Pulmonary Function Tests for the Generalist: A Brief Review

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Learning Objectives: On completion of this article, you should be able to (1) identify and define the common components of the pulmonary function test, (2) recognize when the test should be performed, and (3) interpret the results of the basic pulmonary function test by using a standardized approach.

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Abstract

One of the frequent reasons patients see their primary care physicians is for the symptom of dyspnea. Among the objective tests to quantify this symptom is the pulmonary function test, which includes several different studies: spirometry with flow-volume loop, lung volumes, and diffusing capacity of lung for carbon monoxide. The results may indicate both respiratory and nonrespiratory disorders, including helping in the diagnosis of cardiac or neuromuscular diseases. This review, intended for the generalist, describes common findings of pulmonary function tests and provides a road map for interpretation.

 ■ Mayo Clin Proc. 2018;93(6):763-771

Dyspnea is one of the main reasons patients see primary care physicians, accounting for 1% to 4% of all visits.[1-3] An objective way to differentiate between the multiple causes of dyspnea (a highly subjective symptom) is to order a pulmonary function test (PFT), which assists in the identification and quantification of respiratory system abnormalities.[4] Pulmonary function tests can also identify disorders outside the respiratory system, including neuromuscular weakness and cardiovascular processes. In addition, measurement of pulmonary function allows for long-term monitoring of disease progression and response to therapy.[5]

A PFT may include several different studies, commonly spirometry with flow-volume loop, lung volumes, and diffusing capacity of lung for carbon monoxide (DLCO), though the individual clinician may decide which components of the test they need for their patient. Of note, each laboratory will provide special instructions to the patient before the test, though it is usually recommended that the patient not use inhaled bronchodilators or smoke tobacco on the day of the test.

This review discusses each component of the PFT and provides a basic guide to interpretation by using an illustrative case.

Mr Smith is a 50-year-old man who presents to his primary care physician with increased exertional dyspnea, rash, and muscle weakness for the past 6 months. He has not experienced such dyspnea before, so his physician orders a PFT. The test results are summarized in Table 1.

SPIROMETRY

The most basic and useful PFT is spirometry. It includes measurement of exhaled or inhaled air during forced maneuvers. The forced vital capacity (FVC) is the amount of air that can be forcefully expelled, beginning with the lungs completely full (at total lung capacity [TLC]) and blowing maximally until as empty as possible (at residual volume [RV]). The forced expiratory volume in the first second (FEV_1) is the amount expelled during the first second of the FVC maneuver. The ratio of FEV_1 and FVC (FEV_1/FVC) is used as an indicator of obstruction. The forced expiratory flow at 25% to 75% of the pulmonary volume was developed as an indicator of "small airway disease"; however, it is nonspecific. Many laboratories no longer report it, and we do not recommend using it for interpretation.

The graphic display from spirometry is typically called a *flow-volume curve* if it includes only expiratory flow or a *flow-volume loop* if it includes both expiratory and inspiratory maneuvers (for simplicity, the rest of this review refers only to the flow-volume loop).[6] The flow-volume loop provides important clues about the quality, acceptability, and reproducibility of the maneuver, which is determined by national standards and controlled by each individual laboratory. It can also indicate unusual abnormalities, such as obstructive lesions of the central airways. Inspiratory flows are disproportionately reduced by lesions of the upper (extrathoracic) airway. Conversely, lesions in the lower trachea and main stem bronchi primarily affect expiratory flows whereas a plateau on both the inspiratory and expiratory curves suggests a fixed lesion. Figure 1 illustrates common examples of flow-volume loops and associated abnormalities.[6]

The abnormal results of spirometry separate into 2 large classes of disorders: obstructive and restrictive. Obstructive disorders are suggested by a low FEV_1/FVC ratio, whereas restrictive disorders are suggested by a normal FEV_1/FVC ratio with a low FVC. The American Thoracic Society (ATS) and European Respiratory Society (ERS) define an *obstructive process* as a FEV_1/FVC ratio below the 5th percentile of the predicted value, often called the *lower limit of normal* (LLN).[7] Some, including the Global Initiative for Chronic Obstructive Lung Disease, define an *abnormal FEV_1/FVC ratio* as one below 0.70, or 70%.[8]

