Screening Pulmonary Function Tests

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The role of the Pulmonary Function Laboratory has been expanded in recent years by the commercial development and marketing of equipment capable of measuring accurately and easily static lung volumes, diffusing capacity, and arterial blood gases. These sophisticated measurements, which were once the purview of research physiologists, are now readily attainable as screening measurements in most community hospitals. This review is intended not as a summary of the entire field or as a technical guide for performance of pulmonary function tests but as a survey of some clinical applications and pitfalls of screening tests and a statement of guidelines for their use. It is assumed that the reader already has some experience in ordering and interpreting routine spirograms and arterial blood gases.

Pulmonary function tests are intended to answer four questions:

1) Is the patient restricted?
2) Is the patient obstructed?
3) Does the patient have abnormalities of gas exchange?
4) Are the observed abnormalities compatible with the patient's symptoms and clinical diagnosis?

Restriction is a reduction of total lung capacity or one of its subvolumes (Fig 1) as a result of collapse or volume displacement of the lung (fibrothorax), increased elastic recoil of the lungs (pulmonary fibrosis), increased elastic recoil of the rib cage or abdomen (obesity), or loss of forces needed to overcome normal elastic recoil (muscular dystrophy). It is important to realize that a routine spirometric vital capacity measurement may not adequately describe the presence or degree of restriction. For example, some patients with advanced emphysema may have reduced vital capacity in the face of a large residual volume, with increased total lung capacity caused by obstructive air trapping; it is misleading to label such patients as "restricted" on the basis of reduced vital capacity when, in fact, they are overinflated. On the other hand, true early restriction may occur in the face of normal vital capacity. An example of this is obesity, a condition in which the abdominal mass renders the chest wall less compliant by hindering downward displacement of the diaphragm. The earliest change in the restrictive pattern of obesity is a marked reduction in expiratory reserve volume (ERV) (see Fig 1) but only minor alterations of the total lung and vital capacities. Therefore, accurate evaluation of patients with suspected restrictive disorders should include, in addition to routine spirometry, a measurement of total lung capacity and its subdivisions by inert gas or plethysmographic techniques. The following case illustrates the use of pulmonary function studies in following the course of a restrictive lung disorder:

Case 1. A 53-year-old white woman developed exertional dyspnea and cough in 1971. A chest roentgenogram revealed bilateral basilar "ground-glass" opacities. In April 1972, an open lung biopsy showed desquamative interstitial pneumonia. She was placed on 20 mg prednisone daily in August 1972, and sequential pulmonary function tests were performed (Table 1). The initial vital and total lung capacities were consistent with moderately severe restriction, and there was a correspondingly severe reduction in diffusing capacity. After two years of prednisone therapy, these abnormalities improved substantially (October 1974). When steroids were stopped she experienced a severe relapse

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(February 1976) which was reversed by their resumption (February 1977). In 1977 she was in remission while taking 20 mg prednisone on alternate days. *The pulmonary function studies provided quantitative objective evidence that a prolonged course of steroid therapy was necessary.*

Obstructive impairment, defined as a reduction in inspiratory or expiratory air-flow rates, is a result of intrinsic airway disease or loss of lung elastic recoil. The latter causes airways to lose their structural support. Intrinsic airway disease may be caused by a variety of conditions ranging from totally reversible asthmatic bronchoconstriction to irreversible advanced chronic bronchitis with bronchiolitis obliterans. Loss of elastic recoil almost always is a result of localized or generalized emphysema.

