CHAPTER 1

Forced Spirometry and Related Tests

Introduction

Forced spirometry, often referred to as *spirometry*, is an essential component in the medical evaluation of patients complaining of shortness of breath. It is also widely used to evaluate the beneficial effects and adverse reactions of therapeutic interventions and to monitor the effects of environmental and occupational exposures. In addition, forced spirometry is used in disability/impairment evaluations, in preoperative assessments, and to monitor lung function over time.

Spirometry has shown considerable growth in the past 30 years, for several reasons: (*a*) published standards and testing guidelines,[1-6] (*b*) improved spirometers and software, (*c*) evidence that both patients and physicians have inaccurate perceptions of the severity of airflow obstruction,[7-11] (*d*) evidence that history taking and physical examination by themselves are not

helpful in identifying patterns of lung disease,[12,13] (*e*) recommendations that spirometry be included in the assessment of patients suspected of having asthma,[14,15] and recommendations for objective measurements to reduce the impact of chronic obstructive pulmonary disease (COPD).[16]

This chapter will provide information for both the student and the practitioner by discussing relevant physiology, instrumentation, techniques of performance and calculations, and basic elements of interpretation. Because spirometry is frequently performed before and after administration of a bronchodilator, this chapter will discuss how to administer bronchodilators in the pulmonary function laboratory and how to assess patient response. Also, because they are related and often performed with spirometry, included in this chapter are discussions on maximum voluntary ventilation and peak expiratory flow rate monitoring.

Definitions

VC	Vital capacity is the maximum volume of air exhaled after a maximum inspiration.
FVC	Forced vital capacity is the maximum volume of air exhaled with maximum force from a maximum inspiration.
FEV_1	Forced expiratory volume in 1 second is the volume of air exhaled in the first second of an FVC maneuver.
$FEF_{25–75\%}$	Forced expiratory flow between 25% and 75% is the average flow during the middle half of an FVC maneuver.
PEFR	Peak expiratory flow rate is the maximum flow attained during an FVC maneuver.
MVV	Maximum voluntary ventilation is the volume of air a patient can breathe rapidly and forcefully over a specified period of time (e.g., 12 seconds).

Physiology

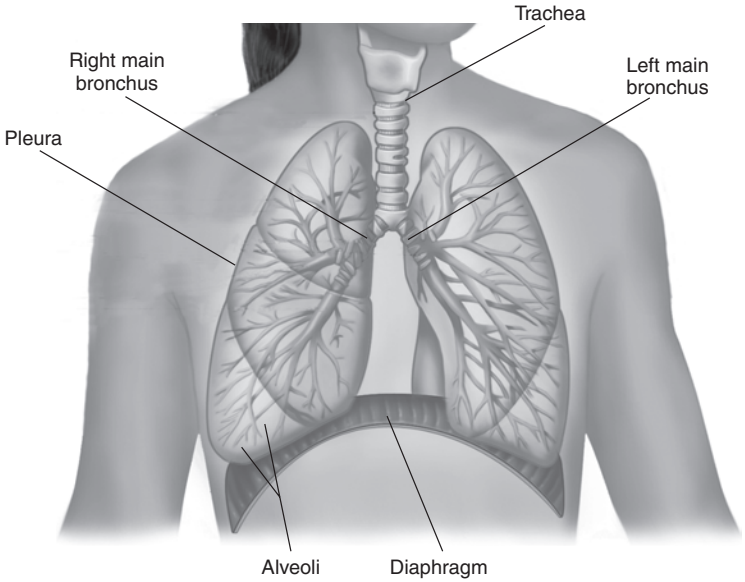
Although the lung is sometimes regarded simply as sort of a bellows system that moves air in and out of the body, it is a complex organ involved in many physiologic processes, such as gas transfer between the environment and blood and defense against harmful agents (e.g., pollutants), and in biochemical processes that produce important substances in the body.

The lower airways, as shown in **Figure 1.1**, begin with the trachea and divide into a right and left main stem bronchus. These main stem bronchi (referred to as the first generation of airways) divide into small branches, which become narrower and more numerous as they go deeper into the lung, ending 16 generations later in the terminal bronchioles. These are the conducting airways and contain no alveoli. Beyond the terminal bronchioles are the alveoli, of which there are approximately 300 million.

Inspiration is an active process that occurs when the respiratory muscles contract. The major respiratory muscle is the diaphragm, and when it contracts, it pushes down toward the abdomen. Other respiratory muscles, including the external intercostals, scalenes, and sternocleidomastoids, increase the lateral and anteroposterior diameter of the thorax.

Figure 1.1

The lower airways showing the trachea, right and left main stem bronchi, and branches developing to the alveoli.



During quiet breathing expiration is passive—occurring with relaxation of the respiratory muscles and the return of the lungs and thorax to resting volume. However, during fast, hard breathing, expiration becomes active and the abdominal muscles contract, pushing the diaphragm upward. Additionally, during fast, hard breathing, the internal intercostal muscles pull the ribs down and inward, decreasing the diameter of the thorax.

During spirometry, the forced expiratory maneuver consists of a maximal inspiration and then a rapid, forceful, and complete expiration. A number of physiologic factors influence the gas flow during this maneuver, but they can be broadly divided into two groups: (*a*) mechanical properties of the lungs and (*b*) resistive elements.

The *mechanical properties of the lung* refer to the compliance and elastic recoil. *Compliance* (CL) describes stiffness and is the change in volume of air in the lung divided by the pressure change. When we take a deep breath, the respiratory muscles contract, the chest wall moves outward, and the diaphragm moves downward. The result is a negative pressure in the thorax and lungs, allowing air to enter. Lung tissue that is stiff, or less compliant, requires relatively greater negative pressure. Conversely, lung tissue that is not stiff, or more compliant, requires relatively less negative pressure for the same amount of volume. **Figure 1.2** shows examples of three different pressure–volume relationships during a maximum inhalation from the tidal volume end-expiratory level, which is also known as functional residual capacity (FRC). FRC is explained in detail in Chapter 2.

In Figure 1.2A, a pressure change of 3 cm H_2O results in a 0.5 liter volume change above FRC. This means that an additional 3 cm H_2O pressure was required to produce the 0.5 liter volume change. It took approximately 30 cm H_2O of additional pressure to reach maximum inhalation volume (i.e., total lung capacity [TLC]), which is approximately 6 liters in this figure. C_L near FRC can be calculated by dividing the volume change (ΔV) on the vertical axis by the transpulmonary pressure change (ΔP) on the horizontal axis, which in this example equals 0.17 liter/cm H_2O. The shape of the pressure–volume relationship in Figure 1.2A, as well as the C_L near FRC, are normal.

In Figure 1.2B, a pressure change of 9 cm H_2O results in a 0.5 liter volume change above FRC, equaling a C_L of 0.06 liter/cm H_2O. In other words, it took more pressure to move the lung tissue to allow 0.5 liter of air to enter the lung. This is an example of stiff lungs, found in various forms of pulmonary fibrosis.

In Figure 1.2C a pressure change of 1.5 cm H_2O results in a 0.5 liter volume change above FRC, equaling a C_L of 0.33 liter/cm H_2O. It took less pressure to move the lung tissue to allow 0.5 liter of air to enter the lung. This is an example of overly compliant lungs, found in patients with emphysema.

Elastic recoil refers to the lungs' tendency to return to their resting or relaxed state. The more the lung tissue is stretched, the stronger the elastic recoil and the higher the maximal flow in the airways. Thus, the elastic recoil pressure and maximal flow are greatest when the lungs are fully inflated and the least when the lungs are nearly emptied. Elastic recoil also varies with disease. Patients with emphysema have lower elastic recoil because of tissue loss. Patients with pulmonary fibrosis have increased elastic recoil.

The second major factor that influences gas flow is the *resistance to airflow*. The caliber of the conducting airways plays the major role. The smaller the diameter of the conducting airway, the more the resistance. Two main factors affect airway caliber: (*a*) lung volume and (*b*) bronchial smooth muscles.

During inspiration the airways are pulled open and become wider and longer. Airway caliber is greatest when the lungs are full. As the lungs are emptied and lung volume decreases, the airways become smaller and airway resistance increases. When the bronchial smooth muscles contract, the airway caliber decreases. This process is amplified if there is airway wall thickening or an increase in mucus in the airways.

Airway collapsibility also affects airway caliber and is best explained by the pressure–flow relationship and the single equal-pressure-point model (**Figure 1.3**). When there is no flow in

Figure 1.2

Three pressure–volume curves illustrating the relationship between transpulmonary pressure and volume. A. Normal pressure–volume curve where the change in volume divided by the change in pressure between FRC and 0.5 liter above FRC (i.e., 0.17 liter/cm H_2O) is in the normal range of 0.12 to 0.25 liter/cm H_2O. B. Pressure–volume curve where the change in volume divided by the change in pressure between FRC and 0.5 liter above FRC (i.e., 0.06 liter/cm H_2O) is lower than the normal range, which might be seen in individuals with stiff lungs (e.g., pulmonary fibrosis). C. Pressure–volume curve where the change in volume divided by the change in pressure between FRC and 0.5 liter above FRC (i.e., 0.33 liter/cm H_2O) is higher than the normal range, which might be seen in individuals with overly compliant lungs (e.g., emphysema).

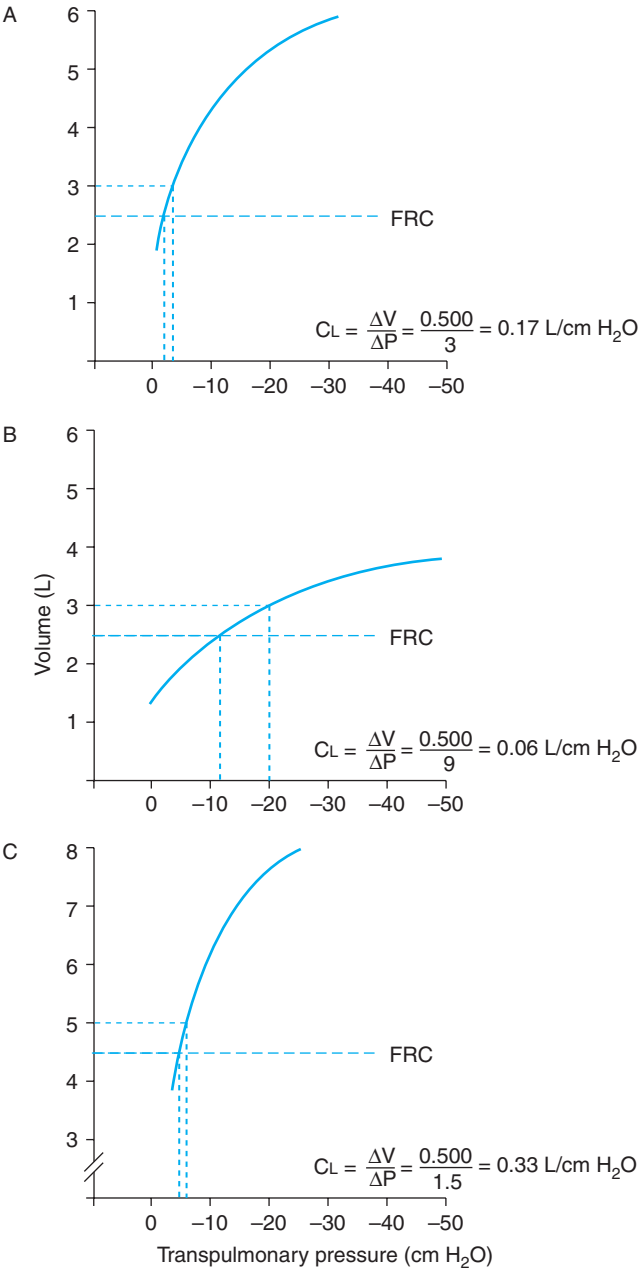
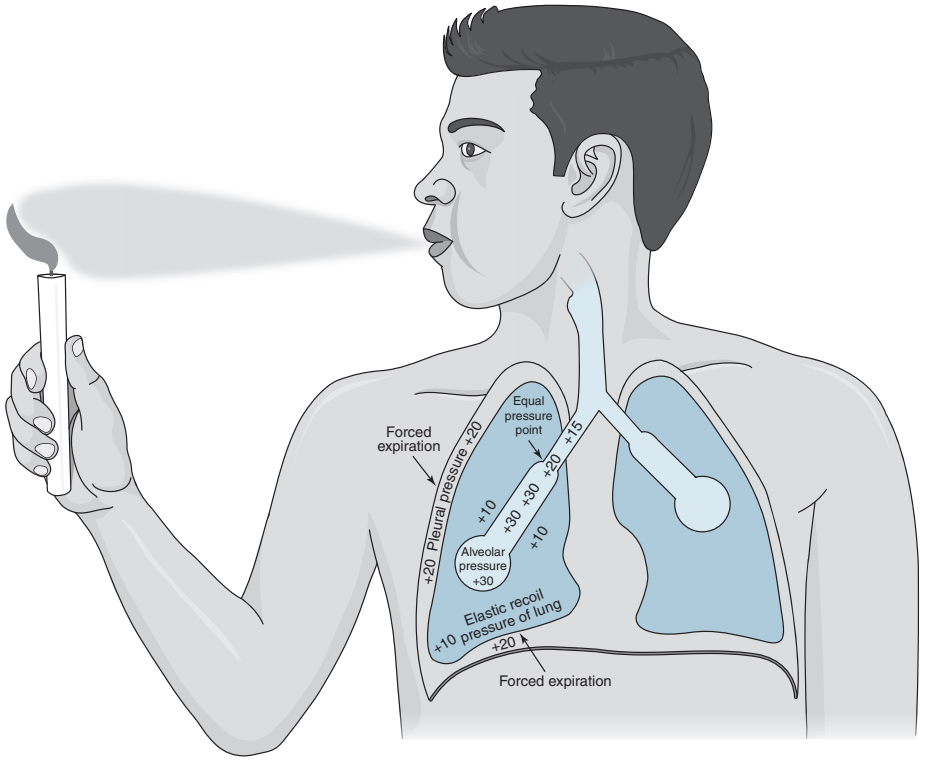


Figure 1.3

The dynamic compression of the airways showing the EPP. During the forced expiration the respiratory muscles compress the thorax. Alveolar pressure (P_{alv}) is the sum of the pleural pressure (P_{pl}) and the elastic recoil pressure (P_{el}). In this example, P_{pl} is 20 cm H_2O, P_{el} is 10 cm H_2O, and thus P_{alv} is 30 cm H_2O. The pressure in the airways falls as the mouth is approached. The EPP is reached when P_{pl} equals P_{alv}. Downstream from that point (toward the mouth) the airways narrow, limiting airflow.



the airways, the alveolar pressure and the airway pressure are equal and approximately atmospheric. During an inspiration, alveolar and pleural pressures become subatmospheric and air rushes into the lungs. During expiration, alveolar and pleural pressures become positive and exceed atmospheric pressure. During a forced expiration this pressure change is amplified, as shown in Figure 1.3. The airways are forced to narrow at the point when pressure in the thorax becomes greater than the airway pressure. The point where these two pressures (thorax and airway) are exactly equal is called the equal pressure point (EPP). The airways on the alveolar side of the EPP are referred to as the *upstream airways*, and those on the mouth side of the EPP are called the *downstream airways*.

The maximal flow that can be achieved, as explained by the EPP model, can be shown mathematically by the following formula:

$$\text{Maximal flow} = \frac{\text{Pressure change}}{\text{Resistance}}$$

The pressure change is the difference between the pressure in the alveolus (P_{alv}) and the pressure at the EPP (P_{EPP}). Thus,

$$\text{Maximal flow} = \frac{P_{alv} - P_{EPP}}{\text{Resistance}}$$

Because P_{alv} is the sum of the pressure created by the muscles of the chest wall, which is called pleural pressure (P_{pl}) and the elastic recoil pressure (P_{el}), or $P_{alv} = P_{pl} + P_{el}$, and the EPP equals P_{pl}, then the pressure change is P_{el}.

$$\text{Maximal flow} = \frac{(P_{pl} + P_{el}) - P_{pl}}{\text{Resistance}} = \frac{P_{el}}{\text{Resistance}}$$

The resistance to airflow is the resistance of the upstream airways (Rus). Thus,

$$\text{Maximal flow} = \frac{P_{el}}{\text{Rus}}$$

Hence, airflow is determined by the driving pressure (P_{el}) and the resistance of the airways upstream (Rus) of the EPP.

Patients with obstructive lung disease have reduced airflow (i.e., airflow limitation). Patients with asthma have increased resistance because bronchial smooth muscle contraction reduces maximal flow. In patients with emphysema the primary cause of reduced airflow is a loss of elastic recoil. Some asthmatics may also demonstrate a loss of elastic recoil, which compounds the effect of increased resistance.

Spirometry Instrumentation

Available spirometers can be classified as: (*a*) *volume-displacing* or (*b*) *flow-sensing*. The usually large and bulky volume-displacement spirometer collects exhaled air or acts as a reservoir for inhaled air. The flow-sensing devices are smaller, more portable, and measure flow, which is then integrated electronically to give volume.

Volume-Displacing Spirometers

The volume-displacement spirometer has a very long history and was the type John Hutchinson used in his experiments around 1840. These spirometers were the mainstay for more than a century but have been mostly replaced in clinical practice with smaller and more portable devices. There are four main types of volume-displacement spirometers: (*a*) water seal, (*b*) rolling seal, (*c*) bellows, and (*d*) diaphragm.

Water Seal

Figures 1.4A and 1.5 show a water-seal spirometer (*Stead-Wells spirometer*), which is considered to be the gold standard. This spirometer consists of three cylinders: an outer hollow cylinder open on the top, a second cylinder approximately one-half inch smaller in diameter and closed on the top except for one or two large holes, and a third cylinder of lightweight plastic with its open bottom placed into the space between the first and second cylinders. The space between the first and second cylinders is also filled with water. The third cylinder (sometimes called the bell) moves up and down in the water when a patient is connected to it. When the patient exhales into the mouthpiece and the tubing, exhaled air forces the bell upward. The water acts as a seal and keeps this air from escaping—a water seal. A pen connected to the bell writes on paper affixed to a rotating drum (the kymograph). Volumes used to be measured manually with a pencil and ruler and were corrected for temperature, pressure, and water saturation. The time-consuming manual measurements were eventually replaced by electronic measurements, with the addition of a potentiometer (a device for measuring the potential or voltage in a circuit) to the bell.

The Stead-Wells water-seal spirometer has several potential problems, including leaks, making sure there is an appropriate water level, and infection control concerns. Because of these issues and technology advancement, this type of spirometer was eventually replaced in practice with the dry-seal spirometer, shown in **Figure 1.4B**

Rolling Seal

The *dry rolling-seal spirometer* is another type of volume-displacement spirometer (**Figure 1.6**). The piston-in-cylinder configuration can be vertical or horizontal. A silicone-based elastic material seals the spirometer contents by rolling with the piston as it moves (thus the name rolling-seal spirometer). Volume is measured by a potentiometer that is mechanically connected to the piston rod with a slide wire. Flow data are obtained by electronic differentiation of the volume signal. Like the bellows spirometer, the rolling-seal spirometer can display results electronically or mechanically with a pen.

Figure 1.4A

The water-seal Stead-Wells spirometer.

Source: Courtesy of nSpira Health, Inc.

Figure 1.4B

The dry-seal Stead-Wells spirometer.

Source: Courtesy of nSpira Health, Inc.

