Some Factors Affecting the Relationship of Maximal Expiratory Flow to Lung Volume in Health and Disease*

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INTRODUCTION

THE FLOW-VOLUME (FV) LOOP WAS introduced by Hyatt and associates[1] in 1958. Its potential as a means of assessing lung function has been discussed.[2-4] There are, however, few reports of its use in clinical studies. The purpose of this study was to add to the data on normal subjects and to quantify the differences between normals and patients with selected types of lung disease.

MATERIAL AND METHODS

Thirty-four normal volunteers from among medical and paramedical staff of the Mayo Clinic were studied. These subjects were free of respiratory disease as judged from history, physical examination, and chest roentgenograms. Forty-three patients were selected from among those who had undergone pulmonary function tests in the course of their medical examination. The patients were divided into three groups on the basis of history, physical examination, and the results of routine pulmonary function tests. Thirteen were placed in the asthmatic group because of a typical history of episodic dyspnea, allergic symptoms, and symptom-free periods during which exercise tolerance was normal. Twenty patients who had obstructive airway disease but no clear-cut allergic history were placed in the obstructive group. The restrictive group was composed of ten patients who showed primarily a reduction in lung volumes and in most instances had evidence

of widespread parenchymal infiltration on chest roentgenograms.

All subjects were studied while seated in a volume-displacement body plethysmograph of the type described by Mead.[7] Volume recorded by the attached spirometer was that due to motion of the thorax and reflects changes in thoracic gas volume. Airflow was recorded at the mouth by a pneumotachograph (Fleisch) with appropriate pressure transducer. In 30 subjects, pressure was recorded from the lower one-third of the esophagus by a latex balloon-catheter system previously described,[8] and lateral oral pressure was subtracted from this to obtain transpulmonary pressure. All signals were recorded simultaneously on a multichannel recorder (Sanborn) and a
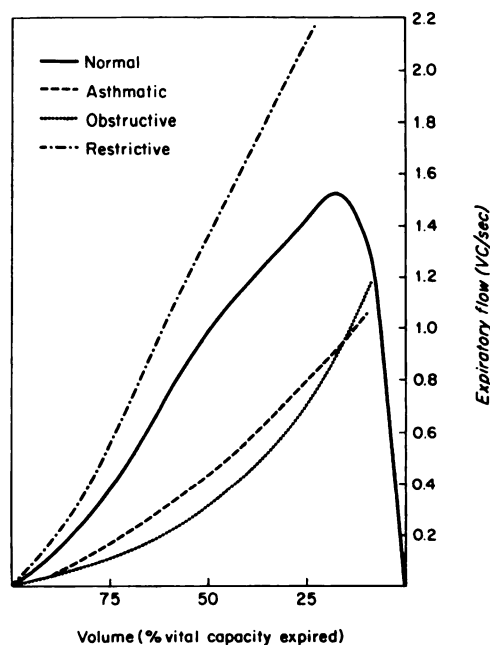

FIGURE 1: Mean flow-volume curves for normal, asthmatic, obstructive, and restrictive groups. Volume is given as percentage of vital capacity expired. Flow is expressed as vital capacities per second (VC/sec). For clarity, the complete FV plot is shown for only the normals. The other plots begin at the greatest expiratory flow achieved.

TABLE 1—MEAN VALUES OF VENTILATORY AND MECHANICAL DATA

Factor	Group			
	Normal	Asthmatic	Obstructive	Restrictive
No. of subjects	34	13	20	10
Height, cm	168	171	173	171
Age, yr	47	45	57	54
Vital capacity, % predicted normal	101	92	67	47
Total lung capacity, % predicted normal	109	119	120	62
No. of subjects	4	6	10	10
Static lung compliance, L/cm H_2O	0.282* (0.092)	0.245 (0.053)	0.385 (0.06)	0.072 (0.017)
Pulmonary airflow resistance, cm H_2O/L	2.2 (0.68)	4.7 (0.94)	5.0 (1.07)	4.3 (0.38)
Lung retractive-force at total lung capacity, cm H_2O	−48 (5.57)	−24 (3.27)	−19 (2.2)	−66 (7.15)

*Number in parentheses is the standard error of the mean.

frequency-modulated magnetic tape recorder (Ampex). Flow-volume and pressure-volume curves were plotted from the magnetic tape on a mechanical X-Y plotter (Moseley) after appropriate reduction in time base.

