CHAPTER 2

Lung Volumes

Introduction

In the pulmonary function laboratory, the *measurement of lung volumes* or *measurement of static lung volumes* usually refers to the measurement of total lung capacity (TLC), residual volume (RV), functional residual capacity (FRC), and vital capacity (VC). These measurements are essential for analyzing lung function; they provide information to further the diagnostic process and assess therapy. There are two major steps in measuring lung volumes: (*a*) determining FRC and (*b*) measurement of slow vital capacity (SVC) and its subdivisions.

FRC is most commonly determined with one of three basic techniques: (*a*) body plethysmography, (*b*) multiple-breath closed-circuit helium (He) dilution, or (*c*) multiple-breath open-circuit nitrogen (N_2) washout. This chapter will discuss these techniques in detail focusing on instrumentation, relevant physiology, calculations, and testing techniques. In addition, this chapter will discuss the measurement of SVC and its subdivisions.

Other methods of measuring static lung volumes include the single-breath N_2 test, the single-breath He (or other inert gas) test, the chest roentgenogram (x-ray), and computed tomography (CT). The single-breath N_2 and chest x-ray methods were much less commonly used as of 2010 and thus will be discussed only briefly. The single-breath He (or other inert gas) method

is performed in conjunction with the single-breath carbon monoxide diffusing capacity test ($D_{L,CO}$) and is discussed only briefly in this chapter. It is discussed more extensively in Chapter 3. The use of CT scans has increased significantly and will be briefly discussed.

Lung Subdivisions: Volumes and Capacities

The total lung volume can be divided into several subdivisions or compartments (**Figure 2.1**), which can then be grouped into *volumes* and *capacities*. There are four volumes: inspiratory reserve volume (IRV), tidal volume (TV), expiratory reserve volume (ERV), and residual volume (RV). Two or more of these volumes make up a capacity. For example, the sum of IRV and TV is inspiratory capacity (IC). There are four capacities: vital capacity (VC), inspiratory capacity (IC), functional residual capacity (FRC), and total lung capacity (TLC).

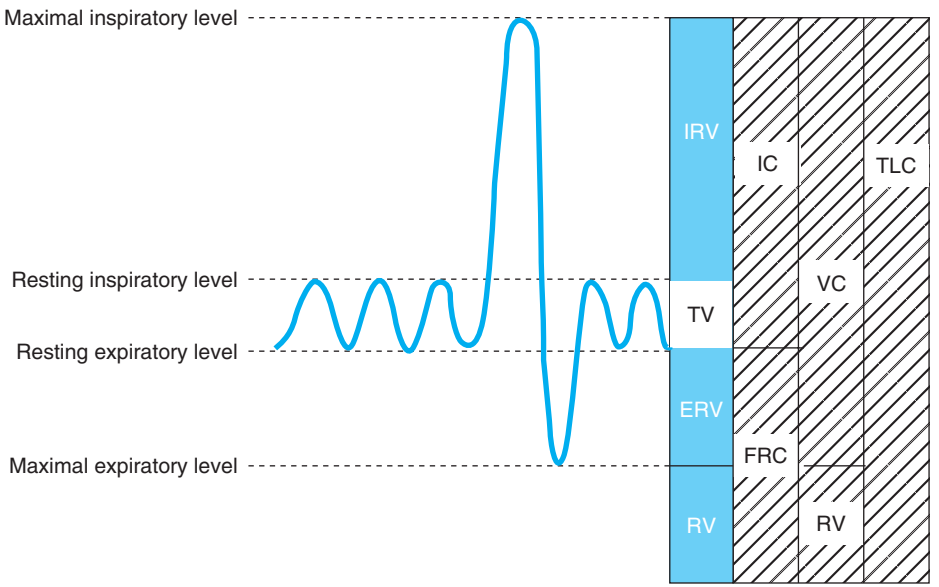
TV (**Figure 2.2A**) is the volume of air inspired and expired with each breath during normal breathing. The end of the inspiratory phase is called the *end-inspiratory level*, and the end of the expiratory phase is called the *end-expiratory level*.

IRV (**Figure 2.2B**) is the maximum volume of air that can be inhaled from the end-inspiratory level during quiet or normal tidal breathing. The ERV (**Figure 2.2C**) is the maximum

Figure 2.1

Lung volume compartments and subdivisions based on a volume–time spirogram. The four volumes are IRV, TV, ERV, and RV. The capacities (VC, IC, FRC, and TLC) consist of two or more volumes.

Source: Adapted from Forster RE, DuBois AB, Briscoe WA, Fisher AB. The lung: Physiologic basis of pulmonary function tests. 3rd ed. Chicago: Year Book Medical Publishers, 1986.

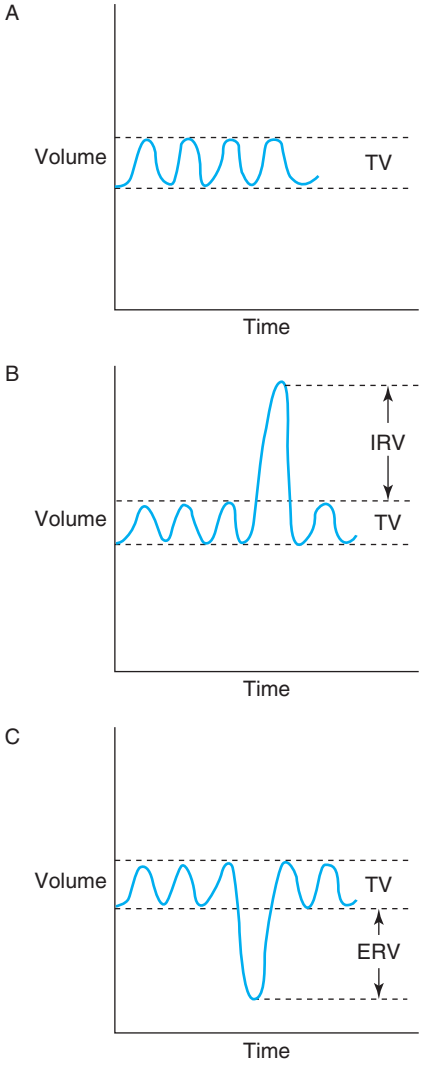


volume of air that can be exhaled from the end-expiratory level during quiet or normal tidal breathing (i.e., from FRC).

RV is the volume of air remaining in the lungs at the end of a maximum expiration. Unlike the other three volumes, RV must be measured indirectly using a two-step process. First, the

Figure 2.2

The three volumes that can be measured directly from the spirogram. A. Tidal volume (TV). B. Inspiratory reserve volume (IRV) C. Expiratory reserve volume (ERV).



FRC is measured using one of several techniques. Then an SVC is obtained and subdivided (i.e., TV, IRV, ERV). When the FRC and SVC have been obtained, RV can be calculated in the following way:

$$RV = FRC - ERV$$

The VC is the volume change at the mouth and can be an expiratory VC or an inspiratory VC. The expiratory VC is the volume of air that can be exhaled from the lungs after a maximum inspiration. The inspiratory VC is the volume of air that can be inhaled from a position of full expiration to full inspiration.

The VC can also be performed forcefully or slowly. When done forcefully it is called the forced vital capacity (FVC), which is defined as the volume of air that is exhaled forcefully starting from a position of full inspiration and ending at complete expiration. When the VC is exhaled slowly, it is called the SVC, which is defined as the volume of air that is exhaled without force from a position of full inspiration to full expiration. The VC can also be described as the sum of the TV, IRV, and ERV. In a healthy individual, the VC makes up approximately 70% of the TLC.

The IC is the maximum amount of air that can be inhaled from the TV end-expiratory level. It is the sum of the TV and IRV. This capacity usually makes up 60% to 70% of the VC in healthy individuals.

The FRC is the volume of air remaining in the lungs at the TV end-expiratory level. At this point in the respiratory cycle (i.e., end expiration), the elastic force of the chest wall (acting to expand the chest) is exactly balanced by the elastic force of the lungs (acting to deflate the lungs). As shown in Figure 2.1, the FRC consists of the ERV and RV, and its determination is a critical step in measuring lung volumes.

The TLC is the volume of air in the lungs after a maximum inspiration. It consists of all four volumes (IRV, TV, ERV, and RV) and two capacities (IC and FRC).

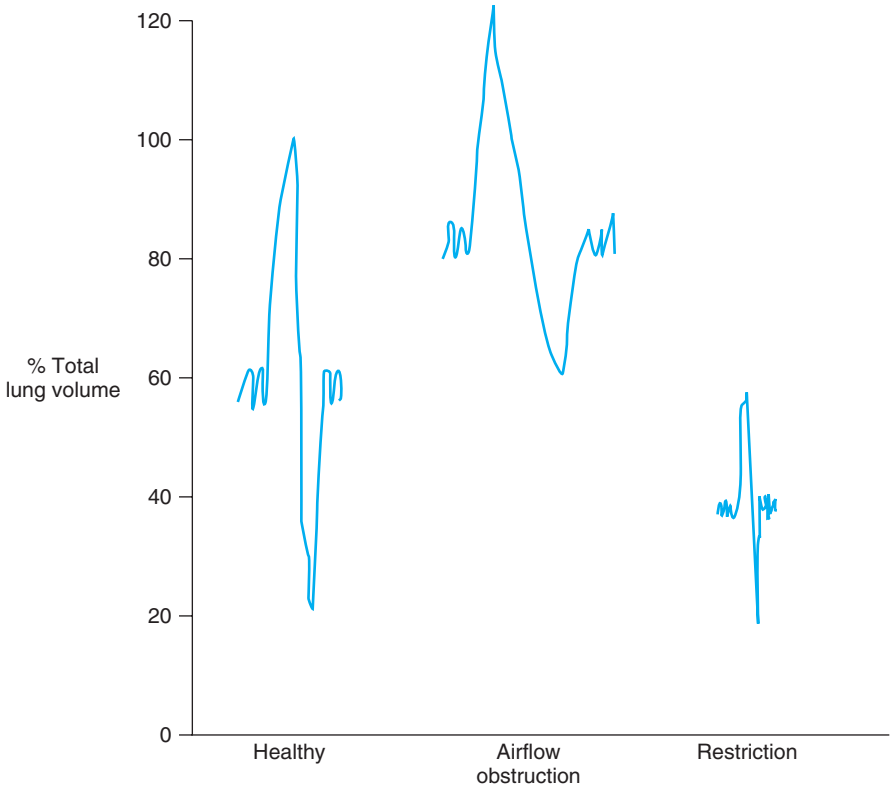
The size of the lung volume compartments varies among individuals, depending on age, gender, height, weight, race, and disease. In healthy individuals the lung volume compartments vary from the factors previously described, but the proportional relationships are similar. Typically, in healthy individuals the FRC is approximately 40% to 50% of the TLC, and the RV is approximately 25% to 30% of the TLC (**Figure 2.3**). In individuals with lung disease, forced spirometry alone does not always provide adequate information. For example, in individuals with airflow obstruction (e.g., emphysema), it is common to see a reduced FVC and forced expiratory volume in 1 second (FEV_1) and a reduced FEV_1/FVC ratio. Similarly, an individual with a restrictive process (e.g., interstitial lung disease) will also have a reduced FVC and FEV_1; however, the FEV_1/FVC ratio is typically increased. Although the FEV_1/FVC ratio may be helpful in differentiating obstructive and restrictive diseases, it is not the acid test. The only true way to differentiate the two disease processes is to measure all the lung volume compartments.

In addition to a reduced FVC, FEV_1, and FEV_1/FVC ratio, patients with airflow obstruction usually have an increased FRC and a decreased ERV. Hence, the RV and the TLC are increased (Figure 2.3). The amount of increase depends on the severity of obstruction.

As noted earlier, in individuals with restrictive patterns, the FVC and FEV_1 are reduced and the FEV_1/FVC ratio is usually increased. Additionally, the lung volume compartments are all proportionally reduced (Figure 2.3).

Figure 2.3

SVCs in healthy and diseased patterns plotted as a percentage of total lung volume. The healthy pattern shows maximum inspiration (TLC) at 100% of total lung volume, and the maximum expiration (RV) is approximately 20% of total lung volume. The airflow obstruction pattern shows a reduced SVC with elevated TLC and RV. The restrictive pattern also shows a reduced SVC, as well as a reduced TLC and RV.



In mixed obstructive and restrictive disorders, some compartments are normal, some are increased, and some are reduced, making interpretation difficult. **Table 2.1** shows the various static lung volume compartments and their status for a particular disease pattern.

Measurement of VC

The SVC is the maximum volume of air that can be *slowly* exhaled from the lungs after a maximum inspiration to a full expiration. In healthy individuals, there is little difference between the SVC and the FVC. However, in individuals with airflow obstruction, the FVC maneuver causes gas trapping and thus is smaller than the SVC.

