Medical Education Systems, Inc.

Course 208

PULMONARY FUNCTION TESTING

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PULMONARY FUNCTION TESTING

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- Learning Objectives

Upon completion of this section, given and open-book, multiple-choice exam, you will be able to apply the information learned to correctly anser a minimum of 90% of the test items. Successful completion of this exam will require you to have mastered the following learning objectives:

1. Give five indications for pulmonary function evaluation.
2. Identify the major muscles of breathing during inspiration and expiration.

3. Distinguish between dead space ventilation and effective ventilation.
4. Describe the production and function of surfactant in the lungs.
5. Define the following terms:
   a. Compliance
   b. Elastance
   c. Resistance
6. Describe the three main components of pulmonary resistance and indicated the overall importance of each of these components in the total resistance.
7. Describe the factors affecting dynamic airway compression and indicate the effect of disease states on dynamic airway compression.
8. Describe the breathing patterns associated with obstructive and restrictive pulmonary diseases.
9. List, define, and give normal values for the lung volumes and capacities in an average adult male.
10. Given values for lung volumes and/or lung capacities, calculate other lung volumes and/or capacities.
11. Describe the procedures for obtaining a slow vital capacity maneuver and forced vital capacity maneuver.
12. Given a tracing of a forced vital capacity maneuver, label the following flow values:
    a. FEV.5
    b. FEV1
    c. FEF200=1200
    d. FEF25-75
13. Describe the appearance of the MVV tracing in the normal, obstructive, and restrictive patient.
14. Label the axis and significant points on a flow-volume loop.
15. Describe the basic principle involved in measuring the residual volume by each of the following methods:
    a. Closed circuit method
    b. Open circuit method
    c. Plethysmographic method
    d. Radiologic method
16. Indicate the methods for obtaining the residual volume that takes into account "trapped gas."
17. Describe the significance of each of the four phases of the single breath nitrogen test.
18. Describe how the anatomy and distribution of gases in the lungs affect the single breath nitrogen test.
19. Describe the purpose of measuring the diffusing capacity and indicate factors which can affect it.

20. Indicate three means by which predicted values for pulmonary function studies can be generated.
21. Name five primary obstructive diseases and five primary restrictive pulmonary diseases.
22. Describe the typical pulmonary function findings associated with obstructive pulmonary diseases.
23. Describe the typical pulmonary function findings associated with restrictive pulmonary diseases.

Ferguson GT, Enright PL, Buist AS, Higgins MW: Office spirometry for lung health assessment in adults: A consensus statement from the National Lung Health Education Program. Chest 2000 Apr; 117(4): 1146-61

Introduction

Pulmonary function testing is essentially a diagnostic patient assessment tool. There is a wide variety of testing techniques available to the clinician. The testing can be extremely complex or exceedingly simple, each adding information of its own.There are many reasons for obtaining pulmonary function tests on patients. These include but are not limited to:

1. Evaluation of surgical risk
2. Early detection of pulmonary disease
3. Evaluating effect of occupation on lung function
4. Evaluation of treatment efficacy
5. Differentiating primary causative abnormalities
6. Evaluation of disability
7. Assessment of degree of dysfunction
8. Fitness for work or sport

This diagnostic information is a very helpful aid in tailoring the delivery of care to the patient's needs. Often it is the practitioner's knowledge of the patient's condition that results in the effective delivery of therapy to the patient.

Pulmonary function testing involves the evaluation of lung function, which includes the mechanical movement of gas in and out of the lung

(ventilation) and the exchange of gas molecules across the alveolar-capillary membrane.

Physiology Review

It is essential that basic lung anatomy and physiology be understood before proceeding into pulmonary function testing. After all, these diagnostic studies are the measuring stick of lung physiology and the values obtained reflect the physiological and anatomical state of the lungs. The following discussion is meant as a concentrated review of important concepts used in pulmonary function testing.

Ventilation

Ventilation is the movement of gas into (inspiration) and out of (expiration) the lung. Minute ventilation is the amount of gas moved over a specific period of time. This can be expressed as follows:

Minute Ventilation =
breathing frequency x volume of each breath - tidal volume

Ventilation is accomplished by synchronized muscle movement in conjunction with the relatively rigid chest wall. The major muscles of breathing include the diaphragm, external and internal intercostals, abdominal muscles, and accessory muscles (scalenes, sternocleidomastoid, and pectoralis major).

The diaphragm is the primary muscle of ventilation. Its structures include right and left hemidiaphragms and the central tendon. Contraction of the diaphragm forces the abdominal contents downward (enhanced by abdominal muscle relaxation) causing transverse chest enlargement, and gas moves inward until pressure equilibration is achieved.

External intercostal muscles will pull the ribs upward and forward creating future chest enlargement. In situations requiring increased work of breathing, accessory muscles will also aid in creating inspiratory chest enlargement.

In normal expiration the diaphragm relaxes, and exhalation occurs passively due to the elastic recoil of the chest wall and lungs. The

major muscles of expiration are the external oblique, internal oblique, rectus abdominus, and transverse abdominus. When these muscles contract, abdominal contents are forced upwards, and the chest wall is stabilized reducing the chest cavity volume. This causes an increase in the intrathoracic pressure, forcing gas out of the lungs.