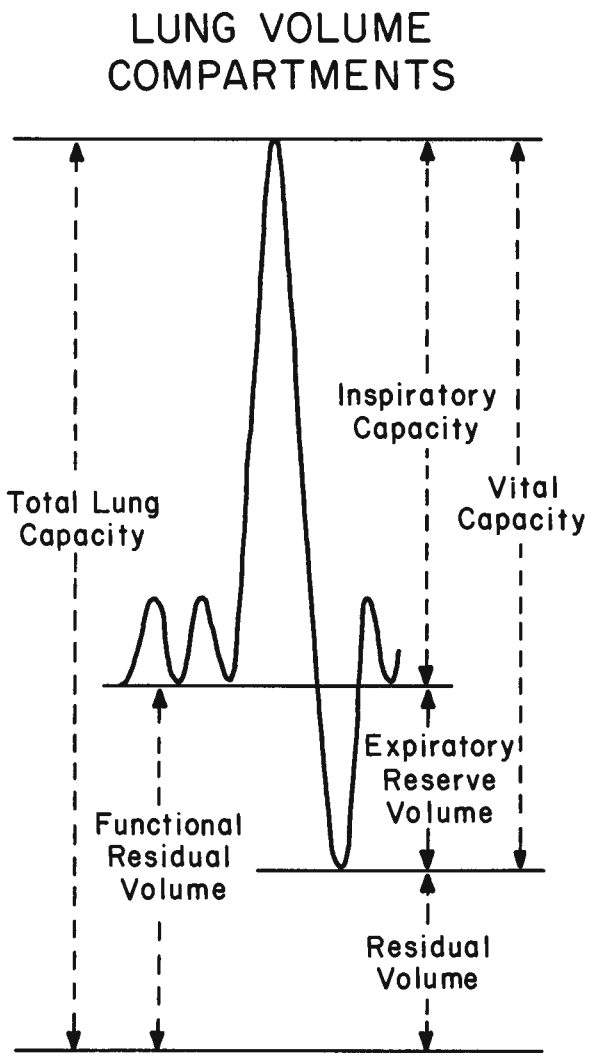

Fig 1—Spirogram with various subdivisions of total lung capacity. Initial deflections at left are tidal volumes recorded on slowly moving recording paper. Large deflection upward is inspiration to total lung capacity, followed by expiration to residual volume and resumption of tidal breathing. Residual volume is not measured directly, but has been previously determined by inert gas study. Time is on the horizontal axis, volume on the vertical.

Because the conditions causing airways obstruction tend to become more exaggerated during forced expiration (during which alveoli and airways are rapidly diminishing in both length and diameter), the conventional method of assessing obstructive impairment is by measuring averaged flow rates on a volume-time curve of an ordinary spirogram during a maximally forced expiration of the vital capacity. (Fig 2). Although one could arbitrarily measure flow at a multitude of points on the curve, three measurements have been standardized and used most frequently (see Fig 2): the timed vital capacity (FEV_1); the ratio of FEV_1 to total vital capacity; and the maximum mid-expiratory flow rate (MMEF) (the averaged flow over the mid-half of the vital capacity). Ordinarily all three measurements are made and abnormalities of one tend to correlate with those of the others. Additional measurements such as peak flow, total expiratory time, and forced expiratory volume in three seconds, or "FEV_3," add little new information but may be sensitive indicators of changes when evaluating drug effects in population samples.

Obstruction is conventionally quantitated during expiration; however, patients develop dyspnea from obstructive impairment because of the increased work of breathing during *inspiration.* In most cases, obstruction during inspiration is inferred by abnormalities in the FEV_1 and MMEF; unfortunately, there are several important exceptions to this. Individuals with obstruction isolated to the trachea or larynx (for example, tracheomalacia following endotracheal intubation) may not have evidence of ex-

TABLE 1
Sequential Function Studies in a Patient with Desquamative Interstitial Pneumonia.

	August 1972	October 1974	February 1976	February 1977	Predicted
Vital capacity, liters	2.06	3.45	2.30	3.12	3.97
Total lung capacity, liters	3.55	5.24	3.79	4.95	6.32
Arterial Po_2, torr	66	73	67	76	90
Diffusing capacity, ml/min/torr	8.5	17.0	7.9	11.2	22.0

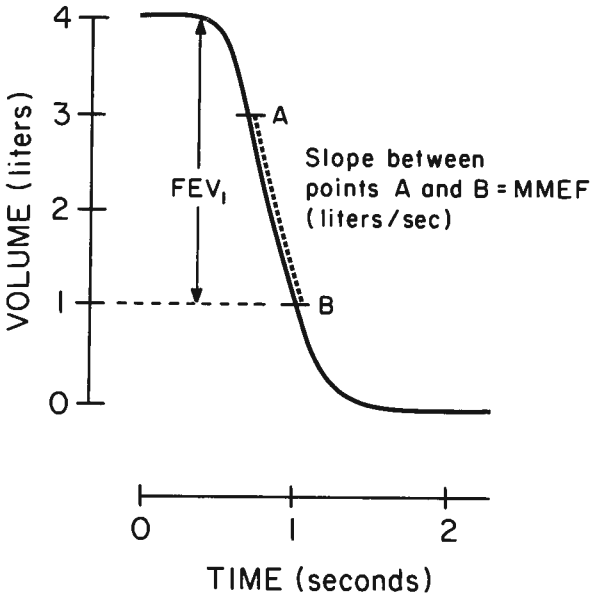

Fig 2—Forced vital capacity shown on rapidly moving recording paper. Total downward excursion of curve (vertical axis) is vital capacity. Volume exhaled during the first second is FEV_1. MMEF is slope of line connecting points A and B. Time is on the horizontal axis.

