A Method of Assuring Maximal Flow in Forced Expiratory Maneuvers*

Bruce J. Sobol, M.D., F.C.C.P.

The most common forms of pulmonary function testing require a forced expiratory effort, recorded either as a forced vital capacity or a maximum expiratory flow volume curve. Proper performance is always in doubt, with regard to the volume used as well as the flow rate. This work offers a practical approach to assuring maximal flow, at least in the later portion of the expiratory curve. During the later portion of the curve, the airways behave as a Starling resistor. One feature of such a resistance is that the addition of a downstream resistance does not alter flow. If a resistance is rapidly added and removed at the mouth and flow does not change, then the airways are behaving as Starling resistors and maximum flow has been achieved. This approach appeared validated by the following: 1. During the later portion of the expiratory effort, flow was altered only during efforts which were consciously limited by the subject. 2. These consciously limited efforts also resulted in lower flow rates than when the Starling effect was operative. 3. The early, or effort-dependent portion of the curve, is altered by the resistor. 4. Beginning the forced expiratory effort at something less than total lung capacity truncates or eliminates the portion of the curve altered by the external resistance.

The most commonly used discriminatory test of pulmonary function is the forced expiratory volume, recorded either as the forced vital capacity (FVC) or as the maximum expiratory flow volume curve (MEFV). However, the forced expiratory volume suffers from two major drawbacks: (1) the uncertainty that the maximum volume has been expelled; and (2) whether or not an optimum expiratory effort was made. The present work concerns the latter problem, whether or not an optimum effort was made.

In 1961, Hyatt and Fry1 pointed out that with the exception of the earliest portion of the expiratory flow curve, for each lung volume there is an optimal effort so that additional effort does not result in any increment in flow. Subsequent work has confirmed their finding.2 Other workers have accounted for this maximal maintainable expiratory flow by likening the airways to Starling resistors3-5 during the later portion of the expired volume.

The two factors which characterize a Starling resistor are: (1) an increase in upstream pressure does not result in an increase in flow; and (2) within limits, altering downstream resistance does not alter flow. A great deal of work has been done in the study of the first feature. Unfortunately, the techniques involved do not lend themselves to widespread application, since they require the use of the esophageal balloon for the determination of the forcefulness of the expiratory effort.

The work presented here utilizes the second feature of the Starling resistor, that altering downstream resistance does not alter flow. The technique is a noninvasive one, requiring only measurements made at the mouth. The subject expels the entire expiratory volume through a flow meter and into a device which rapidly introduces and removes a resistance. If an optimal effort has been made by the subject, then introduction and removal of the resistance results in no change in flow during the later portion of the flow curve. During this later portion, an optimal effort causes the airways to behave as

*From the Cardiopulmonary Laboratory, Grasslands Hospital, Valhalla, New York; and the Department of Medicine, New York Medical College.
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Reprint requests: Dr. Sobol, Grasslands Hospital, Valhalla, New York 10595
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Starling resistors and as long as no change in flow is seen with this alteration in resistance at the mouth, both optimal effort and maximal flow have been assured. As a corollary, flow during the effort-dependent early portion of the expiration will always be altered by the introduction and removal of a resistor, since the airways do not behave as a Starling resistor during this portion of the curve, regardless of effort.

Because of the high flow rates and pressure to which the device is subjected during a forced expiratory effort, its configuration has been changed since the previous work.6,7 However, the principles of the technique are the same, i.e., the addition of a resistor at the mouth will reduce flow from the mouth proportional to the relationship of the added resistor and the subject's respiratory resistance. The theory need not be restated here. However, in addition to the square wave deviation of flow produced by adding and removing the resistor (Fig 1A, B), there may be transient alterations in flow which bear on the application of the device described here and will be reviewed.

As a resistance is added at the mouth not only is flow diminished, but intraluminal pressure, including the mouth, is increased during expiration and decreased during inspiration. During expiration as intraluminal pressure is increased, the airways, being somewhat compliant, tend to increase in bore, becoming more capacious. The additional air they take up reduces flow through the flow meter for a transient period by a like amount. As the resistance is removed, the airways return to their normal bore and release the stored air, which then transiently increases flow through the flow meter. During inspiration, the addition of the resistance at the mouth produces an increase in the negative pressure in the

Figure 1. Illustration of types of patterns produced when known resistance (K) is added and removed in series with unknown resistance (X). A. Ratio of flows with K in or out of circuit illustrates ratio of height to trough of square waves in determining respiratory resistance. B. Illustrates that determination of respiratory resistance is not function of driving pressure (alveolar pressure), and technique is applicable during changing rates of air flow as occur in normal breathing. Principles of technique used to determine respiratory resistance have been dealt with previously.6,7 C. Flow pattern when resistance is "infinite" and there are distributed compliant elements between X and ground (ambient pressure). No square wave deviation is seen with addition and removal of K. In lung, "spikes" are considered due to the compliance of airways which alternately store and release air as volume of airways change, due to intraluminal pressure changes induced by introduction and removal of K. D. Combination of high resistance with distributed compliant elements as in C.