The intrathoracic pressures generated during quiet breathing are represented by intrapleural pressures of -2.5 mmHg to -6.0 mmHg with end inspiratory negative pressure being returned to normal due to the elastic recoil of the lung (Figure 1). Forced inspiratory efforts can generate negative pressures up to -30 to -35 mmHg.

Ventilation in areas of the lung where gas exchange doesn't occur is called deadspace ventilation or "wasted" ventilation. Ventilation to areas of the lung where gas exchange does occur is called "effective" ventilation. There are essentially two types of deadspace: anatomical and physiological. Anatomical deadspace is normal and consists of the connecting airways. Physiological deadspace includes the improperly functioning portions of the lung that normally participate in gas exchange. Effective ventilation is frequently called alveolar ventilation and can be expressed as:

Effective Ventilation =
total expired ventilation - total deadspace ventilation

The breathing pattern can influence effective ventilation considerably. A deeper breath usually results in a lower percentage contribution of deadspace ventilation per breath.

Elastic recoil is the tendency of the chest and lungs to return to their normal position after expansion. Lung elasticity is a function of its architecture and internal surface tension forces.

Complete lung collapse is prevented by the subatomospheric pressure of the pleural space and the cohesiveness of the pleural fluid maintaining close contact between the chest wall and the lung (visceral and parietal layers of the pleura).

Elastance is the ability of an object to return to its original shape. Elastance is the reciprocal of compliance and is expressed as:

Elastic Resistance = Change in Pressure (P)
/ Change in Volume (V)

Pulmonary surfactant is a substance important in stabilizing the alveoli. The exact chemical composition is still being investigated but the major component is the phospholipid, dipalmitoze lecithin. Production of surfactant occurs in the Type II epithelial alveolar cells and is secreted into the alveoli becoming part of the alveolar lining. As alveolar surface are decreases, surfactant molecules are drawn closer together, decreasing the surface tension and preventing alveolar collapse. Loss of pulmonary surfactant results in a decreased lung compliance, increased work of breathing, mismatched ventilation/perfusion, alveolar hyperventilation, and diffusion-perfusion abnormalities.

Resistance

There are resistive properties that oppose gas flow through the respiratory system. The main factors are pulmonary tissue resistance, airway resistance, and chest wall resistance.

Tissue and chest wall resistance (also called viscous resistance) account for approximately 20% of the total pulmonary resistance in the normal lung. This type of resistance is primarily due to friction between the parietal and visceral pleura and between pulmonary lobes. This resistance will increase in the presence of certain disease processes.

Airway resistance accounts for approximately 80% of the total pulmonary resistance in the normal lung. It is gas flow resistance caused by friction between gas molecules themselves and between gas molecules and the airway wall. The gas's internal molecular friction is due to its resistance to changing its shape as it moves through a tube (airway). The movement of gas through a tube can be described by Poiseuille's Law.

V = r4 x .....P

Poiseuille's Law indicates that small changes in tube radius will dramatically alter the pressure gradient required to generate the same gas flow.

The above discussion primarily refers to laminar or linear gas flow. The velocity of the gas moving through the tube is not the same across the tube. the velocity of the gas in the center of the tube is higher than the velocity at the sides of a tube. This changing velocity across the diameter of the tube is called the velocity profile. However, when gas flow reaches critical linear velocity , it changes from laminar flow to turbulent and non-linear flow. The degeneration of linear to non-linear flow is a function of density, flow velocity, and tube radius. The

velocity profile is the same across the entire diameter of the tube in turbulent flow. Resistance increases with turbulent flow and is most likely to occur in the medium-sized bronchi.

The point at which lung deflation and expansion forces are in balance (atmospheric and Internal pressures become equal) is commonly referred to as the resting end tidal point. At this point no gas flow occurs.