Figure 1.5

An illustration of the water-seal Stead-Wells spirometer showing how the air moves in and out of the spirometer bell.

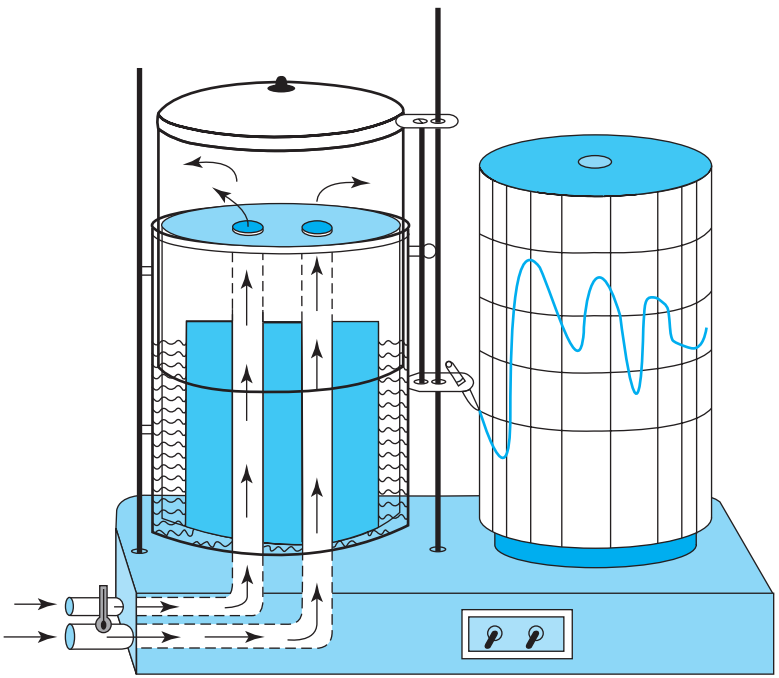
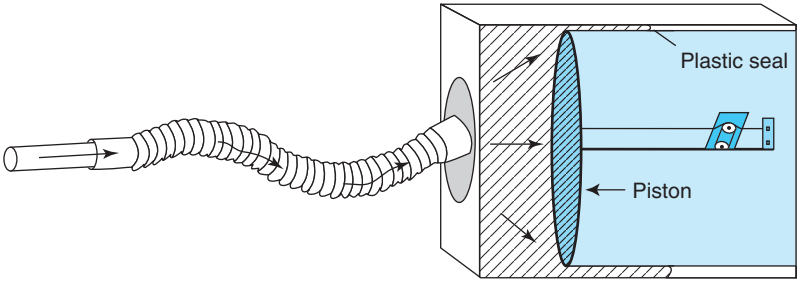


Figure 1.6

An illustration of the horizontal rolling-seal spirometer showing how the piston-cylinder mechanism collects and seals exhaled air.



Bellows

The *bellows-type spirometer* is another example of the volume-displacement spirometer. Exhaled air is collected in a bellows, much like the one used to coax flames from fireplace coals. Bellows spirometers are usually made of plastic, and the material expands as exhaled air enters and contracts as air exits. The vertical bellows or *wedge spirometer***,** shown in **Figure 1.7**, is large and bulky and was popular in the 1960s and 1970s. The horizontal bellows shown in **Figures 1.8 and 1.9** is smaller and more practical. Both of these bellows systems can display results electronically with a computer or microprocessor or mechanically with a pen and kymograph.

Diaphragm

The fourth type of volume-displacement spirometer, one that incorporates a *diaphragm*, is shown in **Figure 1.10**. Such spirometers are small, lightweight, and simple to use and come with or without a microprocessor. As shown in Figure 1.10, the patient breathing tube connects

Figure 1.7

An illustration of the vertical bellows type of spirometer showing how the bellows-like action collects exhaled air and senses movement.

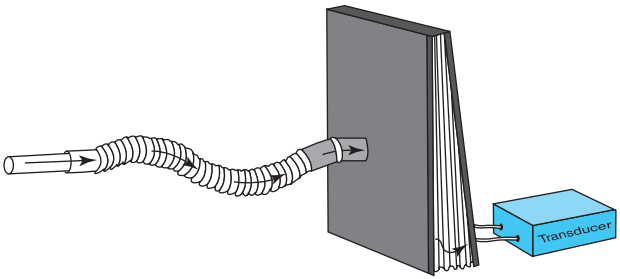


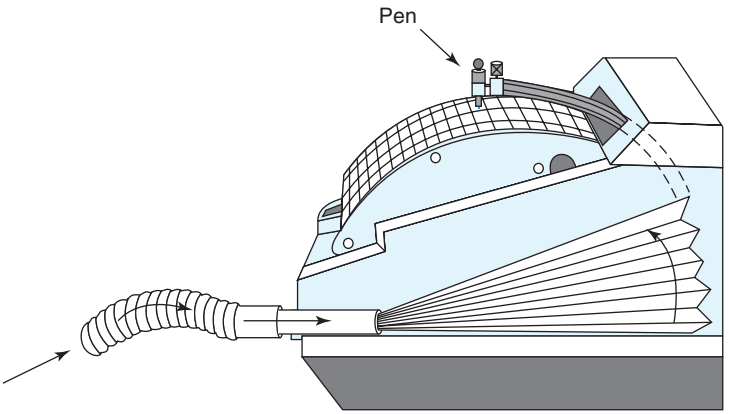
Figure 1.8

The horizontal bellows spirometer.

Source: Courtesy of Vitalograph Limited.

Figure 1.9

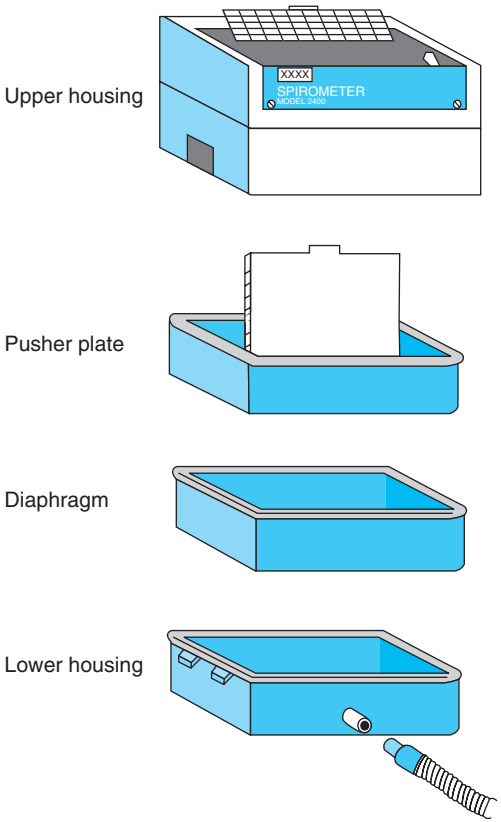
An illustration of the horizontal bellows type of spirometer showing how the bellows collects expired air and records the volume.



to the bottom of the unit. A rubber diaphragm fits snugly into the lower housing. As the patient's exhaled air enters the lower housing, it moves the bottom side of the diaphragm upward. As the diaphragm moves upward, it moves a pusher plate upward, and volume is then measured. The exhaled air escapes back out of the patient breathing tube when the patient's mouth is removed. A volume–time tracing can be obtained, and if the instrument is equipped with a microprocessor, this device will calculate several parameters.

Figure 1.10

The diaphragm-type spirometer, which collects exhaled air beneath a diaphragm and pushes upward on a pusher plate and writing mechanism.



Advantages and Disadvantages

The volume-displacing spirometers are generally designed to measure exhaled volumes and, before testing starts, contain no air. However, certain types (e.g., rolling seal) do allow the user to add air by moving the resting position. This allows the patient to both inhale deeply from and exhale into the spirometer (i.e., closed-circuit breathing). This feature allows the measurement of inspired vital capacity as well as maximal voluntary ventilation.

The major disadvantage with volume-displacing spirometers is they can develop leaks. If they leak, the volume cannot be collected accurately. Therefore, one of the most important quality control activities is to leak test these devices. This can be done when calibration checks are performed on some types of spirometers, but on others it may take a bit more ingenuity.

Summary of Characteristics of Volume-Displacing Spirometers

Desirable
- Directly measures volume
- Low cost
- Ease of operation
- Water-seal spirometer is considered to be the gold standard

Possibly undesirable
- Some are very large and bulky
- Less portable
- Water in water-seal devices needs to be changed and levels need to be checked frequently
- Leaks
- Without microprocessor or computer, manual calculations are necessary
- Infection control issues

Flow-Sensing Spirometers

The shortcomings of volume-displacing spirometers (e.g., large, bulky) as well as improved electronic technology and software led to the development of flow-sensing devices.

Flow-sensing spirometers directly measure flow (volume per unit of time) using various methodologies. Volume is then calculated by multiplying flow by time, which is known as *integration*. This process requires a computer or microprocessor with appropriate software. The accuracy of the calculated volume measurement requires careful calibration and detection of low flow. Several types of airflow measuring devices are available, including: (*a*) differential pressure device (pneumotachograph), (*b*) thermistor or heated-wire anemometer, (*c*) turbine or impeller device, and (*d*) ultrasonic.

Pneumotachograph

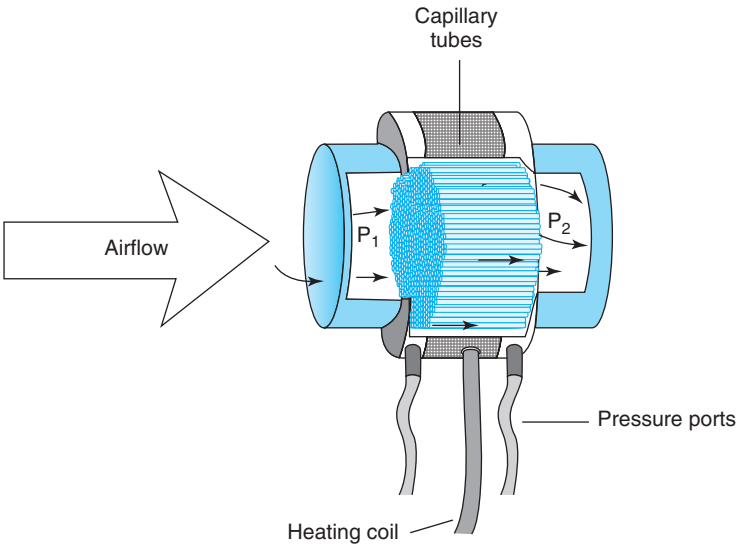
An example of the *differential pressure device (pneumotachograph* or *pneumotach)* is shown in **Figure 1.11**. The device consists of a tube with fixed resistance. The fixed resistance, which is very small and not sensed by the patient, can be a bundle of capillary tubes running parallel to the flow (Fleisch type) or a fine mesh screen or set of screens. As air flows through the tube in either direction, it meets the fixed resistance. The pressure on the side from which the flow originates becomes greater than the pressure on the other side. The greater the flow, the greater the pressure difference. The pressure difference is measured with a pressure transducer, and the signal is sent electronically to amplifiers and then to a computer or microprocessor.

The relationship among flow, pressure, and resistance can be explained mathematically with the following formula:

$$\text{Flow} = \frac{\text{Pressure}}{\text{Resistance}}$$

Figure 1.11

An illustration of the pneumotachograph flow-sensing device showing the differential pressure principle. As airflow enters the pneumotachograph it meets the resistive element (capillary tubes). The pressure on the airflow side of the element (P_1) is greater than the pressure on the other side of the resistive element (P_2). The two pressures are transmitted through the pressure ports to a transducer, which is connected to electronic amplifiers and computers or recorders. The heating coil heats the resistive element to reduce moisture buildup. If heated to 37° C, airflow is measured at body temperature.



The accuracy of a pneumotachograph depends on assuring that the resistance remains constant. One can see from the preceding formula that with constant resistance, pressure is directly proportional to flow. However, if the resistance changes from when the device was calibrated (e.g., increases with secretions or exhaled water vapor that can collect on the screens or in the capillary tubes), this relationship changes and flow can be incorrectly measured.

One unique type of pneumotach, manufactured by Medical Graphics Corporation (St. Paul, Minn.), is a pitot-type sensor that measures impact pressure with proprietary signal processing (**Figures 1.12 and 1.13**). The lack of a resistive element makes this flow-measuring device impervious to condensed water vapor and secretions. This device combines the mouthpiece and flow-sensing mechanism into one piece, and it is disposable.

Thermistor or Heated-Wire Anemometer

The *thermistor* or *heated-wire anemometer* (also referred to as a mass-flow sensor) consists of a fine piece of wire (e.g., platinum) in the center of a tube as shown in **Figures 1.14 and 1.15**. As air moves through the tube, it cools the heated wire. More electrical current is then needed

Figure 1.12

An illustration of the preVent Pneumotach (Medical Graphics Corporation, St. Paul, Minn.). A. Side view. B. Front view. The device consists of an open-ended barrel and one pair of integrally molded ribs intersecting to form a cross. The ribs include a series of small apertures and a pair of inner lumens. The impact pressure is measured in the paired lumens of the ribs as respiratory gases pass over the exterior of the ribs during inspiration and expiration.

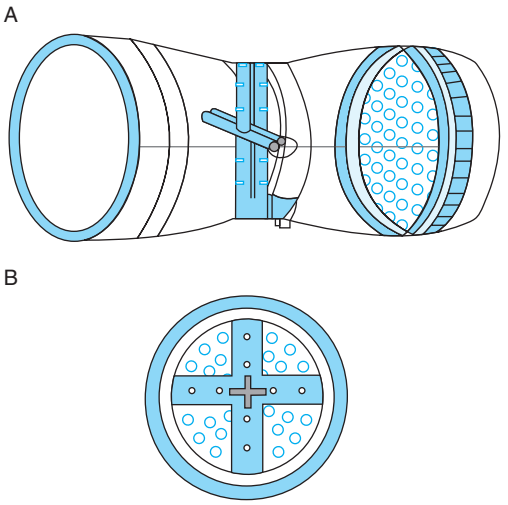


Figure 1.13

Photograph of preVent Pneumotach.

Source: Courtesy of Medical Graphics Corporation

to reheat the wire and maintain it at a specific temperature. The current, which rises with the airflow, is measured, electronically linearized, and read as flow through the device. The device is very sensitive to flow, and some devices incorporate two wires to improve accuracy.

Heated-wire devices have some problems. Turbulent flow cannot be measured accurately, and laminar flow must be ensured by providing a long tube between the patient and the heated-wire

Figure 1.14

The heated-wire anemometer (thermistor) type of flow-sensing device.

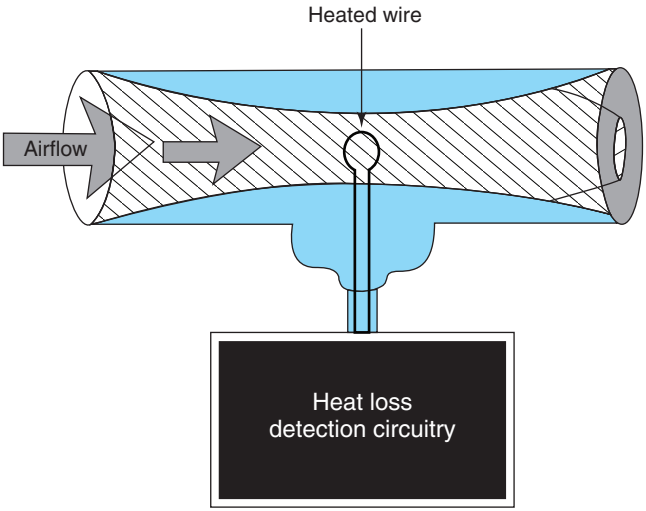


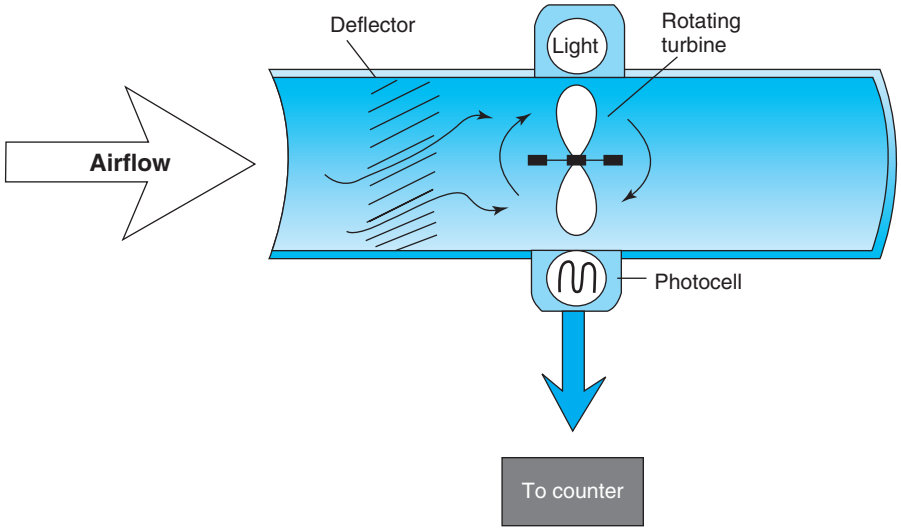
Figure 1.15

Photograph of the mass-flow sensor (i.e., heated-wire anemometer).

Source: Courtesy of CareFusion Corporation

Figure 1.16

The turbine or rotating type of flow-sensing device.



housing. Manufacturers have improved on these problems by employing a second heated wire. Also, the heated wire is fragile and responds to movement when the device is handheld.

Turbine

A *turbine* device is shown in **Figure 1.16.** It consists of a vane or wheel connected to gears. As air flows into the device, the vane turns at a speed proportional to airflow. An electronic circuit counts the revolutions and calculates flow. The Wright Respirometer, which is a mainstay in respiratory care for measuring volumes at the bedside, is based on this principle. Accuracy is not affected by turbulent flow, water vapor, or gas composition, but turbine inertia introduces inaccuracies with changing airflow. Newer designs have tried to improve on this problem by decreasing the weight of the rotating vanes.

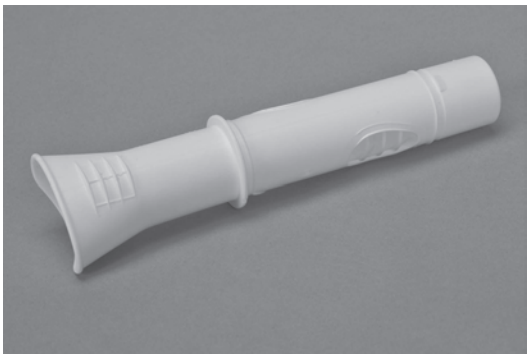
Ultrasonic

The *ultrasonic* flow measurement device shown in **Figure 1.17** consists of a flow sensor with a disposable mouthpiece tube (spirette). Transducers are located on opposite sides of the spirette cavity and emit and receive sound in alternating directions. When airflow is present in the tube, an ultrasonic sound pulse that travels against the flow is slowed down and takes a longer time to reach the opposite transducer. Conversely, a sound pulse traveling with the flow is sped up and takes a shorter time to reach the opposite transducer. The transit time of the sound pulses is accurately measured with a digital clock, and gas flow can then be calculated. This calculation is not affected by gas composition, pressure, temperature, or humidity. The disposable mouthpiece acts as a hygienic shield and allows the ultrasonic pulses to travel

Figure 1.17

The ultrasonic mouthpiece/tube.

Source: Courtesy of ndd Medical Technologies, Inc.



between the measurement transducers. It has no sensor elements, does not actually perform a measurement function, and thus does not require calibration.