Table 2.1

Lung Volume Compartments and Their Status for Obstructive, Restrictive, and Mixed Obstructive and Restrictive Lung Disease Patterns

	Obstructive	Restrictive	Mixed
VC	D or N	D	D
TLC	I	D	N or D
IC	N	D	N or D
FRC	I	D	N or D
ERV	D or N	D	D
RV	I	D	N or D

I, increased; D, decreased; N, normal.

The same instrumentation is used to measure SVC and FVC. Many computerized pulmonary function testing systems contain software that can measure the SVC and its subdivisions. It is recommended that if both SVC and FVC are to be measured, SVC should be performed before FVC maneuvers because of the potential for muscular fatigue and gas trapping.[1] The SVC can be done as an inspiratory SVC (often referred to as IVC) or as an expiratory SVC (often referred to as EVC).

As in forced spirometry and prior to testing, provide the patient with instructions on the appropriate technique, and demonstrate the SVC maneuver. It is important to stress that the maneuver is not forced but is done in a relaxed manner except near end-inspiration and end-expiration. A nose clip should be worn by the patient during the maneuver. The maneuver for performing the expiratory SVC (or EVC) should include several tidal breaths to establish a stable FRC level, followed by a maximum inspiration and then a slow, complete expiration (**Figure 2.4**). The maneuver for performing the inspiratory SVC (or IVC) includes several tidal breaths to establish a stable FRC level, followed by a maximum expiration and then a slow, complete inspiration (**Figure 2.5**).

One additional variation of measuring the SVC that is less commonly used employs the concept that the VC is the sum of the TV, IRV, and ERV. After breathing at TV for several breaths, the patient inspires maximally and then returns to quiet breathing at the tidal breathing level. After again breathing at TV for several breaths, the patient slowly expires maximally. This two-step technique (**Figure 2.6**) measures the SVC in parts, which then can be summed.

Repeatability and Reporting

As with forced spirometry, at least three acceptable VC maneuvers should be obtained. The two highest SVC values should agree within 0.150 liters. If this is not achieved, additional maneuvers should be performed.[1] The largest value from at least three acceptable maneuvers should be reported. For IC, the mean of at least three acceptable maneuvers should be reported.[1]

Figure 2.4

Typical SVC maneuver as expressed on a volume–time spirogram with *tidal breathing* followed by a maximum *inspiration* and then a slow, complete *expiration*.

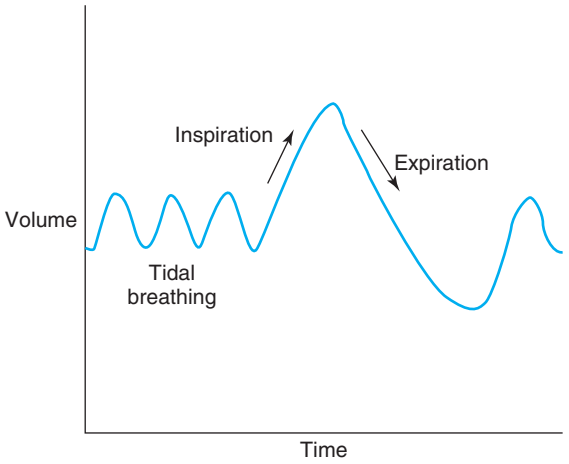


Figure 2.5

The reverse of the typical expiratory SVC is the inspiratory SVC. On a volume–time spirogram, *tidal breathing* is followed by a slow, complete *expiration* and then a maximum *inspiration*.

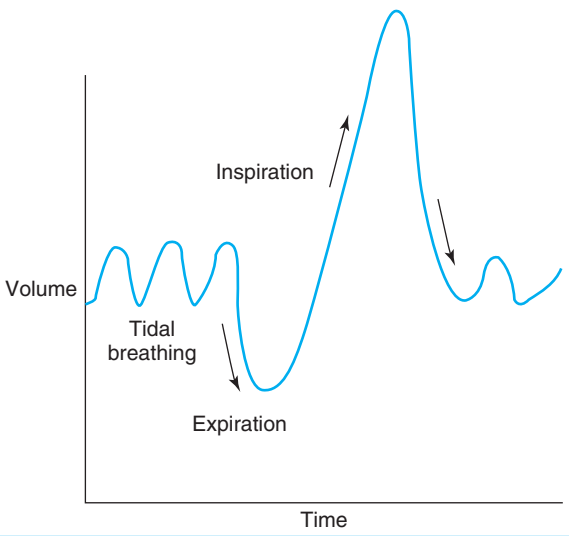
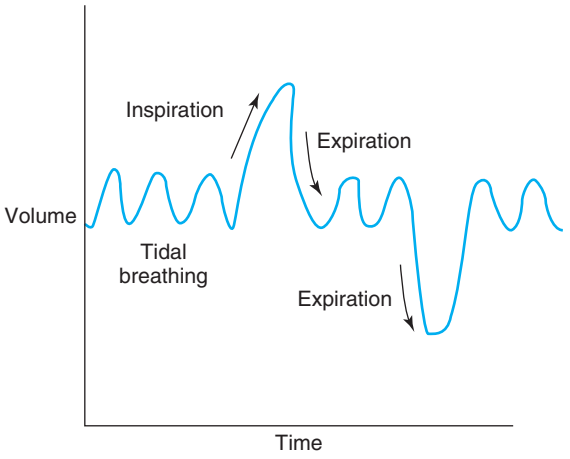


Figure 2.6

The two-step VC, as shown on a volume–time spirogram, consists of *tidal breathing* followed by a maximal *inspiration*, then a return to *tidal breathing* followed by a complete *expiration*.



Determining Lung Subdivisions

The determination of RV and TLC can be complicated. There are two recommended methods to determine these values after FRC has been determined.[2]

The first and preferred method is to measure ERV immediately after the acquisition of the FRC measurement followed by slow inspiratory vital capacity. All measurements should be performed as a linked maneuver, that is, without the patient coming off the mouthpiece prior to completion of the maneuvers.[2] The reported values for RV and TLC are:

$$\text{RV} = \text{Mean of FRC} - \text{Mean of ERV}$$

$$\text{TLC} = \text{Reported value for RV} + \text{Largest IVC}$$

The second recommended method includes the measurement of IC immediately after the FRC determination.[2] This method may be necessary in patients with severe dyspnea who cannot perform the ERV immediately after the FRC measurement. With this approach, patients can come off the mouthpiece between successive linked FRC and IC determinations and also between the separate VC maneuvers. The reported values for RV and TLC using this second approach are:

$$\text{RV} = \text{Mean TLC} - \text{Largest VC measured}$$

$$\text{TLC} = \text{Mean of the three largest sums of FRC values and linked IC values}$$

Measurement of FRC

As noted previously, determining FRC is one of two main steps in determining lung volumes. The three most commonly used FRC determination techniques are: (*a*) body plethysmography (also called *body box* and abbreviated FRC_{pleth}), (*b*) multiple-breath He dilution (abbreviated FRC_{He}) and (*c*) multiple-breath N_2 washout (abbreviated FRC_{N_2}). In healthy subjects and individuals with pure restrictive lung disease, these three methods show good agreement.[3-6] In individuals with obstructive lung disease, however, there is generally poor agreement between gas dilution values (He dilution and N_2 washout) and values from the body box.

The body plethysmograph or body box measures the volume of gas in the thoracic cage and is considered the most accurate method of measuring FRC. However, the body box is more expensive, technically more complicated, and requires more patient cooperation and effort than gas dilution–washout methods. Additionally, the body box may overestimate FRC slightly.[7-11] The suspected overestimation error stems from the fact that in severe obstructive lung disease, alveolar pressure may be underestimated. This matter is discussed later in this chapter.

The multiple-breath gas dilution–washout methods are relatively simple to perform and require little effort from the patient. However, in individuals with obstructive lung disease, the gas dilution–washout methods underestimate the true FRC because they measure only those areas of the lung in communication with the mouth. They do not measure areas of the lung that contain trapped gas. A large number of obstructive lung disease patterns are thus falsely classified as mixed obstructive–restrictive lung disease patterns because FRC is underestimated.

Both the gas dilution–washout and plethysmographic methods for determining FRC are considered acceptable.[2,3,12] The gas dilution methods underestimate the true FRC in patients with airflow obstruction. The plethysmograph method includes those air spaces not measured by gas dilution–washout methods and thus is the method of choice in patients with airflow obstruction. The use of both methods provides useful information about the volume of noncommunicating gas (i.e., trapped gas).

Measuring FRC with Body Plethysmography

The body plethysmograph or body box is the first of three methods that will be discussed to measure FRC. According to Comroe,[13] Pfluger was the first to apply Boyle's law to measure RV in 1882 by constructing a large metal container. The English translation of the German name for Pfluger's device was *man-box* or *man-can*. However, DuBois and coworkers are usually credited with the modern application.[6]

To measure FRC_{pleth}, the patient, sitting inside a sealed box, breathes quietly for several breaths and then pants against a closed shutter. The gas volume trapped in the lungs when the shutter is closed can then be measured by applying Boyle's law. As previously mentioned, this method is generally considered the most accurate of the three methods for measuring FRC because it measures the total gas volume in the thoracic cage or thoracic gas volume (TGV).

The body box is also used to measure airway resistance (Raw). The patient uses the same panting technique, or even a quiet breathing technique in some systems, but first with the shutter open and then with the shutter closed. Raw is used to assess airflow obstruction rather than lung volumes. It is discussed in Chapter 4.

The discussion of FRC_{pleth} determination includes: (*a*) physiology and instrumentation and (*b*) testing technique.

Physiology and Instrumentation

The operating principle of the body box is based on Boyle's law, which states that a volume of gas at constant temperature varies inversely with the pressure applied to it. In other words, when gas in a closed container is compressed, the volume decreases while the pressure inside the container increases. The reverse is true if the gas in the closed container is decompressed. Mathematically, Boyle's law is written as:

$$P_1V_1 = P_2V_2 \qquad \text{(Eq. 2.1)}$$

The individual to be tested sits in the sealed body box, attaches to the mouthpiece, wears a nose clip, and breathes quietly. When a valve (i.e., shutter) to which the mouthpiece is connected is closed at the TV end-expiratory position (i.e., FRC), it traps that volume of gas in the lungs. By trying to pant in and out against the closed shutter, the patient compresses and decompresses that trapped volume of gas in the thorax while the temperature remains constant. By panting out (i.e., against the shutter), the chest wall moves inward, which compresses the thoracic gas. Because the chest wall moves inward there is a proportional decompression of the gas in the sealed body box. Conversely, the decompression of the thoracic gas results in a proportional compression of the gas in the box. Because there is no airflow, the pressure changes inside the lung (measured at the mouth) and volume changes in the TGV (measured by changes in body box volume) allow the trapped TGV to be determined by applying Boyle's law. The derivation of the formula for determining TGV using Boyle's law is shown in Appendix C.

The final form of the formula as shown in Appendix C is:

$$V_1 = \frac{P_1\Delta V}{\Delta P} \qquad \text{(Eq. 2.2)}$$

where

P_1 = Alveolar pressure
ΔV = Change in body box volume when panting
ΔP = Change in alveolar pressure (measured at the mouth) when panting against a closed shutter
V_1 = TGV when the shutter is closed, usually at FRC

In practice, the operator observes a computer monitor that displays the relationship between alveolar pressure measured at the mouth and body box volume or pressure (**Figure 2.7**). The ΔV and ΔP are measured as the slope of the line fitting the panting lines. The slope (rise over run) is $\Delta P/\Delta V$, but equation 2.2 requires $\Delta V/\Delta P$. Thus, the inverse of the slope is required. The inverse of the slope is then multiplied by the calibration factors for body box volume and mouth pressure. Thus, equation 2.2 can be rewritten as:

$$\text{TGV} = \text{P} \times \frac{1}{\text{Slope}} \times \frac{\text{Body box calibration factor}}{\text{Mouth pressure calibration factor}}$$

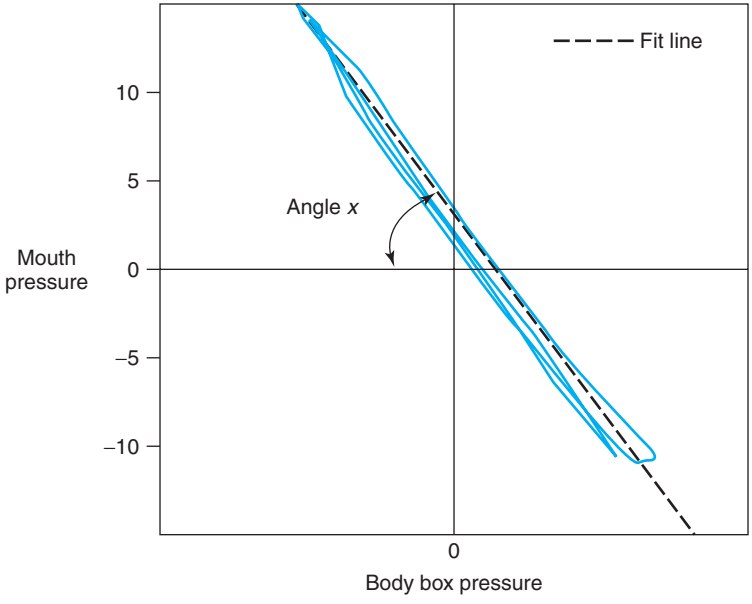
where

TGV = Thoracic gas volume
P = Barometric pressure in cm H_2O less water vapor
Slope = $\Delta P/\Delta V$