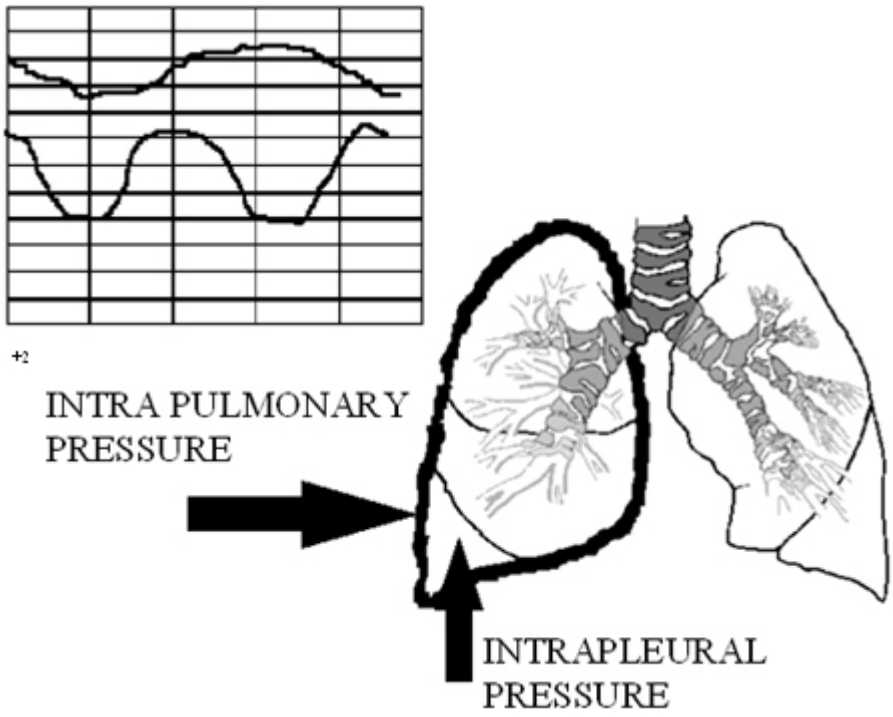


Figure 1
Changes and Interrelationships Of Lung Volume, Intrapulmonic Pressure, and Intraplueral Pressure During a Breathing Cycle

Compliance
Compliance is the volume/pressure relationship of chest wall and lung. This can be Expressed as:

$$\text{compliance} = \frac{\text{Change in volume}}{\text{Change in Pressure}} \quad \frac{V}{P}$$

Dynamic Airway Compression
Lung volume also influences resistance. When lung volume decreases (with exhalation) Resistance increases as the diameter of the airway decreases. At very low lung volumes, The small airways may close of completely.

Dynamic compression of the airways most frequently occurs in forced expiratory efforts And is dependent upon the airway tone and the generated transthoracic pressures. Flow Through the airways will increase as pressure increases up to the point of maximum flow (Vmax). Beyond that point, pressure may increase, but not the flow. As the pleural Pressures increase, they can exceed the airway pressures resulting in airway collapse at That point. The point where the pleural and airway pressures are equal is called the equal Pressure point. The equal pressure point occurs in the upper airways at high lung volumes. And at low lung volumes in the small airways and alveoli (figure 2).

