible for their diminished expiratory flows. The measurement of such factors has not yet been achieved (13–15). However, the fact remains that a reduction in maximal expiratory flow is not necessarily associated with an increase in flow resistance. This is an important consideration in any attempt to select a single test to detect early cases of emphysema.

The presence of pneumoconiosis in many of the subjects might conceivably have modified the mechanical behavior of the lung. This investigation does not permit any conclusions in this regard. However, a recent study of this problem revealed no correlation between compliance or flow resistance and roentgenographic severity of pneumoconiosis (16).

Summary

A method of studying the simultaneous interrelationships of pressure, flow, and lung inflation is presented. Twelve normal and 14 emphysematous subjects were studied by this integrated approach to ventilatory mechanics.

Values for pressure, flow, and lung inflation during certain clinically important respiratory maneuvers are presented. Such data provide a physiologic basis for the evaluation of many tests of ventilatory function. This is particularly true for tests quantifying maximal flow during forced expiration and for the maximal breathing capacity test.

Certain important physiologic phenomena which have received little attention in the past are particularly well visualized by this technique. For example, in emphysema, flow-volume plots show that maximal expiratory flow is reduced out of proportion to maximal inspiratory flow. Furthermore, the patient with severe emphysema at rest breathes near or at his maximal achievable expiratory flow levels. The effects of these factors on the ventilatory patterns of the emphysematous subject are discussed.

Sumario

Las Interrelaciones de la Presión, la Corriente y el Volumen durante Varias Maniobras Respiratorias en Sujetos Normales y Enfisematosos

Se presenta un método para estudiar las interrelaciones simultáneas de la presión, la corriente, y la inflación pulmonar. Con este aborde integrado a la mecánica ventiladora se estudió a 12 sujetos normales y a 14 enfisematosos.

Se presentan los valores para la presión, la corriente y la inflación pulmonar durante ciertas maniobras respiratorias clínicamente importantes. Eso datos ofrecen una base fisiológica para la justipreciación de muchas pruebas de la función ventiladora. Esto reza en particular con las pruebas que acuantian la corriente máxima durante la espiración forzada y para la prueba de la capacidad respiratoria máxima.

Ciertos importantes fenómenos fisiológicos que han recibido poca atención en el pasado se visualizan en particular bien con esta técnica. Por ejemplo, en el enfisema, las gráficas de volumen-corriente muestran que la corriente espiratoria máxima se reduce fuera de toda proporción con la corriente aspiratoria máxima. Además, el enfermo que padece de enfisema grave en reposo respira casi a, o hasta, los niveles máximos obtenibles de corriente espiratoria. Se discuten los efectos de estos factores sobre los patrones ventiladores del sujeto enfisematoso.

Resume

Les corrélations de pression, débit et volume pendant les différentes manoeuvres respiratoires chez des sujets normaux et des emphysémateux

Les auteurs présentent une méthode d'étude des corrélations simultanées de pression, débit et remplissage du poumon. Il étudia douze sujets normaux et 14 emphysémateux, grace à ce moyen d'approche complet de la mécanique de ventilation.

L'auteur présente des valeurs de pression, de débit, de remplissage du poumon pendant certaines manoeuvres respiratoires importantes en clinique. De telles données offrent une base physiologique pour l'evaluation de nombreux examens de la fonction de ventilation. Ceci est particuliérement vrai pour les examens renseignent sur le débit maximum en expiration forcée et pour l'examen de la capacité maxima de respiration.

Cette technique met particuliérement bien en évidence certains phénomènes physiologiques importants qui ont reçu peu d'attention dans le passé. Dans l'emphysème, par exemple, des tracés débit-volume montrèrent que le débit expiratoire maximum est reduit sans aucune relation avec le débit maximum inspiratoire. En outre, le malade avec un emphysème sévère, respire, au repos, à des valeurs maxima—ou presque—de son débit expiratoire. L'auteur discute les effets de ces facteurs sur les modes de ventilation du sujet emphysèmateux.

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Addendum

Since the preparation of this manuscript, the following studies which utilize the same methods as those in the present report have come to the writer's attention: (*1*) Woldring, S.: The mechanics of breathing: General principles and technique of measurement, Proc Tuberc Res Council (Royal Netherlands Tuberc Ass), 1959, No. 46, 5; (*2*) Burger, H. C.: The significance of the flow/volume diagram in the study of the mechanics of breathing, Proc Tuberc Res Council (Royal Netherlands Tuberc Ass), 1959, No. 46, 28.

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