TABLE 1. Patient Pulmonary Function Test Results (in Liters)

Variable	Normal	LLN	Found	% Predicted	Found	% Change
TLC	6.53	5.38	4.18	64		
VC	4.03	3.16	1.80	45		
RV	2.19	2.86	2.38	109		
FVC	4.03	3.16	1.47	36	1.72	17
FEV_1	3.21	2.46	1.07	33	1.41	32
FEV_1/FVC	79.8	69.3	72.6	91	82.1	13
MVV	141	108	55	39		
DLCO (adjusted)	28.6	20.6	15.0	52		

DLCO = diffusing capacity of lung for carbon monoxide; FEV_1 = forced expiratory volume in the first second; FVC = forced vital capacity; LLN = lower limit of normal; MVV = maximum voluntary ventilation; RV = residual volume; TLC = total lung capacity; VC = vital capacity.

Mayo Clin Proc. ■ June 2018;93(6):763-771 ■ https://doi.org/10.1016/j.mayocp.2018.04.009
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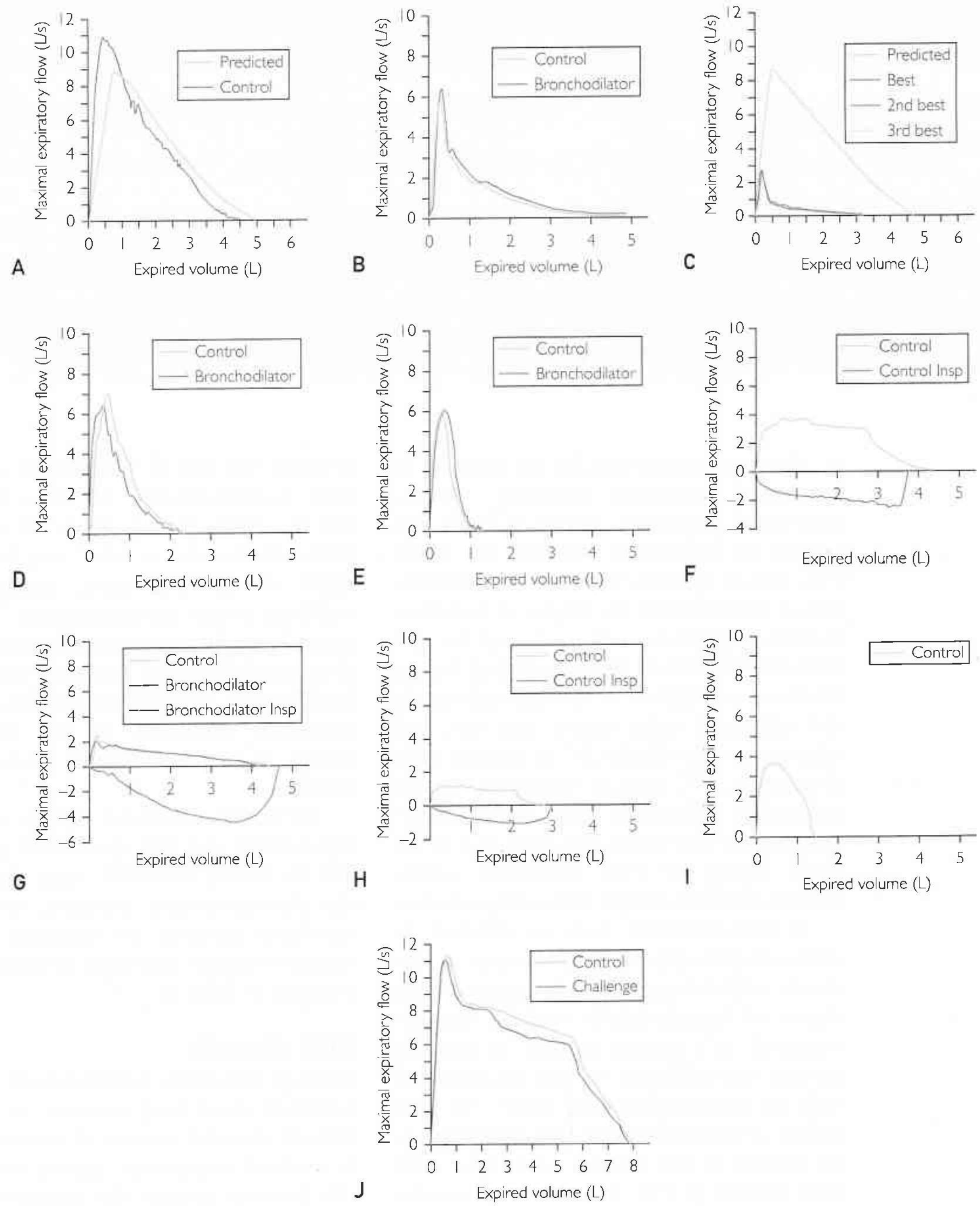