Let us use some hypothetical numbers. The closed shutter panting produced the display shown in Figure 2.7. Angle *x* is measured to be 45 degrees, and the slope or tangent of 45 degrees is 1.00. The body box pressure calibration factor, which is typically determined by injecting a known volume into the sealed body box and measuring the horizontal deflection, is 10 mL/cm. The mouth pressure calibration factor, which is typically determined by applying a known pressure to the mouth pressure transducer and measuring the vertical deflection,

Figure 2.7

Plethysmograph display showing mouth pressure and body box pressure relationship during closed-shutter panting. The dashed line is the fit of the several panting lines. Angle *x* is used to calculate TGV.



is 2.5 cm H_2O/cm. If the barometric pressure is 760 mmHg and the water vapor pressure at 37° C is 47 mmHg, then

$$P = 760 - 47 = 713 \text{ mmHg} = 970 \text{ cm } H_2O^*$$

Plugging these values into the rewritten equation 2.2 results in the following:

$$TGV = P \times \frac{1}{\text{Slope}} \times \frac{\text{Body box calibration factor}}{\text{Mouth pressure calibration factor}}$$

$$TGV = 970 \text{ cm } H_2O \times \frac{1}{1} \times \frac{10 \text{ mL/cm}}{2.5 \text{ cm } H_2O/\text{cm}}$$

$$TGV = 970 \text{ cm } H_2O \times 4 \text{ mL/cm } H_2O$$

$$TGV = 3{,}880 \text{ mL or } 3.880 \text{ liters}$$

The alveolar pressure changes caused by the compression and decompression of air in the lungs are estimated at the mouth. As mentioned earlier, the assumption that alveolar pressure equilibrates and is correctly measured at the mouth when the glottis is open and the cheeks are held firmly has been questioned.[7-10] In the presence of severe airflow obstruction there is a phase lag between pressures at the mouth and in the alveoli. This leads to underestimation of alveolar pressure and overestimation of TGV. This problem can be minimized by reducing the patient's panting frequency to 0.5 to 1.0 breaths/sec.

The TGV changes caused by the compression and decompression of the chest wall during the panting maneuver are estimated by measuring changes in the body box volume. The sealed box allows for measurement of the small changes in volume (e.g., 200 to 500 mL). The three major types of body boxes (variable-pressure box, flow box, and volume-displacement box) are classified based on how each type measures the body box volume change.

Variable-Pressure Box

The *variable-pressure box* (**Figure 2.8**) uses a pressure transducer to measure body box pressure changes that are caused by the compression and decompression of the chest in a constant volume container. Hence, it is also known as a *constant-volume box*. This transducer, which is attached to the wall of the box, is calibrated by injecting known volumes into the sealed box, creating a relationship between box volume change and box pressure change. This type of box requires a correction for body weight and frequent venting of excess pressure caused by rising temperatures when the patient is inside.

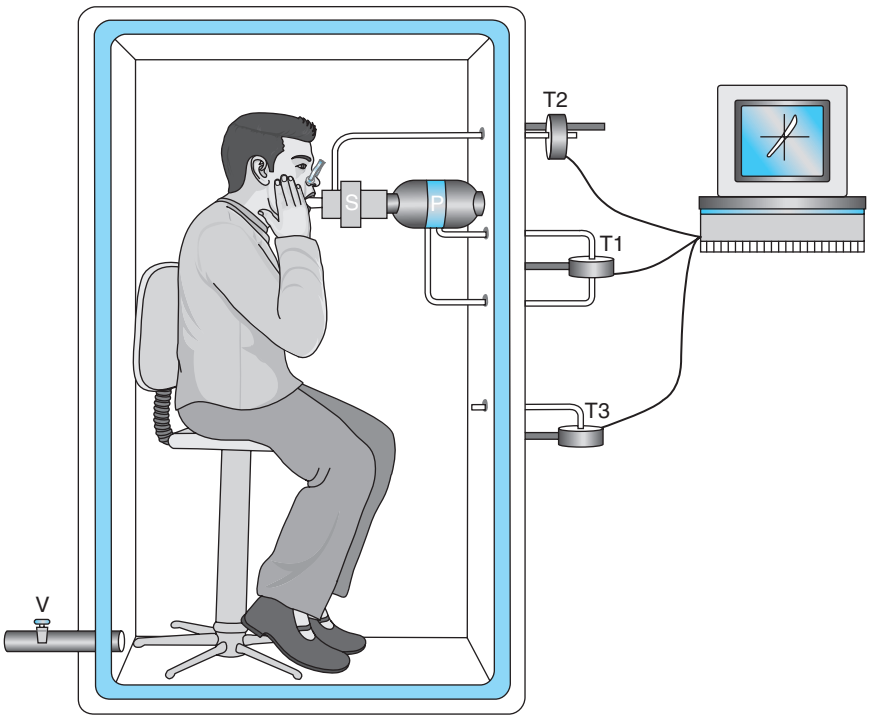
Flow Box

The *flow box* (**Figure 2.9**) measures box volume changes within a constant pressure chamber using a large pneumotachograph (which measures flow) placed in the box wall. When the thorax compresses and decompresses, the air in the body box will flow in and out of the box

*1.36 converts mmHg to cm H_2O.

Figure 2.8

Variable-pressure body plethysmograph (constant volume). The patient, wearing a nose clip, attaches to the mouthpiece and breathes through a shutter–pneumotach apparatus. The shutter (S) is open for tidal breathing and for measurements of Raw and closed for measurements of TGV. When the shutter is closed, mouth pressure is measured by a transducer (T2). The pneumotach (P) measures flow using the transducer T1, and in modern body plethysmographs the flow signal is electronically integrated to obtain volume. The body plethysmograph (or body box) pressure is measured by a transducer (T3). The signals from the three transducers are processed by a computer. Excess body box pressure from temperature changes caused by the patient sitting in the closed box is vented through a valve (V).

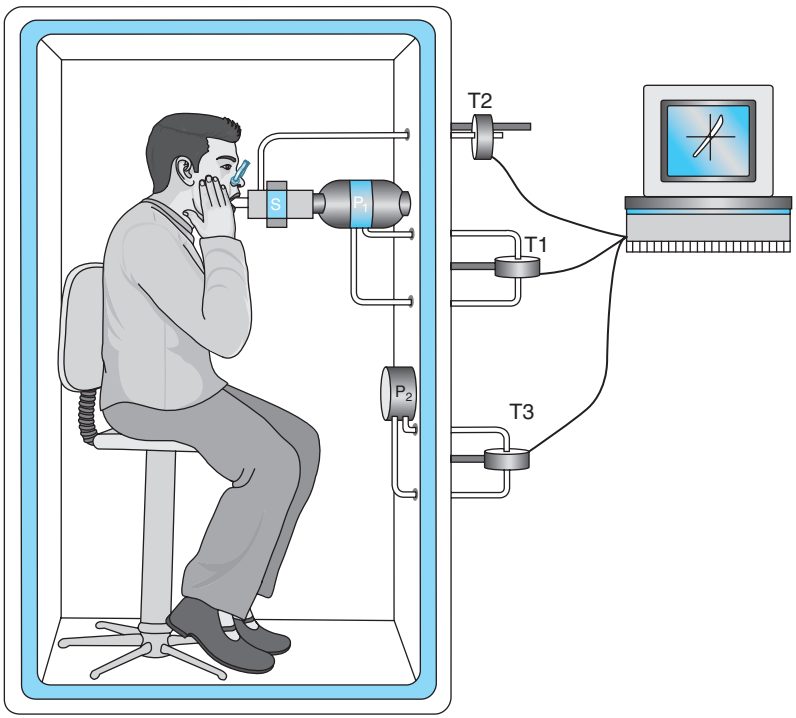


through this pneumotachograph. The measured flow is then integrated to obtain volume. The frequency response can be corrected. The flow and mouth pressure signals must be in phase, either by mechanical adjustments or computer software.

The flow box can be converted into a pressure box simply by occluding the pathway through the pneumotachograph, which combines the flow and pressure box approaches. This type of body box is commonly sold commercially. This combination allows for the measurement of TGV using the pressure box mode (the pathway to the pneumotachograph is closed) and the flow–volume curve using the flow box mode (the pathway to the pneumotachograph is open).

Figure 2.9

Flow body plethysmograph (variable volume). The patient, wearing a nose clip, attaches to the mouthpiece and breathes through a shutter–pneumotach apparatus. The shutter (S) is open for tidal breathing, measurement of Raw, and spirometry. It is closed for measurement of TGV. When the shutter is closed, mouth pressure is measured by a transducer (T2). The pneumotach (P_1) measures flow through transducer T1. The flow can then be electronically integrated to obtain volume. Modern systems allow the user to perform SVC and FVC. Changes in plethysmograph (body box) volume, which occur with chest-wall movement, are measured by electronic integration of flow through pneumotach P_2 and transducer T3. The signals from the three transducers are processed by a computer.



Volume-Displacement Box

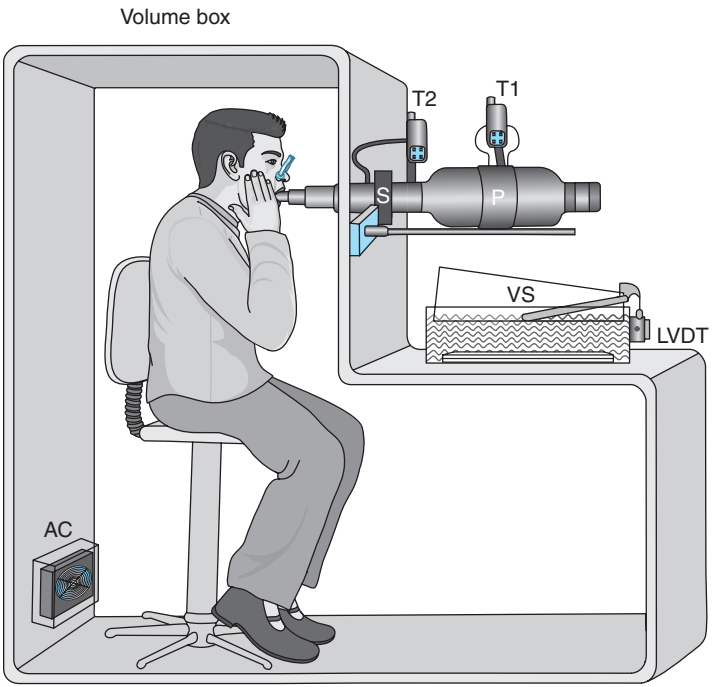
The *volume-displacement box* (**Figure 2.10**) measures box volume changes within a constant pressure chamber with an attached spirometer. It is easily calibrated by injecting a known volume into the sealed box. The frequency response of the spirometer must be taken into account or corrected, and the warming of the air in the plethysmograph can be overcome by air conditioning. The volume-displacement box can measure large volume changes (e.g., VC) and both the volume expired at the mouth and the volume compressed by the chest wall. There

can be a considerable difference between these two volumes in individuals with severe airway obstruction.[14]

In the past, the relationship between mouth pressure (which estimates alveolar pressure) and box volume changes was hand measured. Today, excellent software can calculate this measurement and make the body box easier to use. Additionally, software and instrumentation advances for the body box allow for the performance and measurement of many pulmonary function tests, including spirometry (SVC and FVC), diffusing capacity, single- and multiple-breath N_2 washout, pressure–volume characteristics, and maximal inspiratory and expiratory pressures.

Figure 2.10

Volume-displacement body plethysmograph (variable volume). The patient, wearing a nose clip, attaches to the mouthpiece and breathes through a shutter–pneumotach apparatus, which is usually located outside the plethysmograph (body box). The shutter (S) is open for tidal breathing, measurement of Raw, and spirometry. It is closed for measurement of TGV. When the shutter is closed, mouth pressure is measured by a transducer (T2). The pneumotach (P) measures flow through transducer T1. The flow can then be electronically integrated to obtain volume. Changes in body box volume, which occur with chest-wall movement, are measured by a volume-displacement spirometer (VS) and a linear volume-displacement transducer (LVDT). The type of spirometer shown is a Krogh water-sealed spirometer. Signal processing is done by a computer, and modern systems allow the user to perform SVC and FVC.



Testing Technique

The testing technique for measuring FRC_{pleth} includes: (*a*) equipment preparation and calibration, (*b*) patient preparation and instructions, (*c*) testing, and (*d*) quality control.