Summary of Characteristics of Flow-Sensing Spirometers

Desirable
- Smaller and usually more portable
- Computerized; thus no manual calculations
- Bidirectional devices provide flow–volume loop capability
- Easier infection control with some models

Possibly undesirable
- Frequent and careful calibration checks needed for some models
- Moisture and secretions can cause problems
- Gas composition can affect results
- May not sense low flows

Spirometer Display

There are two ways to display the spirogram: (*a*) volume–time and (*b*) flow–volume. Both are considered useful and important for operator and interpreter inspection, as well as quality assurance.

The volume–time display (**Figure 1.18**) puts volume (in liters) on the *y* (vertical) axis and time (in seconds) on the *x* (horizontal) axis. This display is most useful in assessing the length of and viewing the terminal portion of the spirometry maneuver to assess whether a plateau was achieved and the patient exhales fully.

The flow–volume display (**Figure 1.19**) puts flow (in liters/sec) on the *y* axis and volume (in liters) on the *x* axis. This display is most useful in assessing the initial portion of the

Figure 1.18

The volume–time curve as might be seen during an FVC maneuver. The advantage of this display is the ability to view small changes in volume as the maneuver ends, thus helping the operator better detect the end of the test.

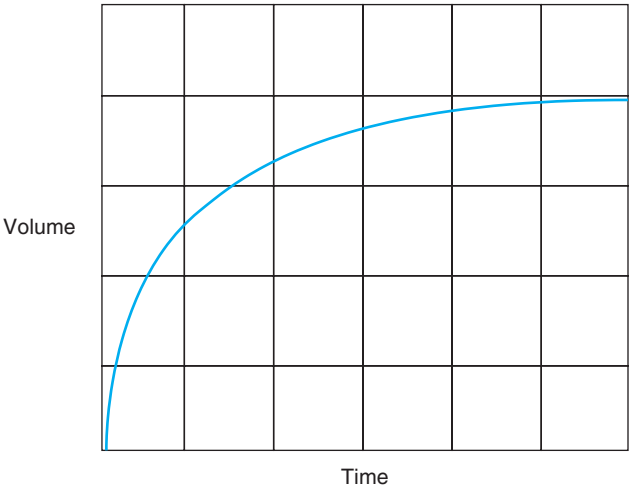
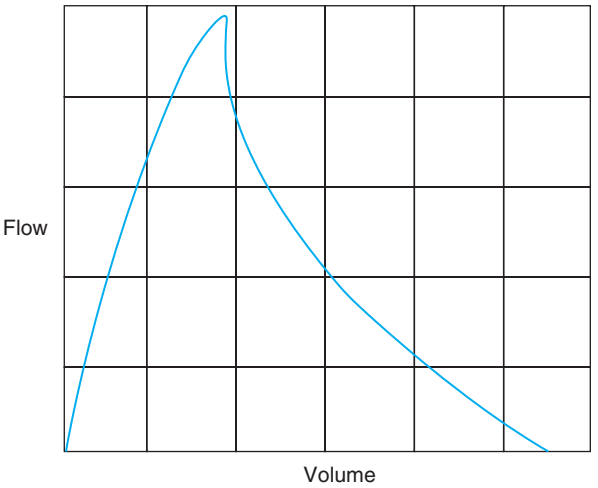


Figure 1.19

The flow–volume curve as might be seen during an FVC maneuver. The advantage of this display is the ability to see peak flow (which provides information on patient effort and technique at the start of the test).



spirometry maneuver including peak expiratory flow (PEF). Typically, this plot is scaled so that flow is twice that of volume (i.e., a 2:1 ratio).

The 2005 American Thoracic Society/European Respiratory Society (ATS/ERS) recommendations suggest the volume–time display include at least 0.25 to 1 second before exhalation starts. This is helpful in viewing back-extrapolation volume and to evaluate effort during the initial portion of the maneuver. It is also recommended that the last 2 seconds of the maneuver be displayed to assure the patient has exhaled fully.[6]

Calibration

Spirometers, like other monitoring and diagnostic instruments, can generate erroneous information. However, if they have calibration checked and they are leak tested (volume-displacing spirometers) every day of use, the likelihood of error is greatly reduced.

Calibration of spirometers is usually done by the manufacturer. It establishes the relationship between the flow or volume sensed by the spirometer and the actual flow or volume. A calibration check or verification is different from calibration in that it ensures the spirometer is within the calibration limits of the known value. If a spirometer does not meet the calibration check limits (e.g., ±3.5%), a calibration is indicated. Calibration checks should be done at least every day the spirometer is used and ideally before any patients are tested.

Every laboratory or office should obtain a *calibration syringe* (**Figure 1.20**) with a volume of at least 3 liters that has been checked against a standard. The manufacturer should provide recommendations concerning appropriate intervals for having the syringe checked for leaks and accuracy. Typically this interval is 1 year.

Volume-displacing spirometers should have the patient testing tube attached during the calibration check so it too can be included in the calibration and leak testing process. Visual

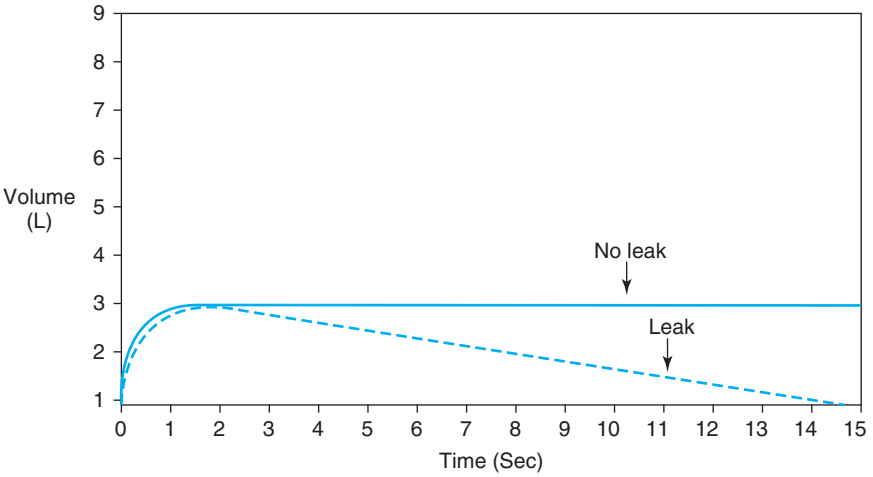
Figure 1.20

Photograph of several calibration (known-volume) syringes.

Source: Printed with permission from: Hans Rudolph, Inc.

Figure 1.21

A volume–time trace illustrating a proper calibration and leak test (solid line) of a volume-displacement spirometer with a 3-liter calibration syringe, and an unacceptable calibration and leak test (dashed line).



inspection alone may not reveal tears resulting from use and cleaning. The procedure for checking calibration and leak testing the volume-displacing spirometer is easy. Inject the entire syringe volume and observe the spirometer or mechanical pen tracing. If the bell falls or the pen line does not travel in a straight line (**Figure 1.21**), a leak is present. Knowledgeable staff should locate and repair leaks. If no leak is present, the volume shown on the chart paper or on the computer should equal the syringe volume within ±3.5%. For example, if a 3-liter syringe is used, the acceptable range would be 2.90 to 3.11 liters.

The calibration syringe is used to make at least three different injections at different flows varying between 0.5 (very slow) and 12 (very fast) liters/sec. This corresponds to injection times of approximately 6 seconds and less than 0.5 second. The process of injecting a known volume (e.g., 3 liters) at different speeds assures the device is linear in the range of flows used. The volume reported by the spirometer at each flow should meet the accuracy requirement (i.e., ±3.5%).[6]

If the spirometer cannot measure the calibration syringe volume within ±3.5%, do not use it until it is serviced or repaired.

Establish a calibration log or notebook for each spirometer, and enter the date and time, expected or known volume, measured volume, and technologist's initials. Many computerized models allow the user to store or print a page with all this information. This log is useful in verifying that the device was checked for accuracy and for noting trends that may indicate equipment problems. The log should also be used to document quality control procedures, repairs, and computer software or hardware updates.

Quality Control

Along with daily calibration checks, several other procedures will help ensure quality.

Biological Controls

Choose two or three healthy nonsmokers to serve as biological controls. Gather spirometry data on each of these biological controls and record the results in a quality control or calibration log. Repeat this procedure on a regular basis (e.g., weekly or monthly). Establish a mean and standard deviation (SD) (see Appendix E) for several parameters (e.g., FVC and FEV_1). Values measured during regularly scheduled biological control testing, or at other times when the spirometer data are suspect, should fall within a range of ± 2 SDs of the mean. If the value is outside that range, remedial action for the spirometer should be taken.

The coefficient of variation (CV) can also be obtained for these data. It is calculated as the SD divided by the mean. Ideally the CV is less than 5% for FVC and FEV_1 values.

Recorder Time Sweep

If the spirometer is a volume-displacement device that has a recorder with a time sweep, check the speed against a stopwatch.

Entire Range

Check volume-displacement spirometers over their entire range using the calibration syringe or equivalent volume standard. Use a larger calibration syringe (e.g., 7 liters) for this procedure. Another option is to calibrate this type of spirometer at other starting points besides the zero position, and check it against the chart paper.

Technologist Monitoring and Feedback

The importance of a monitoring and feedback program has been shown.[17] This type of program may involve some sort of scoring system that objectively evaluates test quality and repeatability. Feedback should be provided on a regular basis and should include unacceptable test information as well as recognition for good performance. One example of a scoring system for evaluating technologists who performed spirometry in clinical research trials is shown in **Table 1.1**. This system can be modified to meet your laboratory's needs. For example, you may want to exclude the use of PEFR.

What Spirometer to Choose for Your Needs

The ATS first published recommendations for spirometer standards in 1979 and updated them in 1987 and 1995.[1-3] The ERS published similar recommendations in 1983 and 1993.[18,19] The ATS and ERS appointed a task force to combine these spirometry recommendations, which were published in 2005.[6] Manufacturers are very much aware of these standards and design their instruments to comply with them. However, you should be aware of some specific standards before you select a spirometer.

If the spirometer measures FVC, it should be able to accumulate volume for at least 15 seconds and measure volumes of at least 8 liters, and it should be able to measure flow rates

Table 1.1

Scoring System for the Objective Evaluation of Technologists Performing Spirometry

	Grade	Criterion
Acceptability	4 or A	≥ 3 acceptable maneuvers with comments
	3 or B	< 3 acceptable maneuvers with comments
	2 or C	< 3 acceptable maneuvers, no comments
	1 or D	< 2 acceptable maneuvers, with obvious errors or inappropriate comments
Repeatability (FVC)	4 or A	2 highest of acceptable maneuvers agree within 0.100 L
	3 or B	2 highest of acceptable maneuvers agree within 0.110 to 0.150 L
	2 or C	2 highest of acceptable maneuvers agree within 0.160 to 0.200 L
	1 or D	2 highest of acceptable maneuvers do not agree within 0.210 L
Repeatability (FEV_1)	4 or A	2 highest of acceptable maneuvers agree within 0.100 L
	3 or B	2 highest of acceptable maneuvers agree within 0.110 to 150 L
	2 or C	2 highest of acceptable maneuvers agree within 0.160 to 0.200 L
	1 or D	2 highest of acceptable maneuvers do not agree within 0.210 L
Repeatability (PEFR)	4 or A	2 highest agree within 5%
	3 or B	2 highest agree within 5.1% to 10%
	2 or C	2 highest agree within 10.1% to 15%
	1 or D	2 highest do not agree within 15%

between 0 and 14 liters/sec. Although it is rare to find patients with vital capacity greater than 7 liters, they do exist. Also, one rarely sees maximum flow rates greater than 14 liters/sec, but many healthy individuals can achieve flows in the 12 to 14 liters/sec range. The total resistance to airflow at 14 liters/sec must be less than 1.5 cm H_2O/liter/sec. This total resistance must be measured with any tubing, valves, and filters that might be inserted between the patient and the spirometer.

An evaluation of spirometers in 1990 found that 12% of the spirometers did not accurately measure a 3-liter calibration syringe, and 29% of the spirometers performed "unacceptably" when an FVC simulator introduced 24 different waveforms. Additionally, this evaluation found software errors in 25% of the computerized systems.[20] A more recent evaluation of smaller flow-sensing office spirometers reported differences among these smaller devices and the standard (laboratory) devices.[21] Thus, spirometers should be carefully evaluated before purchase.

The companies that make and design the spirometers in use today are continually developing new devices or modifying and upgrading existing ones. Users usually benefit from this process and from the competition among companies. This text will not recommend specific brands or types but will present a method designed to enable the user to decide what is best for a particular application.

First, be clear about your needs. The answers to some of the following questions should help you narrow the choices:

- Who will conduct the tests, and what is that person's level of knowledge?
- How many tests per day will be performed?
- What pulmonary function values are needed? Will FVC and FEV_1 be enough, or will other values, such as inspiratory flows, be needed?
- How much money is available?
- Must the system be portable?
- Is a computer necessary to operate the device?

When you have chosen a type of spirometer, you must decide which brand to purchase. Criteria to examine include price, service, ease of cleaning, delivery time, and the user-friendliness of the software.

Request a demonstrator unit to evaluate. The evaluation process should consist of at least the following:

- Check the unit's specifications against ATS/ERS recommendations.
- Use a known-volume calibration syringe to inject or withdraw known volumes at different speeds. Do this step in the patient testing mode, not the calibration mode. The results from the instrument will be at body temperature and pressure saturated (BTPS), which means that if you use a 3-liter syringe, the reported FVC should be approximately 3.3 liters (BTPS).
- Test yourself or other laboratory staff members and simulate problem patients. For example, perform a poor start of test and an early termination to observe the instrument's response. Does it warn you about back-extrapolation error? Does it start prematurely from moving the mouthpiece around before actually blowing into the spirometer? Does it end the maneuver prematurely?
- Ask the salesperson for the names of other users who have purchased the instrument. Call or write to them and ask for their opinions and experiences.

Spirometry Testing Techniques

Successful spirometry depends on numerous factors, including: (*a*) proper patient preparation, (*b*) explaining and demonstrating the maneuver, and (*c*) proper performance and careful inspection of each maneuver.

Patient Preparation

In many hospitals and offices, patient preparation really begins when the patient is scheduled. At that time, the patient is usually instructed about which medications (if any) to stop taking, whether to stop smoking for a specific time, and so on.

When the patient arrives at the laboratory for testing, patient preparation consists of: (*a*) explaining the purpose of the test and completing necessary paperwork, (*b*) determining if there are any contraindications to performing spirometry, (*c*) obtaining the patient's age, height, and weight, and (*d*) positioning the patient.

Explaining the Purpose of the Test

Whenever a patient visits a physician's office or hospital laboratory for a new procedure, that individual is usually anxious or fearful of what lies ahead. Is it going to hurt? Are they going to poke a needle in my arm? Is it going to take a long time? These and other questions are going through the patient's mind, and therefore a brief explanation of the test, how it will be done, and why it should be done is important. Keep the explanation of spirometry simple, and be brief. Do not try to second-guess the ordering physician (e.g., questioning the orders for spirometry or type of bronchodilator) in front of the patient, and do not make statements that might make the patient more uncomfortable. The following explanation works well: "I am going to have you blow into a machine to see how big your lungs are and how fast the air comes out. It doesn't hurt, but it will require your cooperation and lots of effort."

Some laboratories include a questionnaire that the patient completes prior to testing. Common questions include: How are you feeling today? What medications have you taken today and when? Has a doctor ever told you that you have lung disease (e.g., asthma)? Have you ever been hospitalized for respiratory problems? Have you ever experienced respiratory symptoms like shortness of breath, wheezing, or chest tightness? Have you experienced any of these symptoms in the last 2 weeks? If you are a smoker, when did you last smoke? Have you had a respiratory infection in the past 3 weeks? Do you have high blood pressure? Are you pregnant?

Determining Contraindications

Spirometry can be significantly influenced by the patient's condition. Therefore, postponing testing for an hour or two, for a day, or even for several weeks is not out of the question. Several important relative criteria that would contraindicate spirometry include: (*a*) recent use of a bronchodilator when spirometry is ordered for before and after bronchodilator administration; (*b*) a current or recent viral infection (within 2 to 3 weeks) or other acute illness, especially when occupational or other screenings are being done for longitudinal studies (comparisons over time); (*c*) a serious illness, such as recent myocardial infarction, pulmonary emboli, etc.; and (*d*) smoking or a heavy meal within an hour of testing.

Other conditions that may interfere with obtaining optimal or repeatable results include chest or abdominal pain from any cause, oral or facial pain, stress incontinence, and dementia or confusion.[6]

Age, Height, and Weight

Spirometric results are usually compared to reference or predicted values. To do this correctly, the patient's age (on the day of the test), height (without shoes), and sometimes weight (wearing indoor clothes) are needed. In patients with spinal deformities, such as kyphoscoliosis, and for patients who cannot stand, the measurement of the arm span from fingertip to fingertip closely approximates the person's standing height.[22,23]

Positioning the Patient

Getting the patient comfortable and in the proper position is the next important step. Have the patient loosen any tight clothing, such as neckties, belts, or bras. Dentures should be left in place unless they are loose and interfere with performance of the test.

There is no significant difference in spirometric results between the sitting and standing positions, but the sitting position is preferred for safety reasons (avoid falling due to syncope).

If the patient sits, be sure the patient sits up straight and the patient's legs are uncrossed. Ideally, the chair should have arms and be without wheels. If the standing position is used, a chair can be placed behind the patient in case the patient needs to be moved into a sitting position if he or she becomes dizzy or lightheaded during the maneuver. Obese patients, especially those with large midsections, are likely to do better in the standing position. The test position should be noted, and the same position should be used each time the patient is tested.

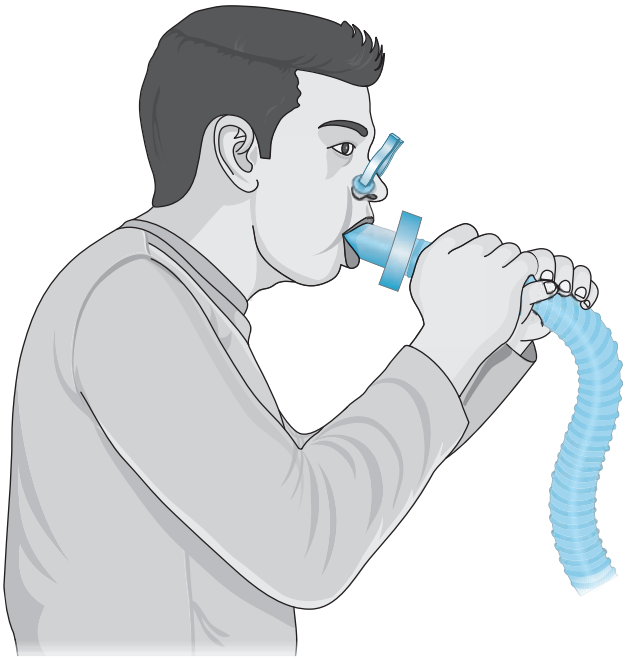
Explaining and Demonstrating the Maneuver

Show the patient the mouthpiece and nose clip. The use of a nose clip or manual occlusion of the nares is recommended by the ATS and ERS,[6] and it is something I always insist on. However, some data shows no clear advantage of wearing nose clips when performing open-circuit spirometry, and some patients express discomfort when wearing nose clips.[24,25] Explain how the mouthpiece fits into the mouth. In the case of plastic or cardboard disposable mouthpieces, be sure to tell the patient not to bite down because this will obstruct the tubing hole. The patient's lips should be sealed tightly, and the tongue should not stick out into the mouthpiece.