FIGURE 1. Common examples of flow-volume loops and associated abnormalities. A, Normal. B, Moderate obstruction with "scooping." C, Severe obstruction. D, Moderate restriction. E, Severe restriction. F, Variable extrathoracic obstruction with flattening of the inspiratory portion of the flow-volume loop (granulomatosis with polyangiitis). G, Variable intrathoracic obstruction with flattening of the expiratory portion of the flow-volume loop (relapsing polychondritis). H, Fixed obstruction with flattening of both portions of the flow-volume loop (tracheal stenosis). I, Weak effort (myopathy). J, Normal but with a prominent tracheal plateau. Insp = inspiratory. Adapted from Chapter 85 of *Goldman-Cecil Medicine*, 25th ed, Elsevier 2016, with permission.[6]

This is controversial because it is known that the LLN for FEV_1/FVC is age-dependent. Using a fixed ratio, such as 70%, results in overestimation of the presence of obstruction in older patients and underestimation in younger patients.[7,9-12]

TABLE 2. Grading Obstruction Severity[a,b]

Obstruction grading	1986 ATS guidelines[13]	2005 ATS guidelines[7]	GOLD guidelines[8]
Mild	60% to LLN	>70%	>80%
Moderate	41%-59%	60%-69%	>50% and <80%
Moderately severe	NA	50%-59%	NA
Severe	31%-40%	35%-49%	>30% and <50%
Very severe	<30%	<35%	<30%
FEV_1/FVC cutoff	Below the LLN	Below the LLN	<70%

[a] FEV_1 = forced expiratory volume in the first second; FVC = forced vital capacity; GOLD = Global Initiative for Chronic Obstructive Lung Disease; LLN = lower limit of normal; NA = not applicable.

[b] Cutoff points for the severity of obstructive diseases based on different guidelines are provided in this table; however, the grading systems are controversial and vary among laboratories. The 2005 American Thoracic Society/European Respiratory Society guidelines are likely the most often used, but not all laboratories follow it, including our own.[7,8,13]

Spirometry is essential for the diagnosis of obstructive processes including chronic obstructive pulmonary disease (COPD) and asthma. In obstructive disorders, the FEV_1/FVC ratio is reduced. The severity of obstruction is quantified by the degree of reduction in FEV_1 (expressed as a percentage of the predicted normal value), which is derived from a reference population of normal individuals and calculated using height, age, sex, and ethnicity or race (Table 2).[7] In patients with obstruction, FVC may be normal but can be reduced in individuals with "air trapping," meaning air that would not come out of the lungs during the FVC maneuver, usually because of airway collapse at low lung volumes.

A bronchodilator, such as albuterol, is often administered during spirometry so that airway responsiveness can be assessed. The degree of bronchodilator response may be expressed as a percent increase or absolute increase (in milliliters) or both as compared with the pre-bronchodilator value. The ATS defines a marked bronchodilator response as an increase of 200 mL and 12% (must meet both criteria) in FVC or FEV_1.[7] It has some discriminative value to distinguish asthma from COPD and some predictive value for the risk of exacerbations of COPD and asthma as well as for the expected rate of decline in lung function.[14,15] Despite this, it has poor reproducibility and its diagnostic value is limited.