Equipment Preparation and Calibration

Calibrate the body box every day it is used. Follow the calibration process described in the operator's manual provided by the manufacturer. Usually the process consists of calibrating the box volume with a calibration syringe and the mouth pressure transducer with a water manometer. Additionally, calibrate any flow-sensing device attached to the breathing tube with a calibration syringe. Maintain a log of calibration results showing date and time, calibration values, barometric pressure, and the identification of the individual performing the calibration. It is common to print the calibration pages and store them in a notebook for review.

Patient Preparation and Instructions

Give the patient some instructions before he or she enters the box, such as how to use the mouthpiece and nose clip. Tell the patient that after he or she sits inside the door will be closed. Many patients are apprehensive about being closed in a small space. Assure the patient that the door can be opened at any time between maneuvers. Additionally, most boxes today are constructed with clear plastic walls, which promote a feeling of openness.

Patients who are receiving intravenous (IV) or O_2 therapy present a problem. If the patient is receiving IV therapy, the bags and pumps must be temporarily disconnected before testing in the body box. Similarly, patients receiving O_2 therapy (including transtracheal) should have their O_2 temporarily turned off while measurements are made.

Carefully explain the panting maneuver. Usually the patient is asked to pant (shallow breaths) at a rate of 0.5 to 1 breath/sec. When the shutter closes and the airflow stops, panting is more difficult. Explain that although air movement really stops when the shutter closes, the pressure of the panting is being measured, and therefore the patient must try to continue the panting maneuver. Next, demonstrate the open (if Raw is to be measured) and closed-shutter maneuvers.

Practicing with the patient is the next step. With the door closed and sealed, communication is hampered. Most of the intercom systems on the boxes do not provide good sound quality and therefore can cause delays as the patient tries to understand and perform this tricky maneuver. One recommendation is to leave the door open and show the patient what it feels like to pant against the closed shutter and give additional instructions or suggestions. When you think the patient is ready, seal the door and proceed with the testing. The patient still may have some problems with the maneuver (described next), but you can do any fine-tuning over the intercom system.

Testing

The common problems encountered in getting the patient to do the panting maneuver correctly include incorrect panting frequency (i.e., too fast or too slow), failure to inspire and expire against the closed shutter, panting too hard, lips failing to seal around mouthpiece, and glottis closure. Additionally, unsatisfactory results may occur when the patient allows the cheeks to puff in and out with the closed-shutter panting. Correct this by having the patient place his or her hands on the cheeks and prevent them from moving (**Figure 2.11**).

Figure 2.11

To keep a patient's cheeks from puffing in and out during the closed-shutter maneuver, his or her hands should be placed on the cheeks and pressed firmly toward the face.

Careful instruction and good feedback can reduce problems. During the closed-shutter panting maneuver, carefully monitor the graphic plot showing the change in mouth pressure and box volume. Ideally, you will observe a series of superimposed lines (**Figure 2.12**). Looping or bending can occur with glottis closure or box leaks or when the cheeks move (**Figure 2.13**).

As noted earlier, the relationship (i.e., the slope) of mouth pressure and body box volume changes during the closed-shutter maneuver was hand measured in the past. Current body box systems contain software that can estimate this slope. The advantage of allowing the computer to analyze all the data points and fit a line include: (*a*) faster analysis, (*b*) analysis of each individual panting breath, (*c*) greater accuracy by elimination of observer bias, and (*d*) better consistency.[15]

It has been recommended that the operator acquire at least three to five satisfactory panting maneuvers, with at least three FRC_{pleth} values that agree within 5% (i.e., the difference between the highest and lowest value divided by the mean is less than 0.05).[2] If significant variability exists, obtain additional values. The mean value of all acceptable and repeatable FRC_{pleth} values should be reported in liters at BTPS, rounded to two decimals (e.g., 3.13 liters).

Figure 2.12

Plethysmograph display of a properly done closed-shutter panting maneuver. It demonstrates the relationship between mouth pressure and body box pressure as a series of overlapping straight lines.

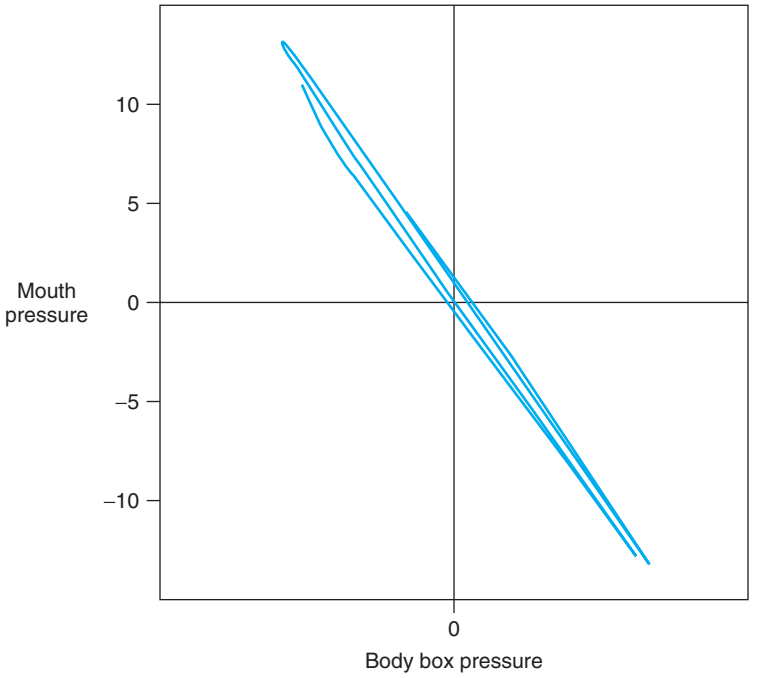
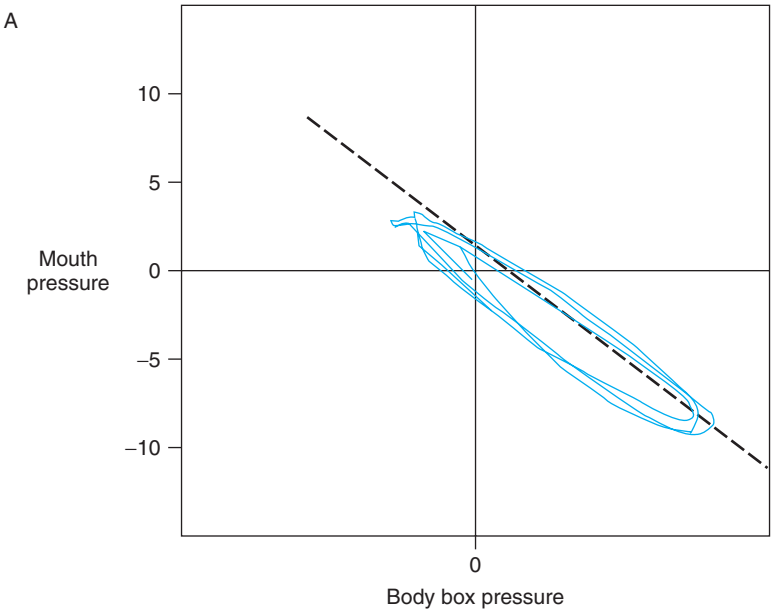
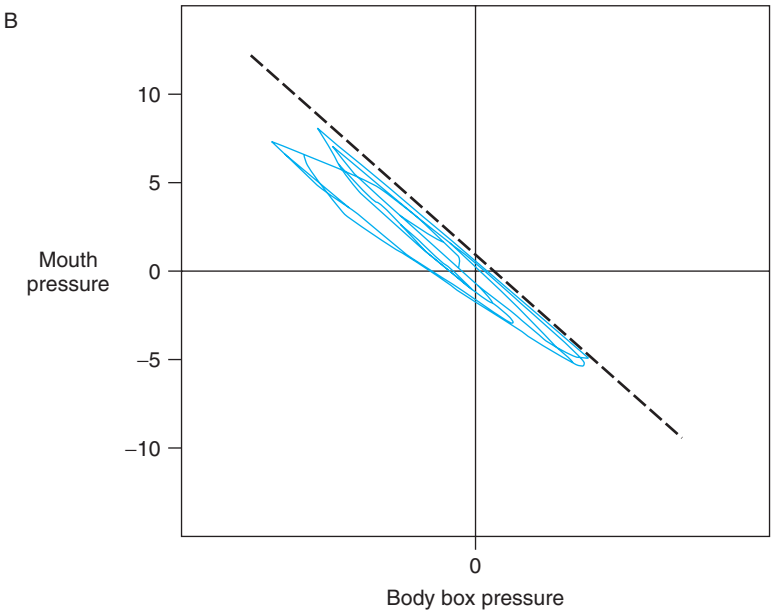


Figure 2.13

Plethysmograph displays of poorly done panting maneuvers. The relationship between mouth pressure and body box pressure is a series of open (A) or bent loops (B), usually caused by thermal drifting or patient technique (panting too rapidly or panting too deeply), which makes measurement difficult. The dashed lines represent the best fit if these measurements were used, but the operator should work hard with the patient to correct the problems and achieve a better measurement.





Quality Control

The accuracy of the body plethysmograph in measuring FRC using a mechanical model has been described.[16,17] This technique uses a container of known volume as a model lung (e.g., 3- or 4-liter glass flask filled with copper wool, with a two-holed rubber stopper at the opening). One hole is connected to the body box mouthpiece, and the second hole is connected to a rubber bulb. The bulb can be squeezed at the appropriate frequency by an individual sitting inside the box (holding his or her breath). The volume measured should equal the volume in the flask less the volume of copper wool (calculated from weight and density) within 50 mL or 3%, whichever is greater based on a mean of five determinations.[18] Some manufacturers of body plethysmographs provide variations of this early mechanical model.

Biological controls (healthy nonsmoking individuals) should be tested at least monthly or whenever errors are suspected. Measurements should include FRC_{pleth}, RV, and TLC. Values that differ by more than 10% for FRC_{pleth} and TLC, or more than 20% for RV from previously established means on the same biological control, suggest errors.

Another approach to ensure accuracy is to measure FRC_{pleth} and compare the value to FRC_{He} and/or FRC_{N_2}. Values for FRC using the different techniques should be very similar in healthy individuals.

Measuring FRC by Multiple-Breath Closed-Circuit He Dilution

The second method for determining FRC is by *multiple-breath closed-circuit He dilution* (FRC_{He}).[19,20] This method involves diluting He, an inert gas, in the lungs by rebreathing the gas in a closed system over a short time (usually 2 to 10 minutes).

This method is widely used in pulmonary function laboratories because: (*a*) it is a very easy test for the patient to perform, since it requires only tidal breathing and minimal learning and effort, and (*b*) the instrumentation is simple and inexpensive. However, as mentioned earlier, a major drawback of this method is that it measures only the lung volume in communication with the mouth. This becomes a problem in individuals with airflow obstruction because significant amounts of lung volume may not communicate with the mouth. The result underestimates FRC, which leads to an underestimation of RV and TLC.

The discussion of this method includes: (*a*) instrumentation, (*b*) physiology and calculations, and (*c*) testing technique.

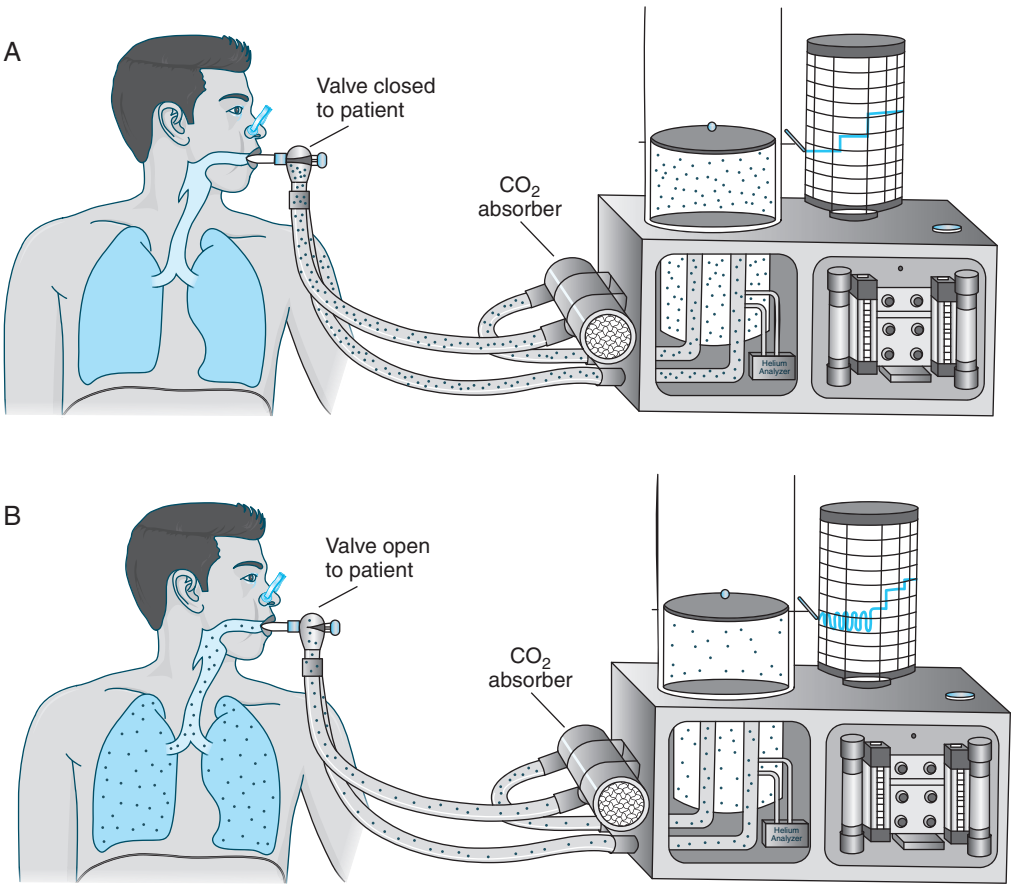
Instrumentation

The most commonly used *He analyzer* operates on a thermal conductivity principle. This principle is based on the facts that gases are able to conduct heat and different gases conduct heat at different rates. By introducing gas molecules into a sampling chamber containing a heated wire, the temperature of that wire decreases, allowing more current to flow through the wire. To be specific for He, other gases must either be removed or be compared with a reference. Therefore, CO_2 is scrubbed from the sample gas using a chemical absorber, and O_2 and N_2 are negated by comparing the thermal conductivity of the sample gas with a dry room-air reference. A Wheatstone bridge is incorporated to measure the resistance difference of the sample and reference chambers. Moisture in the circuit gas results in changes in H_2O vapor pressure, which affects the He analyzer. Thus, H_2O is also removed with a chemical absorber.