Flow-volume plots of forced expiratory vital capacity (FVC) maneuvers were obtained on all subjects. At least three FVC efforts were recorded and the largest of these was analyzed. From these, the flow at 50 per cent of vital capacity expired ($\dot{V}_{50}$) was measured and corrected for vital capacity ($\dot{V}_{50}$/FVC) to adjust for differences in lung size. The slope of the flow-volume curve between the points corresponding to 50 and 75 per cent of vital capacity expired (FV slope) was obtained from the FV plot of a forced expiration. Total lung capacity (TLC) was measured by modification of the technique of Du-Bois and co-workers.[8] In 30 subjects, the static pressure-volume diagram of the lung over the range from total lung capacity to near residual volume was obtained by the method of Stead and associates.[10] Lung re-
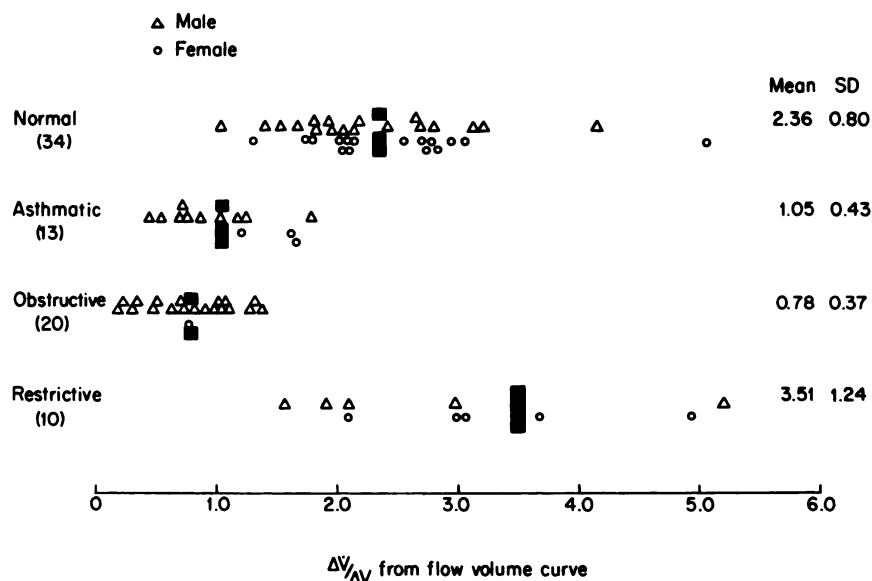

FIGURE 2: Frequency plot of flow-volume slope for each group of subjects. Number of subjects in each group is shown within parentheses. Solid bars are placed at the mean values for each group.

tractive force at TLC and static lung compliance for the portion of the expiratory limb in the tidal volume range were calculated from the pressure-volume curve. In the same subjects, pulmonary airflow resistance was measured during quiet breathing by the method of Frank and co-workers.[11]

Two time constants of lung emptying were calculated. In one case, the ratio of change in volume to change in flow over the 50 to 75 per cent expired volume range of the FVC was measured from the FV plots. This relationship has the units of time:

$$\frac{V}{\dot{V}} = t,$$

in which V is lung volume in liters, $\dot{V}$ is flow in liters per second, and t is time in seconds. An additional time constant was calculated from the product of pulmonary airflow resistance and static lung compliance, both measured in the tidal range of breathing. This is illustrated by the equation:

$$RC = t,$$

in which R is pulmonary airflow resistance in centimeters of H_2O per liter per second, C is lung compliance in liters per centimeter H_2O, and t is time in seconds.