The maximal voluntary ventilation (MVV) is a measure of the patient's ability to breathe in and out as deeply and rapidly as possible. It is included as part of routine spirometry by some, but not all, laboratories. A normal value is approximately 40 times the FEV_1, and the lower limit is about 30 times the FEV_1.[4] A decrease in MVV may be due to upper airway obstruction, neuromuscular weakness, or poor test performance.[6] If neuromuscular weakness is suspected, measurement of maximal respiratory pressures can be helpful. Likewise, if upper airway obstruction is suspected, evaluation of the inspiratory portion of the flow-volume loop may be revealing.

Mr Smith's spirometry reports a severely reduced FEV_1 and FVC (both <40% of normal) with the normal FEV_1/FVC ratio. His MVV is also disproportionately decreased, so maximal respiratory pressures are measured and are reduced (maximal respiratory pressures are not presented in Table 1).

LUNG VOLUMES

Although spirometry provides much useful information about lung function, it does not measure the total amount of air in the lungs at maximal inspiration, known as *TLC*. It also does not measure the amount of air left in the lungs after maximal expiration, known as RV, or the volume of the lungs at which the outward recoil of the resting chest wall is counterbalanced by the inward recoil of the lungs, known as *functional residual capacity*. Although many laboratories report functional residual capacity, we find it too variable to provide a diagnostic value.

There are several methods available to make these measurements, including body plethysmography, helium (or inert gas) dilution, and

Mayo Clin Proc. ■ June 2018;93(6):763-771 ■ https://doi.org/10.1016/j.mayocp.2018.04.009
www.mayoclinicproceedings.org

nitrogen washout. Body plethysmography, using Boyle's law ($P_1V_1=P_2V_2$), is considered the most accurate technique.[10] To perform this test, the patient sits in a sealed box and changes in pressure and volume are measured during a series of respiratory maneuvers. Helium (or inert gas) dilution involves the calculation of lung volumes after the patient breathes to reach the equilibrium with a known volume and concentration of helium. The nitrogen washout technique involves volume calculations based on the expired volume and concentration of nitrogen while breathing 100% oxygen.

Measurement of lung volumes is helpful for patients whose spirometry suggests restriction (reduced FVC, but normal FEV_1/FVC ratio). A restrictive disorder is characterized by a TLC below the LLN and can be seen in patients with interstitial lung disease, neuromuscular weakness, or chest wall limitation (such as obesity).[7] The severity of restriction may be based on the decrease in TLC or, alternatively, FVC if no lung volumes are performed (but a previous PFT documented a TLC below the LLN). One way of grading the severity of restriction is presented in Table 3.

Of all patients whose spirometry suggests restriction, only about half will have a reduced TLC (unpublished data, 2018). The remainder have a normal TLC in what we call a "nonspecific pattern" (low FEV_1 and FVC, normal FEV_1/FVC ratio, and normal TLC), which is a pattern seen in about 10% of all complete PFTs. About 50% to 60% of patients with a nonspecific pattern have evidence of obstruction (eg, "scooping" of the expiratory flow-volume curve, increased airway resistance, and clinical evidence of an obstructive disorder), while the remaining 40% to 50% have chest wall limitation, muscle weakness, or poor performance.[16,17] If a nonspecific pattern is found and is not consistent with obstruction, measurement of maximal respiratory pressures can be used to identify neuromuscular weakness. Imaging of the chest often clarifies the nature of other contributing factors, such as chest wall deformity, obesity, heart failure, mass lesion, or pleural effusion. If these are thought to be due to poor test performance, a repeat test by another experienced technologist is sometimes useful.

TABLE 3. Grading Restriction Severity[a,b]

Restriction grading[c]	TLC	FVC[d]
Mild	<80%	<80%
Moderate	<60%	<60%
Severe	<50%	<50%
Very severe	<35%	NA

[a]ATS = American Thoracic Society; FEV_1 = forced expiratory volume in the first second; FVC = forced vital capacity; LLN = lower limit of normal; NA = not available; TLC = total lung capacity.