A small pump draws the gas from the breathing circuit and passes it over the chemical absorbers (one for CO_2 and one for H_2O), passes it to the He analyzer, and then passes it back into the breathing circuit. A volume-displacement spirometer with a capacity of at least 7 liters is commonly used. A mixing fan is incorporated to circulate and mix the air throughout the breathing circuit. A breathing valve, corrugated tubing, and mouthpiece are used and become part of the circuit dead space. These items are usually disassembled and disinfected or sterilized between uses. The complete system is shown in **Figure 2.14**.

Figure 2.14

Closed-circuit He dilution for determining FRC. A. The known concentration and volume of He in the spirometer system is separated from the patient by a closed valve. B. The valve is opened, and He (dots) is redistributed by rebreathing until it is equilibrated in the lungs and the circuit.



Physiology and Calculations

The closed-circuit He dilution technique uses a spirometer and breathing circuit that contains a known volume (V_S) and concentration (C_S) of He (Figure 2.14). The patient, wearing a nose clip, is connected to the mouthpiece. After a valve is opened (connecting the patient to the spirometer and test gas, which contains He, O_2, and N_2), the patient breathes into and out of this closed spirometer circuit. The initial concentration of He in the spirometer (C_S), commonly 10%, is diluted proportionately by adding the patient's lung volume (V_L), resulting in a final He concentration that reflects the concentration in both the spirometer circuit and the lungs (C_{LS}).

If the patient is turned in to the spirometer at TV end-expiratory level (FRC), then the V_L that will be measured is FRC. However, the patient could be turned in above or below FRC, allowing a lung volume other than FRC to be measured. If this occurs, it is referred to as a *switching error*, and a mathematical correction is usually made to ensure that FRC is correctly measured (see more discussion on switching error in the next section).

When the patient is turned in to the spirometer circuit and begins to breathe and rebreathe the circuit gas, the rebreathing will continue until the He concentration is equilibrated (Figure 2.14). In healthy individuals, the equilibration time takes approximately 2 to 3 minutes. However, in individuals with obstructive lung disease, it may take as long as 5 to 10 minutes, but it rarely exceeds 10 minutes. One technique that is sometimes used to speed up the equilibration process and thus reduce testing time is a periodic deep breath.

Looking at the calculation more closely, it can be seen that:

$$\begin{array}{c}\text{Volumes and concentrations}\\ \text{at beginning of test}\end{array} = \begin{array}{c}\text{Volumes and concentrations}\\ \text{at end of test}\end{array}$$

or

$$V_SC_S + V_LC_L = V_SC_{LS} + V_LC_{LS}$$

Because $C_L = 0$ at the beginning of the test:

$$V_SC_S = V_SC_{LS} + V_LC_{LS}$$

Solving for V_L:

$$V_L = \frac{V_SC_S - C_{LS}V_S}{C_{LS}}$$

$$V_L = \frac{V_S(C_S - C_{LS})}{C_{LS}}$$

If the concentration of He in the spirometer at the start of the test (C_S) is called C_1, and the concentration of He in the spirometer and patient's lungs at the end of the test (C_{LS}) is called C_2, and V_L is called FRC, then:

$$\text{FRC} = \frac{V_S(C_1 - C_2)}{C_2} - \text{He Abs Corr} \qquad \text{(Eq. 2.3)}$$

where

FRC = Functional residual capacity
V_S = Volume in spirometer and circuit
C_1 = Concentration of He in spirometer
C_2 = Concentration of He at the end of the test after equilibration of lungs and spirometer
He Abs Corr = Volume of theoretical He absorption by the blood during rebreathing (usually 0.1 liter); this is a controversial correction

The volume in the spirometer and circuit (V_S) includes the known volume of He and a dead space that consists of the tubing, the analyzer, and the space in the CO_2 absorber. This dead space must be measured. In most automated systems, this is accomplished by initially adding a small amount of He to the closed circuit and taking an initial reading. A known volume of air is then added, and after a short time to allow equilibration, a second He concentration reading is taken. This additional step modifies equation 2.3. Because the initial volume in the spirometer and circuit (V_S) can be calculated by taking another He concentration reading, the equation for FRC by He dilution then becomes:

$$\text{FRC} = \frac{C_1}{C_3} \times \frac{C_2 - C_3}{C_1 - C_2} \times V_{\text{added}} - \text{He Abs Corr} \qquad \text{(Eq. 2.4)}$$

where

FRC = Functional residual capacity
C_1 = Concentration of He in spirometer and circuit at the start of the test
C_2 = Concentration of He in spirometer and circuit after a known volume of air is added to estimate the spirometer and circuit dead space
C_3 = Concentration of He in spirometer and circuit at the end of the test after equilibration of lungs and spirometer system
V_{added} = Volume of air added to spirometer and circuit between C_1 and C_2
He Abs Corr = Volume of theoretical He absorption by the blood during rebreathing (usually 0.1 liter); this is a controversial correction

An example of calculating an FRC by closed-circuit He dilution (FRC_{He}) is as follows:

Volume of air added	= 1.20 liters
Initial He concentration (C_1)	= 10.0%
He concentration after air added (C_2)	= 8.6%
He concentration after subject equilibration (C_3)	= 6.2%
Spirometer temperature	= 23° C
He absorption correction	= 0.1 liter
Switching error	= 0

$$FRC_{He} = \frac{C_1}{C_3} \times \frac{C_2 - C_3}{C_1 - C_2} \times V_{added} - \text{He Abs Corr}$$

$$FRC_{He} = \frac{10.0}{6.2} \times \frac{8.6 - 6.2}{10.0 - 8.6} \times 1.200 \text{ @ ambient temperature and pressure, saturated with water vapor (ATPS)} - 0.10$$

$$FRC_{He} = 1.61 \times \frac{2.4}{1.4} \times 1.20 - 0.10$$

$$FRC_{He} = 3.21 \times \text{ATPS to BTPS factor of } 1.084$$

$$FRC_{He} = 3.48 \text{ liters}$$

Testing Technique

The testing technique for measuring FRC_{He} includes: (*a*) equipment preparation and calibration, (*b*) patient preparation and instruction, (*c*) testing, and (*d*) quality control.

Equipment Preparation and Calibration

Calibrate the spirometer used for He dilution systems as recommended by the manufacturer and test it for leaks every day it is used. The CO_2 and H_2O absorbers should be fresh. These absorbers usually contain color indicators. The CO_2 absorber (soda lime) is usually white with color indicators that change to blue as they become saturated with CO_2. The H_2O absorber (calcium sulfate) is usually light blue with color indicators that change to pink as they become saturated with H_2O. Have an adequate supply of He and O_2 available.

Patient Preparation and Instruction

The patient should be seated comfortably and told how to use the mouthpiece and nose clip. Tell the patient that the test requires sitting quietly and breathing through the mouthpiece with the lips tightly sealed for several minutes. Remind the patient not to remove the mouthpiece until you say so. Because perforated eardrums can result in leaks to the system circuit and thus result in erroneous FRC values, ascertain if the patient has this condition. If so, supply earplugs.

Testing

With the patient wearing a nose clip and breathing room air while attached to the mouthpiece, observe tidal breathing for 30 to 60 seconds as the patient becomes accustomed to breathing on a mouthpiece. When a stable breathing pattern exists, turn the valve that connects the patient to the spirometer system and test gas at TV end-expiratory level (FRC). Often, the switch-in of the valve to connect the patient to the spirometer system is not done exactly at FRC. The patient may be a little above or a little below FRC. This is not a problem because a mathematical correction for this switching error is made in the calculations. Because it can be difficult to see the patient's chest movement to turn him or her into the system exactly at FRC, try placing your hand on the patient's back or shoulder to feel the chest movement and help determine the correct turn-in point.

The calculation of FRC_{He} by the closed-circuit He dilution technique (equations 2.3 and 2.4) assumes that the volumes in the spirometer and lungs will not change between the start and end of the test. The CO_2 produced by the patient will increase the spirometer volume.

The O_2 consumed by the patient will decrease the spirometer volume. Hence, CO_2 must be absorbed, and O_2 must be added.

The CO_2 produced by the patient is continually being absorbed by chemical absorption as the He mixture circulates in the spirometer, circuit, and patient. The O_2 is added by one of two techniques. The first and most common technique is a *continuous-addition technique*, which keeps the spirometer system volume constant by continually adding O_2 in small quantities that equal the volume loss caused by the patient's O_2 consumption. Typically, an adult individual on this type of system has an O_2 consumption of 300 to 600 mL/min.

The second O_2 addition technique, found on some older systems, is the *bulk-addition technique*. Systems that use this technique put a bolus of O_2 (e.g., 1000 mL) into the spirometer before the patient is turned in. When the patient is turned in, all of the added O_2 must be consumed before the test can conclude. Otherwise, the volume of the spirometer and circuit will have changed, causing a greater He concentration change than would normally be seen.

The patient should continue to breathe on the mouthpiece until equilibration is reached. The He concentration is monitored every 15 seconds. Equilibration is usually defined by a plateau in the He concentration (i.e., the change in He concentration is less than 0.02% over 30 seconds).[2] If the He concentration continues to fall steadily with no trend toward equilibration, suspect a leak. Leaks typically occur around the patient's mouth or from a loose nose clip. If equilibration has not been reached 10 minutes after the beginning of the test, end the test. For patients who may become hypoxic, use pulse oximetry monitoring.

At the end of the test (i.e., equilibration), perform an SVC maneuver before removing the mouthpiece (linked to FRC determination); some patients, however, may not be able to perform this additional test after being on the mouthpiece for several minutes. If the patient cannot perform the linked SVC maneuver before being disconnected, have the patient perform it as soon as possible after FRC determination and disconnection.

When the patient comes off the mouthpiece, saliva and secretions spill out, so have a good supply of tissues nearby.

Perform at least one technically acceptable FRC_{He} determination. If more than one determination is performed, allow at least 5 minutes between them.[2,21] For practical purposes, differences of less than 10% between two FRC_{He} determinations are acceptable.[2,22] Report the mean FRC_{He} in liters at BTPS rounded to two decimals (e.g., 3.13 liters).

Quality Control

The accuracy of the He dilution device can be determined by using a 3-liter calibration syringe. The He dilution system should be prepared to test a patient. Connect the 3-liter syringe and inject a known amount of air (e.g., 3 liters) into the spirometer. Close the valve to the syringe, if possible, to avoid mixing the dead space of the syringe after injecting the volume of air. After approximately 30 seconds, when the meter reading is stable, end the test. The calculated volume (at ATPS) should equal the injected volume within 3%. If this is not the case, evaluate the system. Perform this quality control check at least weekly.[12]

In addition, the measurement of values in biological controls is useful and assures the testing values are stable. At least monthly, test two or three reference individuals (i.e., nonsmoking and healthy) on the system. Values obtained for FRC_{He} that differ by more than 10% from previously established means for a given individual should alert you to investigate the system.