piratory obstruction if their defect is above the thoracic outlet, or they may have spirometric abnormalities which are misinterpreted as generalized airways obstruction if their defect is below the thoracic outlet. In addition, individuals with substantial narrowing of bronchioles but normal patency of bronchi (for example, young smokers with early chronic bronchitis) may have completely normal spirometric flow rates but isolated abnormalities of MMEF which are difficult to interpret because of the large standard deviation of this test in the normal population.

When either of these exceptions is suspected, additional information may be obtained by a recording of a flow-volume curve, or graphical representation of instantaneous mouth flow and expired volume during a forced inspiration and expiration of the vital capacity (Fig 3). The normal configuration of this curve is shown in Figure 3a. Fixed obstruction in the trachea produces a characteristic fixed limitation to flow which is independent of volume (Fig 3b). An additional advantage of the flow-volume curve is its depiction of inspiratory events, thus facilitating the detection of variable extrathoracic upper-airway obstruction (Fig 3c). Generalized bronchiolar narrowing produces flow limitations which are detectable

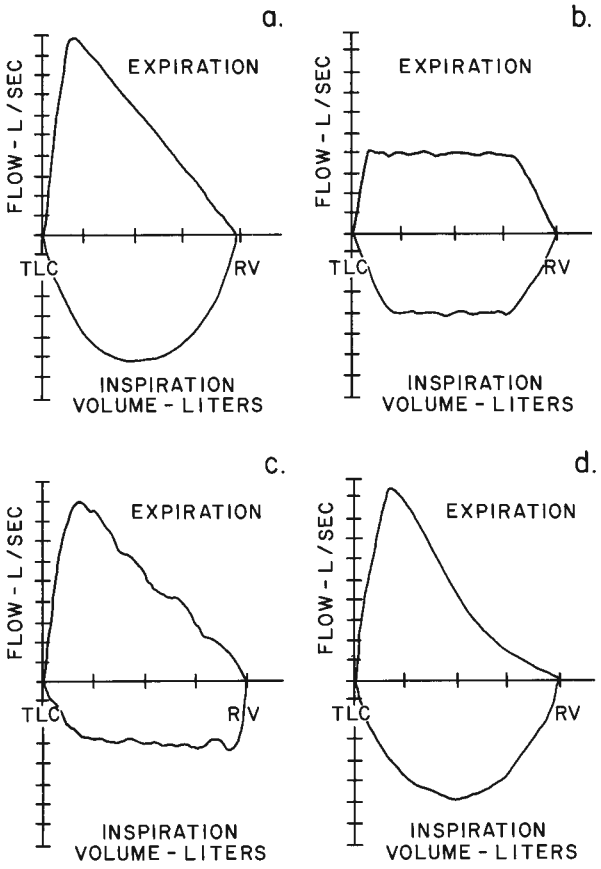

Fig 3a—Inspiratory-expiratory flow-volume curve shows normal configuration in a 28-year-old man.

Fig 3b—Fixed upper-airway obstruction seen in a 32-year-old man with stenosis of intrathoracic trachea.

Fig 3c—Curve shows variable extrathoracic obstruction as a result of loss of cartilagenous tracheal support in the subglottic region. The weakened area collapses on inspiration but is distended during expiration by positive airway pressure.