[b]Severity grading for restrictive diseases in our laboratory is loosely based on the 1986 ATS guidelines.[13] Of note, the cutoff points for grading the severity of decrease in diffusing capacity of lung for carbon monoxide are the same as the values provided in this table and based on the 2005 ATS guidelines.[7]

[c]The FEV_1/FVC ratio must be normal.

[d]If lung volumes are not measured and a previous TLC value is below the LLN.

In obstructive disorders, measurement of lung volumes may be helpful to identify "air trapping," indicated by an increased RV and RV/TLC ratio, or less commonly "hyperinflation," meaning a TLC well above the upper limit of normal. The ATS/ERS guidelines do not provide reference values or discuss these abnormalities. In fact, measurement of lung volumes in patients with obstructive disorders has somewhat limited value, because most diagnoses and clinical decision making use spirometry results plus imaging, with relatively little contribution from lung volumes.[18]

Some individuals will have both obstruction and restriction, a so-called mixed disorder. This is indicated by a low TLC (hence restriction) plus a low FEV_1/FVC ratio. Although the mixed pattern is well known, it accounts for just over 1% of complete PFTs in our laboratory (P.D. Scanlon, MD, unpublished data, December 2017). It can be caused by a single disorder that causes a mixed pattern, such as cystic fibrosis, sarcoidosis, Langerhans cell histiocytosis, or heart failure, or, more commonly, the combination of an obstructive disorder, such as COPD, and a restrictive disorder, such as pulmonary fibrosis.

DIFFUSING CAPACITY OF LUNG FOR CARBON MONOXIDE

The third component of the PFT is D_{LCO}, which is used as a measure of gas exchange, sometimes in conjunction with pulse oximetry

