

# Factors determining maximum inspiratory flow and maximum expiratory flow of the lung

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The factors determining maximum expiratory flow and maximum inspiratory flow of the lung are reviewed with particular reference to a model which compares the lung on forced expiration to a Starling resistor. The theoretical significance of the slope of the expiratory maximum flow-volume curve is discussed. A method of comparing maximum expiratory flow with maximum inspiratory flow at similar lung volumes is suggested; this may be applied either to a maximum flow-volume curve or to a forced expiratory and inspiratory spirogram.

During the last 15 to 20 years a number of tests based on the forced vital capacity manoeuvre have come into widespread use for the assessment of the ventilatory function of the lungs. Originally the forced vital capacity manoeuvre was introduced as a substitute for measurement of the maximum breathing capacity, and to a large extent the use of such tests as the forced expiratory volume in one second (F.E.V.<sub>1.0</sub>) has continued to be empirical and descriptive. In 1958 Hyatt, Schilder, and Fry examined the factors determining maximum expiratory flow and demonstrated that this flow was extremely dependent on lung volume. As a result of their analysis they introduced a new test of ventilatory function, the plotting of expiratory flow against lung volume during a forced vital capacity manoeuvre. The advantages in plotting this maximum flow-volume (M.F.-V.) curve were that a large part of it was relatively uninfluenced by the subject's effort or by the resistance of the upper airways. This test appears to have been used very little outside the United States of America. More recently, further studies have been made which help to elucidate the physiological factors responsible for the shape of the M.F.-V. curve and reinforce the claims made for it by the original authors.

In the present paper the factors determining maximum flow are reviewed and the theoretical significance of two measurements derived from the M.F.-V. curve is discussed.

In the following paper (this journal, p. 38) a comparison of the M.F.-V. curves obtained in healthy subjects and in subjects with emphysema, severe asthma, and fibrosis of the lungs is presented.

## FACTORS DETERMINING MAXIMUM FLOW AT A GIVEN LUNG VOLUME

**ISO-VOLUME PRESSURE-FLOW CURVES** These curves were introduced by Fry and Hyatt (1960), who measured oesophageal pressure and the simultaneous flow during a series of vital capacity manoeuvres made with varying effort. From these records they constructed plots of the relation between oesophageal pressure and flow at selected lung volumes. For the present purpose it is more useful to plot the actual driving pressure—alveolar pressure—against flow. Alveolar pressure equals, to a close approximation, the sum of the pleural (or oesophageal) pressure and the pressure of elastic recoil of the lung ( $P_{el}$ ) at the volume considered. An alveolar pressure-flow plot for a normal subject studied at 50% vital capacity is shown in Figure 1. While inspiratory flow goes on increasing until the subject reaches his most negative value of alveolar pressure ( $P_{alv,min}$ ), on expiration flow at first increases with increasing alveolar pressure, but, when a critical level of alveolar pressure is generated ( $P_{alv'}$ ), maximum expiratory flow (M.E.F.) is reached. With further increases in alveolar pressure expiratory flow remains at the maximum level or is even slightly reduced. Similar relationships are found in disease except that in some subjects with emphysema expiratory flow is considerably below the maximum level when alveolar pressure is high. Since airways resistance equals the ratio of alveolar pressure over flow it is represented on this curve as the reciprocal of the slope of the line from the origin to the appropriate point on the pressure-flow curve.

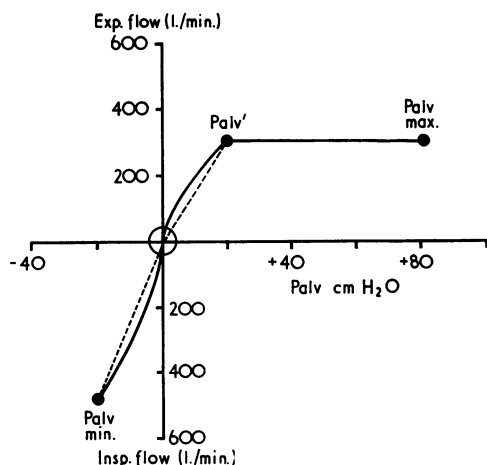


FIG. 1. Diagrammatic iso-volume pressure-flow curve for a normal subject at 50% vital capacity. Flow on vertical axis, alveolar pressure on horizontal axis. The slopes of the interrupted lines equal the reciprocal of the airways resistance at driving pressures of  $Palv'$  and  $Palv,min.$  Mouth pressure is assumed to equal atmospheric pressure.

