Clinical Experience with a New Test of Pulmonary Function*

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One hundred consecutive adult patients referred for cardiac or pulmonary evaluation were studied by routine pulmonary function tests as well as by a new test of pulmonary function. The new test has the advantage that no special ventilatory maneuvers are required of the subject. The subject merely breathes quietly into the device. The device measures total respiratory resistance. This correlated quite well ($r = 0.88$) with airway resistance as measured by body plethysmography. The incidence of positive findings with this technique in subjects with ventilatory abnormality compares favorably with other tests of ventilatory function. The test should prove useful in survey work and in testing sick, debilitated and disinterested subjects.

The dependence of pulmonary function tests on the subject's ability and willingness to perform specific ventilatory maneuvers is a drawback which characterizes tests in common use today. This undesirable aspect of existing techniques has prompted efforts to develop tests which require a minimum of subject cooperation and understanding. The current work presents the results of an extensive clinical trial of a new test of pulmonary function. This presentation indicates the usefulness of this simple approach in the detection of pulmonary disease, particularly obstructive pulmonary disease.

**METHODS**

The method used has been described in detail elsewhere.1 In brief it is based on a simple electrical principle illustrated in Figure 1. RX is an unknown resistance, RK is known. The change in current through the ammeter when the switch is opened and RK introduced in series with RX is proportional to the relationship of the two resistors. The solution for RX is $F(RK) = \frac{1}{F}$, where $F$ equals the current flow when both RX and RK are in the circuit divided by the current flow when only RX is in the circuit. Rapid introduction and removal of RK from the circuit results in a change in current which is proportional to the relationship of RK to RX as seen in Figure 1.

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In applying this concept to the human respiratory system, the driving pressure of respiration takes the place of the battery voltage, the airway resistance (RA) plus the tissue resistance of the lungs and chest wall replace RX, a flow meter replaces the ammeter and RK becomes a screen-type resistor. RK was added and removed at the mouth ten times per second. This frequency is too rapid to permit changes in subject effort during the period of addition or removal of the resistance. Therefore, during this brief interval, the driving pressure (as with the battery in the electrical analogue) remains constant. The value of resistance thus obtained represents total respiratory resistance (TRR), the sum of the airway resistance plus the tissue resistance of the lung and chest wall.

However, there are not only resistive elements in the circuit but reactive ones as well. The reactive elements which are of concern in a device such as this have been assumed to be the compliance of the airways.2 In normal subjects the compliance of the airways is sufficiently small, relative to the low airway resistance, so that it does not interfere with the test. For all practical purposes the wave form produced is square, as seen in the electrical analogue (Fig 1) and from a normal subject (Fig 2A). However, in subjects with obstructive lung disease, resistance is sufficiently high so that this parallel reactive element is evident and manifests itself on the flow tracing as a "spike" as RK is introduced and removed (Fig 2B). This makes analysis of the records slightly more difficult, but is circumvented by reading the portion of the flow curve at which only "direct current" flow is occurring (Fig 3).

Since the determination of RX is dependent only on the ratio of RK to RX the device need not be calibrated. Obviously the resistance used must be constant over the flow ranges measured. In these tests a resistance of 2 cm $H_2O/L/sec$ was used and did not appear to produce any discomfort. Determination of the subject's resistance is ac-
FIGURE 1. A—The electrical analogue. A = ammeter, B = battery, S = switch, RX = unknown resistance, RK = known resistance. As the switch is opened and closed RK is added and removed from the circuit altering the current flow through the circuit which registers on the ammeter. B—Changes in the relationship of current flows with different ratios of RX:RK. 0 = zero current flow. The upper portion of each square wave represents the current flow through RX only while the lower portion represents the current flow through RX + RK. The ratio of current flows to zero current flow to each other are shown for three different relationships of RX:RK, when RX equals RK, and when RX is three and four times the value of RK. As the resistance of RX increases the current flow with RK in the circuit (switch open, see A) approximates the current flow with RX alone (switch closed, see A). C—The relationship of current flow with varying battery voltage. With varying battery voltage the ratio of the currents remains constant and is proportional to the relationship of RK to RX. The driving pressure, therefore, is immaterial both in the case of the electrical analogue and in the case of the respiratory system.

FIGURE 2. I = inspiration, E = expiration. The flow meter used in this device is of the “hot wire” type and inspiration and expiration are recorded in the same direction. 2A—Record from a normal subject. 2B—Record from a subject with severe obstructive lung disease. Note that during expiration no “direct current” flow can be distinguished. This sign alone is sufficient for the diagnosis of obstructive lung disease. However, it cannot be quantitated and not all patients with obstructive lung disease manifested this phenomenon.

COMPLETED BY MEASURING THE RATIOS OF THE FLOWS DURING SEVERAL RESPIRATIONS. FIVE TO TWELVE COMPLEXES ARE MEASURED, RESISTANCE COMPUTED FOR EACH COMPLEX AND THEN AVERAGED. COMPLEXES WERE ONLY MEASURED DURING INSPIRATION SINCE IN MANY SUBJECTS WITH INCREASED AIRWAY RESISTANCE NO “DIRECT CURRENT” PORTION OF THE EXPIRATORY CURVE COULD BE FOUND (FIG. 2B).