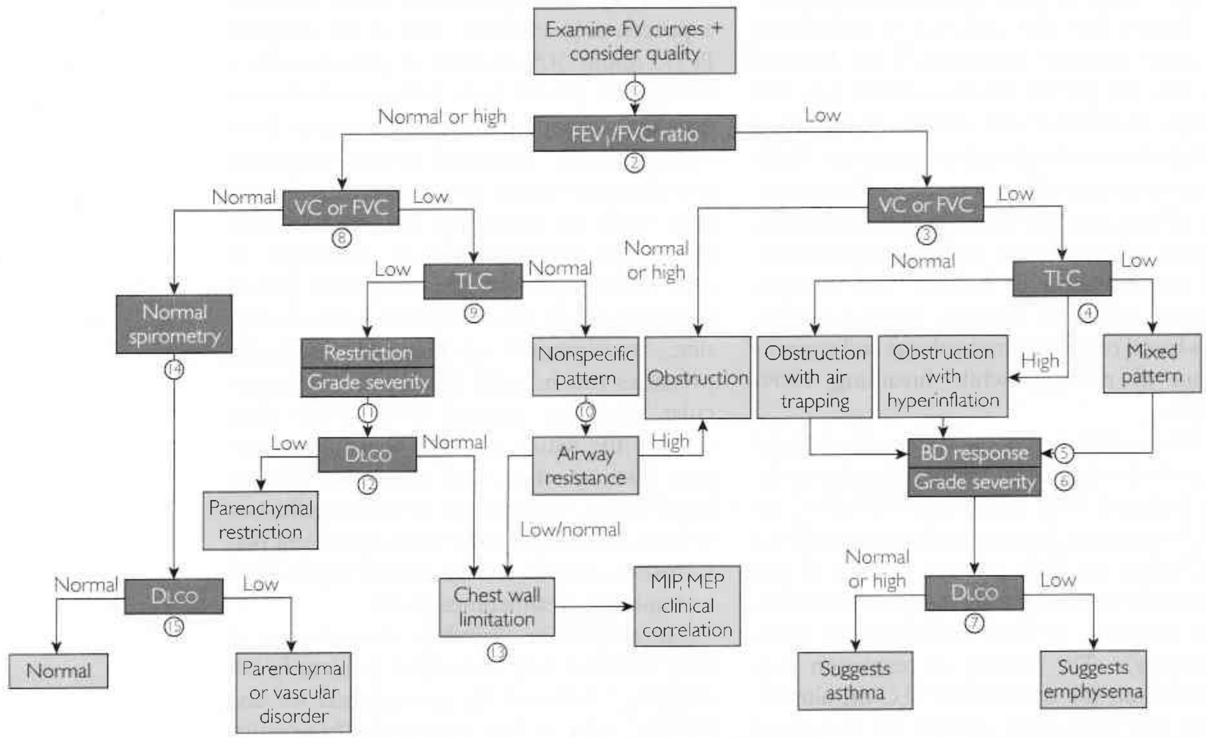

FIGURE 2. An algorithm for interpreting pulmonary function tests. Please see accompanying text below for further explanation. BD = bronchodilator; DLCO = diffusing capacity of lung for carbon monoxide; FEV_1 = forced expiratory volume in the first second; FV = flow volume; FVC = forced vital capacity; MEP = maximal respiratory pressure; MIP = maximal inspiratory pressure; TLC = total lung capacity; VC = vital capacity. Adapted from Chapter 85 of *Goldman-Cecil Medicine*, 25th ed, Elsevier 2016, with permission.[6]

at rest or during exercise. This is determined using the single-breath method, in which the patient exhales to RV and then inhales a vital capacity of air with small concentrations of carbon monoxide and helium or other inert gas. At maximal inspiration, the patient holds his or her breath for 10 seconds and then exhales quickly. Exhaled gas is sampled to determine concentrations of helium and carbon monoxide as a function of exhaled volume. From that, alveolar volume and DLCO are calculated. The DLCO is decreased if anemia is present, so it is often adjusted to a "corrected" value (if hemoglobin is available). The DLCO can be adversely affected by reductions in lung volume as well as various pulmonary parenchymal diseases (such as interstitial lung diseases and emphysema) or pulmonary vascular disorders (such as pulmonary hypertension).

The DLCO can be increased as well. In most cases, this is due to asthma or obesity or may be due to measurement during a nonresting state. Less common causes include pregnancy, current smoking status, diffuse alveolar hemorrhage, polycythemia, early heart failure, or left-to-right shunt.[19]

The DLCO for Mr Smith is moderately reduced. Mr Smith's lung volumes reveal a TLC 64% of normal, suggesting a mild restrictive process. However, unlike most patients with a parenchymal restrictive disorder, his RV is increased and his FVC is disproportionately severely reduced compared to his TLC.

SPECIAL CASES

Typical obstructive and restrictive patterns are commonly identified by PFTs. However, there are frequent cases that do not fit the standard patterns of obstruction and restriction, such as the previously discussed "nonspecific pattern." A second recently described process is called *complex restriction*. This occurs when TLC is low (ie, a restrictive process), and FVC is reduced disproportionately compared with TLC (>10% lower than TLC).[20] A study of 200 such cases found that patients with complex restriction are more often female and younger than those with typical restrictive processes. The conditions most commonly associated with complex restriction include (in decreasing order) atelectasis, diaphragmatic paralysis, radiographic evidence of small airway disease, obesity, underweight, and neuromuscular weakness.[20] These should be considered, along with poor test performance, when FVC is reduced out of proportion to TLC in the absence of obstruction.

BASIC GUIDE TO INTERPRETATION

Now that the basic mechanisms behind the PFT have been explained, one way to consider interpretation of these tests is provided in Figure 2 and the accompanying text.[6]

Obstructive Pathway

1. First, examine the flow-volume loop and decide whether it looks like an obstructive pattern ("scooping" of the expiratory flow-volume curve) or a restrictive pattern (a tall, narrow, or "peaked" expiratory flow-volume curve, sometimes described as a "witch's hat") or if a variable or fixed obstruction is present by looking for flattening of the inspiratory or expiratory portions of the loop. Refer to Figure 1 for examples of these abnormalities.
2. If FEV_1/FVC is low and FVC is normal or high, simple obstruction is present.
3. If FVC is low, check TLC.
4. A low TLC suggests superimposed restriction (a mixed abnormality), while a high TLC suggests "air trapping".
5. For patients with obstruction, the response to a bronchodilator may be assessed to determine whether FEV_1 or FVC meets criteria for a positive response (a $\geq$12% improvement with an absolute increase of $\geq$200 mL).
6. The severity of obstruction is graded on the basis of the FEV_1 percent predicted (see Table 2).[7,8,13] The cutoff points for mild, moderate, and severe obstruction are arbitrary (not based on solid evidence) and vary among standards. Some standards interpret using the post-bronchodilator value (such as current ATS guidelines).[7] Others use the pre-bronchodilator value.
7. In current or former smokers with obstruction, a low DLCO suggests emphysema or other pulmonary parenchymal or vascular disorder. A normal DLCO may suggest asthma or bronchitis.