Fig 3d—"Inwardly concave" distortion of the expired curve at lower lung volumes is seen in a 30-year-old chronic cigarette smoker with a normal spirogram. The distortion is due to bronchiolar obstruction.

only on expiration at lower lung volumes and tend to worsen as volume diminishes. This will result in an "inwardly concave" appearance to the flow-volume curve in patients with obstruction limited to the bronchioles (Fig 3d). It should be pointed out that this "inwardly concave" configuration is not specific for peripheral small airways obstruction; if the spirogram also indicates obstruction, the curve is not use-

ful for differentiating generalized obstruction from that isolated to peripheral airways. The following case is an example of obstructive impairment and also illustrates the value of lung volume determinations by the helium dilutional method in differentiating obstructive from restrictive impairment:

> **Case 2.** A 19-year-old male gas station attendant abruptly developed exertional dyspnea in January 1976. Seven months later a carefully taken history revealed that he had been caring for his brother's homing pigeons since late December 1975. The chest roentgenogram was normal, although symptoms persisted. Pulmonary function studies (Table 2, July 1976) revealed a reduced vital capacity; however, the total lung capacity and residual volume suggested probable obstructive air trapping rather than restriction. The FEV_1 and MMEF confirmed obstruction. *Without specific treatment other than ceasing the pigeon exposure, his symptoms resolved and objective improvement was evident on sequential studies (September 1976).* Although both restriction and obstruction may occur in allergic alveolitis, restriction is usually the dominant impairment. However, in this patient's case, obstruction occurred without restriction.

Arterial hypoxemia is a sequela of impaired gas exchange; however, measurement of resting arterial oxygen tension (Po_2) alone may not be sufficiently sensitive to detect such impairment. Impaired gas exchange is also present if there is an increase in the observed oxygen tension difference between alveolar air and arterial blood (DA-a O_2) or if there is an abnormality in the diffusing capacity for carbon monoxide. For ambulatory patients breathing room air, DA-a O_2 can be estimated by obtaining a sample of arterial blood under steady-state conditions. Alveolar oxygen tension is calculated by the standard alveolar air equation:

$$P_AO_2 = F_IO_2(713) = Paco_2 \left(F_IO_2 + \frac{1 - F_IO_2}{RQ}\right)$$

F_IO_2 = fraction of O_2 in inspired air

$Paco_2$ = arterial Pco_2 (identical to mean alveolar Pco_2)

RQ = respiratory quotient

The achievement of steady-state conditions is an essential prerequisite for this test because the estimation of alveolar oxygen tension is based on the assumption that the ratio of CO_2 produced to O_2 consumed (RQ) is 0.8. Transient hyperventilation caused by anxiety or pain will invalidate this assumption. Direct measurement of RQ may provide a more refined estimation of P_AO_2; however, this also requires sampling under steady-state conditions. For either approach, hyperventilation may be avoided by inserting an arterial cannula and allowing the patient to rest prior to sample collection.

TABLE 2
Sequential Function Studies in a Patient with Allergic Alveolitis Due to Pigeon Exposure.

	July 1976	September 1976	Predicted
Vital capacity, liters	3.98	4.42	5.62
Total lung capacity, liters	6.95	6.68	7.34
Residual volume, liters	2.97	2.26	1.72
FEV_1, liters	2.51	3.09	4.54
FEV_1/Vital Capacity, %	63	70	80
MMEF, liters/sec.	1.24	2.03	4.90

The measurement of carbon monoxide diffusing capacity by the simplified single-breath technique requires the patient to breathhold at total lung capacity for ten seconds. Patients who are markedly dyspneic at rest may not be able to perform this test. Despite these limitations, useful results are forthcoming for most cooperative subjects.

The precise pathophysiologic explanation for impaired diffusion of carbon monoxide in lung diseases is unknown. Most authorities agree that it is a sign of alveolar or capillary destruction. Therefore, impaired CO uptake may occur in parenchymal destructive processes such as idiopathic fibrosing alveolitis, scleroderma, advanced sarcoidosis, and in vascular obliterative processes such as idiopathic pulmonary hypertension or multiple small pulmonary emboli. It is also impaired in processes causing reversible loss of functioning alveoli, examples of which are bacterial pneumonia and alveolar proteinosis. CO uptake is impaired in generalized emphysema due to emphysematous destruction of alveoli but remains nearly normal in chronic bronchitis because the destructive process is confined to airways and centrilobular elements of the parenchyma. Diffusing capacity may be spuriously impaired by several conditions. The first is the presence of severe anemia, which limits the availability of hemoglobin CO receptors; the second is that failure to achieve true total lung capacity during the breathhold will reduce CO uptake in proportion to the reduction in potential lung volume. The following case illustrates the value of the