Show the patient the proper chin and neck position. As shown in **Figure 1.22**, the chin should be slightly elevated and the neck slightly extended. This position should be maintained

Figure 1.22

The correct chin and neck position when performing forced spirometry. Note that the chin is not bent excessively toward the chest.



throughout the forced expiratory procedure. Do not let the patient bend the chin to the chest. Some bending at the waist is common and acceptable, but discourage the patient from bending all the way over.

Oxygen Use

Many patients require the use of supplemental oxygen. Stop the oxygen supply during the testing maneuver, and restart it during rest periods between maneuvers.

Placing the Mouthpiece

There are two techniques for placing the mouthpiece into the patient's mouth: (*a*) *open circuit* and (*b*) *closed circuit*.

The open-circuit technique has the patient perform the maximum inhalation before putting the mouthpiece in his or her mouth. It is preferred because of infection control concerns, and some spirometers are not designed for the closed-circuit technique. However, it requires the patient to place the mouthpiece in his or her mouth correctly and seal the lips well while holding the lungs completely full. Some patients find this difficult.

The closed-circuit technique has the patient rebreathe on the mouthpiece and spirometer. This is easier for the patient and also allows inspiratory flow and volume to be assessed.

Instructions

Give specific instructions in simple terms that describe the rapid and maximal inspiration, a strong exhalation (blasting the air out), and continued exhalation until all the air is exhaled. For example, when using the open-circuit technique, you could say, "I want you to take the deepest breath possible, put the mouthpiece in your mouth and seal your lips tightly, and then blast all of your air into the tube as hard and as fast as you can in one long complete breath." For spirometers that allow the patient to breathe through the mouthpiece before the test (i.e., closed circuit), the instructions would be simpler. An additional statement that can be used to explain the maneuver further is "it's like blowing out the candles on a birthday cake and they all don't go out, so you need to keep blowing in the same breath until they do."

Demonstrate the Maneuver

Many patients will forget some or all of the instructions, so a demonstration reinforces exactly what they are supposed to do. Show the patient the proper chin and neck position, how to get the mouthpiece in at the right time, and how to *blast* (not just blow) the air out and continue to blow.

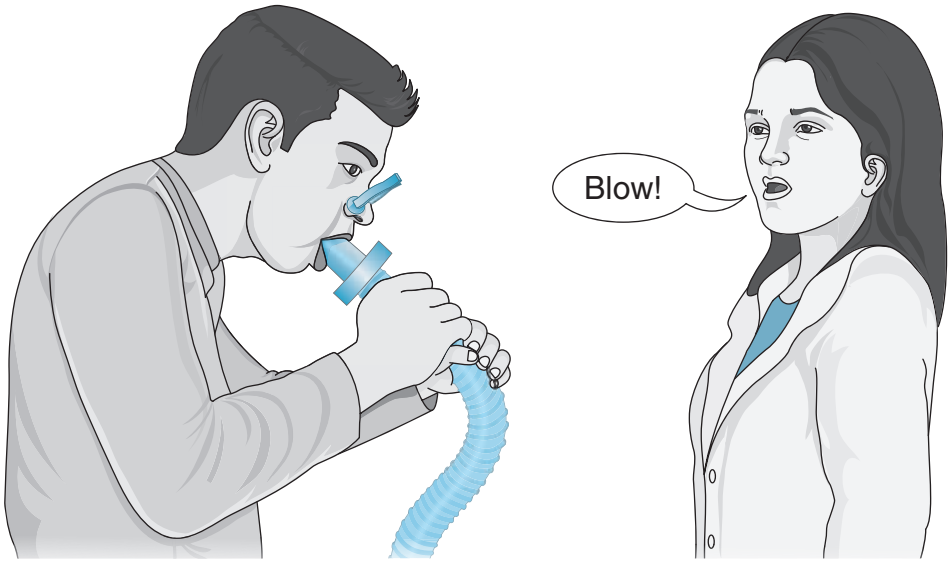
When the demonstration is done, remind the patient of a few key points: "Be sure to take as deep a breath as possible, blast out hard and fast, and don't stop blowing until I tell you." If inspiratory flow–volume curves are desired, remind the patient to inhale deeply and as fast as possible.

Summary of Important Points for Procedure Explanation

1. Keep the explanation simple, and be brief.
2. Demonstrate how to place the mouthpiece, the proper chin and neck position, and the maneuver.
3. Remind the patient of key points (e.g., take as deep a breath as possible, *BLAST* the air out, and keep blowing in one long breath until all the air is expired).

Figure 1.23

Use good coaching during forced spirometry.



Coaching and Encouragement During Testing

Use enthusiastic, active, and forceful coaching to help the patient perform the maneuver (**Figure 1.23**). You may need to raise your voice with some urgency, using such phrases as "BLAST your air out," "blow, blow, blow," "keep blowing, keep blowing," or "don't stop blowing." However, some patients perform better with softer coaching. A good technologist recognizes when to use a raised voice and when not to.

Patient Observation and Feedback

Observe both the patient and the spirogram during the test by having the spirometer and the patient positioned in such a way that both can be watched with minimal head movement. Sometimes the mouthpiece comes out of the patient's mouth and the operator is watching only the spirometer monitor, encouraging the patient to keep blowing, keep blowing.

After a test maneuver, give the patient feedback on the quality of the test and describe what improvements, if any, could be made. For example, statements like "that was great, Mr. Smith, but on this next maneuver *BLAST* out harder at the beginning" or "on this next maneuver, keep blowing out longer." In cases when there is excessive hesitation at the start of the maneuver, which is usually caused by a lack of synchronization between the patient being ready to blast the air out and the operator prompting the patient to blast the air out. It is helpful to tell the patient to *BLAST* out when he or she has completely filled the lungs, even if the operator has not prompted the patient to blast out.

Allow time for the patient to catch his or her breath between maneuvers. This may take a few seconds to a minute after each maneuver. Some patients may need to take oxygen between

maneuvers. When it appears that the patient is once again ready, perform another maneuver. Repeat the process until three acceptable maneuvers are obtained. If no acceptable maneuvers have been obtained after eight attempts, it is reasonable to stop and report that the patient could not perform acceptable spirometry.

General Maneuver Evaluation, Acceptability, and Repeatability

General Maneuver Evaluation

There are three main parts to evaluate when a patient performs the FVC maneuver: (*a*) rapid and maximal inspiration, (*b*) blowing out hard and fast, and (*c*) continued and complete expiration.

The FVC maneuver assumes a rapid and maximal inspiration. Ensure that the patient quickly takes as big a breath as possible. Submaximal inspirations will result in reduced FVC, FEV_1, and PEFR values.

When the maximal inspiration is complete, the patient should be prompted to blow the air out as hard and fast as possible with minimal hesitation. Reductions in PEFR and FEV_1 have been shown when inspiration is slow and there is a pause at total lung capacity.[26] Any pause at full inspiration should be kept to no more than 1 or 2 seconds. When prompted to blow out hard, the patient should *BLAST* the air out, not just blow the air out from the lungs.

The third part is continued and complete exhalation. Throughout the maneuver, the patient should be coached to keep blowing and keep blowing, as previously described. Also as mentioned earlier, keep an eye on both the patient and the spirometer display (spirogram) during the test to ensure continued exhalation and to watch for any signs of dizziness. Incomplete expirations will lead to reduced FVC values.

Within Maneuver Acceptability

There are four main within-maneuver *acceptability criteria*: (*a*) good start of test, (*b*) no artifacts including no cough during the first second, (*c*) no variable flow, and (*d*) no early termination of exhalation. In addition, there should not be glottis closure, a leak at the mouth, or obstruction of the mouthpiece by the tongue or teeth.

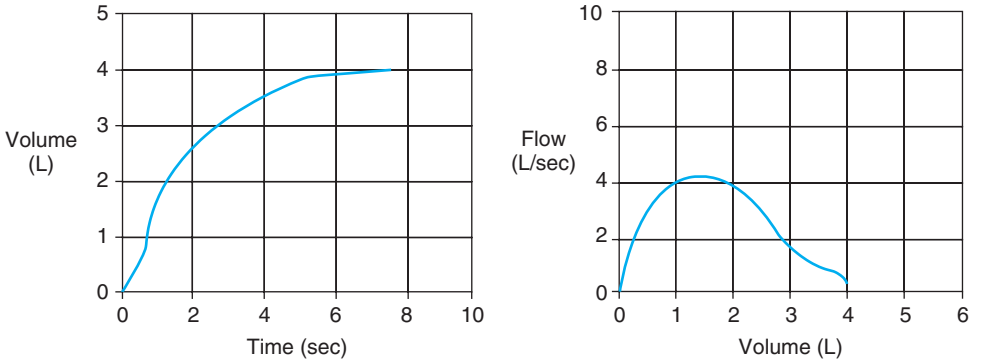
Good Start of Test

There must be a *good start of test*. The beginning of expiration of the forced expiratory maneuver is extremely important in calculating many parameters. Therefore, the start of the expiration must be quick and forceful. An unsatisfactory start is characterized by excessive hesitation, or the extrapolated volume (discussed later in calculations) may be excessive (i.e., greater than 5% of the FVC or 0.150 liter, whichever is greater). **Figure 1.24** shows both a volume–time and a flow–volume display of efforts that had a poor start of test. However, the flow–volume display (as opposed to the volume–time display) is most useful in assessing the first 1 or 2 seconds of a maneuver. If it appears that the start of test is not acceptable, remind the patient about blasting out or not hesitating (or both).

FEV_1 is determined by using the back-extrapolation technique, which is discussed in detail later in the chapter. This technique, which helps define *time zero*, can be performed manually, but it is more commonly performed by the spirometer computer.

Figure 1.24

Unacceptable spirometry because of poor start of test as illustrated in the volume–time and flow–volume spirograms. Note the rounded shape of the flow–volume graph at the highest point (peak flow).

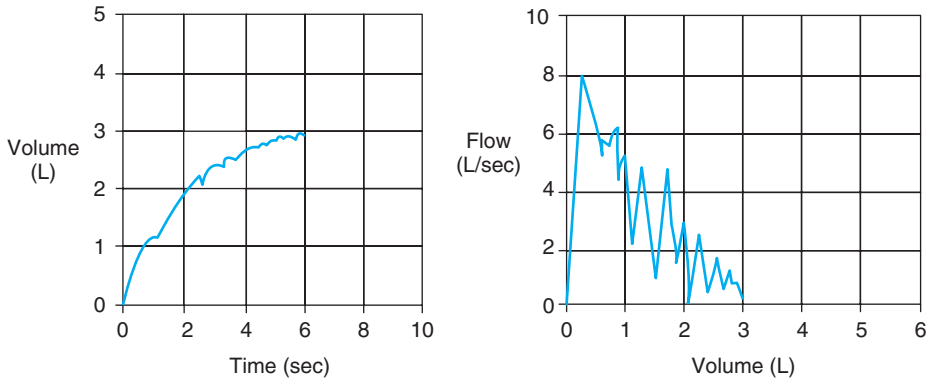


Coughing

The maneuver should contain no coughing during the first second. Many patients, however, cough with each effort toward the end of the test. If this happens, the technologist should comment that the patient coughed during the maneuver and whether or not the coughing interfered with obtaining accurate results. **Figure 1.25** shows an example of a spirogram where the patient coughed.

Figure 1.25

Unacceptable spirometry because of significant coughing as illustrated in the volume–time and flow–volume spirograms.



The cough, however, can also be used as a tool. Occasionally a patient's efforts are questioned because the individual does not appear to be blowing as hard or as fast as possible or because the peak flow rates vary considerably between maneuvers. Because submaximal efforts can result in errors and variability in the FEV_1, PEFR, and other measurements, a technique can be taught that helps the operator determine whether a patient is blowing out as fast as possible at the beginning of the test. This technique requires the patient to take a full deep breath and purposely cough into the spirometer tube. The cough should be forceful, and only a small amount of air should be coughed out, not the entire vital capacity. The resulting cough PEFR represents a good approximation of the peak flow that should be obtained during the FVC when the patient is instructed to blow the air out as fast and as hard as possible. If the difference between the cough PEFR and the FVC PEFR is more than 1 liter/sec, poor patient effort or technique is likely.

Variable Flow

The spirogram should not have variable flow rates. This means the flow should be consistent and as fast as possible throughout the exhaled vital capacity. **Figure 1.26** shows an example of variable flow.

Early Termination

There should be no early termination of expiration, and patients should be coached to keep blowing and keep going. There are two main end-of-test criteria used to determine if the patient exhaled long enough: (*a*) the patient cannot or should not continue further exhalation, and (*b*) the volume–time spirogram shows a plateau or no change in volume for at least 1 second, and the patient has tried to exhale for at least 6 seconds for adults and 3 seconds for children younger than age 10 years (**Figure 1.27**). When the forced maneuver ends early (a common

Figure 1.26

Unacceptable spirometry because of variable flow rates. Patients must be coached and instructed to blow as fast and as hard as possible throughout the test.

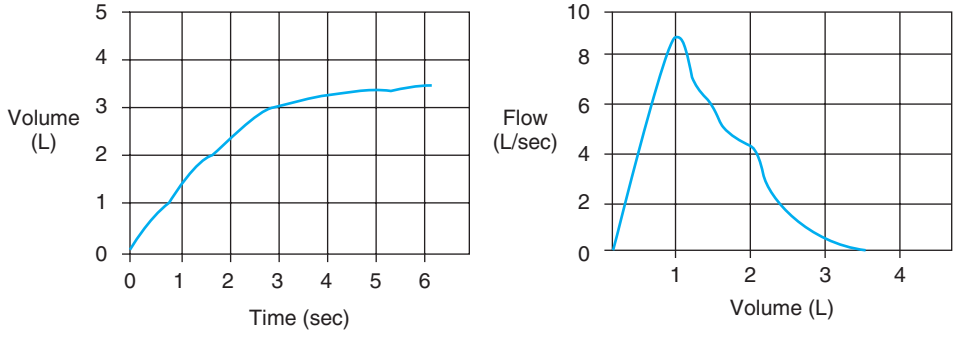
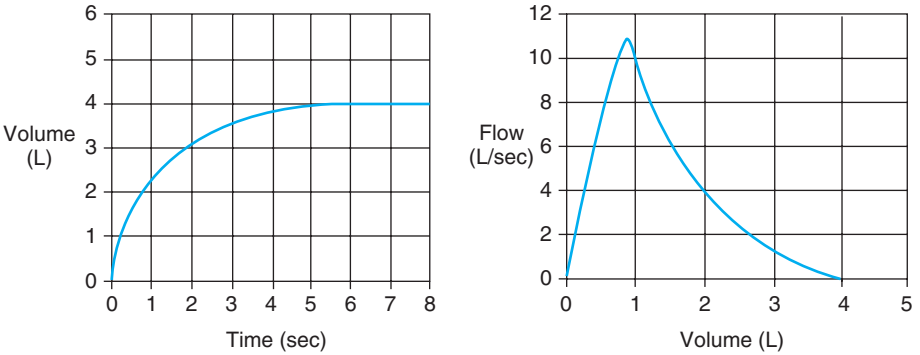


Figure 1.27

Acceptable spirometry. Spirograms show good start of test, no coughing or variable flow, and no early termination of exhalation. Note the obvious plateau at the end of the trial on the volume–time spirogram.



problem in young children), there is no obvious plateau and there is a cliff-like appearance at the end of the flow–volume curve (**Figure 1.28**). Pay close attention to the expiratory time and the appearance of a plateau, and coach the patient to blow at least 6 seconds up to a maximum of 15 to 20 seconds. Although some patients can blow longer than 15 to 20 seconds, the volume collected beyond that point is probably not clinically significant. Not meeting this criterion is frequently the result of poor coaching, so keep urging the patient to "keep blowing, keep blowing, don't stop yet, keep blowing." The operator should note if a patient cannot meet this criterion because of discomfort or another reason. Maneuvers that do not meet the end-of-test criteria, while not acceptable in the strictest sense of the word, do provide useful information about FEV_1 and PEFR.

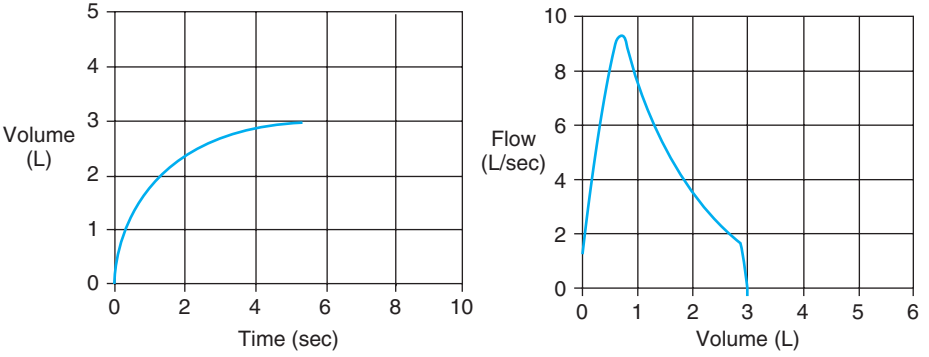
The 2005 ATS/ERS standardization of spirometry guideline describes a "usable" curve versus an acceptable curve. A usable curve or maneuver is one that has a good start of test and no coughing in the first second. An acceptable curve or maneuver meets all acceptability criteria. In clinical practice there are times when patients cannot meet all the acceptability criteria, but there are still valuable spirometric data that can be used to evaluate respiratory problems or response to treatment.

Summary of Acceptability Criteria

1. Good start of test
2. No artifacts, including coughing, during first second
3. No variable flow
4. No early termination of expiration
5. No evidence of glottis closure, leak at mouth, extra breaths, or obstruction of mouthpiece

Figure 1.28

Unacceptable spirometry because of early termination of exhalation. Note that there is no plateau in the volume–time graph. A cliff at the end of the flow–volume graph indicates an abrupt end to flow.



Between Maneuver Repeatability

After at least three acceptable maneuvers have been obtained, the *repeatability between maneuvers* should be evaluated. Because spirometry is an effort-dependent test, repeatable FVC and FEV_1 values occur if the patient is trying as hard as possible with each maneuver. The two largest FVC values from acceptable maneuvers should agree within 0.150 liter, and the two largest FEV_1 values from acceptable maneuvers should agree within 0.150 liter. **Figure 1.29** demonstrates three acceptable spirometric maneuvers where the two largest FVC values agree within 0.150 liter. **Figure 1.30** demonstrates three acceptable maneuvers that are not repeatable and more maneuvers are needed.

Occasionally, a patient will have *spirometry-induced worsening (bronchospasm)*, meaning that each effort is worse, in terms of airflow, than the previous one. Most patients with this characteristic will eventually stop getting worse with each trial and will reach a plateau, but the patient may be too short of breath at that point to go on. An interesting problem arises when spirometry worsens with each effort. Which maneuver should be selected for the final report? The best maneuver in terms of highest FVC and FEV_1 is likely the first, as shown in **Figure 1.31**. However, if before-and-after bronchodilator studies are being done, the last maneuver (maneuver 4), which is also the lowest in terms of FVC and FEV_1, might be more appropriate.