RESULTS

Data on age, height, lung volume, and mechanical properties for the subjects are shown in Table 1. It should be noted that the mechanical properties were not measured in all subjects. When the patient groups were compared with the control group, static lung compliance was found to be increased in the obstructive group and decreased in the restrictive group while no striking change was observed in the asthmatic group. Pulmonary airflow resistance was elevated in all of the patient groups. Lung retractive force at TLC was diminished in both the asthmatic group and the obstructive group and increased in the restrictive group.

FV curves plotted from mean data for each group are illustrated in Fig. 1. Volume is presented as a percentage of the vital capacity exhaled. We attempted to normalize expiratory flow to correct for the differences in lung size by dividing flow by the subject's observed vital capacity. Thus expiratory flow is presented as vital capacities expired per second (VC/sec). For the sake of clarity the complete curve for the normals only is shown. Inspection of these curves reveals differences in slope between the normal and patient groups. The asthmatic and the obstructive group each had a slope that was less steep than the slope of the normal group. The restrictive group, despite its marked reduction in absolute vital capacity, had a steeper slope than the normal.
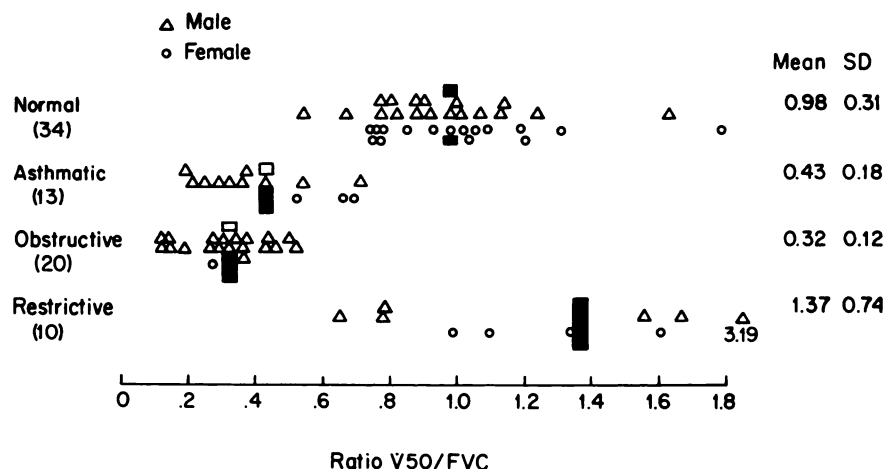

FIGURE 3: Frequency plot of ratio of flow at 50 per cent of vital capacity expired to forced vital capacity for each group. Number of subjects in each group shown within parentheses. Solid bars are placed at the mean values for each group.

Figure 2 is a frequency diagram of the FV slope for each group studied. The mean slope for the entire normal group was 2.36 (SD=0.80). Analyzed separately, the mean slope for men was 2.53 and for women 2.22, a difference that was not significant (P>0.20). The asthmatic group had a mean slope of 1.05 (SD=0.43), whereas the mean slope for the obstructive group was 0.78 (SD=0.37). The restrictive group had a slope of 3.51 (SD=1.24), but it can be seen that there was considerable scatter within the group. The FV slope was effective in discriminating between the normal group and the patient groups (asthmatic P<.001; obstructive P<.001; restrictive P<.01), but did not distinguish between the asthmatic and the obstructive group (P>.50).

The ratio of V_{50} to FVC was calculated to correct the flow at mid-vital capacity for the differences in vital capacity between subjects. A frequency diagram for these data is shown in Fig. 3. The mean values for each group were: normal 0.98 (SD= 0.31), asthmatic 0.43 (SD=0.18), obstructive 0.32 (SD=0.12), and restrictive 1.37 (SD=0.74). No significant difference was

found between the normal men and women (P>.40). This ratio effectively discriminated between the normal and patient groups (asthmatic P<.001; obstructive P<.001; restrictive P<.02). The ratio, however, did not clearly distinguish between the asthmatic group and the obstructive group (P>.20).