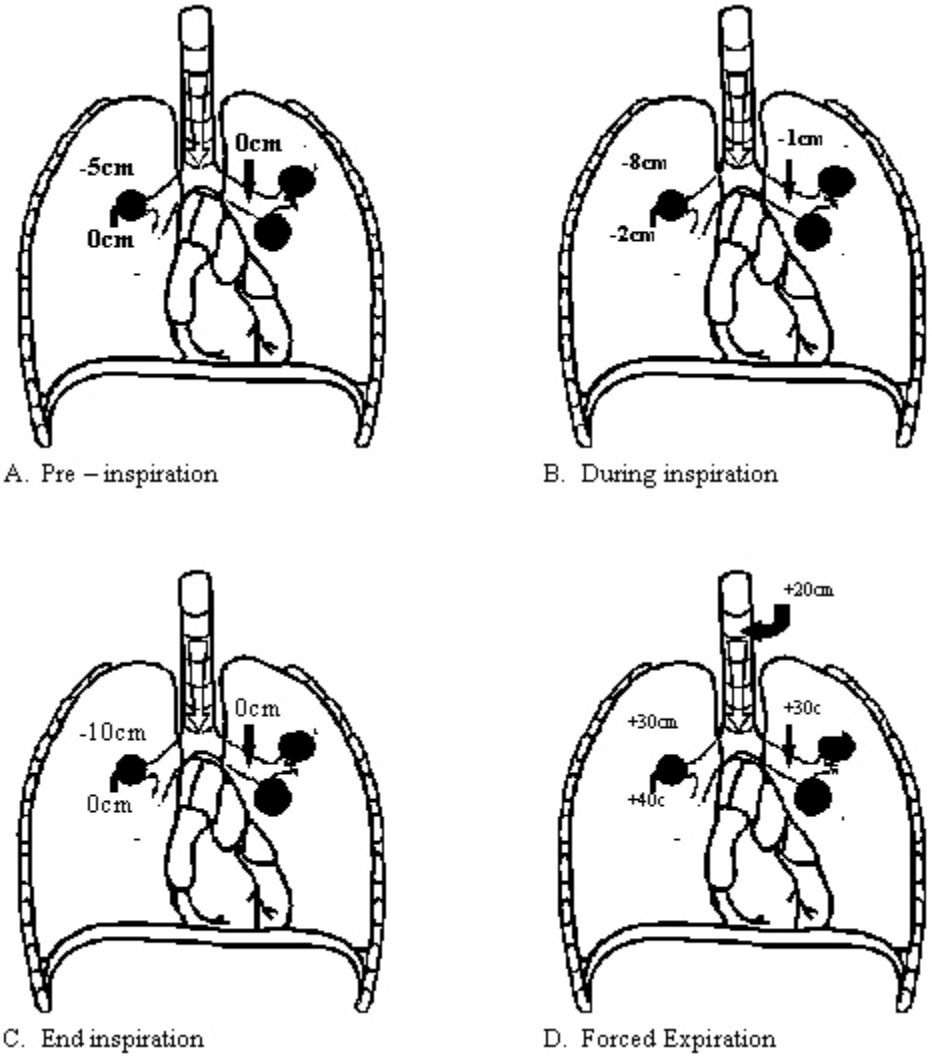


Figure 2
Intrapulmonic Pressures

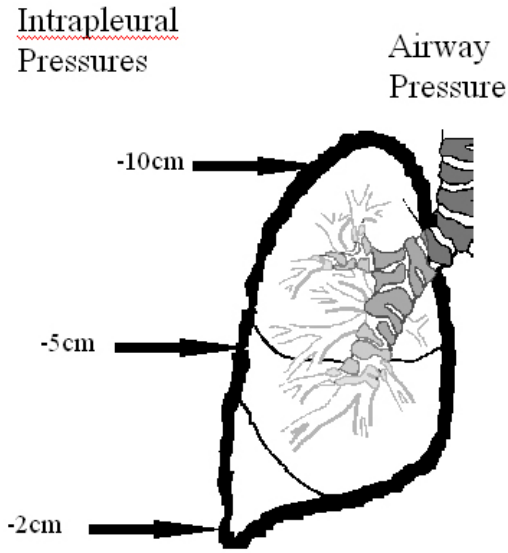


Figure 3
Regional Ventilation

Regional Ventilation

The normal lung has regional differences in ventilation from top to bottom. In the upright Lung, gravity's pull on the supported lung combined with the hydro static forces of the pulmonary blood flow create greater pleural pressure (more positive at the lung base, resulting in lower alveolar volumes (Figure 3). The compliance of the reduced volume alveoli is greater with the result that they will more readily accept proportionately larger gas volumes overall than the alveoli. In the apical alveoli during normal tidal breathing, the first part of each breath goes to the apical lung segments and after these segments fill the gas is direct towards the basilar segments.

Work of Breathing

To breathe, elastic and resistive forces must be overcome. At normal breathing frequencies, the force need to over come airway and tissue resistance is very small. In deep breathing with large lung volumes and low frequencies the resistive forces are higher due to the increased elastic forces of the lung tissue and chest wall. In a shallow breathing with high frequencies there will be an increase in resistive forces due primarily to an increased airway resistance.

Optimal breathing frequency is one which requires the least amount of work. The level of work can be correlated with oxygen consumption. The normal resting individual will consume less than 5% of the total resting oxygen consumption for the work of breathing.

Action related to the work of breathing may increase 10 times for individuals with sever respiratory disorders. These subjects will show altered breathing patterns in order to minimize their work of breathing. The patient with primarily a restrictive pulmonary dysfunction will tend to breathe with small tidal volumes and increased frequencies while the patient with primarily an obstructive pulmonary

dysfunction will tend to breathe with larger tidal volumes and decreased frequencies.

Lung Volume Subdivisions

There are a variety of pulmonary function tests available. We will discuss various spirometry and total lung capacity determinations as well as special procedures such as flow volume loops, diffusing capacities, and plethsysmography. We will be interested with what information the various tests provide, rather than the exact methods of obtaining the information.

In the basic spirometric tracing of a vital capacity maneuver there are four standard lung subdivisions or compartments which are not overlapping. Each subdivision of the total lung capacity is referred to as a volume. Most of the divisions are measured from "the resting expiratory level" (The respiratory level of a resting subject, neither inspiring or expiring). This "resting expiratory level" defines the volume of gas in the lungs at the end of a spontaneous expiration where the thoracic forces tending to collapse the chest are equal to the forces tending to expand the chest. The volume of air routinely inhaled and exhaled during normal breathing is called the tidal volume (VT). The maximum amount of air that can be inspired from the end of the normal VT inspiration is called the inspiratory reserve volume (IRV). The maximum amount of air that can be exhaled from the "resting expiration level" is called the expiratory reserve volume (ERV). The air left in the lung after maximum expiration is called the residual volume (RV). The VT, IRV, ERV and RV are the four non-overlapping lung volumes (Figure 4).