Measuring FRC by Multiple-Breath Open-Circuit N_2 Washout

The third method of determining FRC is the *multiple-breath open-circuit N_2 washout (FRC_{N_2})*. This method involves removing or washing out the N_2 gas in a patient's lungs while the patient breathes 100% O_2 for several minutes. It is easy for the patient to perform and requires minimal learning and effort. Like the He dilution method, the N_2 washout method has the drawback of measuring only the lung spaces that communicate with the mouth. Thus it also underestimates FRC in individuals with airflow obstruction. The discussion of this method includes: (*a*) physiology and instrumentation and (*b*) testing technique.

Physiology and Instrumentation

The early modern technique[23] for the open-circuit method used the apparatus shown in **Figure 2.15**. This technique is cumbersome compared to today's techniques. It involved acquiring three gas samples (an alveolar sample prior to starting the test, a second alveolar sample after the test, and a sample of the exhaled gas during the 100% O_2 breathing period). The first sample was taken with the patient attached to the system mouthpiece and breathing room air. The patient was instructed to exhale maximally, at which time the alveolar gas sample was taken, which represented the average lung N_2 concentration on room air. Following this sample, the patient breathed room air for 2 more minutes to restore quiet breathing. Then a valve was turned at FRC so the patient could breathe 100% O_2 from a reservoir bag for 7 minutes. The exhaled gas was collected in a 100-liter gasometer (Tissot). After 7 minutes, the patient was instructed to exhale fully, and the second alveolar sample was taken. The patient was then disconnected, the breathing circuit was flushed, and the third gas sample was taken from the gasometer.

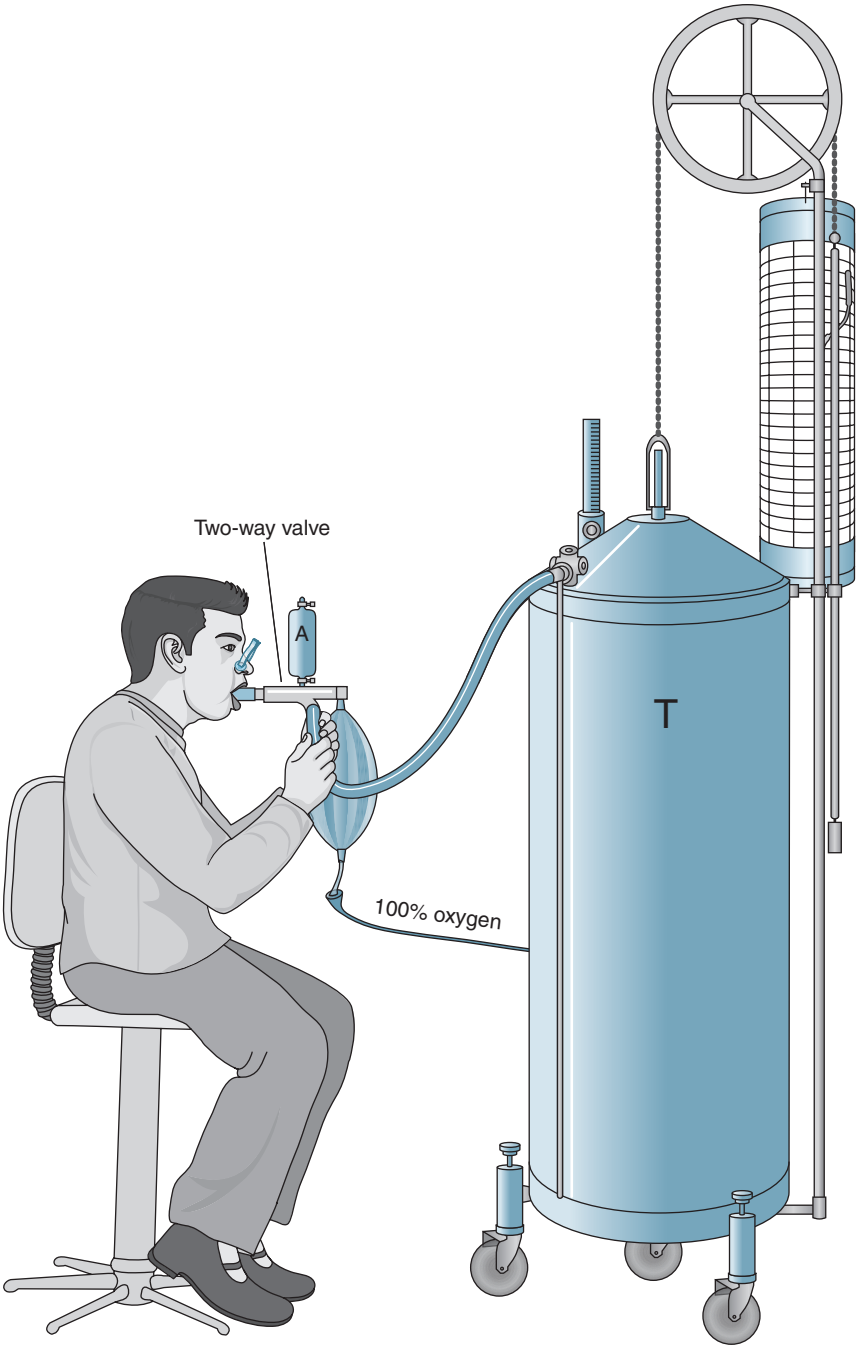
The three N_2 samples were analyzed using the volumetric methods (e.g., Van Slyke manometer), which depended on chemical absorption. This analyzation process, which was common in the early 1960s, took 10 to 20 minutes for each sample and was extremely technique dependent.

Today, the large gasometer has been replaced by flow meters, and the volumetric gas analyzers have been replaced by electronic N_2 analyzers that can analyze the N_2 concentration of each breath. Additionally, the second alveolar sample at the end of the O_2 breathing period has been eliminated from the technique.[24]

The concept of the N_2 washout is based on the fact that at the start of the test the unknown FRC contains 80% N_2 and an unknown concentration of O_2 (probably between 16% and 21%)

Figure. 2.15

The early modern open-circuit N_2 washout circuit for determining FRC. The patient breathes through a two-way valve to which a vacuum bottle (A) is connected for collecting the alveolar sample. The inspiratory side is connected to a 100% oxygen reservoir, and the expiratory side is connected to a large water-sealed spirometer (T). This spirometer, which is also known as a *Tissot* (pronounced TEE-so), is usually 100 to 200 liters, which is large enough to collect the expired air during 7 minutes of quiet breathing.



and CO_2 (probably between 0.4% and 5.0%). By measuring the volume of N_2 in the FRC and applying a concentration dilution formula, the FRC volume can be determined. Thus,

$$C_1V_1 = C_2V_2$$

where

C_1 = N_2 concentration at start of test
V_1 = FRC volume
C_2 = N_2 concentration in exhaled volume
V_2 = Total exhaled volume during O_2 breathing period

As stated earlier, the N_2 washout measures the lung volume that can be ventilated by the mouth. Thus, it will underestimate FRC in those individuals with large amounts of trapped air or areas of lung that are poorly ventilated. Early data[23,25] showed that increased breathing periods (i.e., 11 to 15 minutes) obtained larger FRCs in individuals with obstructive lung disease. However, longer durations are more uncomfortable for the patient, and in some patients (e.g., those with COPD) who breathe 100% O_2 for more than a few minutes, it may result in CO_2 retention.[26]

The measurement of N_2 can be performed using N_2 analyzers (most common), mass spectrometers, or indirectly by subtracting measurements of O_2 and CO_2. The N_2 analyzers used with modern systems operate on a photoelectric principle. Gas is pulled through a needle valve into an ionization chamber by a vacuum pump. The molecules are ionized and emit light. This light is then filtered and collected by a photo resistor, which converts the light into an electrical signal. The intensity of the light is directly related to the concentration of N_2 in the sample. The use of computers has allowed for the signal from the N_2 analyzer to be combined with the volume signal from a spirometer to provide instantaneous or breath-by-breath measurements of N_2 and volume. This technology allows for faster detection of leaks, which is an advantage over the He dilution technique.

The basic equation used with the early technique was:

$$FRC_{N_2} = \frac{(\text{Tissot volume})\,(FEN_2 - FIN_2)}{FAN_2\text{initial} - FAN_2\text{final}} - DS$$

An example of calculating an FRC by N_2 washout using the previous equation is as follows. An open-circuit N_2 washout was performed with the patient inspiring 100% O_2, and the exhaled air was collected in a 120-liter Tissot gasometer. The following information was obtained:

Barometric pressure (PB)	= 631 mmHg
Tissot temperature (T)	= 24° C
Tissot volume after 7 minutes of breathing	= 56.3 liters ATPS
FEN_2 (fractional concentration of expired N_2 in Tissot)	= 0.0368
FIN_2 (fractional concentration of inspired N_2)	= 0.001
FAN_2 initial (alveolar N_2 concentration at start of test)	= 0.80
FAN_2 final (alveolar N_2 concentration at end of test)	= 0.015
DS (valve dead space, liters)	= 0.090

$$FRC_{N_2} = \frac{(\text{Tissot volume})\,(FEN_2 - FIN_2)}{FAN_2\text{initial} - FAN_2\text{final}} - DS$$

VE Tissot (i.e., Tissot volume @ ATPS including system dead space) = 56.3 liters

$$\text{VE Tissot @ BTPS} = \frac{\text{VE Tissot}}{\text{@ ATPS}} \times \frac{310}{273 + T} \times \frac{PB - PH_2O \text{ at } 24°C}{PB - PH_2O \text{ at } 37°C}$$

$$\text{VE Tissot @ BTPS} = 56.3 \times \frac{310}{273 + 24} \times \frac{631 - 22}{631 - 47}$$

$$\text{VE Tissot @ BTPS} = 61.30 \text{ liters}$$

$$FRC_{N_2} = \frac{(61.30)(0.0368 - 0.001)}{0.80 - 0.015}$$

$$FRC_{N_2} = \frac{(61.30)(0.0358)}{0.785} = 2.80 \text{ liters @ BTPS}$$

Today, the computerization and simplification of this technique has greatly shortened the time needed to calculate FRC_{N_2}.

Testing Technique

The testing technique for measuring FRC_{N_2} includes: (*a*) equipment preparation and calibration, (*b*) patient preparation and instruction, (*c*) testing, and (*d*) quality control.

Equipment Preparation and Calibration

Calibrate the flow-meter device and N_2 analyzer every day of use, following the manufacturers instructions. There should be an ample supply of O_2.

Patient Preparation and Instruction

The patient should be seated comfortably and given instructions on how to use the mouthpiece and nose clip. Tell the patient that the test requires sitting quietly and breathing on the mouthpiece with the lips tightly sealed for several minutes. Remind the patient to keep the mouthpiece in place with the lips sealed until you say to remove it. Because perforated eardrums can result in leaks to the system circuit and thus result in erroneous FRC values, ascertain if the patient has this condition. If so, supply earplugs.

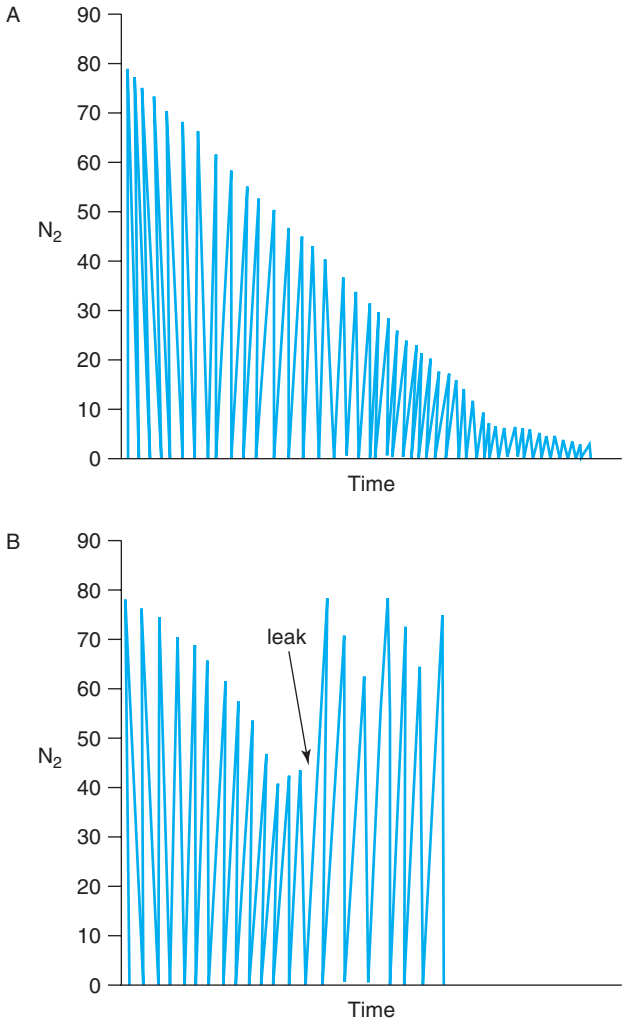
Testing

The patient breathes on the mouthpiece for 30 to 60 seconds to become comfortable on the mouthpiece and to assure a stable FRC level. When a stable FRC level has been established, the patient is turned in to the system and starts breathing 100% O_2. The N_2 concentration and the patient are monitored during the washout period to assure that no leaks occur. A large increase in N_2 concentration indicates a leak. If this occurs, the test should be stopped and repeated after the appropriate waiting period (i.e., 15 minutes). The test is usually stopped when the expired N_2 concentration falls below 1.5% for at least three successive breaths.[2]

Monitor the N_2 concentration throughout the test. When no leaks are present, the N_2 concentration appears as shown in **Figure 2.16A**. If a leak occurs, N_2 from room air enters the system, and the N_2 concentration abruptly rises (**Figure 2.16B**).