The time constant of lung emptying derived from the FV curve was plotted against pulmonary airflow resistance for subjects from each group (Fig. 4). There is a general tendency for the time constant to increase with increase in flow resistance, but the scatter is considerable and the number of subjects small. In Fig. 5, the FV time constant is plotted against static lung compliance. Increases in compliance tend to be associated with an increase in time constant, but the association is weak. In Fig. 6, the FV time constant is plotted against the time constant derived from the product of pulmonary airflow resistance and static lung compliance. There is a rather strong association between these two methods of estimating the time constant of lung emptying.
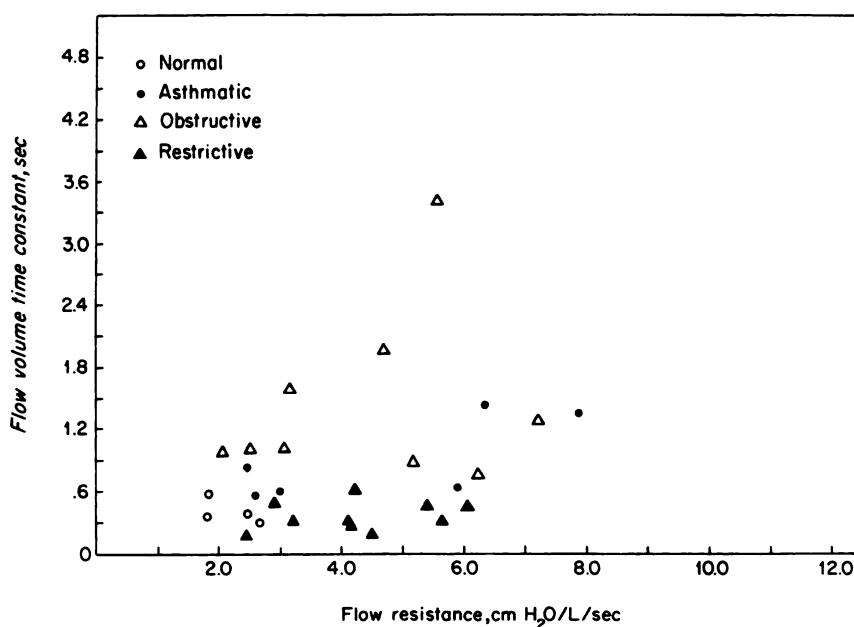

Figure 4:   Flow-volume time constant in seconds versus pulmonary airflow resistance in centimeters H_2O per liter per second.
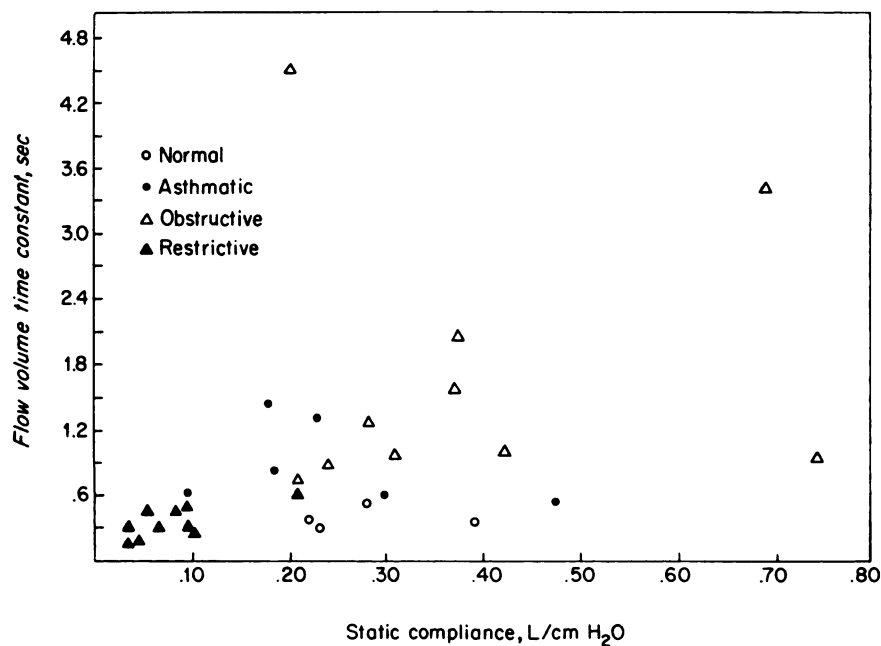
FIGURE 5:   Flow-volume time constant in seconds versus static lung compliance in liters per centimeter H₂O.