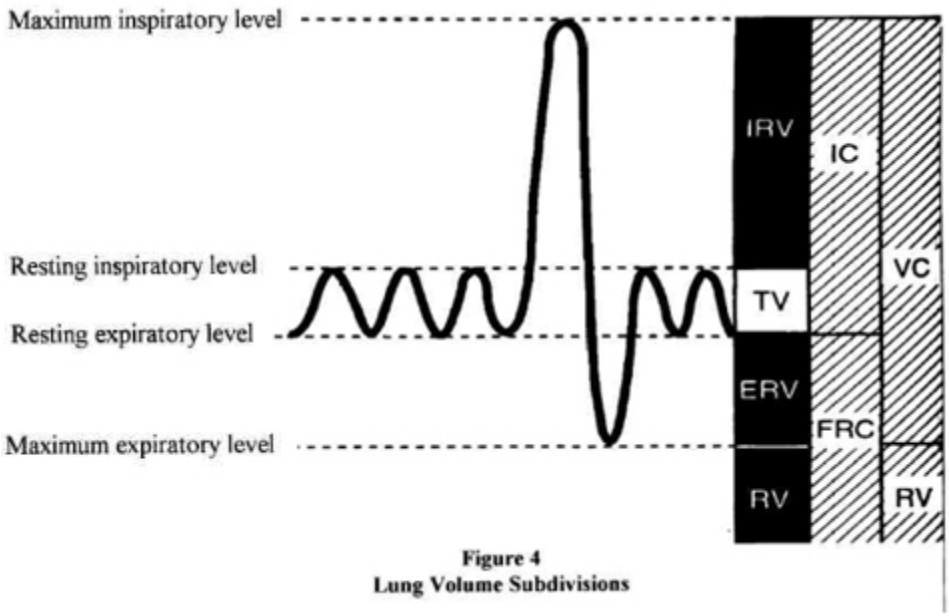


Figure 4
Lung Volume Subdivisions

The standard combinations of two or more primary lung subdivisions are called capacities. The sum of the tidal volume and the inspiratory reserve volume is called the inspiratory capacity (IC). The sum of the expiratory reserve volume and the residual volume is called the functional residual capacity (FRC). The sum of the tidal volume and the inspiratory and expiratory reserve volumes is the vital capacity (VC). The sum of the four distinct lung subdivisions is the total lung capacity (TLC).

Summary of the Lung Capacities

IC = VT + IRV

FRC = ERV + RV

VC = VT + IRV + ERV

TLC = VT + IRV + ERV + RV

Definitions For Lung Volumes And Capacities

Inspiratory Reserve Volume - The maximum amount of gas that can be inspired from the inspiratory point of a normal tidal volume.

Tidal Volume - The average volume of gas inspired and exhaled during normal breathing.

Expiratory Reserve Volume - The maximum volume of gas that can be exhaled from the resting end-expiratory level.

Residual Volume - The volume of gas that remains in the lungs after a maximum exhalation.

Inspiratory Capacity - The maximum volume of gas that can be inspired from the resting end-expiratory level.

Vital Capacity - The maximum amount of gas that can be exhaled after a maximum inspiration.

Functional Residual Capacity - The volume of gas that remains in the lungs at the end of a normal exhalation.

Tidal Lung Capacity - The total volume of gas contained in the lungs after a maximum inspiration.

Normal Values For Lung Volumes And Capacities
(For The Normal Adult Male)

Volumes		Capacities	
IRV	3100 ml	IC	3600 ml
V_T	500 ml	VC	4800 ml
ERV	1200 ml	FRC	2400 ml
RV	1200 ml	TLC	6000 ml

- Simple Spirometry

Obtaining Slow Effect Volumes

All lung subdivisions may be measured by spirometry except for the residual volume which must be measured indirectly. The measurement of the lung subdivisions is usually recorded with a "spirometer" which is a device capable of collecting and accurately recording changes in volume over time. There are may types of spirometric devices utilizing various methods of measuring the lung subdivisions during passive maneuvers, but also are used in determining flowrates during forced maneuvers. (This will be discussed more in detail later).

Simple spirometry is used for recording the resting values for the tidal volume, inspiratory reserve volume, expiratory reserve volume and

vital capacity. The test subject is attached to the connecting tubing, allowed to breathe normally for a few breaths and then instructed to inspire as much gas as possible until the lungs are completely filled. The subject then slowly exhales all of the gas from the lungs. This maneuver is called the slow vital capacity. The purpose of the slow vital capacity maneuver is to obtain volume measurements produced under the condition of low flowrates. The patient should not force gas in and out of the lungs rapidly, but should inspire and exhaled slowly and maximally. The slow vital capacity maneuver avoids the generation of increased intrathoracic pressures which can result in early airway closure, gas trapping, and a reduced vital capacity measurement in patients with damaged airways. This is particularly true in the patient with emphysema.

Obtaining Forced Effort Volumes

The lung volume measurements obtained for forced effort maneuvers are directly measurable by simple spirometry. The tests can be done with adults in either the standing or sitting position. When testing children, however, the standing position tends to produce larger volumes. It is the recommended position.

The subject is attached to the prepared spirometer connecting tubing and is allowed to breathe normally for a few breaths. The subject must provide a tight seal around the connecting tubing and nose clips should be used to prevent leakage of any exhaled gases.

Once properly attached to the spirometer, the subject is instructed to inspire as much gas as possible until the lungs are completely filled. The subject then exhales completely, emptying the lungs as rapidly as possible. The subject should be encouraged to force all of the gas from the lungs immediately and completely. Three "acceptable" FEVC maneuvers must be obtained. The tracings should be smooth and continuous with no hesitations. Also, the three tracings should not vary by more than 5% of the reading or plus/minus 0.1 liters, whichever is greater.

In Figure 5, the FEVC is measured as the vertical distance from end inspiration to end exhalation as represented by the spirometer tracing.