Summary of Repeatability Criteria

1. Two largest FVC values from acceptable maneuvers agree within 0.150 liter
2. Two largest FEV_1 values from acceptable maneuvers agree within 0.150 liter

Figure 1.29

Acceptable spirometry as illustrated with volume–time and flow–volume graphs. Note that three acceptable maneuvers have been recorded, of which two maneuvers have FVC and FEV_1 values that agree within 0.150 liter.

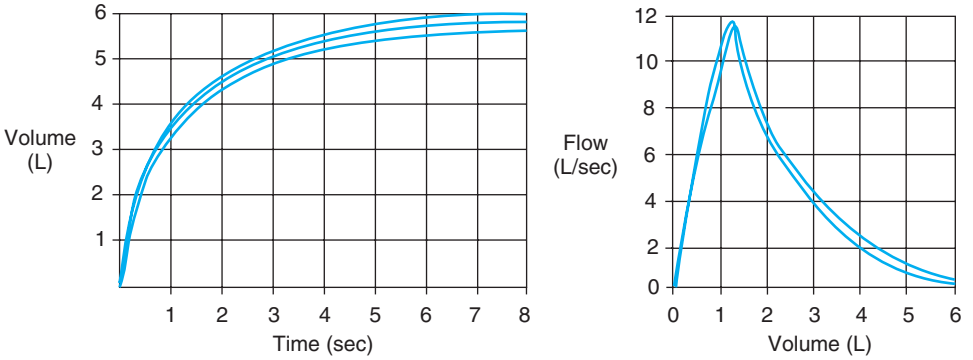
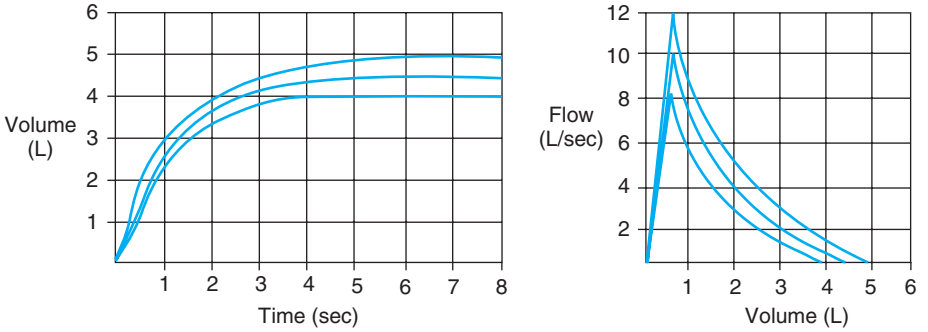


Figure 1.30

Unacceptable spirometry because of poor repeatability. The two highest FVC values and the two highest FEV_1 values must agree within 0.150 liter.

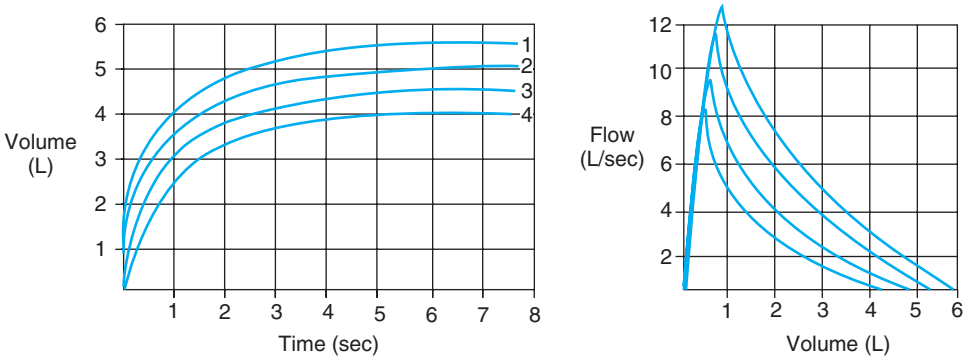


Flow–Volume Loops

In many laboratories, a full expiratory and inspiratory loop is performed. The patient is asked to take a big deep breath and fill the lungs, blast the air out hard and fast until no more air can be exhaled, and follow up with a fast and deep inspiration (**Figure 1.32**). This procedure is slightly more involved, and not all spirometers have the ability to measure both inspiratory and expiratory flow. In some cases, patients are unable to perform a satisfactory inspiratory portion immediately following a maximal forced expiration. When this happens it may be necessary to have the patient perform the fast and deep inspiration before the forced expiration,

Figure 1.31

Forced spirometry on a patient who worsens with each effort. Maneuver 1 was done first, maneuver 2 was done second, etc.



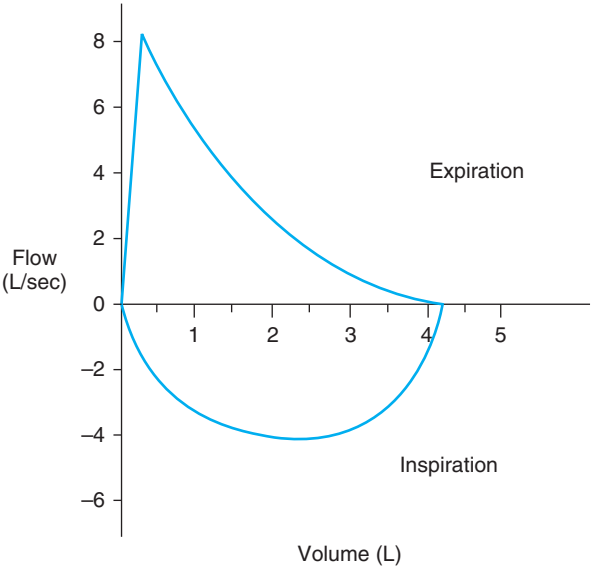
or record the inspiratory portion separately from the expiratory portion. There are two important criteria to examine in flow–volume loops: (*a*) the inspiratory vital capacity should be at least 95% of the expiratory vital capacity, and (*b*) the two highest peak inspiratory flows from several trials should agree within 1 liter/sec. A more detailed explanation of flow–volume loop patterns is provided later in this chapter.

Summary and Reminders for Good Spirometry Testing

- Assure spirometer has been checked for accuracy (calibration check)
- Assure proper patient preparation
  - Explain the test
  - Determine any contraindications
  - Obtain age, height, and possibly weight
  - Correctly position the patient
- Explain and demonstrate the maneuver
  - Keep explanation simple and brief
  - Demonstrate attaching to mouthpiece, proper chin and neck position, and the maneuver
  - Reemphasize key points
- Perform the maneuvers
  - Attach nose clip, place mouthpiece in mouth, and seal lips (closed circuit)
  - Have patient inhale completely and rapidly
  - Instruct patient to BLAST the air out as hard and fast as possible with minimal pause; provide enthusiastic coaching
  - Provide feedback to patient on quality of each maneuver
  - Repeat test to obtain *at least* three acceptable maneuvers
  - Assess repeatability and perform additional maneuvers, if necessary

Figure 1.32

An acceptable flow–volume loop showing both forced expiration and forced inspiration maneuvers. Performing the flow–volume loop can be helpful in detecting upper airway obstruction.



Calculations and Reporting Results

Most new pulmonary function equipment is equipped with a computer or microprocessor that eliminates the need for manual calculation. However, manual calculations are required for the many manual volume-displacement spirometers still in use. Additionally, both the student and the technologist should understand the basic calculations involved to validate the computer calculations and to better comprehend what the computer or microprocessor is doing.

The specific manual calculations vary depending on the type of volume-displacement spirometer and the chart paper it uses. Spirometers designed with zero time-and-volume starting points (i.e., no air in the spirometer) and supplied with temperature-corrected chart paper are the simplest and fastest to use. The calculations for spirometers that have a rotating chart for the spirogram or operate at volumes other than zero and do not have temperature-corrected chart paper take longer, but the results are considered more accurate. Before getting into these two different methods, you must first understand the issue of temperature correction.

Temperature Correction

When a patient blows into a spirometer tube, the exhaled air coming from the lungs is 37°C and saturated with water vapor. This exhaled air cools as it travels toward the spirometer. Charles's law states that the volume occupied by a given quantity of gas is directly related to

temperature. The air exhaled into a volume-displacement spirometer will equilibrate, given enough time, at approximately the temperature of the spirometer (which is near room or ambient temperature). The air exhaled into a nonheated flow-sensing device does not totally equilibrate to room temperature until after it has passed out of the device.

It has long been the accepted practice to express the volumes and flows measured during spirometry at body temperature. To convert volumes measured at *ambient temperature and pressure saturated with water vapor (ATPS)* to volumes at *body temperature and pressure saturated with water vapor (BTPS)*, a factor must be applied (i.e., $V_{BTPS} = V_{ATPS} \times$ factor). The formula for determining that factor is:

$$V_{BTPS} = V_{ATPS} \times \frac{PB - PH_2O}{PB - 47} \times \frac{310}{273 + Ta}$$

where

PB = Barometric pressure in mmHg
PH_2O = Water vapor pressure at spirometer temperature
Ta = Room (ambient) temperature (degrees C)
47 = Water vapor pressure in mmHg at 37° C
310 = Absolute body temperature (Kelvin +37, or 273 + 37)
V_{ATPS} = Volume at ambient temperature and pressure saturated
V_{BTPS} = Volume at body temperature and pressure saturated

The laboratory must be equipped or able to measure or determine barometric pressure and temperature. The temperature can either be measured inside the spirometer or with a thermometer in the room near the spirometer. When the temperature and barometric pressure are determined, the PH_2O is taken from a chart, and the correction factor can be calculated. When ATPS volumes are multiplied by this factor, BTPS volumes are obtained.

This method of correcting volumes is controversial. Can the ATPS-to-BTPS factor be correctly applied to both volume-displacing and flow-sensing spirometers? Does room temperature accurately reflect spirometer temperature at the end of the FVC maneuver? These and other issues have been the subject of several studies.[27-30]

Despite these concerns, temperature correction of spirometric values is still the convention and is done in the manner previously described. The computerized devices make this correction automatically, some by assuming a barometric pressure and others by having the user enter a barometer reading.

To help the reader calculate the BTPS factor, **Table 1.2** lists the water vapor pressures at various temperatures, which is needed for the preceding formula. **Table 1.3** presents some common BTPS factors at two different altitudes.

FVC and FEV_1 Measurement

The manual calculation of FVC and FEV_1 for the volume-displacement spirometer that begins the test at zero volume (i.e., empty) is relatively simple when special lined chart paper is used. Typically, this chart paper shows time on the *x* axis and volume at BTPS on the *y* axis. **Figure 1.33** shows an example of three acceptable spirometry maneuvers starting from the zero time-and-volume point.

Table 1.2

Water Vapor Pressure (PH_2O) at Different Temperatures

°C	°F	PH_2O
20	68	18
21	70	19
22	72	20
23	73	21
24	75	22
25	77	24
26	79	25
27	81	27

Table 1.3

Temperature Correction (ATPS to BTPS)

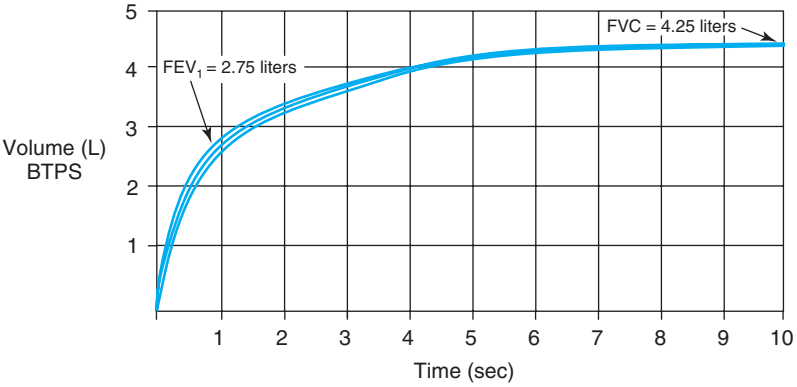
Room or spirometer temperature		ATPS to BTPS factor	
°C	°F	Sea level*	5,000 feet†
20	68	1.101	1.111
21	70	1.096	1.106
22	72	1.091	1.100
23	73	1.086	1.094
24	75	1.080	1.089
25	77	1.074	1.082
26	79	1.069	1.076
27	81	1.062	1.069

*Barometric pressure = 760 mmHg
†Barometric pressure = 625 mmHg

The largest FVC is easily identified and is shown as 4.25 liters. Note the repeatability and good end-of-test technique (i.e., plateau). The largest FEV_1 (2.75 liters) is easily selected from the three volumes and is found on the 1-second line (the curves started exactly from the zero point). The values are read in liters at BTPS, but note that the chart paper states the BTPS correction is for 23° C. If the room or spirometer temperature varies by more than 2 degrees from 23 degrees, the BTPS correction may need to be recalculated.

Figure 1.33

Acceptable spirometry displayed in a volume–time format on chart paper frequently used on spirometers that are empty at the beginning of the test. The FVC is read in liters on the volume axis at the highest pen deflection. The FEV_1 is read in liters on the volume axis where the pen deflection line crosses the 1-second line.

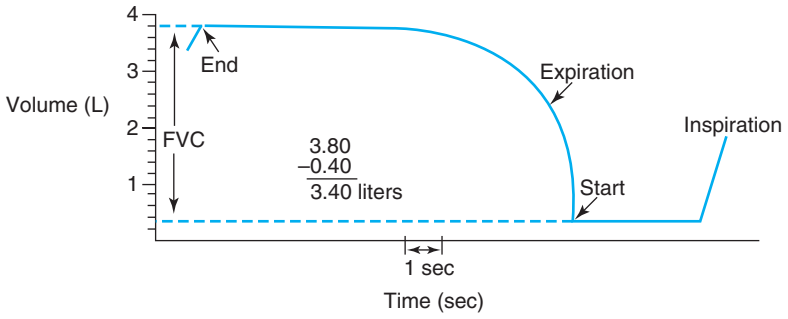


The calculation of FVC and FEV_1 from spirometers that have kymographs that can continually rotate or that operate at zero or other-than-zero volumes involves slightly more work. The advantage of this type of spirometer is the ability to do the closed-circuit technique where the patient can attach to and breathe on the mouthpiece before the forced spirometric maneuver. Additionally, these spirometers can collect volume for an unlimited time. Usually the chart paper on these devices comes preprinted with ATPS volumes, although some have BTPS volume grids. To measure the FVC, subtract the starting volume from the ending volume as shown in **Figure 1.34**. If the value is read in liters at ATPS, then a correction to BTPS is needed.

The FEV_1 is determined by using the *back-extrapolation technique*. Because the FEV_1 is defined as the volume exhaled in the first second of the FVC, it is critical to identify the point from which time begins (i.e., the point when the patient started blowing as fast as possible). The back-extrapolation technique, which helps define *time zero*, is shown in **Figure 1.35A**. The computer will make this measurement; however, it is important to understand how it is done. To manually measure back-extrapolation volume, use a ruler and draw a line through the steepest portion of the forced expiratory volume–time curve. Where that line crosses the horizontal line drawn from maximum inhalation is the point known as time zero (t_0). When this point is known, measure 1 second over, and then measure the volume for FEV_1. The extrapolated volume, shown in **Figure 1.35B**, is the volume from the maximum inhalation line to the forced expiratory curve at time zero. An extrapolated volume greater than 5% of the total FVC, or greater than 0.150 liter (whichever is larger), is considered excessive, and any trial with excessive extrapolated volume should be considered unacceptable. When the extrapolated volume exceeds this limit, it is usually because the patient had a poor start of test.

Figure 1.34

Forced spirometry maneuver displayed in a volume–time format on chart paper frequently used on spirometers that rotate and are not necessarily empty at the beginning of the test (e.g., Stead-Wells water seal). The spirogram appears backwards, but with this type of instrumentation, the pen writes from right to left. The FVC is read in liters on the volume axis as the difference between the highest and lowest pen deflections.



When the FVC and FEV_1 have been determined and corrected to BTPS, you can calculate the FEV_1/FVC ratio. Simply divide FEV_1 by FVC and multiply by 100.

Other Spirometry Values

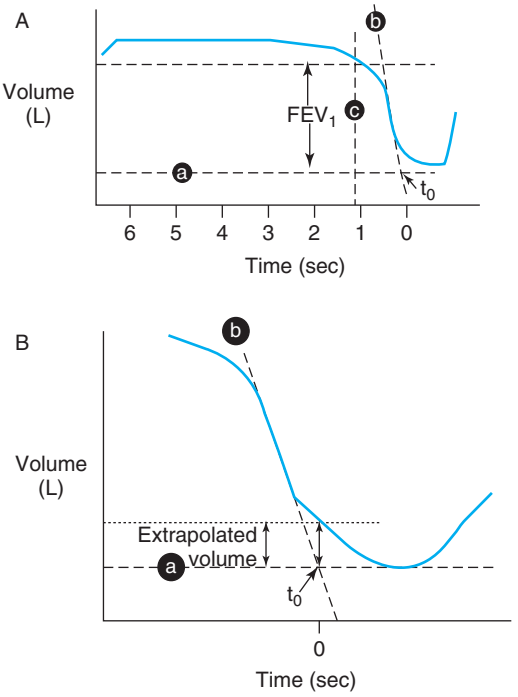
Many values and measurements can be calculated from the forced spirometry maneuver. This chapter will not demonstrate how each one is calculated by hand. Instead, it will discuss the more commonly used measurements in terms of what they measure and their pitfalls.

The $FEF_{25–75\%}$ is defined as the mean forced expiratory flow during the middle half of the FVC. In other words, it is the flow over the interval that starts after 25% of the FVC has been exhaled up to the point when 75% has been exhaled. It was originally described as the *MMEF* (*maximal midexpiratory flow*) and is reported in liters/sec.[31] Many clinicians believe it comes from a part of the spirogram that is relatively effort independent and it describes the status of the small airways, which are thought to reflect early airway obstruction. For these reasons, it is frequently used to assess bronchodilator and provocation response. However, the $FEF_{25–75\%}$ has two major disadvantages: (*a*) it is highly variable from maneuver to maneuver in the same patient and (*b*) it depends heavily on the size of the FVC. Because it depends on the size of the FVC, it is somewhat common to see improvements in FEV_1 after bronchodilator administration but no change (or even a decrease) in the $FEF_{25–75\%}$. Investigators have described a volume-adjustment technique (using the before-bronchodilator FVC to define the 25% and 75% points for the after-bronchodilator $FEF_{25–75\%}$ measurement).[32,33] The volume-adjustment technique shown in **Figure 1.36** merely transposes the 25% and 75% points from the before-bronchodilator curve to the after-bronchodilator curve. The resulting $FEF_{25–75\%}$ is sometimes referred to as *isovolume* $FEF_{25–75\%}$.

In conjunction with the $FEF_{25–75\%}$ is the *midexpiratory time (MET)*. Unlike the $FEF_{25–75\%}$, this measurement is the time (not the flow) required to exhale the mid-50% of the expiratory curve.

Figure 1.35

Measurement of FEV_1 using the back–extrapolation technique to define time zero (used to designate the true beginning of the test). A. The technique requires a horizontal line at maximum inhalation, *a*, and a semivertical line passing through the steepest (most vertical) portion of the volume–time trace, *b*. The intersection of *lines a* and *b* becomes time zero (t_0), from which time can be started and the true 1-second line can be drawn (*c*). B. A closeup of the figure in A showing the extrapolated volume as the vertical distance from line *a* at t_0 to the forced expiratory curve.