Figure 2.16

A. A typical display of an N_2 washout test using an N_2 analyzer. B. When leaks occur (e.g., the patient does not keep the lips sealed tightly), room air enters the circuit, and the N_2 concentration spikes to near ambient levels (i.e., near 80%).



At least one technically satisfactory measurement should be obtained. If additional washouts are performed, allow at least 15 minutes between maneuvers. Repeat the N_2 washout procedure with a 15-minute interval between trials until you obtain two FRC measurements that agree within 10%.[2] The mean FRC_{N_2} measurements that agree within 10% should be reported in liters at BTPS, rounded to two decimals (e.g., 3.78 liters).

Quality Control

The main cause of erroneous results with the open-circuit N_2 washout test is leaks. These can be easily detected during the test by observing the N_2 signal. As with the He dilution and body box techniques, the testing of biological controls is recommended at least monthly.

Measurement of Lung Volumes by Other Methods

There are other less commonly used methods for measuring lung volumes, and these will only be briefly discussed.

The *single-breath N_2 method* can be used to estimate RV and TLC.[21] The test involves diluting the ambient N_2 in the lungs by inhaling a VC (from RV to TLC) of 100% oxygen. An analysis of the single-breath N_2 curve produced in this test yields several other parameters of pulmonary function, including *closing volume* and *slope of phase III*. However, this method has never been standardized and is not widely used.

The *single-breath He method* estimates TLC and is performed during the single-breath carbon-monoxide uptake ($D_{L,CO}$) (discussed in Chapter 3). This $D_{L,CO}$ test employs an inert tracer gas (e.g., He), which is diluted into the lung volume, and an estimate of TLC can be calculated. This estimate of TLC is referred to as alveolar volume (VA) and is lower than the true TLC in individuals with airflow obstruction.

The TLC can also be estimated from the chest roentgenogram (radiograph) using the posteroanterior (PA) and lateral (LAT) views when the patient is at full lung inflation. The two basic methods that use the chest radiograph to measure lung volumes are (*a*) the planimeter method[27,28] and (*b*) the ellipse method.[29]

A planimeter is a device with two arms that pivot around a fixed joint, allowing one to trace over the lines of any two-dimensional shape (**Figure 2.17**). By outlining all the lung fields on the PA and LAT films, including the heart but excluding the sternum, the radiographic chest volume can be calculated. Digital technology has been developed to replace the manual method.

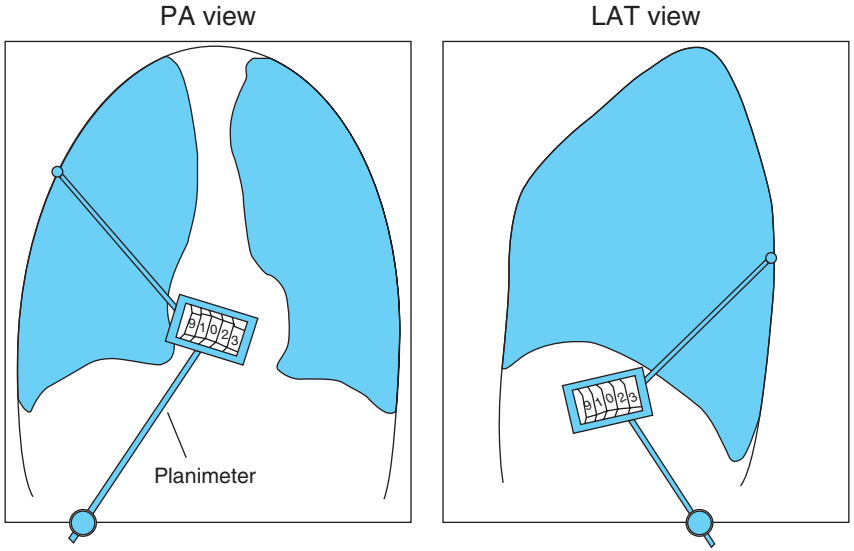
The ellipse method assumes that the lungs can be divided into a large number of elliptical cross sections (**Figure 2.18**). The area of the elliptical sections is determined from the PA and LAT view chest films and then converted to volume. The area of the heart, the domes of the diaphragm, and the pulmonary blood and tissue are subtracted out.

Both methods compare well with each other as well as with TLC measured by plethysmographic and dilution–washout techniques.[30-33]

The drawbacks of using the chest film are: (*a*) only TLC can be measured and (*b*) TLC can be underestimated if the patient does not maximally inspire when the film is exposed. Additionally, the technique depends on good-quality film to define the lung boundaries.

Figure 2.17

Measurement of TLC from chest roentgenograms using the planimetry technique. The two-armed planimeter is placed on the PA and LAT view of the chest at full inspiration. With one end fixed, the other end is used to trace the periphery of each view. A mechanical counter measures the distance traveled, which can be converted to volume.



However, the advantages of being unaffected by poorly ventilated areas and the ability to compare films retrospectively when pulmonary function tests are not available or comparable make this technique valuable. The use of computers has shortened the time required to measure and calculate the data.

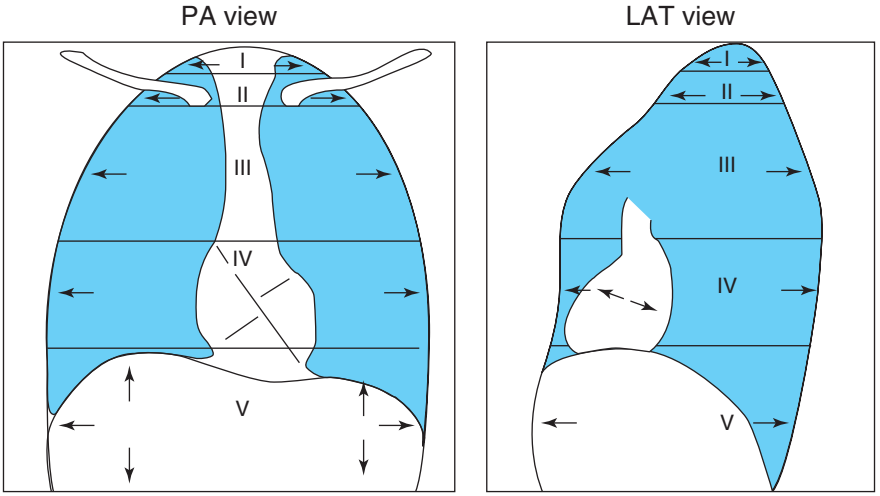
CT scans can provide estimates of lung volumes and can estimate the volume of the lung with increased or decreased density.[34] Magnetic resonance imaging (MRI) offers the advantage of scanning specific regions of the lung. However, MRIs are costly, so their use for measuring lung volumes is limited.

Reference Values

As in forced spirometry, it is common practice to report reference or predicted values for static lung volumes. Unfortunately, no one set of lung volume reference values was recommended by the most recent guidelines.[2] One survey[35] found that the most commonly used study for lung volume reference values was that of Goldman and Becklake.[36] This study used hydrogen (H) dilution (similar to He dilution) to measure FRC on 44 male and 50 female subjects near Johannesburg, South Africa (altitude 5,700 feet).

Figure 2.18

Measurement of TLC from chest roentgenograms using the ellipse method. The PA and LAT views of the chest at full inspiration are divided into five elliptical cross sections or segments. The area of each section is measured (arrows indicate the points between which to measure) and then converted to volume.



The techniques used in the many reference studies vary and include He dilution, H dilution, N_2 washout, single-breath N_2, and body plethysmography.[37-41] This fact complicates the task of selecting reference equations for one's laboratory. When selecting reference values, consider the following criteria: (*a*) use of similar equipment and methods and (*b*) similar populations (i.e., age, body size, gender, and race). When a tentative selection has been made, a laboratory should consider comparing the measurements from 10 to 20 healthy individuals selected from a representative sample of the laboratory's population with the tentative reference values. If the differences between the values of the 10 to 20 healthy individuals and reference values are small (e.g., within ± 10%), then the laboratory can be reasonably confident that the chosen reference values are appropriate. If the differences are greater, consider using other reference values.

Infection Control

In determining FRC and the lung volume compartments, the patient continually rebreathes on the breathing circuit. Thus, the possibility of cross contamination exists. The laboratory should have procedures in place to help ensure patient and technologist safety.

The Centers for Disease Control and Prevention has published guidelines for preventing transmission of infectious agents in healthcare settings.[42] In addition, Kendrick and coworkers published an excellent review and practical approach to infection control in the pulmonary function laboratory.[43]

If the patient has known *Mycobacterium tuberculosis* and is considered infectious, several additional precautions are recommended. Test the patient at the end of the day to ensure no other patient uses the instrument that day. The room in which the test is performed should at least meet current Centers for Disease Control and Prevention guidelines for air changes and ventilation. The airflow should be biased into the contaminated area from adjacent hallways and rooms (i.e., negative pressure). The use of ultraviolet light is controversial, but some centers use it. The technologist performing the testing should wear a personal respirator that meets current Occupational Safety and Health Administration (OSHA) recommendations. After testing is complete, disassemble the tubing and removable parts from the testing system and clean them with a high-level disinfectant. Reassemble the system the next day after all the parts have thoroughly dried.

Case Presentations

Case 2.1

A 68-year-old Caucasian woman with a complaint of worsening dyspnea was seen in the pulmonologist's office. She admitted to having been a heavy smoker (90 pack years, where one pack year is defined as one package of cigarettes per day for 1 year) but had recently quit. This office was equipped to measure spirometry and lung volumes, and the results of her tests are shown in **Table 2.2** and **Figure 2.19**. Her chest film had an emphysematous appearance with increased diameters.

After seeing the results of the office pulmonary function test, the doctor ordered another pulmonary function test at the area hospital, and the results are shown in **Table 2.3** and **Figure 2.20**.

Table 2.2

Office Pulmonary Function Data Before and After a Bronchodilator

	Predicted	Before*	After
TLC (L)	4.82	4.63 (96)	
FRC_{He} (L)†	2.80	2.58 (92)	
RV (L)	1.91	2.08 (109)	
SVC (L)	3.59	2.55 (71)	
FVC (L)	3.63	2.18 (60)	2.38
FEV_1 (L)	2.57	1.08 (42)	1.18
FEV_1/FVC (%)	71	50	50
$FEF_{25–75\%}$ (L/sec)	2.50	0.65 (26)	0.67

*Values in parentheses are percent predicted

†Measured by He dilution

Figure 2.19

Volume–time spirogram from patient in Case 2.1 performed in the doctor's office before and after administration of a bronchodilator.