From these relationships simple equations predicting the values of maximum inspiratory flow and maximum expiratory flow at 50% of the vital capacity ( $M.I.F._{50\%}$ ,  $M.E.F._{50\%}$ ) can be written.

$$M.I.F._{50\%} = \frac{Palv,min}{Raw,i} \quad (1)$$

where  $Raw,i$  is inspiratory airways resistance at a driving pressure of  $Palv,min$

$$M.E.F._{50\%} = \frac{Palv'}{Raw,e} \quad (2)$$

where  $Raw,e$  is expiratory airways resistance at a driving pressure of  $Palv'$ .

Thus while  $M.I.F._{50\%}$  is critically dependent on the effort employed by the subject,  $M.E.F._{50\%}$  is only effort dependent to the extent that an alveolar pressure of at least +20 cm.  $H_2O$  must be developed, which compares with the average of +82 cm.  $H_2O$  which can be generated by a healthy subject on maximum effort (Hyatt, 1961).

Combining equations (1) and (2),

$$\frac{M.E.F._{50\%}}{M.I.F._{50\%}} = \left( \frac{Palv'}{Palv,min} \right) \cdot \left( \frac{Raw,i}{Raw,e} \right) \quad (3)$$

Equation (3) shows that conclusions about the relative change in inspiratory and expiratory resistance can be drawn from measurements of maximum flow only if there are no changes in the ratio  $Palv'/Palv,min$ .

If iso-volume pressure-flow curves are constructed for different lung volumes it is found that they are of a similar shape over almost all the vital capacity in patients with airways obstruction and over the lower 70% of the vital capacity in healthy subjects. Although of similar contour, the values of  $Palv'$  and  $M.E.F.$  become progressively smaller with declining lung volumes. At volumes greater than 70% of the vital capacity in health expiratory flow continues to rise with increases in alveolar pressure, so that at these volumes expiratory flow is effort dependent.

**DETERMINANTS OF  $Palv'$  AND  $M.E.F.$ : THE 'STARLING RESISTOR' ANALOGY** Two broadly similar attempts to analyse the factors determining  $M.E.F.$  and  $Palv'$  in health and in various types of airways obstruction have been published recently (Mead, Turner, Macklem, and Little, 1967; Pride, Permutt, Riley, and Bromberger-Barnea, 1967). These analyses propose that the lung can be considered to act as a 'Starling resistor' when  $M.E.F.$  is reached during a forced expiration.

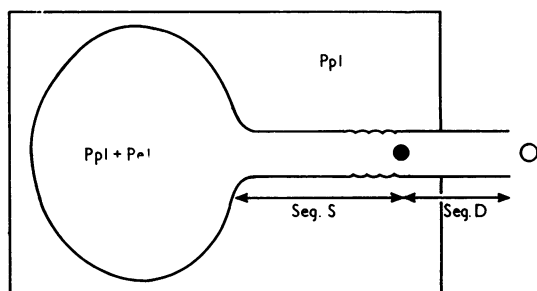


FIG. 2. Model of lung as a Starling resistor. The alveoli are represented as a common sphere emptying by a single airway. Part of the airway (indicated by the wavy lines) is regarded as potentially collapsible. The box represents the thorax.

In the model (Fig. 2) developed by Permutt and Riley part of the airway is regarded as being collapsible and the analogue of the thin-walled tube in the resistor used to control blood pressure in a Starling heart-lung preparation. This collapsible airway is surrounded by pleural pressure ( $Ppl$ ). During expiration the airway pressure will drop from ( $Ppl + Pel$ ) in the alveoli to zero at the mouth. At a certain level of alveolar pressure (which corresponds to  $Palv'$  in Figure 1) pleural pressure will exceed the pressure within the collapsible airway by a sufficient amount for the airway to narrow critically and limit flow. The

collapsible airway will not actually close; if it did the airway pressure on the alveolar side of the point of closure would rise to equal alveolar pressure and the airway would reopen. Since the collapsible airway can neither close completely nor remain wide open, a narrow orifice forms close to its downstream end (marked by the solid circle in Fig. 2) and this acts to limit flow. When this point of critical narrowing develops, it divides the airway into two functional segments—the S segment from alveoli to the point of critical narrowing, and the D segment from this point downstream to the mouth. Expiratory flow from such a system will reach a maximum when the resistive pressure drop down the S segment equals  $(P_{el} - P_{tm}')$ , where  $P_{tm}'$  is the value of transmural pressure at which the airway narrows and forms a flow-controlling orifice. Transmural pressure is considered to equal the lateral airway pressure minus pleural pressure. Once critical narrowing has occurred, further increases in alveolar pressure at the same lung volume do not result in any increase in flow and will be dissipated across segment D while the pressure drop down segment S will remain unchanged at  $(P_{el} - P_{tm}')$ . Hence elevation of alveolar pressure above  $P_{alv}'$  will result in progressive compression of the D segment (the extent of which will depend on the properties of the airways of that segment) but the transmural pressure relations in segment S will be unchanged. The available evidence suggests that segment S probably extends from alveoli to lobar bronchi or the carina and  $P_{tm}'$  probably lies between  $-10$  and  $0$  cm.  $H_2O$  in normal subjects, but little is known about these values in disease. A markedly negative value of  $P_{tm}'$  indicates an airway which resists compression, while a  $P_{tm}'$  close to zero indicates an airway which collapses readily, whether due to weakness of its wall or of its supports, or because closure is aided by an increase in bronchial muscle tone.