DISCUSSION

The technique of plotting flow against volume during the FVC maneuver (FV curve) has provided useful insight into the

overall mechanical behavior of the lung.[5,12] In addition, Fry[4] has indicated that analysis of the curve based on a suitable mathematical model of the lung should yield in-
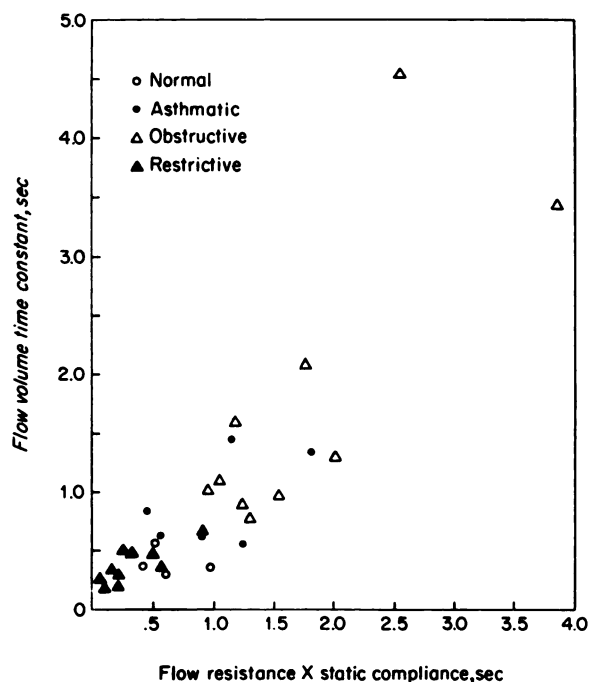

FIGURE 6:   Flow-volume time constant in seconds versus the product of pulmonary airflow resistance and static lung compliance in seconds.

formation regarding the behavior of the various mechanical elements of the system. Such analysis, however, has not yet been published.

The present study deals with empiric approaches to analyzing the flow-volume plot of a forced expiration. The relatively simple method of calculating the ratio of the flow at 50 per cent of the VC to the FVC separated the obstructive groups from the normals. This measurement, however, requires that the full FVC be delivered and is susceptible to variability on this basis. To the extent that the FV plots are nearly linear (Fig. 1), one would expect this measure to provide essentially the same information as the FV slope measurement, which was seen to be the case.

Measurement of the slope of the FV curve was originally suggested by Dayman,[13] who found the slope of the FV curve to be linear over most of its volume course. As is seen in Fig. 1, the middle portions of the curves for the normal group and the restrictive group are nearly linear while the curves for the asthmatic group and the obstructive group are more curvilinear. We chose to measure the average slope over the volume range of 50 to 75 per cent of the FVC where the curves tended to be most linear. As is evident from Fig. 2, this measurement separated the normal group from the asthmatic and the obstructive groups, but, as with the $\dot{V}_{50}$/FVC, failed to distinguish between the asthmatic group and the obstructive group. This is not surprising since the slope reflects, in large part, airway obstruction that may be due to any of a number of factors, among which are bronchospasm, mucosal edema, and airway collapse.