Restrictive Pathway

8. If FEV_1/FVC is normal but FVC is low, this may be due to restriction or a nonspecific abnormality. Total lung capacity can distinguish between the 2 patterns.
9. If TLC is low, a restrictive disorder is present.
10. If FEV_1/FVC is normal and FVC is reduced, a normal TLC indicates the "nonspecific pattern." Although the 2005 ATS/ERS interpretation standard described this as obstruction, a substantial proportion of persons with this pattern do not have evidence of obstruction, but rather chest wall limitation (including obesity and muscle weakness) or poor test performance.[16,17] This can be distinguished by measurement of airway resistance. An increased airway resistance suggests obstruction, whereas a normal airway resistance suggests an alternative cause (see point 13).
11. If restriction is present, severity can be graded on the basis of the TLC percent predicted (see Table 3). As with obstruction, cutoff points are arbitrary and vary among standards.
12. If restriction is reported, a low DLCO indicates a pulmonary parenchymal restrictive process. A normal DLCO suggests a nonparenchymal cause of restriction.
13. Restriction with a normal DLCO or a nonspecific pattern with normal airway resistance suggests an alternative cause (chest wall limitation, weakness, and poor performance). Consider measurement of

maximal respiratory pressures, analyze the study for test performance, and review the available chest image.

Isolated Reduction in DLCO

14. If the results of spirometry are normal, lung volumes are rarely useful.
15. DLCO can be helpful for patients with an isolated gas exchange abnormality. An isolated reduction in DLCO is seen most often in patients with emphysema or interstitial lung disease (eg, pulmonary fibrosis) or both. It less commonly indicates a pulmonary vascular disorder, such as primary pulmonary hypertension.

Comparison to Previous PFTs

16. Comparison to the patient's previous PFTs (if available) can be helpful, as it can assist in determining progression of disease. However, it is important to note that there is an expected decline in FVC and FEV_1 by 20 to 30 mL/y in addition to the possibility of test variability, so this must be taken into account during the comparison.[7]

Mr Smith's PFT suggests a "complex restrictive" process. His TLC is mildly reduced and the FEV_1/FVC ratio is normal, consistent with a restrictive process. His FVC is disproportionately severely decreased, out of proportion to TLC. In light of the recent study, this suggests an additional process, which might include chest wall limitation, neuromuscular weakness, poor performance, or occult obstruction. Given his reduced MVV and maximal respiratory pressures, neuromuscular weakness is favored, especially in the setting of his subjective muscle weakness. With further evaluation, he was found to have dermatomyositis as the cause of his symptoms.

CONCLUSION

Pulmonary function tests are essential to the diagnosis of many lung conditions and help to identify numerous nonpulmonary disease processes. Understanding the basic interpretation of the components of this valuable test is crucial for primary care physicians to aid in the diagnosis of patients with respiratory symptoms.

Abbreviations and Acronyms: ATS = American Thoracic Society; **COPD** = chronic obstructive pulmonary disease; **DLCO** = diffusing capacity of lung for carbon monoxide; **ERS** = European Respiratory Society; **FEV_1** = forced expiratory volume in the first second; **FVC** = forced vital capacity; **LLN** = lower limit of normal; **MVV** = maximum voluntary ventilation; **PFT** = pulmonary function test; **RV** = residual volume; **TLC** = total lung capacity

Potential Competing Interests: Dr Scanlon receives royalties for sales of *Interpretation of Pulmonary Function Tests: A Practical Guide*, published by Lippincott Williams & Wilkins.

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