From this analogue equations can be developed predicting the values of  $P_{alv}'$  and M.E.F.

$$P_{alv}' = (P_{el} - P_{tm}') (I + R_d/R_s) \quad (4)$$

where  $R_d$  and  $R_s$  are the expiratory airways resistances of segment D and S respectively at a driving pressure of  $P_{alv}'$ .

$$M.E.F. = (P_{el} - P_{tm}')/R_s \quad (5)$$

In equation (5) M.E.F. refers to the flow achieved when the pressure-flow curve shows a plateau of expiratory flow. Hence this equation holds good only at volumes below about 70% of the vital capacity in healthy subjects. Inspection of

the equation shows that M.E.F. at these lung volumes is independent of upper airways resistance, as was pointed out by Fry and Hyatt (1960).

Finally, it is possible from this analogue to derive the relationship between M.E.F. and vital capacity ( $V$ ).

Since  $P_{el} = V/C_L$ , where  $C_L$  is the static lung compliance, equation (5) may be rewritten

$$M.E.F. = \frac{V}{C_L R_s} - \frac{P_{tm}'}{R_s} \quad (6)$$

$P_{tm}'/R_s$  is probably a constant fairly independent of lung volume at least at volumes greater than 25% vital capacity. Hence at lung volumes between 25% and 70% of the vital capacity the  $\Delta M.E.F./\Delta V$  slope will approximate to  $1/C_L R_s$ .

The model proposed by Mead *et al.* (1967) differs chiefly in not attempting to consider the effects of changes in  $P_{tm}'$  of the airways and in regarding all airways which are dynamically compressed on expiration as comprising the Starling resistor.

#### THE NORMAL MAXIMUM FLOW-VOLUME CURVE

In conventional spirometric tests volume is plotted against time. To obtain flow-volume curves it is necessary to measure both volume and instantaneous flow rate versus time. If these two measurements are obtained on a strip of recording paper, volume and flow can then be read off at frequent time intervals and plotted against each other on graph paper. However, it is quicker and more accurate to plot the simultaneous values of flow and volume against each other directly on a X-Y recorder.

A curve obtained with a maximum effort vital capacity manoeuvre in a young healthy subject is shown in Figure 3. On expiration, starting from the position of full inspiration (total lung capacity, T.L.C.) flow rapidly increased to a peak level which corresponds to the flow measured by a Wright peak flow meter. Flow then declined in a nearly linear fashion until it reached zero at residual volume (R.V.). On inspiration the curve was sinusoidal with a much broader plateau of maximum or near maximum flow. The striking feature of the curve is the tremendous variation of M.E.F. with lung volume.

In the healthy subject iso-volume pressure-flow curves usually show a plateau of expiratory flow at the maximum level when alveolar pressure is raised above  $P_{alv}'$ . Consequently maximum effort vital capacity manoeuvres will result in maximum expiratory flow. In some subjects with airways

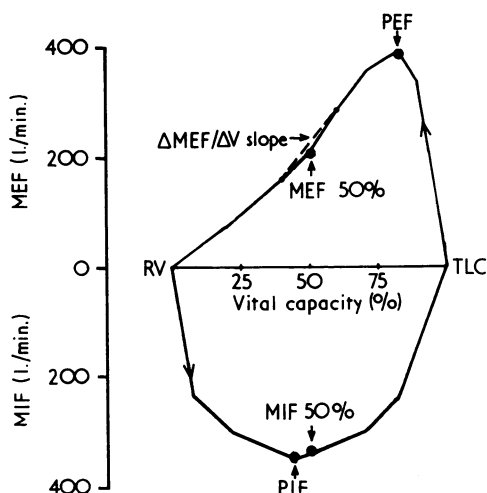


FIG. 3. Normal M.F.-V. curve. Flow in litres/minute is plotted on the vertical axis, lung volume (expressed as % vital capacity) on the horizontal axis. Expiration is shown on the upper part and inspiration on the lower part of the curve. Inscription of the curve starts from the position of full inspiration (T.L.C.) and zero flow. The subject then makes a forced expiration and flow rapidly increases (indicated by arrow pointing upwards) to a peak value (P.E.F.). Expiratory flow then steadily decreases until flow is zero again at R.V. The subject next makes a maximum inspiration, inspiratory flow increases (arrow pointing downwards), reaches a peak (P.I.F.), and then declines until it becomes zero at T.L.C. See text for explanation of the various measurements obtained from these curves.

obstruction, however, there is a substantial drop in flow at a given volume when alveolar pressure is raised above  $P_{alv}'$ . In these subjects maximum effort vital capacity manoeuvres will not result in maximum expiratory flow and a distinction has to be drawn between the maximum effort flow-volume curve (which is the analogue of the  $F.E.V_{1.0}$ ) and the true maximum flow-volume curve which will only be obtained by trial and error with submaximum efforts.