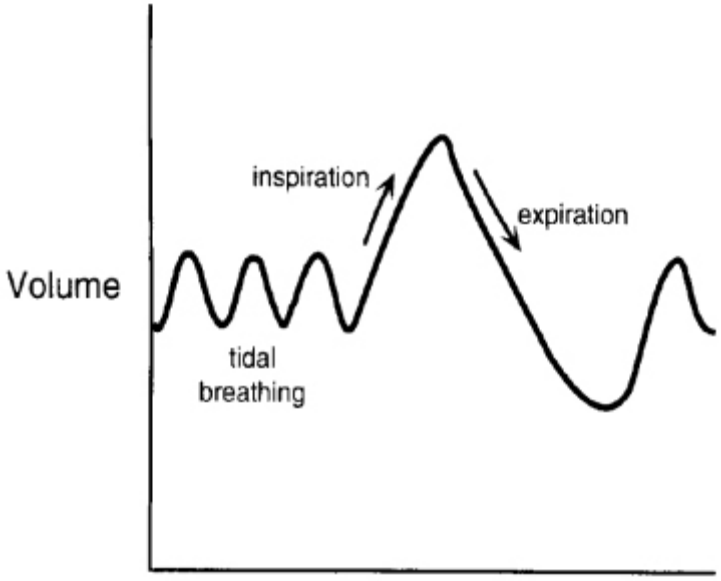


Figure 5
forced Vital Capacity Tracing

The forced expiratory vital capacity maneuver provides a great deal of data that is diagnostically valuable in assessing lung function. From Figure 5 one can also see that the TV, IRV and ERV can be obtained from the forced vital capacity tracing if the first few relaxed breaths that the subject takes are recorded. However, the force expiratory vital capacity maneuver is not concerned with the volume of gas exhaled only. The flowrates of the exhaled gas can also be analyzed.

The movement of gas over a period of time is called flow. The flowrates are determined at specific time increments or are expressed as an average over a specific portion of the FEVC tracing.

Flowrates are generally determined from forced inhalation or exhalation. The most common flowrates evaluated are those produced during a forced expiratory vital capacity maneuver (FVC). The volume of air exhaled during the first 1/2 second of exhalation is termed the Forced Expiratory Volume 0.5 second (intrathoracic). The volume exhaled in the first second of a FVC maneuver is called the Forced Expiratory Volume in one second (FEV1). The volume exhaled in three seconds of a FVC maneuver is called the Forced Expiratory Volume in three seconds (FEVER) (Figure 6).

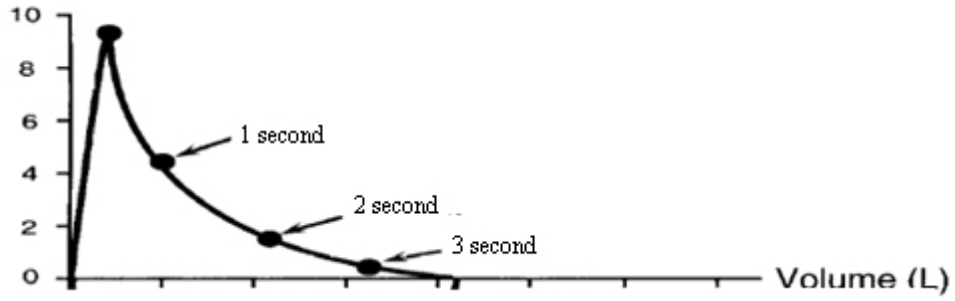


Figure 6
Tracing Of The FEV1,FEV2, And FEV3

The average flow rate that occurs between the 200 ml point and 1200 ml point during an FVC maneuver is called the Forced Expiratory Flow rate between 200 ml and 1200 ml (FEF200-1200), formerly called the Maximum Expiratory Flow rate (MEFR). The average flow rate that occurs between 25 and 75 percent points of the Vital Capacity tracing is known as the Forced Expiratory Flow between 25 and 75 percent of the Vital Capacity (FEF 25-75), formerly known as the Maximal Mid-Expiratory Flow (MMF). The peak flow which can be achieved during an FVC is not consistently detected without the use of more specialized testing such as flow-volume loops and peak flow meters.

The maximum volume of air that can be breathed in and out of the lungs over a one minute period is known as Maximal Voluntary Ventilation (MVV), formerly the Maximum Breathing Capacity (MBC). This is a measurement of the maximum amount of air the subject will voluntarily breathe in and out, usually over a 10-15 second interval and expressed in liter per minute. This procedure is very effort-dependent. Figure 7 shows MVV tracings for three types of patients - normal, restrictive, and obstructive. The restrictive tracing is similar to the normal tracing except that the volumes are much smaller. In the obstructive patient, the patient starts off with moderate volumes and breathing rate, however, with each succeeding exhalation less volume is exhaled, which produces a kind
of volume "stacking."

- Flow-Volume Loops

There is another method of analyzing the flow and volume relationship during forced maneuvers. This is a method of graphically displaying the flow generated during forced maneuvers in relation to the volume at which the flow was generated. The graphically recording of the forced maneuver can accommodate both inspiratory vital capacity and expiratory vital capacity during the same test sequence. The graphic display is quite different from that observed with our conventional spirometer model. The volume is displayed on the horizontal axis. As volume is exhaled from the lungs and plotted along the horizontal axis, the actual flow rate is simultaneously recorded on the vertical axis. The combination of the recorded FEVC and FIVC maneuver produces a graphic display that resembles a loop. Hence, this type of display is called a flow-volume loop (Figure 8).

The flow-volume loop (F-V loops) display does not include the ability to calculate time from the graph, as the display is only demonstrating flow to volume relationships. Equipment manufacturers have solved this problem to a certain extent, by the addition of programmed timing indicators into the graphic display. This is accomplished by the production of "blips" or time marks directly on the tracing. These time marks are preset and are usually set at 0.5 second (to obtain FEV 0.5), 1 second (to obtain FEV1) and 3 seconds (to obtain FEV). These timing markers are only available for the exhalation portion of the curve.