Figure 2. Flow meter used records both inspiration (I) and expiration (E) in same direction. A. Patient who had mild elevation of airways resistance by body plethysmograph and mild elevation of respiratory resistance by this technique. Note that both in inspiration and expiration there is superimposition of "spikes" on square waves as illustrated in Figure 1D. B. Subject with no square waves during expiration (except for first one or two oscillations) similar to illustration in Figure 1C.
airways, tending to reduce their bore. The air thus released is released to the alveoli, reducing the inflow of air through the mouth and, therefore, through the flow meter. As the resistance is removed, the airways enlarge and assume their normal cross-section. This increase in air comes through the mouth and is registered as a transient increase in flow. Thus, superimposed on the changes in flow produced by the addition and removal of a resistor are transient alterations in flow due to expansion and/or contraction of the airways. This phenomenon is readily observed in the ultimate portion of the airways, the mouth, which visibly oscillates, unless the cheeks are held, as the shutter adds and removes the resistance. These transient alterations in flow are recorded as "spikes" on the flow curve (Fig 1C,D, 2A,B). The magnitude of these spikes is a function of the relationship of the resistance of the airways to their compliance, to the alveolar pressure, and to the relationship between the respiratory and the added resistance.

Figure 2B illustrates a type of pattern commonly seen in chronic obstructive pulmonary disease. This is the absence of any square wave pattern during expiration, with the possible exception of the very earliest oscillation or two. The steady state or "DC" level (when the distortions, "spikes," due to change in airway volume have ended and flow has returned to the steady flow condition) is the same whether the added resistor is in or out of the circuit (Fig 1C, 2).

Failure to produce a series of square waves, i.e., failure to alter the steady state flow by the addition of a resistance, can be due to the fact that the respiratory resistance is so large in comparison to the added resistance that for all practical purposes it can be considered infinite. However, it is difficult to conceive that this could be the explanation in a quietly breathing subject. In Figure 2B, deviation of the steady state flow of only 1 mm when flow with the resistor out of the circuit is 800 ml/sec (20 mm) would require a resistance of 38 cm H2O/liters/sec. But no such change is evident. Doubling the sensitivity of the recorder fails to make a square wave evident. Even increasing the added resistor threefold does not produce a semblance of a square wave, although under these circumstances it would require an upstream resistance of 114 cm H2O/liters/sec to produce a change in flow of only 1 mm (800 to 780 ml/sec) when the resistance is added. Figure 3 illustrates the effect of tripling the resistance for an FVC.

The failure to see an alteration in steady state flow with the addition of the resistance is not likely due to such enormous respiratory resistances in these patients. It is more likely due to another phenomenon. It is a common finding that in many patients with obstructive lung disease expiration, particularly the later portion of expiration, is an active and not merely a passive maneuver. Under such circumstances it is entirely possible that airways, even at the low flow and relatively high lung volumes of tidal breathing, are already behaving as a Starling resistor. Such being the case, the addition and removal of an external resistance will not alter the flow from the mouth. The only alterations produced are those engendered by the expansion and contraction of airway volume as the resistor is added and removed.

This pattern of "spiking" with no square waves is also seen in normal subjects when maximum effort is made during the forced expiratory maneuver (Fig 3). With the exception of the earliest portion of the expiratory flow curve when square waves can be detected during the first one or two tenths of a second, the entire expiratory flow shows no change in the flow curve with introduction and removal of the resistance. In contrast, expiratory flow curves

![Figure 3](http://journal.publications.chestnet.org/pdfaccess.ashx?url=/data/journals/chest/20943/ on 06/24/2017)

In each instance upper trace is at 20 mm/sec, lower at 100. FVC in A and B performed by same subject. A. FVC with added resistance having value of 2 cm H2O/liter/sec. B. FVC with added resistance having value of 5.3 cm H2O/liter/sec. Note that with exception of size of "spikes," increasing value of added resistance does not change flow curve nor does it produce square waves. This is in conformity with theory that adding or removing downstream resistance does not alter flow through Starling resistor.
performed with less than optimal effort demonstrate a change in flow with addition and removal of the resistance. However, even when an optimal effort is not made, if an effort is made to expel the entire FVC down to residual volume (RV), then the square wave pattern disappears as residual volume is approached. This occurs because forceful expiratory effort sufficient to invoke the Starling phenomenon is required to reach RV, and maximal flow is reached in the process.

As residual volume is approached, even the "spikes" tend to disappear and the flow curve becomes relatively smooth. This may be due to the very small flows at this point, the compression of the airways with reduction in their compliance, and the reduction in total airway volume due to compression and airway closure.

These patterns, square waves with FVC consciously performed poorly and the pattern seen in Figure 4 with well performed FVC, have been found to be characteristic of both normal subjects and patients.

This technique may also be applied to the MEFV (Fig 4). Here the effort-dependent portion is more evident because the square wave is attenuated by being plotted against volume rather than time. As seen in this figure, there is good confluence between a maximum effort made through the device and a maximum effort made simply through the hot wire flow meter. A less than maximal inspiration prior to the forced expiratory effort causes the effort-dependent portion to be attenuated or disappear, and the entire remaining flow curve reflects the Starling phenomenon.

Although an absence of square waves is commonly seen in the later portion of a normal expiration in obstructive lung disease, this phenomenon has not been seen during inspiration. This is also in conformity with the view of the airways as Starling resistors, since they do not behave in this fashion during inspiration. Therefore, although what has been presented here is an indirect validation of a theory, there would appear to be considerable evidence justifying it: (1) The Starling phenomenon is seen in patients with high airway resistance during expiration, never inspiration. (2) Maximal expiratory effort, recorded either as the FVC or MEFV shows changes in flow consistent with the theory that the early portion is effort-dependent and the later portion behaves as flow through a Starling resistor. (3) Expiratory flows produced without a substantial effort result in a pattern which indicates the airways are not behaving as Starling resistors, ie, a change in the downstream resistance produces a change in flow. (4) Commencing a forced expiratory effort with less than a maximal inspiration results in an attenuation or elimination of the effort-dependent portion of the curve.

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