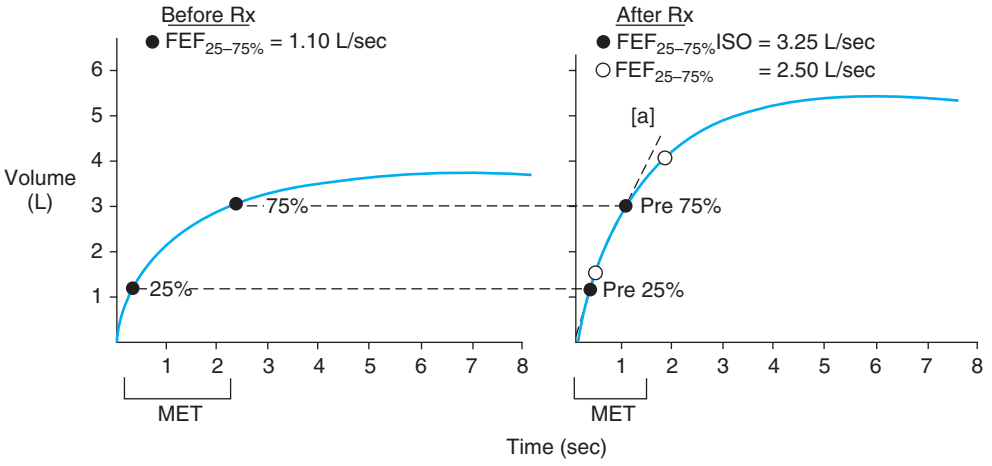
An example of the MET can be seen in Figure 1.36, where it is approximately 2.25 seconds before bronchodilator (Rx) and 1.50 seconds after Rx.

The flow–volume display in conjunction with measuring lung volumes can be very useful. These graphic displays of flow and volume plotted at absolute lung volume (i.e., TLC, obtained by first measuring FRC and then immediately performing the FVC maneuver) are by far the best representation of pulmonary mechanics (**Figure 1.37**).

The *PEFR*, also called the *maximal forced expiratory flow (FEFmax)*, is the highest flow achieved during the FVC maneuver. It is not apparent from the conventional volume–time spirogram because it is an instantaneous flow. It is usually reported in liters/sec. This parameter is a very effort-dependent value, and its poor repeatability in a series of maneuvers should alert the operator to questionable patient efforts. **Figure 1.38** shows two flow–volume curves. Note the sharp point or peak with a good effort and the rounded pattern of a poor effort. Figure 1.38

Figure 1.36

Volume adjustment technique for calculating isovolume $FEF_{25–75\%}$. The $FEF_{25–75\%}$ is calculated from a line connecting two points on the volume–time graph of the forced spirogram. One point is marked when 25% of the vital capacity has been exhaled; the other point is marked when 75% of the vital capacity has been exhaled. In the Before-Rx graph, the solid circles mark the 25% and 75% points. In the After-Rx graph, the solid circles have been moved over from the Before-Rx graph (transposed) based on the Before-Rx volumes. The open circles mark the After-Rx 25% and 75% points based on the After-Rx volume. The volume adjusted $FEF_{25–75\%}$ would be determined from a line connecting the solid circles on line [a] of the After-Rx graph. The MET is the midexpiratory time.



also illustrates the $FEF_{25\%}$, $FEF_{50\%}$, and $FEF_{75\%}$, which are also commonly reported expiratory flows. The 25%, 50%, and 75% modifiers refer to the amount of the exhaled FVC. Like the FEFmax, these parameters are instantaneous flows and are usually reported in liters/sec.

Inspiratory Flow and Flow–Volume Loop

As noted earlier, inspiration is an active process caused by contraction of the respiratory muscles. The alveolar pressure (P_{alv}) becomes lower than atmospheric pressure (P_{atm}) and air rushes into the lungs. Thus,

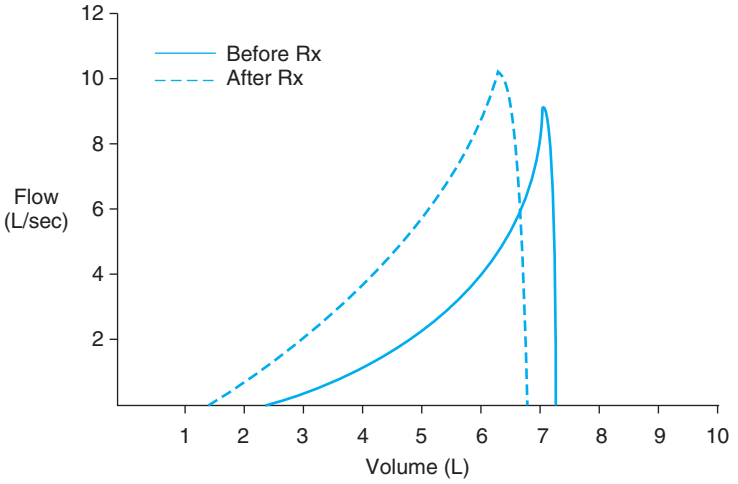
$$\text{Maximal inspiratory airflow} = \frac{P_{atm} - P_{alv}}{\text{Resistance}}$$

During inspiration, airway resistance usually does not limit flow because the airways are pulled open and are wider.

When a patient inspires as fast as possible directly before or after a forced expiration, a maximal flow–volume loop is formed. **Figure 1.39** shows the flow–volume loop with commonly

Figure 1.37

Flow–volume graph of forced spirometry showing the measured curves before and after bronchodilator (Rx). The placement of the curves is at absolute lung volumes, determined by first measuring FRC (e.g., through body box) and then immediately performing forced spirometry with the patient staying on the mouthpiece for both parts. The maximum inhalation level (i.e., TLC) can be measured (FRC + inspiratory capacity) and used as the absolute volume level to place the curve.



reported instantaneous inspiratory flows: *FIFmax*, $FIF_{25\%}$, $FIF_{50\%}$, and $FIF_{75\%}$. The 25%, 50%, and 75% modifiers in these inspiratory flows usually refer to the volume inspired from residual volume. A commonly reported ratio when the flow–volume loop is performed is the $FEF_{50\%}$ *divided by the* $FIF_{50\%}$ ($FEF_{50\%}/FIF_{50\%}$).

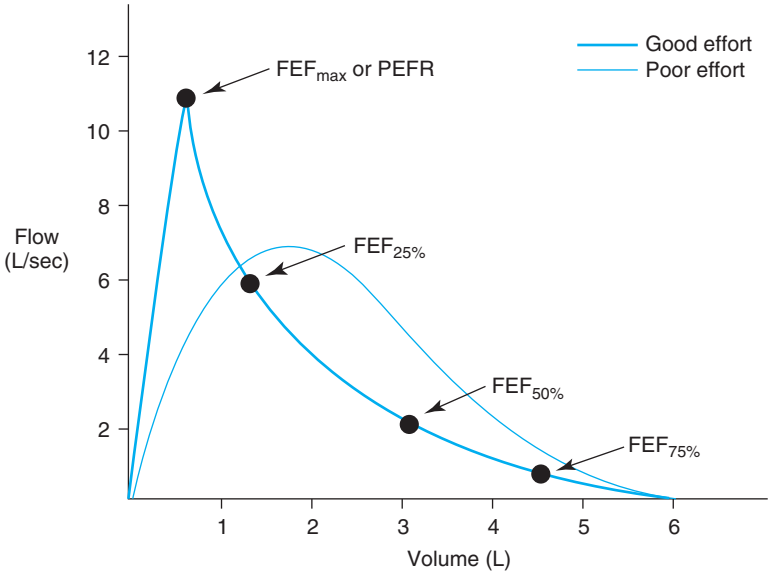
The flow–volume loop, as a picture, can be very informative. **Figure 1.40** presents a flow–volume loop that shows a *variable intrathoracic obstruction*, commonly seen in patients with obstructive lung disease such as asthma or emphysema. During forced expiration, the airways collapse because of the high pleural pressure, and expiratory flow is reduced. Note the scooped-out appearance of the expiratory portion. During forced inspiration, the airways widen because of the negative intrathoracic pressure, and inspiratory flow is normal. The $FEF_{50\%}/FIF_{50\%}$ ratio in this case would be low (i.e., less than 0.8).

Figure 1.41 presents a flow–volume loop that shows a *variable extrathoracic obstruction*. The forced expiratory flow rates are normal and higher than those achieved during the forced inspiration. During the forced inspiration, flow rates are reduced because the airway pressure above the thoracic cage (extrathoracic) is less than atmospheric pressure, causing collapse. The $FEF_{50\%}/FIF_{50\%}$ ratio in this case would be increased (i.e., greater than 1.2).

Figure 1.42 presents a flow–volume loop that shows a *fixed obstruction*. The airway is minimally affected by airway pressure because of an intrathoracic or extrathoracic blockage. Airflow during forced inspiration and expiration is equally reduced, and the flow–volume loop

Figure 1.38

Flow–volume graph of two forced spirometry efforts. The thick line represents a good effort, and the thin line represents a poor effort. Note the difference in the peak flows between the two efforts. The poor effort is rounded and has a lower FEFmax, which in some patients can result in a higher FEV_1 and FVC. The acceptable effort has a sharp peak and contains solid circles that mark the FEFmax, $FEF_{25\%}$ (the flow after 25% of the vital capacity has been exhaled), $FEF_{50\%}$ (the flow after 50% of the vital capacity has been exhaled), and $FEF_{75\%}$ (the flow after 75% of the vital capacity has been exhaled).



appears rectangular. The $FEF_{50\%}/FIF_{50\%}$ ratio in this case may be normal (i.e., between 0.8 and 1.2), but the instantaneous flow rates are reduced.

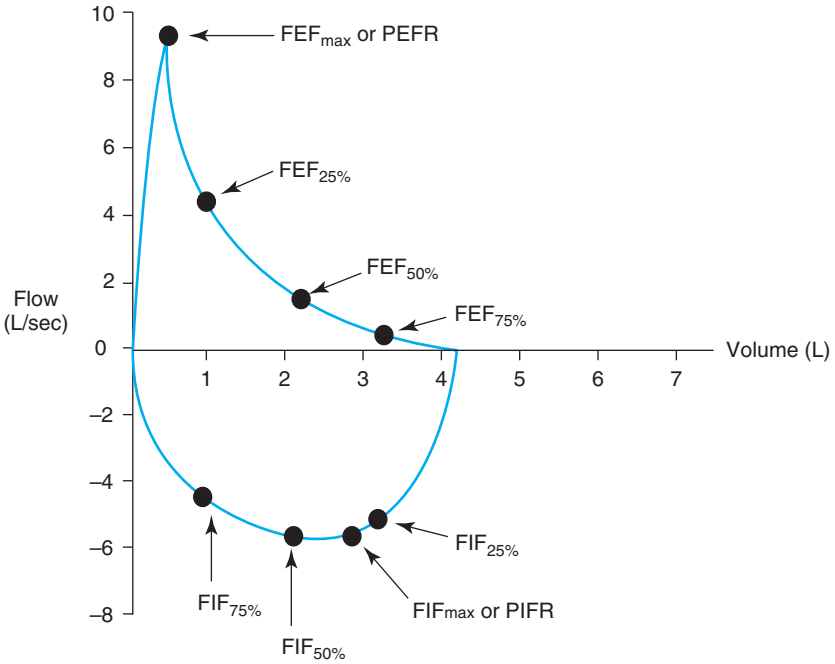
Figure 1.43 presents some additional examples of abnormal and normal flow–volume loops. The severe emphysema pattern (Figure 1.43A) shows significant air trapping and a scooped-out appearance. This is contrasted with the more mild forms of intrathoracic obstruction (Figure 1.43B). Flow–volume curves in patients with a restriction process (Figure 1.43C) have no air trapping and a normal flow–volume shape, but there is a reduced FVC. When airflow obstruction is mainly in the large airways (e.g., tumor), a slightly different variable intrathoracic pattern is observed (Figure 1.43D).

Reporting Results

After obtaining at least three acceptable maneuvers, two of which are repeatable, which maneuver or values should be used on the report? Usually, just one FVC, one FEV_1, and one each of all the other values are reported. How does one choose?

Figure 1.39

Flow–volume graph (flow–volume loop) of forced spirometry with inspiratory and expiratory portions completing a loop. The inspiratory portion contains solid circles marking commonly measured points: $FIF_{25\%}$ (forced inspiratory flow after 25% of the vital capacity has been inhaled from residual volume or maximum expiratory level), $FIF_{50\%}$ (forced inspiratory flow after 50% of the vital capacity has been inhaled), $FIF_{75\%}$ (forced inspiratory flow after 75% of the vital capacity has been inhaled), and FIFmax (maximum inspiratory flow, also known as peak inspiratory flow rate).



The largest FVC and the largest FEV_1 (BTPS) should be reported, even if the two values come from different curves.[2,3] Other measurements (e.g., $FEF_{25–75\%}$ or instantaneous flows) should be obtained from the single best test curve. The best test curve is the acceptable curve that has the largest sum of FVC and FEV_1. **Figure 1.44** shows three acceptable efforts on a volume–time display. Effort 1 has the largest FVC, and effort 2 has the largest FEV_1. The best test curve (the curve with the largest sum of FVC and FEV_1) is effort 2, and it is the curve from which the $FEF_{25–75\%}$ should be taken.

All results should be expressed in liters at BTPS, rounded to two decimal points.

Comments on Testing

Pulmonary function test reports should always contain comments from the technologist to aid in interpretation of data and to provide the reviewer additional information on the conditions

Figure 1.40

Flow–volume loop showing a variable intrathoracic obstruction commonly seen in patients with obstructive lung disease. During forced inspiration, the airways widen because of the negative intrathoracic pressure, and inspiratory flow is normal. During forced expiration, the increased pleural pressure causes airways to collapse, resulting in an exaggerated reduction in airflow.

Source: Printed with permission from Irvin CG, Corbridge T. Physiologic evaluation of patients for pulmonary rehabilitation. *Semin Resp Med* 1993;14:417–429.

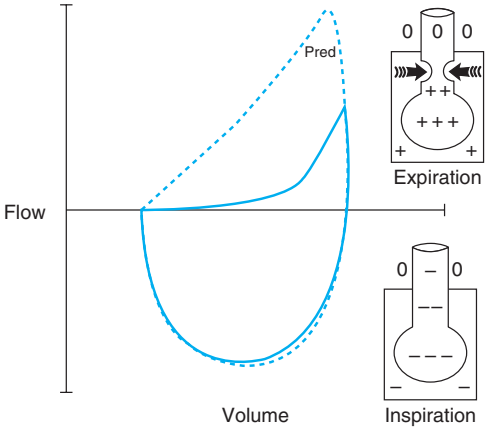


Figure 1.41

Flow–volume loop showing a variable extrathoracic obstruction. During forced inspiration, flow rates are reduced because airway pressure outside the thoracic cage (i.e., extrathoracic) is less than atmospheric pressure, as indicated by the arrows. During forced expiration, airflow is commonly normal.

Source: Printed with permission from Irvin CG, Corbridge T. Physiologic evaluation of patients for pulmonary rehabilitation. *Semin Resp Med* 1993;14:417–429.

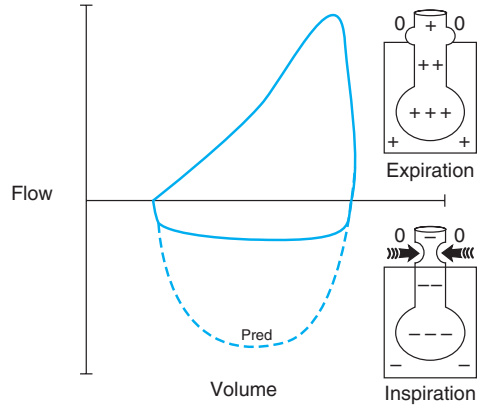
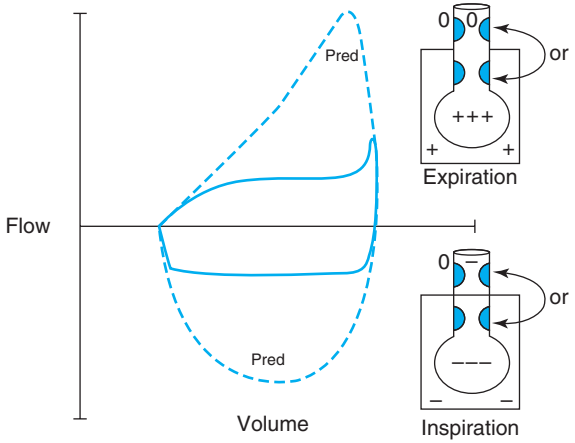


Figure 1.42

Flow–volume loop showing a fixed obstruction, which can result from an intrathoracic or extrathoracic problem. Typically, airflow is equally limited during expiration and inspiration.

Source: Printed with permission from Irvin CG, Corbridge T. Physiologic evaluation of patients for pulmonary rehabilitation. *Semin Resp Med* 1993;14:417–429.



of the patient at the time of testing and the quality of the test. The comments should be clear, concise, and accurate, including comments about test quality, reliability of data, and any deviations from recommended guidelines.

If the testing was well done and the data are good quality, make simple statement such as, "Excellent patient effort and technique." If the testing was not done well you could state something like, "Good effort, but patient unable to perform spirometry maneuver consistently, resulting in considerable variability."

Spirometry Reference (Predicted) Values

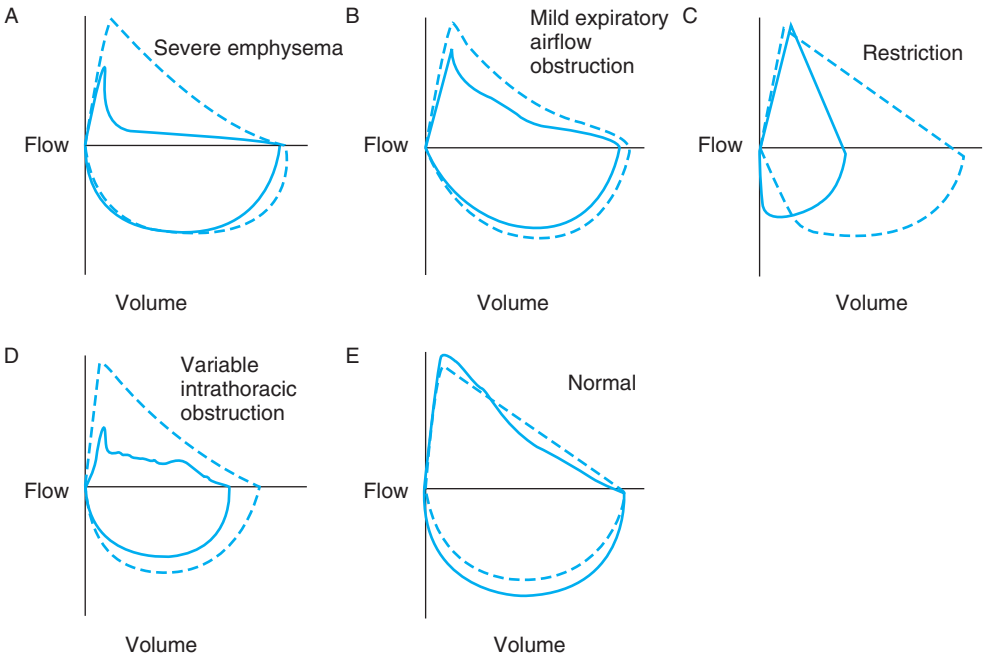
It is common practice to compare each measured or calculated variable in a patient's pulmonary function test with a reference or predicted value. This comparison provides the basis for interpretation. An in-depth discussion of how reference values are established and determining the lower limit of normal are presented in Chapter 12.