The test is performed by having the patient breathe normally into a tubular mouthpiece in series with the device. The nose is occluded. The subject places his hands against his cheeks (if this is not done the cheeks will flutter as the resistance is introduced and removed, adding another compliant element to the system). Several breaths are recorded to accustom the subject to the device and then several more for analysis. The entire time that the subject is on the device (hereafter referred to as the “shutter”) need not exceed 30 seconds and the instructions given are merely those to “breathe normally.” An occasional subject will have such shallow respirations that the deflections will be too small to analyze accurately. In that case he is asked to breathe more deeply. In subjects with normal depth of respiration the instruction to breathe more deeply has not resulted in any change in measured resistance so that the requirement that a subject breathe deeper than his chosen tidal volume would not appear to invalidate the test.

One hundred consecutive patients over the age of 21 who were referred to the laboratory were studied on the shutter. They consisted of 22 patients referred for cardiac catheterization or coronary angiography and 78 for evaluation of respiratory symptoms or known pulmonary disease. There were 39 women and 61 men. In addition, 5 women and 13 men, considered normal, were recruited from the hospital staff. Patients and normal subjects were studied by body plethysmography, spirometry in the seated position on a Jones Pulmonor, and by the shutter in a seated position. The tests were performed in random order. One person performed all shutter tests and analysis without knowledge of the patient’s condition or the results of the other tests which were per-
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FIGURE 3. When "spikes" appear on the flow curve they are not included in the measurement of the complex. Measurement is made from the flat portion of the complex indicated by the dotted lines A and B to the zero (0) flow point which is not shown. The ratio of the flows is given by the distances BO/AO.

formed by other personnel. However, the normal subjects were known to be normal by all personnel involved.

Patients were placed in five groups categorized in the following manner: Obstructive disease (30 men and 14 women) by a first second timed vital capacity (FEV$_1$%) of less than 75 percent and/or a maximal mid-expiratory flow (MMF) of less than -20 percent of 85 percent of the predicted forced vital capacity (FVC). Restrictive disease (8 men and 13 women) by a reduction of FVC in excess of two standard errors of the estimate (SEE) below predicted without impairment of FEV$_1$%; however, all patients with pulmonary sarcoidosis on the basis of the chest roentgenogram as well as a positive biopsy or Kveim test were considered to have restrictive lung disease without regard to the functional findings. Cardiac patients—these were divided into two groups, those simply designated "cardiac" (nine men and nine women) and those who in addition to proved heart disease had sarcoidosis (two women) and in whom coexisting obstructive lung disease was suspected (two men). Normal patients (one man and three women) referred to the laboratory for pulmonary symptoms on whom all ventilatory tests were normal.

In order to compare the relative frequency with which the various tests were positive, the number of times each test was positive for each of the five groups was counted. The criteria for considering a test positive were as follows: TRR—greater than two SEE above that predicted for the subject's height; conductance/thoracic gas volume (CA/V) of less than 0.155 liter/sec/cm/H$_2$O/liter (this value is based on studies on 69 normal subjects in this laboratory, 97 percent of whom had

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**FIGURE 4.** Normal: • Male, ▲ Female.

- O: Obstructive
- ■: Restrictive
- △: Cardiac
- ▼: Cardiac with pulmonary disease
- X: Symptomatic subjects with normal ventilatory function

FEV$_1$ = first second volume, liters, MMF = maximum mid-expiratory flow, liters/sec, FEV$_1$% = FEV$_1$/forced vital capacity × 100, TRR = total respiratory resistance, cm H$_2$O/L/sec, RA = airway resistance, cm H$_2$O/L/sec, CA = 1/RA.
values for CA/V in excess of 0.155); FVC—less than two SEE below predicted for the subject’s height, age and sex; FEV$_1$%—less than 75 percent (of 384 normal subjects 95 percent had values of 75 percent or greater). FEV$_1$—less than 75 percent of the subject’s predicted FVC. MMF—less than —20 percent below 85 percent of the subject’s predicted FVC. These criteria may appear somewhat arbitrary, particularly in the case of the MMF. However, satisfactory criteria for normal are not always available, particularly in the case of the MMF. This formulation appeared useful, especially in patients with restrictive lung disease since the use of previously published limits of normal 1.8 L/sec$^6$-7 provide only the absolute lower limit of normal regardless of the patient’s FVC. By this criterion patients with MMFs of 2 or 3 L/sec, for example, with predicted FVC’s of 4 or 5 liters would have to be considered normal.

### Results

In the 18 normal subjects RA ranged from 0.66 to 1.77 and TRR from 1.99 to 4.4 cm H$_2$O/1/sec. The normal values for TRR, therefore, more nearly approximate the normal values for nonelastic pulmonary resistance than they do RA. Among the 100 patients TRR was also consistently higher than RA.