The subject is attached to the spirometer and instructed to first breathe normally. Next, the subject is instructed to inhale as deeply as possible, completely inflating the lungs. As soon as full inspiration has been achieved, the subject should exhale as rapidly and forcefully as possible until the lungs have been completely emptied. When the lungs are completely emptied, the subject then rapidly and forcefully inspires until the lungs are again completely filled. The tracing will have recorded the complete FEVC and the complete FIVC as shown in Figure 8 above.

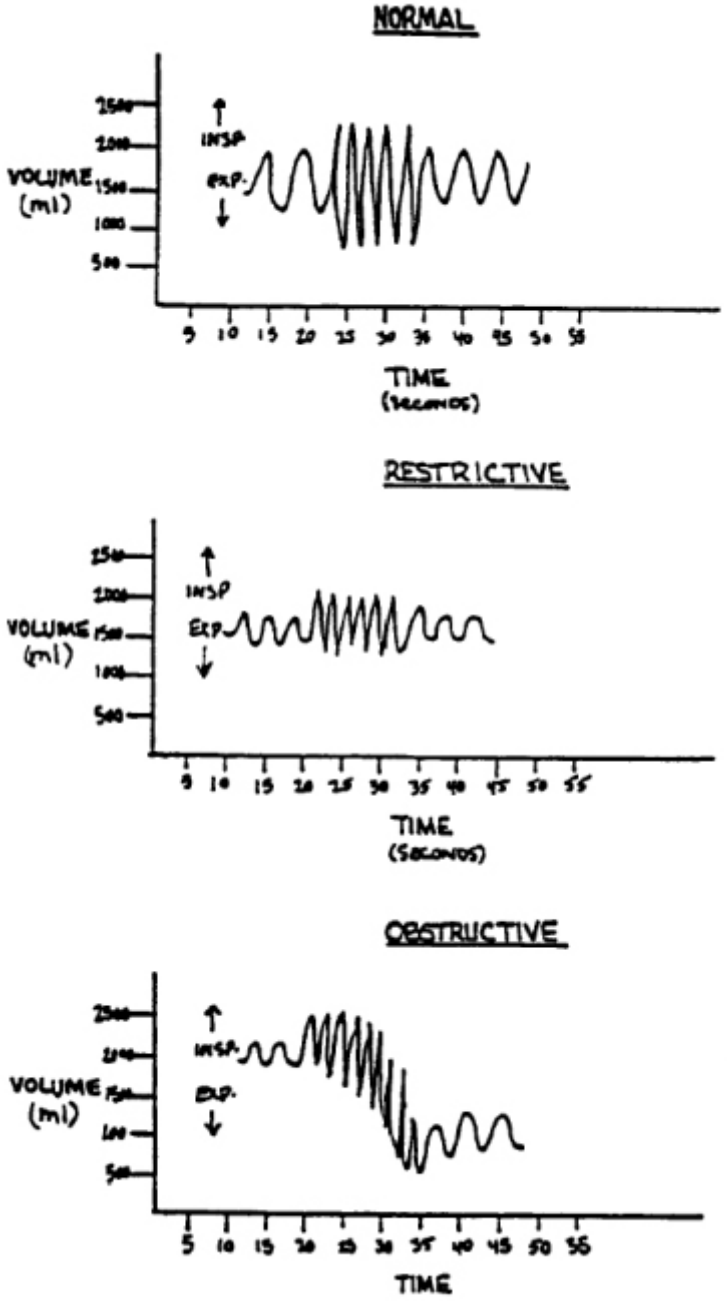


Figure 7
MVV Tracings

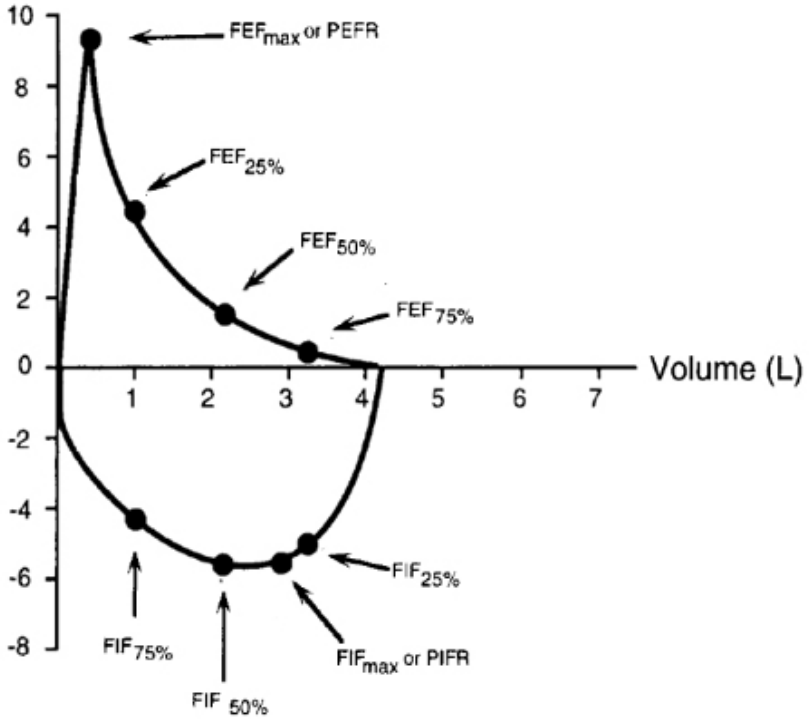


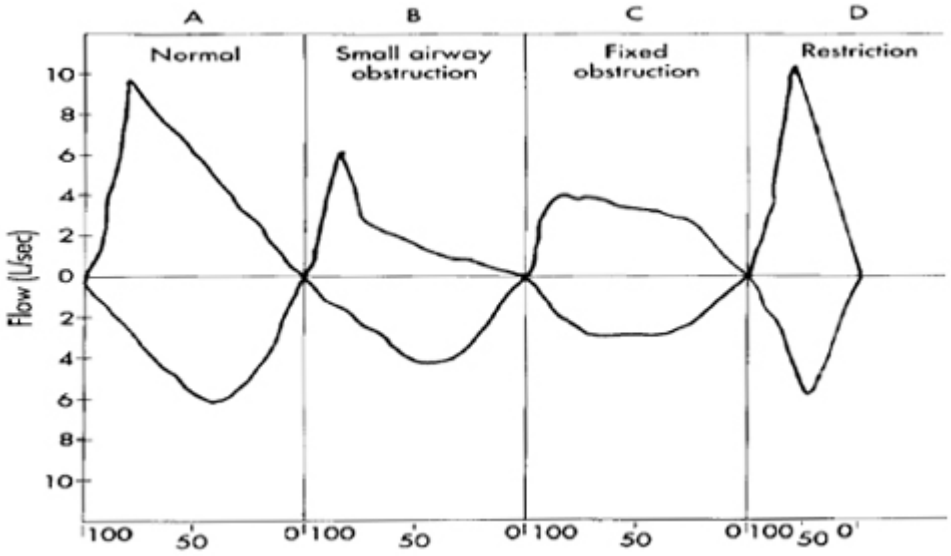
Figure 8
Normal Flow-Volume Loop

The measurements commonly obtained from the flow-volume loops include FEVC, FEV0.5, FEV1, Peak Expiratory Flow, FEF 25%, FEF 50%, FEF 75%, FIVC, Peak Inspiratory Flow, FIF, FIF, and FIF. An additional volume that is sometimes obtained is the 25%, 50%, 75% volume expired up to the point that peak flow has been generated.

The measurement of volumes takes place along the horizontal axis of the flow-volume loop tracing. The volume from the start of expiration to the start of inspiration is the FEVC. The volume from end expiration to tend inspiration is the FIVC. These two values should equal each other. Any discrepancy in the FEVC and FIVC indicates either airtrapping or poor patient effort. Vital capacity volume measurements are obtained by adding horizontal guidelines that intersect the points of the loop that separate inspiration and expiration. The horizontal distance measured from the left side of the tracing to the right side represents volume.

Specific flow rate values can be obtained from the F-V loop tracing. These points are the inspiratory peak flow, expiratory peak flow, and points that relate to specific volumes, both inspiratory and expiratory. The peak flow measurements indicate the highest flow generated over