Following Changes Over Time

It may also be important to observe and compare changes in spirometry over time (a longitudinal study). Sequential tests that are done monthly or yearly, for example, can determine whether a patient's lung function is worsening, improving, or not changing—except for aging. **Figure 1.45** demonstrates why observing and comparing changes in a patient over time can be more valuable than simply comparing results with a reference value. Figure 1.45A is a graph of two patients on a reference regression line for a pulmonary function test value. The regression line of the equation slopes downward (declines) with age, and the shaded area

Figure 1.43

Series of flow–volume loops (expiration and inspiration). The predicted or expected curve is shown with dashed lines (-------), while the curve illustrating a particular disease pattern is shown with solid lines (——). Panel A presents a curve seen in patients with severe emphysema. Panel B presents a milder form of an intrathoracic obstruction (e.g., asthma). Panel C presents a curve seen in patients with a restrictive process (e.g., idiopathic pulmonary fibrosis). Panel D presents a curve seen in patients with a variable intrathoracic obstruction (e.g., tumor in large airway). Panel E presents a flow–volume curve of a healthy individual.



represents the 95% confidence interval. Patient 1 is above the regression line, and in fact is above the 95% confidence interval. Patient 2, however, is below the 95% level, and the result would likely be called abnormal. Figure 1.45B shows the same two patients measured again 2 years later. Patient 2 is still below the 95% level, and the result still would likely be called abnormal, but the results are declining at the expected normal rate. Although the result for patient 1 is still normal, it is declining much faster than expected.

When examining spirometric results over time, it is important to define a meaningful change. The FVC and FEV_1 are the two variables used in this type of evaluation. The expected decrease in these parameters from aging is approximately 25 to 30 mL/year. Additionally, there is the factor of test variability. Hence, for FVC and FEV_1, week-to-week changes that exceed 11% and 12%, respectively, should be considered meaningful. For FVC and FEV_1, yearly changes that exceed 15% should be considered meaningful.[34]

Figure 1.44

Volume–time graph of three acceptable forced spirometry efforts. Effort 1 has the highest FVC (3.55 liters), and effort 2 has the highest FEV_1 (2.02 liters). Effort 2 also has the highest sum of FVC and FEV_1 and would thus be called the best curve.

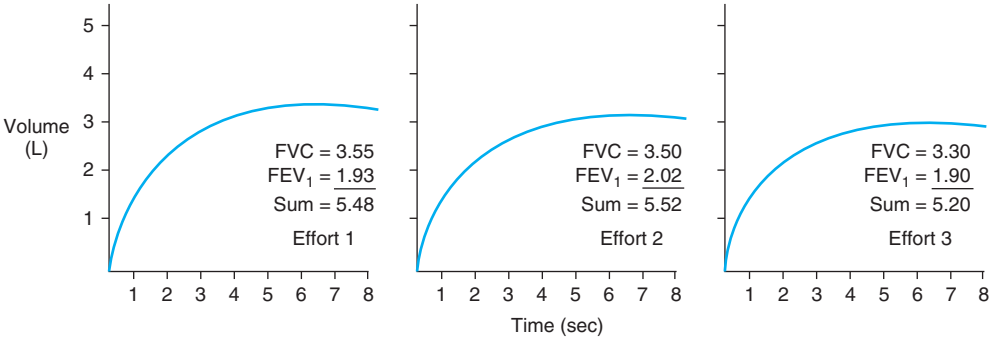
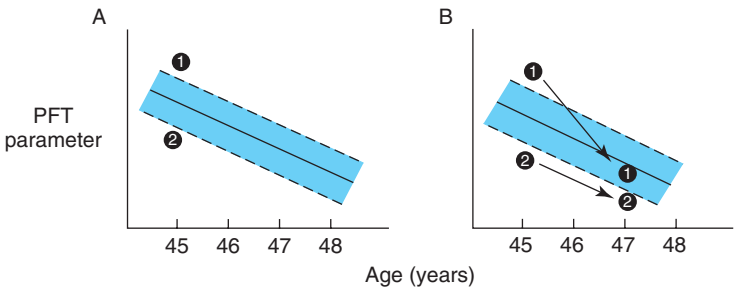


Figure 1.45

Pulmonary function test (PFT) results and reference regression line (solid) with the 95% confidence intervals (dashed) on two patients (1 and 2) of the same age (45 years). A. Patient 1 is above the 95% confidence interval for this particular parameter, and the results would be called normal or even above normal. Patient 2 falls below the 95% confidence interval, and the results would be called abnormal. B. Two years later, both patients are aged 47 years. Patient 2 is still below the 95% confidence interval, and the results would again be called abnormal. Patient 1 is within the 95% confidence interval, and the results would be called normal. However, patient 1 is declining faster than the reference regression line and faster than patient 2. We should be concerned about patient 1.



Reversibility Testing

Bronchodilators are administered routinely in the pulmonary function laboratory to determine whether airflow obstruction is reversible. Some laboratories test all patients for reversible airways obstruction; others do so only if the patient has an abnormality. In the author's opinion, all patients should undergo spirometry testing before *and* after receiving a bronchodilator because of the large variation in normal values and because even a patient with normal values may have significantly higher values after receiving a bronchodilator.

Drugs that reduce bronchospasm or airflow obstruction are called bronchodilators. These drugs are available for administration by several routes: (*a*) inhalation, (*b*) oral, (*c*) intramuscular, or (*d*) intravenous. This section will focus only on drugs administered by inhalation (i.e., aerosolized).

Bronchodilators increase airway caliber by relaxing airway smooth muscle. The aerosolized bronchodilators are usually sympathomimetic (adrenergic) and affect the two primary types of adrenergic receptors located in the bronchial smooth muscle and blood vessels: alpha and beta. The alpha receptors cause vasoconstriction. The beta receptors, which can be divided into two groups (beta 1 and beta 2), cause vasodilatation, bronchodilatation, and increased heart rate, among other things. The beta-1 receptors increase the heart rate more than they dilate bronchi, and the beta 2-receptors cause more bronchodilation than increased heart rate.

The ordering physician usually chooses the drug, dose, and mode of delivery, depending on the question being asked. However, many laboratories have a written procedure for bronchodilator administration if the physician has not specified such information.

Aerosolized bronchodilators can be given in several ways, including: (*a*) metered dose inhalers (MDI), (*b*) jet nebulizers powered by compressed air, and (*c*) ultrasonic nebulizer. The use of a spacer can increase the effectiveness of the MDI in some patients and is used frequently in the laboratory.

The method for using an MDI is important. The technologist should supervise or perform MDI actuation. The procedure is not standardized but should include the following: (*a*) shake the MDI and actuate it several times to prime; (*b*) attach spacer, if appropriate; (*c*) direct the patient to slowly exhale completely; (*d*) direct the patient to slowly inhale, and actuate the MDI just after the inhalation starts; (*e*) direct the patient to continue to inhale slowly, as deeply as possible; (*f*) direct the patient to hold his or her breath for 5 to 10 seconds and slowly exhale; and (*g*) wait 30 to 60 seconds before performing a repeat inhalation of the drug.

In many laboratories, more than two actuations of a beta agonist such as albuterol (a common clinical dose) are administered. The ATS/ERS recommendations are to deliver a high dose (e.g., four actuations) in the laboratory.[6] In some laboratories the actuations continue until side effects are achieved (e.g., increased heart rate, shakiness, or headache). The reason for more than two actuations is to ensure that the patient received a good treatment, which is indicated by the side effects. Any laboratory considering such a method should write a protocol describing the contraindications and side effect limits.

After administering the bronchodilator, the technologist should wait at least 10 to 15 minutes before repeating the pulmonary function tests. This will ensure that the medication is approaching or is at peak effect.

In some cases anticholinergic medications (e.g., ipratropium bromide) are administered in the laboratory to assess bronchodilator response. If these medications are used, the technologist should wait at least 30 minutes before repeating the test.

Summary of Key Points for Spirometry Reversibility Testing

- Use an appropriate bronchodilator (i.e., one ordered by the physician, used clinically by the patient, or specified in the laboratory procedure manual).
- Administer or supervise patient administration of the ordered amount or an amount that is clinically useful.
- Wait at least 10 to 15 minutes before repeating pulmonary tests.
- Note how much of the drug was given, the method of administration, and responses, such as increased heart rate, shakiness, palpitation, or patient comments.

Reporting Bronchodilator Therapy

The pulmonary function test report should include the pulmonary medications taken by the patient before and as part of the test. As previously stated, note how much of the drug was given with the test and the method of administration. To report medications the patient used before testing, ask the patient or check the patient's chart. Because there are numerous medications and combinations of medications, you must know the names of the different drugs (generic and trade names), mode of action, and route of administration. Additionally, because taking certain medications before a pulmonary function test may contraindicate performing the test, you must know the duration of action. **Table 1.4** is a list of medications frequently taken by patients with pulmonary disease.

Table 1.4

Medications Frequently Taken by Patients Being Tested in the Pulmonary Function Laboratory and the Length of Time They Should Be Withheld Before Testing

Medication	Withhold time
Short-acting beta agonists (e.g., albuterol, terbutaline)	4 to 6 hours
Long-acting beta agonists (e.g., salmeterol, formoterol)	12 to 24 hours
Short-acting anticholinergics (e.g., ipratropium bromide)	4 to 6 hours
Long-acting anticholinergics (e.g., tiotropium)	24 hours
Theophyllines	12 to 24 hours
Leukotriene modifiers (e.g., montelukast [Singulair], zafirlukast [Accolate])	24 hours
Inhaled corticosteroids (e.g., beclomethasone dipropionate, budesonide, ciclesonide, fluticasone propionate, flunisolide)	Uncertain, but usually withheld day of testing
Inhaled corticosteroids + long-acting beta agonists (e.g., Advair)	12 to 24 hours

Basic Elements of Interpretation

The pulmonologist is usually responsible for interpreting the results of pulmonary function tests. However, the technologists should know the basic elements of spirometric interpretation to help them obtain better and more useful information when performing the test and to better understand the clinical implications of the results.

The forced spirogram provides information about the flow and volume of air moving in and out of the lungs in one rapid inhalation and forced expiration. When the airways are narrowed, the flow through them will be reduced. Airway narrowing can result from bronchospasm (smooth muscle contraction), inflammation, increased mucus, tumors (either internal or external to the airway), or loss of elasticity resulting in airway collapse. This reduction in airflow is referred to as airflow limitation. Another commonly used term is *obstruction*, as in *airway obstruction* and *obstructive airway disease*. However, the term *obstruction* implies that the reduction in airflow is from material inside the airway, which is only one of many reasons for airway narrowing.

Many parameters can be measured from the forced spirogram or flow–volume loop, but only a few are helpful in the interpretation process. Specifically, this section will address the FVC, FEV_1, and the FEV_1/FVC ratio.

Airflow Limitation Versus Restriction

The FVC is the maximum volume of air forcibly exhaled after a maximum inhalation. An FVC below the lower limits of normal, even though effort was maximal, can be due to: (*a*) airflow limitation wherein air is trapped in the alveoli due to collapsing airways and/or is caused by a reduced driving force due to decreased elasticity or (*b*) reduced lung size caused by a restrictive process (e.g., interstitial lung disease, neuromuscular disease, or chest wall disorders).

The FEV_1 is the volume exhaled in the first second of the FVC. It too can be reduced because of airflow limitation or a restrictive process.

The FEV_1/FVC ratio (usually multiplied by 100 and expressed as a percentage) is the primary variable used to determine the presence of *airflow limitation*. In patients with airflow limitation, the FEV_1/FVC ratio is reduced. When this ratio is borderline, other measurements (e.g., instantaneous and midflows) can be used to assist in the interpretation process. However, the use of the $FEF_{25–75\%}$ and instantaneous flows to diagnose *small airway disease* is not recommended.[34]

Some clinicians prefer to quantitate the severity of airflow limitation, although there is no agreement on what is mild, moderate, or severe. If this is done, it should be based on FEV_1 rather than FEV_1/FVC%. **Table 1.5** presents an example of assessment of airflow limitation severity and is based on FEV_1.[35]

A restrictive process or pattern can be detected from a decreased FVC and FEV_1. However, the primary variable used to determine restriction is the TLC (which is not measured during spirometry). The FEV_1/FVC ratio is typically normal or increased in patients with a restrictive pattern. Thus, if a patient's FVC and FEV_1 are reduced, and the FEV_1/FVC ratio is normal or increased, the interpretation should state that a restrictive pattern cannot be ruled out.

Additionally, there can be a mixed obstructive and restrictive disease process that is very difficult to confirm with spirometry alone. If a mixed disorder is suspected, the static lung volumes, including FRC, residual volume (RV), and TLC, must also be measured.

Table 1.5

Degree of Severity	FEV_1 Percent Predicted
Mild	>70%
Moderate	60% to 69%
Moderately severe	50% to 59%
Severe	35% to 49%
Very severe	<35%

The written interpretation of the forced spirogram will vary depending on the interpreter. Some interpreters will make an observation only such as *airflow limitation* or *reduced* FEV_1, but others will quantify the observations by stating *severe airflow limitation* or *moderately reduced* FEV_1. However, as mentioned earlier, there is no agreement on what is mild, moderate, or severe. Additionally, the current practice is that the written interpretation should always contain a statement on the quality of the test. A very simple flowchart to interpret the forced spirogram with an inspiratory curve is shown in **Figure 1.46**.

Interpretation of Bronchodilator Response

The response to a bronchodilator is determined by calculating percent change from the prebronchodilator values. Percent change is calculated as follows:

$$\% \text{ change} = \frac{\text{Postbronchodilator value} - \text{Prebronchodilator value}}{\text{Prebronchodilator value}} \times 100$$

When evaluating a patient's bronchodilator response it is important to consider such factors as the response of healthy individuals to bronchodilators and the variability of the measurements. Additionally, it is important to consider which measurement(s) should be examined.

In the general population, the response to a bronchodilator for FVC, FEV_1, and $FEF_{25–75\%}$ is an increase of approximately 11%, 8%, and 20%, respectively.[36,37] The variability of the FVC, FEV_1, and $FEF_{25–75\%}$ measurements themselves in patients with asthma is 11%, 13%, and 23%, respectively.[38]

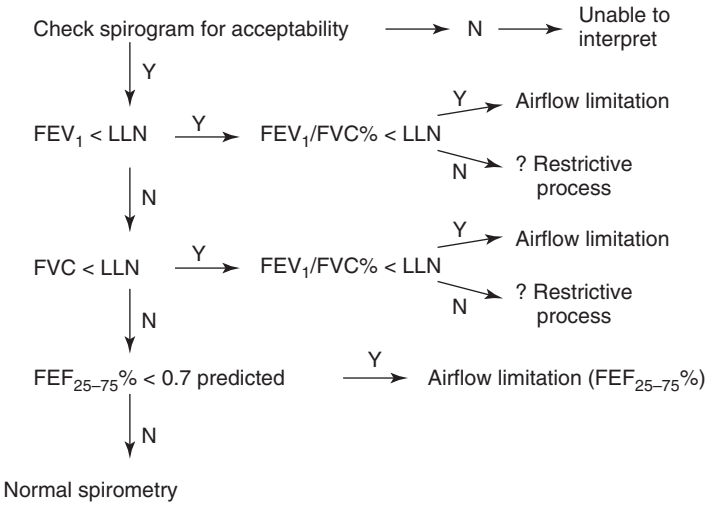
Light and coworkers[39] evaluated a number of pulmonary function measurements before and after bronchodilator. In comparing the magnitude of response with the variability, the FEV_1 had the highest discriminatory ability. Measurements such as specific airway conductance (sGaw) (see Chapter 4) and $FEF_{25–75\%}$, although they increased more, were not better than FEV_1 in identifying responders. Berger and Smith[40] and Sourk and Nugent[41] also showed that the FEV_1 was the better parameter.

The use of FEV_1 and FVC in examining the response, as measured by spirometry, to a bronchodilator has been endorsed by the ATS/ERS. In 2010 a 12% increase in FEV_1 *and* a 200 mL (0.2 liter) increase in either FEV_1 or FVC are recommended as criteria for a positive bronchodilator response in adults.[35] The $FEF_{25–75\%}$ and instantaneous flows should be used only

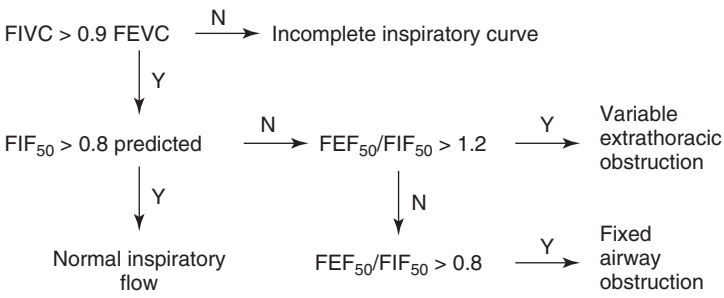
Figure 1.46

Interpretation guide to forced spirometry data.

For the forced expiratory curve:



For the forced inspiratory curve:



secondarily, and, if used at all, they should be adjusted for volume (i.e., measured at isovolume).[32, 33] The FEV_1/FVC ratio should not be used to measure response to a bronchodilator.

Table 1.6 compares the spirometric data of two patients: one with airflow limitation and the other with a restrictive process. It can be seen that the FEV_1/FVC ratio clearly distinguishes the patient with airflow limitation from the patient with a restrictive process. It can also be seen that the patient with airflow limitation responds to bronchodilator (23% improvement in FEV_1 and 18% improvement in FVC), but the FEV_1/FVC ratio does not change significantly.

Table 1.6

Examples of Data from Forced Spirometry Done on Two Patients Before and After Bronchodilator*

		Patient with airflow limitation		Patient with restrictive process	
	Predicted value	Before	After	Before	After
FVC (L)	4.85	2.93 (60)†	3.46 (71)	2.93 (60)	2.95 (61)
FEV_1 (L)	3.82	1.29 (34)	1.59 (42)	2.63 (69)	2.69 (70)
FEV_1/FVC%	79	44	46	90	91

*The reference values are obtained from the NHANES III standards[42] using a 45-year-old man who is 68 inches tall.
†Values in parentheses are percent predicted.

Special Considerations

Obtaining acceptable and repeatable spirometry results is not an easy task. A number of patient, operator, and equipment constraints must be satisfied. What happens when the patient is not cooperative, is unable to follow directions, or is physically unable to do what is asked? When such problems occur, the operator may dismiss the patient and report that the patient is unable to perform spirometry. However, in many of these instances, spirometry can be adequately performed if the operator is skilled, patient, and willing to take extra time.

Patients Who Won't

Most patients come to the hospital or office because they are sincerely seeking help. They are willing to do most things asked of them and are cooperative. A small percentage of patients are not willing to do what is asked of them and are not very cooperative. Sometimes such patients are involved in legal action, and a gain or loss may ride on the test outcome. What does one say to these uncooperative patients? How does one get them to do an effort-dependent test like spirometry? The first step is to have the ordering physician give the patient a pep talk, stressing the importance of trying as hard as possible. Next tell the uncooperative patient that "the data obtained thus far are not reportable, and therefore the doctors or litigation (or both) cannot proceed." You can add, "You must try harder to blow faster and longer." This direct, no-nonsense approach frequently works with these types of patients.

Patients Who Have Difficulty Following Directions

Some patients have difficulty following directions, for example, the very young, the very old, and the hearing impaired. Testing children is a particular challenge, and Chapter 10 discusses approaches to pediatric testing.