TRR correlated with height (Ht) in inches for the normal subjects, the regression equation being, TRR = 13.33 - 0.152 Ht, r = —0.74, SEE = 0.54. The relationship of TRR with height for men alone proved somewhat better, TRR = 17.66 - 0.215 Ht, r = 0.81, SEE = 0.45. However, there were too few women to determine whether or not a significantly different relationship existed between TRR and height for men and women. The regression equation for the total group of normal patients was used for determining normal from abnormal function for both men and women.

The correlation of inspiratory TRR and RA as determined by body plethysmography is shown in Figure 4. Also in this figure are the relationships of FEV$_1$% to RA, and MMF and FEV$_1$ to conductance (CA) (the latter two measures of flow rate have a curvilinear relationship with RA, therefore, CA was used). As seen, the relationship of TRR to RA is as good if not better than the relationship of the other measures of flow rate to either CA or RA.

Table 1 indicates that the incidence of positive findings by the shutter was good in obstructive lung disease. It was considerably better than CA/V among restrictive patients. Among the cardiac patients it produced the same incidence of positive findings as the MMF. The relatively low yield for all tests among restrictive patients is in part due to the fact that four of these patients had pulmonary sarcoidosis without ventilatory abnormality. Of these, one had an abnormal TRR.

Four patients had positive values for TRR with-

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Symbols are the same as in Figure 4.

N = Number; TRR = Total Respiratory Resistance; CA/V = Conductance/Thoracic Gas Volume; FEV$_1$ = First Second Volume; MMF = Maximum Mid-Expiratory Flow; FEV$_1$% = First Second Timed Vital Capacity; FVC = Forced Vital Capacity.

FEV$_1$% was not calculated for the restrictive patients and FVC was not calculated for the obstructive patients since these tests are not helpful in these two circumstances. The bottom line gives the number of times each test was positive relative to the number of times it was used.

out any other ventilatory abnormality. One was a woman in the cardiac group who had previous pulmonary emboli, inferior cava ligation and was studied because of angina pectoris and evidence of left ventricular failure. Pulmonary artery and right and left ventricular diastolic pressures at rest and exercise were elevated. One male cardiac patient complained of shortness of breath since childhood and was studied because of angina pectoris and a history of a myocardial infarction. Coronary arteries were normal. Left ventricular diastolic pressure was elevated and single breath diffusing capacity was 24, 62 percent of predicted. One patient with sarcoid, who in addition to abnormalities on x-ray examination, had a diffusing capacity of 72 percent of predicted. One man in the normal patient group had myelogenous leukemia. He was complaining of shortness of breath on walking on the flat and was producing a cupful of sputum a day. Shortness of breath was not due to anemia; the hematocrit was 41 percent.

### Discussion

The test presented here, despite its simplicity, appears to offer promise of a rapid and accurate method for detecting pulmonary disease, particular-
ly obstructive pulmonary disease. It is suitable for sick and debilitated subjects and patients who find it difficult to make the necessary ventilatory maneuvers required by spirometry and body plethysmography. There is no reason why the test should not be used in tracheotomized or anesthetized patients.

Although the shutter measures TRR while the body plethysmograph measures RA, it was expected that TRR would correlate better with RA than certain measures of flow rate. Recent work has indicated the complexity, in terms of impaired ventilatory function, of what is termed "obstructive lung disease."8-14 The observations of these workers are consistent with the poor correlation of RA or CA with some measures of expiratory flow rate. One would also expect, as was the case (Table 1) that TRR would be abnormal in a higher percentage of restrictive patients than would CA/V. In patients with small lung volumes, a reduced CA may be converted to a normal CA/V by the division of low CA by a small V. Furthermore, as Bachofen and Scherrer15 have pointed out tissue resistance may be significantly elevated in restrictive lung disease and this would contribute to the elevated TRR, while not affecting CA/V.

Although the incidence of positive findings for TRR for these 100 patients is high, it would be unreasonable to expect that it would be as high as the other tests. For example, the criteria used for the detection of obstructive lung disease were FEV1% and MMF. Naturally, these two tests should produce the highest yield of positive results.

The extent to which this test resulted in false positive or negative findings is difficult to state since it implies a reliance on existing tests and their limits of normal which would not be warranted. Furthermore, there is no single test of pulmonary function which is positive with all forms of pulmonary disease. For example, RA was 2.00 cm H2O/L/sec or less in 11 of the 53 subjects who had obstructive lung disease by spirometry and clinical findings. Of these, seven patients had normal CA/V and six had normal TRR. In three instances TRR, RA and CA/V were all normal.

The determination of when functional abnormality exists in a given patient is difficult, particularly in the patient with borderline abnormalities. A discussion of the complexities of this problem is not the purpose of this work. What was done here was to set criteria for the various tests used and then to determine the incidence with which these criteria proved diagnostic. Using this approach the shutter appears to be a useful and simple addition to the armamentarium of pulmonary function testing.

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