TABLE 3
Pulmonary Function Studies in a Patient with Sarcoidosis

	September 1978	Predicted
Vital capacity, liters	2.98	3.63
FEV_1, liters	2.68	2.88
FEV_1/vital capacity, %	90	79
MMEF, liters/second	4.03	3.37
Total lung capacity, liters	3.85	5.12
Residual volume, liters	.76	1.49
Pao_2, torr	92	90
DA-a O_2, torr	13	15
Diffusing capacity, ml/min/torr	12.0	21.7

diffusing capacity in screening patients for the presence of gas exchange impairment:

Case 3. A 32-year-old woman complained of mild exertional dyspnea of two months duration. Chest roentgenogram revealed bilateral hilar adenopathy. Pulmonary function studies (Table 3) showed a modest reduction in total lung capacity (75% predicted) with normal vital capacity and flow rates. Resting arterial oxygen tension and DA-a O_2 were also normal. However, *a moderately severe reduction in diffusing capacity suggested the presence of widespread interstitial disease despite the clear roentgenographic lung fields.* Hemoglobin was normal. A transbronchoscopic lung biopsy showed interstitial non-caseating granulomata consistent with sarcoidosis.

Although measured impairment in pulmonary function frequently provides an objective explanation for the presence of dyspnea, many patients may experience this symptom because of abnormalities which are undetectable on screening evaluations. Negative screening studies should stimulate a careful search for vascular disease or nonpulmonary causes of dyspnea. For example, "metabolically justified" hyperpnea and dyspnea may accompany hyperthyroidism; patients with mitral stenosis or early congestive heart failure may have only mild impairment in lung mechanics despite severe exertional dyspnea; and patients with partial obliteration of the pulmonary vasculature may have normal lung mechanics, arterial oxygen tensions, and diffusing capacities while at rest, only to show abnormalities during exercise.

For a variety of vascular and interstitial pulmonary disorders, it may be appropriate to evaluate

TABLE 4
Guidelines for Ordering Medical or Surgical Screening Pulmonary Function Studies.

1. Asymptomatic non-smoker	No studies; "routine spirogram" (vital capacity, FEV_1, MMEF) if thoracic surgery is planned.
2. Asymptomatic smoker	Routine spirogram; add resting arterial blood gases if thoracic surgery is planned.
3. Heavy smoker with dyspnea and/or chronic bronchitis	Routine spirogram; total lung capacity; diffusing capacity; resting arterial blood gases.
4. Young asthmatic	Spirogram before and after an inhaled bronchodilator.
5. "Old" asthmatic (>30 years)	Spirogram before and after inhaled bronchodilator; total lung capacity; resting arterial blood gases.
6. Suspected tracheal obstruction, stridor, or unexplained obstruction on a previous spirogram	Inspiratory and expiratory flow-volume curve.
7. Suspected interstitial lung disease	Spirogram; total lung capacity; diffusing capacity; steady-state arterial blood gases with DA-a O_2.
8. Suspected pulmonary vascular disease	Same as #7. Add exercise DA-a O_2, physiologic deadspace, end tidal CO_2 gradient.
9. Suspected anatomic right-to-left shunt	Arterial blood gases while breathing 100% O_2. This study should *never* be requested for patients with emphysema or chronic bronchitis who have CO_2 retention.
10. Suspected early small-airways disease	In view of the limited clinical benefits, adequate evaluation is too expensive.

physiology during exercise as resting abnormalities frequently are exaggerated during exercise. However, pulmonary exercise testing, unlike cardiac stress testing, should provide a graded *low level* of exercise (doubling or tripling of the oxygen uptake) rather than maximum stress. In fact, recent experimental evidence[1] has suggested that maximum stress measurements are potentially misleading because normal subjects may demonstrate transient abnormalities in Pao_2 and DA-a O_2 while performing temporary but severe tasks such as rapid stair-climbing. Although a complete discussion of exercise physiology testing is beyond the scope of this paper, some recent reviews of the relevance of pulmonary exercise testing in clinical medicine are included in the bibliography.[1,2]

Table 4 is a suggested modus operandi for ordering screening pulmonary function studies for specific problems. Physicians ordering such tests must realize that measurements of lung mechanics require both cooperation and effort. Too much testing at a single sitting may fatigue the patient and cause spuriously abnormal results. For example, it would be unwise to subject a patient to both screening studies and exercise physiology studies for suspected vascular disease on the same day. Therefore, in the context of the suggestions in Table 4, clinical wisdom and common sense should dictate which tests are appropriate for individual patients.

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