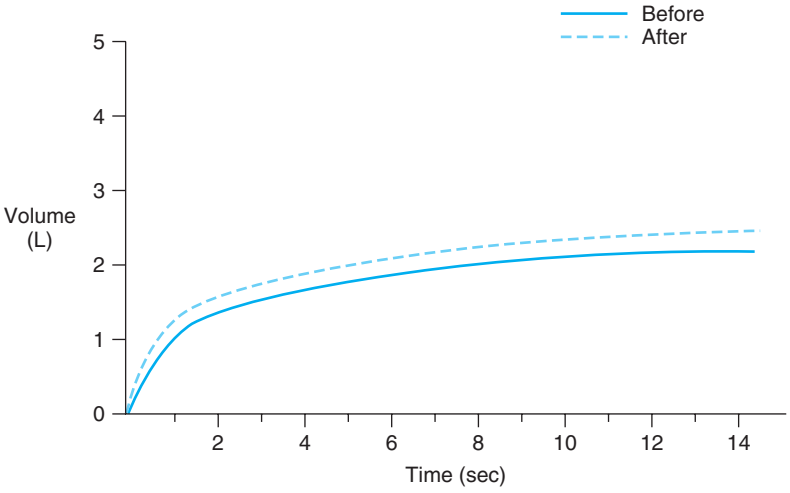


Table 2.3

Hospital Pulmonary Function Laboratory Data Before and After a Bronchodilator

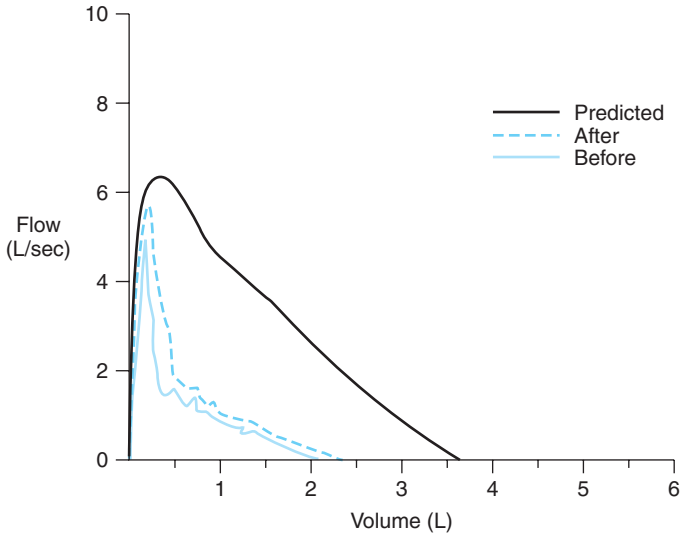
	Predicted	Before*	After
TLC (L)	4.82	5.76 (120)	
FRC_{pleth} (L)†	2.80	3.97 (142)	
RV (L)	1.91	3.13 (164)	
SVC (L)	3.59	2.63 (73)	2.68
FVC (L)	3.63	2.28 (63)	2.43
FEV_1 (L)	2.57	1.11 (43)	1.29
FEV_1/FVC (%)	71	49	53
$FEF_{25–75\%}$(L/sec)	2.50	0.59 (24)	0.83
Raw (cm H_2O/L/sec)		2.93	1.84
sGaw (L/cm H_2O/L/sec)		0.07	0.13
$D_{L,CO}$ (mL/min/mmHg)	23.4	17.30 (74)	
$D_{L,CO}$/VA	4.85	3.64 (75)	

*Values in parentheses are percent of predicted

†Measured by body plethysmograph

Figure 2.20

Flow–volume spirogram from patient in Case 2.1 performed in the hospital pulmonary function laboratory showing before and after administration of a bronchodilator, as well as the reference (i.e., predicted) curve.



Questions

1. How would you interpret the pulmonary function tests done in the doctor's office?
2. How would you interpret the pulmonary function tests done in the hospital?
3. How do you explain the difference in data?

Answers and Discussion

Data from the pulmonary function test done in the office and shown in Table 2.2 reveal normal lung volumes (TLC, FRC_{He}, and RV) and a reduced SVC. These data also reveal severe airflow limitation with minimal response to a bronchodilator. A concern is why the lung volumes do not reveal hyperinflation that would be consistent with this degree of obstruction and the chest film interpretation. Therefore, the final interpretation would most likely state a mixed obstructive and restrictive disorder.

The pulmonary function test data from the hospital (Table 2.3), which used the body plethysmograph, show a different picture. There is still severe airflow limitation and the diffusing capacity is reduced, but the lung volumes are all markedly increased. There is good response to a bronchodilator. The final interpretation from these data is severe airflow limitation, but there is certainly not a mixed disorder.

The major difference between the two interpretations depends on the measurement of FRC. In the doctor's office, the FRC_{He} was 2.55 liters. In the hospital laboratory, the FRC_{pleth} was 3.97 liters, which is significantly higher.

Why are the two FRC determinations so different? Measurement of FRC_{He} uses a gas dilution technique. It requires the patient to breathe into a system that contains a known volume and concentration of He. During the breathing period, the He diffuses and equilibrates into the gas spaces of the lung that communicate with the mouth. Noncommunicating spaces are not measured. Thus, the FRC_{He} can be underestimated.

The body plethysmograph (body box) is another method to determine FRC. Although it is more expensive and requires more technical expertise, it is quick and accurate. It measures the TGV in the thoracic cage when a shutter is closed. This volume includes non-communicating areas and therefore is more accurate than the gas dilution technique.

The difference between the two sets of lung volumes in this patient can be accounted for by the presence of trapped gas spaces or poorly communicating airways. The correct interpretation is that the patient is hyperinflated and does not have a mixed disorder.

Case 2.2

A 58-year-old African American male office worker was tested in the pulmonary function laboratory. Spirometry at a recent physical examination in the doctor's office detected some abnormal results. He denied shortness of breath or cough but claimed to be a 40 pack year smoker. His laboratory results are shown in **Table 2.4** and **Figure 2.21**.

Table 2.4

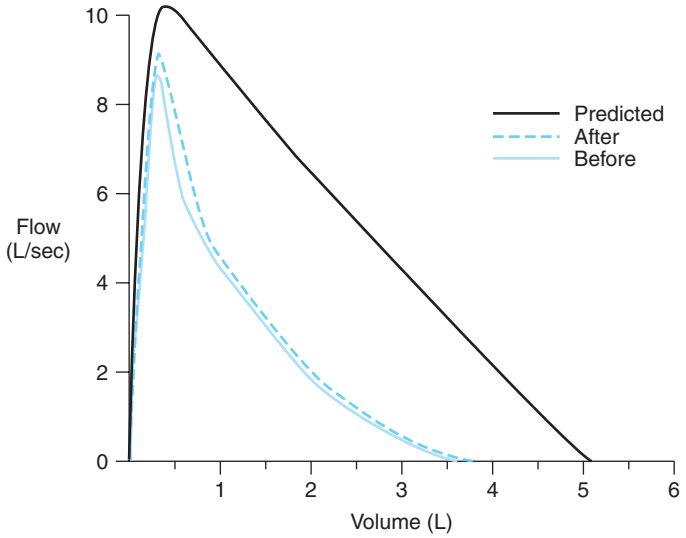
Pulmonary Function Values Before and After a Bronchodilator in the Pulmonary Function Laboratory

	Predicted	Before*	After
FVC (L)	5.04	3.78 (75)	3.93
FEV_1 (L)	3.51	2.00 (57)	2.12
FEV_1/FVC (%)	70	53	54
$FEF_{25–75\%}$ (L/Sec)	3.97	2.34 (59)	2.79
FRC_{pleth} (L)	4.01	2.89 (72)	
RV (L)	1.88	1.94 (103)	
TLC (L)	6.88	5.85 (85)	
SVC (L)	5.01	3.91 (78)	
Raw (cm H_2O/L/sec)		2.13	1.92
sGaw (L/cm H_2O/L/sec)		0.15	0.19

*Values is parentheses are percent predicted

Figure 2.21

Flow–volume spirogram from patient in Case 2.2 showing before and after bronchodilator curves as well as the reference (i.e., predicted) curve.



Questions

1. What is the interpretation and evaluation of these pulmonary function tests?
2. What issues should be raised with the reference values?

Answers and Discussion

The data from Table 2.4 and Figure 2.21 reveal airflow limitation without meaningful response to a bronchodilator. Additionally, the lung volumes are reduced, suggesting a mixed obstructive and restrictive disorder.

The predicted or reference values used by the laboratory do not state whether they are race specific. If they are based on a Caucasian population, then the apparent restrictive process could be an artifact.

Healthy, predicted, or normal values for pulmonary function tests are frequently based on entirely Caucasian populations. The predicted values for the lung volumes (TLC, RV, FRC) shown in Table 2.4 come from a study by Goldman and Becklake,[36] and the other predicted values come from a study by Morris and coworkers.[44] Neither of these particular studies state the race or ethnic background of the subjects who participated.

Several studies have documented that people of African descent have lower lung volumes than do Caucasians.[45-49] This is attributed to the fact that people of African descent have longer

legs and shorter trunks. Thus, standing height, which is a major factor in predicting pulmonary function values, is biased.

When the predicted values are recalculated (shown in **Table 2.5**) based on the studies of Rossiter and Weil[47] and Stinson and colleagues,[48] which used black populations, the interpretation changes to airflow limitation.

In practice, some pulmonary function laboratories use scaling factors when testing African Americans. The process adjusts the Caucasian population's predicted values down approximately 12%. This approach has a major pitfall in that the 12% correction is an average. The difference between Caucasian and African American values varies with each parameter. For TLCs, for example, African Americans have approximately 11% lower predicted values.[47]

A pulmonary function laboratory must carefully consider selecting predicted values. The use of race-specific predicted equations raises the issue of whether the available studies are adequate, because they do not provide criteria for determining race. Many studies assume that racial identity is evident through color distinctions. However, this may not always be true in practice.

The alternative to race-specific predicted values is to take racial issues into consideration at interpretation. For example, in this case, the interpretation of the data in Table 2.4 might have read "airflow limitation without meaningful response to a bronchodilator and normal lung volumes when adjusted for race."

The important consideration is that there is a weakness in using healthy reference equations based on Caucasian populations for non-Caucasian patients. If race-specific reference equations are used, note so on the report.

Table 2.5

Pulmonary Function Values Before and After Bronchodilator

	Predicted	Before*	After
FVC (L)	3.98	3.78 (95)	3.93
FEV_1 (L)	2.82	2.00 (71)	2.12
FEV_1/FVC (%)	71	53	54
$FEF_{25–75\%}$ (L/Sec)	3.60	2.34 (65)	2.79
FRC_{pleth} (L)	3.28	2.89 (88)	
RV (L)	2.04	1.94 (95)	
TLC (L)	6.03	5.85 (97)	
SVC (L)	3.99	3.91 (98)	
Raw (cm H_2O/L/sec)		2.13	1.92
sGaw (L/cm H_2O/L/sec)		0.15	0.19

*Values in parentheses are percent predicted

Self-Assessment Questions

1. All the following are techniques for determining FRC except:
   a. Closed-circuit He dilution
   b. Open-circuit N_2 washout
   c. Single-breath N_2 washout
   d. Body plethysmography
2. Which of the following is the most accurate concerning the ERV?
   a. The maximum amount of air that can be exhaled from the VC
   b. The maximum amount of air that can be exhaled from the TV end-expiratory level
   c. The maximum amount of air that can be inhaled from the TV end-expiratory level
   d. The maximum amount of air that can be exhaled from RV
3. A patient has the following lung volumes:

	Observed	Predicted	% Predicted
SVC (L)	3.50	4.30	81
FRC_{pleth} (L)	3.80	3.00	127
RV (L)	3.00	2.00	150
TLC (L)	6.50	6.30	103

   The interpretation would most likely state:
   a. Normal lung volumes
   b. Hyperinflation
   c. Restrictive pattern
   d. Mixed obstructive and restrictive pattern
4. In patients with obstructive lung disease, the gas dilution methods for FRC determination:
   a. Overestimate FRC
   b. Equal body plethysmograph FRC
   c. Underestimate FRC
   d. Equal radiographic FRC
5. In the body plethysmograph, alveolar pressure changes caused by the compression and decompression of the lungs are estimated by:
   a. Measuring mouth pressure
   b. Measuring body box pressure
   c. Measuring transpulmonary pressure
   d. Measuring transdiaphragmatic pressure
6. The calculation of FRC using the body plethysmograph is based on:
   a. Murphy's law
   b. Boyle's law
   c. Charles's law
   d. Poiseuille's law

7. Which of the following methods for determining TLC best agrees with the results of the radiographic technique in patients with obstructive lung disease?
   a. Body box FRC + IC
   b. Closed-circuit He dilution FRC + IC
   c. Open-circuit N_2 washout FRC + IC
   d. Open-circuit He dilution FRC + IC

8. Which of the following is most accurate about the FRC?
   a. It is the volume of air remaining in the lungs at TV end-expiratory level
   b. It consists of residual volume and expiratory reserve volume
   c. It can be determined by gas dilution and body plethysmography
   d. All of the above
   e. a and c

9. In restrictive lung disease, which lung volume compartment is not decreased?
   a. VC
   b. FRC
   c. TLC
   d. IC
   e. None of the above

10. In obstructive lung disease, the SVC will probably be:
   a. Larger than the TLC
   b. Smaller than the RV
   c. Larger than the FVC
   d. Smaller than the IC

11. Lung volume values for TLC, FRC, and RV should be reported at:
   a. BTPS
   b. ATPS
   c. STPD (standard conditions)
   d. ATPD (ambient temperature and pressure, dry)

12. Which of the following statements best explains why it is important to wait at least 5 minutes between He dilution FRC determinations?
   a. The subject must recover from breathing on the mouthpiece
   b. The subject's CO_2 production must return to resting levels
   c. The He must be cleared from the subject's lungs
   d. To ensure that O_2 saturation has returned to baseline

13. Which of the following should be done to ensure that the volume in the spirometer during a closed-circuit FRC determination remains unchanged?
   a. Ensure adequate He absorption
   b. Ensure adequate CO_2 absorption
   c. Ensure adequate O_2 absorption
   d. Ensure subject starts test at FRC

14. When the N_2 concentration abruptly rises near the end of an open-circuit N_2 washout, it usually means:
   a. The computer has an error
   b. The N_2 analyzer is not calibrated

c. The system has developed a leak
d. The O_2 concentration is varying

15. Which of the following are methods to estimate TLC?
a. Single-breath N_2
b. Single-breath He
c. Measurement of chest radiographs
d. a, b, and c
e. a and c

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