In relating M.E.F. to the simultaneous lung volume (as in equation (6) above), if volume change is indicated in the usual way by an external spirometer the lung volume will be overestimated during a forceful expiration, as the effect of a high pleural pressure in compressing the lung will not be taken into account (Ingram and Schilder, 1966). This effect will be particularly marked in subjects with severe airways obstruction who generate high pressures on forced expiration and have large lung volumes. This error in volume estimation may also account for some of the

apparent tendency for flow to decline on an iso-volume pressure-flow curve at high alveolar pressures in subjects with emphysema.

**MEASUREMENTS FROM THE MAXIMUM FLOW-VOLUME CURVE** Measurements of various parts of the flow-volume curve have been suggested as useful tests of ventilatory function, and these have been summarized by Hyatt (1965). In the following paper we have made two measurements from the maximum flow-volume curves which we believed to have some physiological significance.

*The  $\Delta M.E.F./\Delta V$  Slope* We believe that this slope is related to the intrapulmonary airways resistance and to the lung compliance (see equation (6) above).

We have estimated this slope over the middle range of the vital capacity because this is the volume over which we have most confidence in its physiological significance. We have arbitrarily measured the change in flow between 60% and 40% of the vital capacity in order to obtain the slope, and this will have resulted in some inaccuracies when the slope is curvilinear, as in Figure 2.

*The  $M.E.F_{.50\%}/M.I.F_{.50\%}$  Ratio* We have measured maximum flows in inspiration and expiration at 50% of the expiratory vital capacity to obtain some estimate of the relative degrees of inspiratory and expiratory obstruction. It can be seen from Figure 3 that in the healthy subject M.E.F. exceeds M.I.F. in the upper 25% or so of the vital capacity, but that the reverse is true over the lower 75% of the vital capacity. Because of this complicated relationship we felt it was necessary to compare the flows at a fixed lung volume. We chose 50% of the vital capacity because this point is on an effort independent part of the expiratory curve and away from the part of the inspiratory curve where there is a rapid acceleration or deceleration of flow. The limitations of the  $M.E.F_{.50\%}/M.I.F_{.50\%}$  ratio in comparing expiratory with inspiratory resistance are shown by equation (3) above. These limitations are shared by previous techniques of comparing forced expiration and forced inspiration, such as the ratio of maximum expiratory and inspiratory flow rates (Comroe, Forster, DuBois, Briscoe, and Carlsen, 1962), the ratio of the  $F.E.V_{1.0}$  to the forced inspired volume in one second, and the ratio of peak expiratory flow to peak inspiratory flow (Nairn and McNeill, 1963). These previously described techniques have two additional disadvantages. First, measurements are made at

time when flow is rapidly accelerating, and hence they are particularly dependent on the effort applied by the subject, especially at the onset of inspiration. Secondly, they all compare expiratory flow close to T.L.C. with inspiratory flow measured at a smaller lung volume.

A close approximation to the  $M.E.F._{.50\%}/M.I.F._{.50\%}$  ratio derived from the maximum flow-volume curve can be obtained from forced expiratory and inspiratory spiograms by comparing the maximum mid-expiratory flow (M.M.E.F.) (Leuallen and Fowler, 1955) with maximum mid-inspiratory flow (M.M.I.F.). Both flows would be measured as mean rates between 75% and 25% of the vital capacity. The  $\Delta M.E.F./\Delta V$  slope over this part of the vital capacity is usually fairly linear (at least in healthy subjects and in patients with fibrosis or with severe airways obstruction) so that M.M.E.F. would be close to  $M.E.F._{.50\%}$ ; in inspiration there is usually little change in flow over this part of the vital capacity, so that M.M.I.F. would be close to  $M.I.F._{.50\%}$ . The accuracy of both measurements would be considerably increased by running the kymograph at a faster speed than is used for the  $F.E.V._{1.0}$ . This comparison, like all measurements of maxi-

mum inspiration, will still depend critically on the patient's effort and the apparatus resistance, but will not be so sensitive to the rate at which inspiration is started as the maximum inspiratory flow rate and  $F.I.V._{1.0}$ .

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