Very old patients may have many problems that can affect the outcome of spirometry (e.g., poor coordination, hearing impairment, fatigue, illness). The key to successful pulmonary function testing with these patients, as with children, is patience. Explain the instructions for the procedure carefully, repeat as frequently as the circumstances dictate, and be prepared and willing to take extra time.

Hearing impaired patients and those who do not speak English must be able to hear and understand what you want them to do. In some cases an interpreter is needed to relay instructions. For those who wear hearing aids and still do not hear well, or for those who just do not hear well enough to catch all the details, written instructions may work well. Hearing aids amplify all sounds, and in noisy environments discriminating speech from other sounds may be a problem. Because most hearing impaired people lip-read very well, speak slowly and clearly while looking directly at the patient. Again, patience is the key to success.

Patients Who Can't

Another group of patients who need special considerations are those who are physically unable to perform the test in the standard manner (e.g., patients with tracheostomies, patients who cannot seal the mouthpiece tightly because of paralysis or malformation of the lips or mouth, and patients who have significant muscular weakness). Ingenuity is sometimes the key to working successfully with such patients. For example, an infant positive-pressure mask connected to the spirometer through a tubing adapter can be fitted over the tracheal stoma to assist in spirometry for the patient with a tracheostomy. The ordering physician can only expect the technologist to try as hard as possible to get as much valid information as possible. In some instances valid information cannot be obtained.

Maximum Voluntary Ventilation

The maximum amount of air that can be exhaled in a specified period during rapid and forced breathing is commonly referred to as the maximum voluntary ventilation (MVV). An older term for this volume is the maximum breathing capacity (MBC). MVV depends on a number of physiologic factors, including movement of the thoracic cage and the respiratory muscles and lung resistance.

In the past, the MVV test was commonly performed during routine pulmonary function tests. However, its clinical use declined over the years due to the fact that if FEV_1 is available, it adds little clinical information. Today, the MVV test is most commonly performed as part of the cardiopulmonary exercise test, where it is used as an index of maximum ventilatory capacity.

The test is performed on the same spirometer system used for forced spirometry. The patient should attach to the mouthpiece and place a nose clip on the nose. When directed, the patient should breathe in and out deeply and rapidly for 12 to 15 seconds. The tidal volume during this maneuver should approximate 50% of the vital capacity with a breathing frequency of approximately 90 breaths/min.[6] The expired volume during this short period is extrapolated to 1 minute and reported at BTPS in liters/min. Obtain at least two trials, with a repeatability goal of $\pm 10\%$. If the variability is greater than 20%, additional maneuvers should be obtained. The highest acceptable MVV and MVV rate should be reported.[6]

Table 1.7

Reference Values for the MVV Test

Boren and colleagues[43]	
Males	3.39(Height in inches) − 1.26(Age) − 21.4
Grimby and Soderholm[44]	
Males	79.0(Height in meters) − 1.42(Age) + 76
Females	138 − 0.77(Age)

Patients often settle at a rate and volume that is most comfortable for them. Emphasize in the instructions that a smooth and rhythmic breathing pattern is critical to obtaining optimal results.

Reference (predicted) values for the MVV test have been published and are shown in **Table 1.7**. The MVV will be decreased in patients with airflow obstruction, respiratory muscle weakness, poor coordination, and poor effort. A calculation or approximation of MVV can be made using the following formula:

$$\text{Calculated MVV} = 40 \times FEV_1$$

However some prefer to use $MVV = 35 \times FEV_1$.

Peak Expiratory Flow Rate Monitoring

PEFR is the highest flow achieved from a maximum forced expiratory maneuver. It can be obtained in the laboratory using a spirometer and expressed at BTPS in liters/sec. Or it can be obtained using small portable monitoring instruments and expressed in liters/min. These portable devices can be inexpensive, nonelectronic devices or more expensive electronic devices that can also measure FEV_1. This section will present information about measuring PEFR using small portable instruments that have become an important part of asthma management and monitoring. It is important for the respiratory care student and technologist to understand how to use these devices and the test procedure.

PEFR meters measure flow, and most nonelectronic devices use a similar design. The patient blows with maximum effort and force into a tube that has a movable indicator. The indicator moves in proportion to the airflow through the device. PEFR can then be read directly in liters/min from the calibrated scale on the device. High-flow ranges (e.g., 0 to 850 liters/min) for adults and low-flow ranges (e.g., 0 to 400 liters/min) for children are often available. These devices vary in price from about $10 to $30.

Newer electronic devices measure flow using various flow-sensing technologies and are almost miniature spirometers. PEFR can be read digitally, and these devices vary in price from about $100 to $350.

PEFR greatly depends on patient effort and cooperation and lung volume. To achieve a maximum value, PEFR must be measured when the lungs are completely full (i.e., maximum inspiration) and without expiratory hesitation.[45] Strong coaching and encouragement is important. The patient's neck should not be bent (neck flexion or extension can lower PEFR), and the

patient should not cough or spit during the maneuver (coughing or spitting can falsely increase PEFR in some devices). A nose clip is not necessary.[6]

If PEFR is to be self-measured by the patient at home, it is important that adequate instructions on how to perform the test are provided. Regular checks of the patient's technique and use of a PEFR meter are important quality control steps.

At least three acceptable PEFR maneuvers should be performed. PEFR maneuvers are considered acceptable when the patient takes a maximal inspiration, there is a good seal at the mouth, and no hesitation and no coughing or spitting occurred. The PEFR values and their order must be recorded. The highest two of three acceptable PEFR values should agree within 40 liters/min. If this repeatability is not achieved, additional maneuvers should be obtained. The largest PEFR value from at least three acceptable and two repeatable maneuvers is reported.

Infection Control

The role of respiratory therapy equipment in healthcare-associated infections usually receives great attention. However, the role of pulmonary function equipment in the transmission of infections is not well documented.

Several studies reported that a range of nonpathogenic flora existed in spirometers and associated tubing.[46-49] Burgos and coworkers[50] reported that bacterial colonization of water-sealed spirometers occurred within 3 days of use, but they could not demonstrate any transmission from spirometer to patient. Hiebert and coworkers[51] reported in an interesting study that transfer of *Escherichia coli* organisms does not occur during routine spirometry as long as an interval of at least 5 minutes is allowed between tests. In one case,[52] the transmission of microorganisms to other patients and operators was reported.

Hence it is probably safe to speculate that there is a small risk of cross-contamination when pulmonary function equipment is used. It also seems safe to speculate that this risk is inversely proportional to the frequency of cleaning or changing equipment parts. The use of barrier filters to trap microorganisms might reduce this risk; however, the filters may interfere with accuracy and may cause small reductions in peak flow (although these reductions are probably not clinically meaningful).[53-56]

The Centers for Disease Control and Prevention has published guidelines for preventing transmission of infectious agents in healthcare settings.[57] In addition, Kendrick and coworkers published an excellent review and practical approach to infection control in the pulmonary function laboratory.[58]

Recommendations for Infection Control in the Pulmonary Function Laboratory

- Disposable mouthpieces or flow sensors should be discarded after single patient use. Reusable mouthpieces should be washed, disinfected, and dried after use. The choice of disinfection method varies from laboratory to laboratory. Acceptable methods are chemical disinfection, dishwasher-type systems, and steam.

- External spirometer tubing should be changed after use. The contaminated tubing should receive high-level disinfection and be dried before reuse.
- Flow sensors handled by patients should be wiped with alcohol after use.
- Nose clips should be changed after use and discarded or cleaned with alcohol wipes.
- The water in water-sealed spirometers should be changed at least weekly.
- You should not spend a great amount of time and effort cleaning the surfaces inside the spirometers. Consult with manufacturer on recommendations.
- You should wash your hands thoroughly, using good hand washing technique, before and after performing pulmonary function testing procedures, whether or not gloves were worn.
- If using filters, you should ensure that they are changed after use and that they do not significantly increase resistance.

Case Presentations

Case 1.1

A 16-year-old boy was tested in the pulmonary function laboratory. The ordering doctor noted that the diagnosis is asthma. The results of each spirometry trial are shown in **Table 1.8** and **Figure 1.47**.

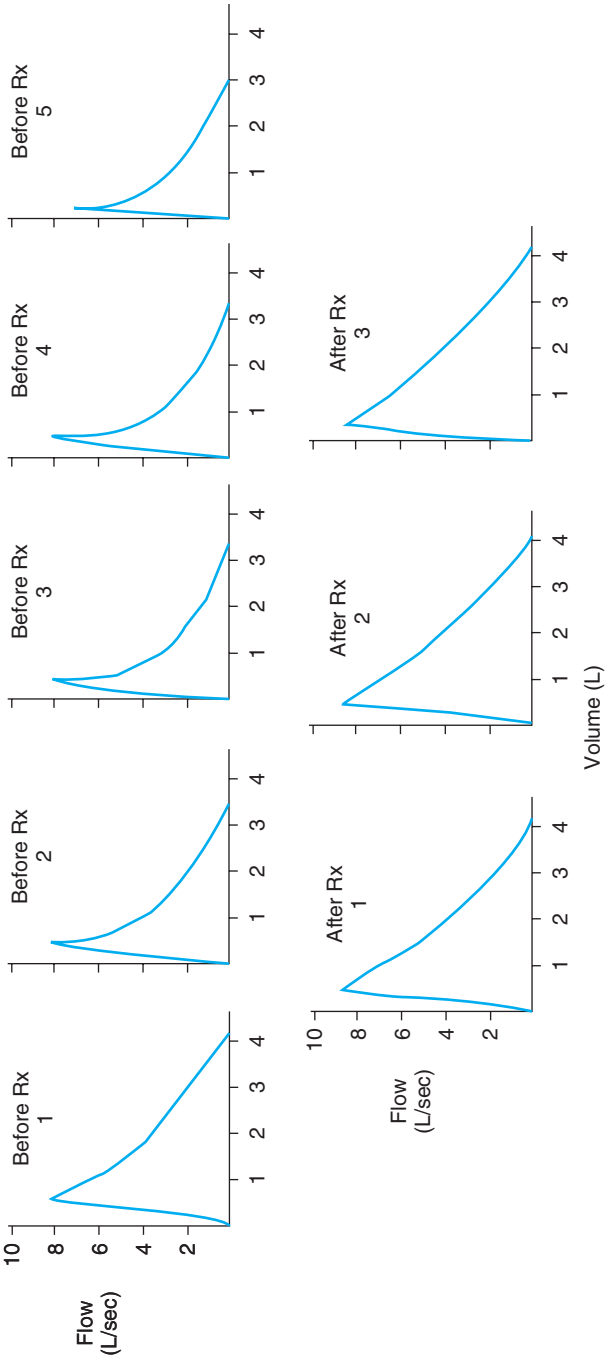
Table 1.8

Spirometric Results of Each Trial Before and After Bronchodilator (Rx) on 16-year-old Male in Case 1.1

	Time	FVC (L)	FEV_1 (L)	$\frac{FEV_1}{FVC}$ %	$FEF_{25-75\%}$ (L/sec)
Before Rx					
Trial 1	9:05	4.13	3.01	73	2.03
Trial 2	9:07	3.61	2.48	69	1.63
Trial 3	9:08	3.42	2.41	70	1.69
Trial 4	9:10	3.12	2.01	64	1.48
Trial 5	9:12	3.09	2.02	65	1.51
After Rx					
Trial 1	9:40	4.33	3.30	76	2.59
Trial 2	9:42	4.29	3.31	77	2.63
Trial 3	9:43	4.32	3.33	77	2.58

Figure 1.47

Spirometric results in flow–volume graph format showing five maneuvers before bronchodilator (Rx) and three maneuvers after Rx.



Questions

1. What is the interpretation/evaluation of these spirometric tests?
2. Which before-and-after efforts should be reported?

Answers and Discussion

The first FVC effort (9:05) shows mild airflow limitation based on the reduced FEV_1/FVC% and $FEF_{25–75\%}$ (43% of predicted). The remaining before-Rx efforts show significant deterioration.

The after-Rx forced expiratory efforts show marked improvement in airflow. The amount of improvement depends on which before-Rx effort is used for comparison.

The deterioration of flow rates in the before-Rx test could be caused by poor effort or spirometry-induced bronchoconstriction. Poor effort is a factor the operator must assess. The diagnosis of asthma makes the spirometry itself the likely cause of the airflow deterioration.

The effects of deep inspiration have been studied and have shown varying effects on airflow. In some asthmatics, a deep inspiration causes bronchoconstriction that comes on rapidly and may disappear spontaneously in 1 or 2 minutes.[59-61] In nonasthmatics a deep inspiration has shown a bronchodilatation effect.[62]

Traditionally, one maneuver from the before-bronchodilator testing and one maneuver from the after-bronchodilator testing are reported. In Case 1.1, if the first before-Rx maneuver is selected (based on highest value), the comparison to after-Rx maneuvers would show only a small improvement. However, if the fifth before-Rx maneuver is selected, which best represents the patient's airflow before the bronchodilator, the interpretation is quite different. Alternatively, both the first and fifth mancuvers could be reported to show the deterioration, or a comment could be made noting the deterioration.

Case 1.2

A 42-year-old Caucasian woman was seen in the pulmonary function laboratory. The ordering doctor had noted asthma as the diagnosis and noted that she was being treated with theophylline and inhaled bronchodilators. The results from her pulmonary function tests are shown in **Table 1.9**.

Table 1.9

Pulmonary Function Results Before and After Bronchodilator (Two Actuations of Albuterol from a Metered Dose Inhaler)

	Predicted	Before*	After	% Change
FVC (L)	3.26	2.90 (89)	3.00	3
FEV_1 (L)	2.73	2.02 (74)	2.18	8
FEV_1/FVC%	84	70	73	
$FEF_{25–75\%}$ (L/sec)	3.26	2.41 (74)	2.62	9

*Values in parentheses are percent predicted.

Questions

1. What is the interpretation/evaluation of these spirometric tests?
2. What issues would be raised with these results, given the diagnosis and medication regimen?

Answers and Discussion

The spirometry data reveal airflow limitation with only minimal response to the two puffs of the albuterol MDI.

One question is whether bronchodilators were withheld before this spirometric test. A short-acting bronchodilator taken within 8 hours of spirometry can affect the results and interpretation. Inhaled short-acting bronchodilators should be withheld for their duration of action (usually 4 to 8 hours) before such a test. Long-acting bronchodilators should be withheld for 12 to 24 hours. The advisability of withholding oral or inhaled bronchodilators for pulmonary function tests is controversial; follow the physician's directive.

Another question is whether the patient has airflow limitation that improves with bronchodilators. If not, she may not need the medications with which she is being treated. A bronchial provocation test (e.g., methacholine) would determine the presence or absence of bronchial hyperreactivity (asthma).

In this particular case, a methacholine challenge revealed moderate airway hyperreactivity, which is surprising given her poor response to the bronchodilator during spirometry. However, patients with hyperreactive airways (asthma) may not respond to inhaled bronchodilators for several reasons:

- The medication delivered by MDI is trapped in the mouth and does not reach the airways.
- The large airways are physically narrowed, with decreased amounts of medication reaching the lower airways.
- The patient has a bronchospastic reaction to the propellant used in the MDI.
- The patient has problems with the technique of MDI administration (e.g., coordination, breath holding, or rate of inhalation).

It is possible that, in this patient, any or several of these reasons played a role. Although the usual clinical dose of albuterol using an MDI is two actuations, it may be necessary to deliver more medication to demonstrate bronchodilator improvement.

The spirometry was repeated several days later. This time, however, the order was for six actuations unless the patient developed side effects (e.g., tremors, tachycardia, palpitations, headache). The results are shown in **Table 1.10**.

These results clearly show that this patient responds to the bronchodilator, which is consistent with the methacholine challenge. In this case, six actuations were enough; possibly four or five would have been enough. The usual dose of two actuations has been established as the dose that *usually* does not cause side effects and *usually* results in improvement, but some patients require more actuations.

Table 1.10

Pulmonary Function Results Before and After Bronchodilator (Six Actuations of Albuterol from a Metered Dose Inhaler)

	Predicted	Before	After	% Change
FVC (L)	3.26	2.83	3.19	13
FEV_1 (L)	2.73	1.98	2.47	25
FEV_1/FVC%	84	70	77	
$FEF_{25–75\%}$ (L/sec)	3.26	2.46	3.39	38

Self-Assessment Questions

1. During a forced expiration, the point in the airways where the pleural pressure equals the airway pressure is called the:
   a. Equal airway pressure
   b. Null pressure point
   c. Equal pressure point
   d. Transpulmonary pressure
2. All the following are examples of a volume-displacement spirometer except:
   a. Water seal
   b. Bellows
   c. Balloon
   d. Rolling seal
3. All the following are examples of flow-sensing spirometers except:
   a. Pneumotachograph
   b. Thermistor
   c. Wedge
   d. Ultrasonic
4. Calibration of spirometers should be done with a good quality syringe of known volume:
   a. Before every patient
   b. Every day it is used
   c. Once per week
   d. Once per month
5. All the following are acceptability criteria for valid spirometry except:
   a. No coughing
   b. No early termination
   c. Good repeatability of FVC and FEV_1
   d. Good start of test
   e. None of the above

6. When calibrating a spirometer with a known-volume calibration syringe, the volume measured should be within what percentage of the known volume?
   a. ± 1%
   b. ± 3.5%
   c. ± 5%
   d. ± 7%
7. Spirometric values are reported as the volume at:
   a. ATPS
   b. BTPS
   c. STPD
   d. ATPD
8. Several concerns have been raised about the use of reference values. Which of the following is not a concern?
   a. Not enough values for certain races and age groups
   b. Use of different types of instrumentation
   c. Inclusion of current and ex-smokers in some studies
   d. Not all values are contained in one study
   e. None of the above
9. When performing reversibility testing, how long after bronchodilator administration should you wait before performing postbronchodilator testing?
   a. 1–5 minutes
   b. 3–6 minutes
   c. 10–15 minutes
   d. 30–35 minutes
10. According to the 2005 ATS/ERS Standardization of Spirometry, the acceptable limit for back-extrapolated volume as a percentage of the vital capacity is less than:
    a. 5% of FVC
    b. 7% of FVC or 0.150 liter, whichever is greater
    c. 5% of FVC or 0.150 liter, whichever is greater
    d. 3% of FVC
11. When performing PEFR measurements using a peak flow meter, the largest two of three acceptable blows should be repeatable within:
    a. 10 liters/min
    b. 20 liters/min
    c. 40 liters/min
    d. 80 liters/min
12. According to the 2005 ATS/ERS Standardization of Spirometry, the repeatability requirement for valid spirometry is:
    a. The two largest FVC values must be within 3% of each other, and the two largest FEV_1 values must be within 3% of each other.
    b. The two largest FVC values must be within 5% of each other, and the two largest FEV_1 values must be within 5% of each other.

c. The two largest FVC values must be within 0.150 liter of each other, and the two largest FEV_1 values must be within 0.150 liter of each other.
d. The two largest FVC values must be within 0.200 liter of each other, and the two largest FEV_1 values must be within 0.200 liter of each other.

13. What is the most likely interpretation of the following spirometric data?
FVC = 2.30 (63% of predicted)
FEV_1 = 2.00 (70% of predicted)
FEV_1/FVC = 87%
a. Normal
b. Unacceptable
c. Airflow limitation
d. Possible restrictive process

14. The minimum number of acceptable spirometric trials that should be obtained is:
a. One
b. Two
c. Three
d. Eight

15. The pneumotachograph measures flow by:
a. Sensing the pressure drop across a fixed resistance
b. Sensing resistance through the tube
c. Measuring volume
d. Measuring volume and time

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