Our values for the slope of the FV curve in both normals and patients agree well with those reported by Dayman[13] and Macklem and Becklake.[14] There was no significant difference found between normal men and women.

Several studies[9,15-17] have suggested that the reciprocal of the slope of the FV plot of a forced expiratory vital capacity breath might be equated to the mechanical time constant, that is RC product, of lung emptying. In the present study, we have explored the usefulness of this concept in normal and diseased subjects. We note from Figs. 4 and 5 that the association between the FV time constant and flow resistance or static compliance, considered separately, is not strong. That the time constant calculated from the FV slope does reflect the mechanical time constant of lung emptying is suggested by Fig. 6. Here a time constant calculated from the product of resistance and static compliance, measured independently, agrees with that estimated from the inverse of the FV slope. This also suggests that the slope of the FV plot of a FVC maneuver is primarily determined by the resistance and static compliance of the lung. Although a number of assumptions are involved in applying this type of analysis to the FV curve, viewing the reciprocal of the slope of the FV curve as a time constant of lung emptying does focus attention on the important physiologic determinants of the curve. This consideration coupled with the relative ease of measuring the slope recommends its continued use as a method of quantifying the FV curve. The small number of subjects in this study precludes any firm statements regarding the trends noted. Further study of larger groups of subjects will be required before it is possible to establish the merit of viewing the FV slope as equivalent to the time constant of lung emptying.

SUMMARY

Flow-volume curves of forced expiration were obtained in normal subjects and in patients with various lung diseases. The slope of the curve from 50 to 75 per cent of vital capacity expired for normal subjects had a mean value of 2.36 liters per second per liter exhaled. No significant difference was found between the mean slopes for normal men and normal women. The FV slope was reasonably effective in distinguishing the normal subjects from those with lung disease but did not provide a clear-cut separation between the subjects

with asthma and those with other obstructive disease.

A time constant of lung emptying, calculated as the reciprocal of the FV slope, correlated with the product of pulmonary airflow resistance and static lung compliance. This relationship was valid for a group of patients in whom resistance or compliance, or both, was altered.

RESUMEN

Hemos obtenido curvas de flujo/volumen en expiración forzada en pacientes con varios tipos de enfermedades respiratorias. El gradiente de la curva entre el 50 y el 75 por ciento de la capacidad vital expirada tiene, en sujetos normales, un valor promedio de 2.36 litros por segundo por litro expirado. No se observaron diferencias de significación entre los gradientes promediales de hombres y mujeres. El gradiente F-V constituye un indicio razonablemente seguro para diferenciar los sujetos afectos de enfermedades respiratorias de los normales, pero no para separar el asma de las demas afecciones respiratorias obstructivas. Es factible obtener una constante de vaciamiento pulmonar correlacionando la recíproca del gradiente FV con el producto de la resistencia pulmonar al flujo respiratorio por la elasticidad estática del pulmón. La validez de esta relación ha sido comprobada en un grupo de sujetos en los que dicha resistencia o la elasticidad o ambas eran normales.

RESUMÉ

Les courbes flux-volume lors de l'expiration forcée ont été obtenues chez des sujets normaux et chez des malades porteurs de diverses affections pulmonaires. La pente des courbes allant de 50 à 75% de la capacité vitale expirée par un sujet normal a une valeur moyenne de 2,36 litres par seconde et par litre expiré. Il n'y a aucune différence entre les pentes moyennes des hommes et celles des femmes. La pente flux volume permet raisonnablement de distinguer les sujets normaux des malades, mais ne permet pas une séparation nette entre les sujets atteints d'asthme et ceux qui sont atteints d'autres affections obstructives. Une constante de temps de vidange pulmonaire calculée comme réciproque de la pente flux-volume, a été rapportée à la résistance pulmonaire et à la compliance statique du poumon. Cette relation est valable pour ce groupe de malades pour qui résistance ou compliance ou les deux à la fois se trouvent être pertubées.

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