the expiratory and inspiratory portions of the F-V loop. Figure 9 shows a characteristic flow-volume loop for a patient with small airway obstruction type disease. The most significant feature is the general reduction of all the flows at all the lung volumes. In particular, the peak flow is noticeable reduced. The vital capacity will be normal or even hyper-normal.



Obstructive Flow-Volume Loop

- Residual Volume Determinations

As noted earlier, all but one of the lung volume subdivisions can be determined directly by having the subject inhale and exhale into a recording device. The residual volume, the volume remaining in the lungs after a maximum exhalation, must be measured by indirect means. There are several ways to determine the residual volume. We will review three of the most commonly encountered methods; the gas analysis method, plethysmographic method, and roentgenographic method.

Gas Analysis Methods

The most commonly used residual volume determination procedure is gas analysis. There are actually two categories of the gas analysis method; closed circuit and open circuit.

Closed circuit method

The closed circuit method is essentially a gas dilution method, in which the test subject "rebreathes" a gas volume with a known concentration of a specific indicator gas until an equilibrium is reached. This method is commonly called the "helium dilution" method. Since helium is the gas traditionally used as the specific indicator. Other indicator gases may be used, such as neon, hydrogen, and even oxygen.

A known volume of test gas (V1) containing a known concentration of indicator gas (C1) is placed in the spirometer (usually 10% helium) (Figure 10). The test subject is attached to the spirometer connecting tubing. The volume of test gas is "rebreathed" until the concentration of test gas in the spirometer reaches a stable plateau value (C2). The achievement of a plateau value indicates that an equilibrium of the test gas has been established in the lung. Basically, the known volume of gas in the spirometer with a known helium concentration has been diluted by an unknown gas volume (V) containing no helium (the 2 subject's lungs). The subject mixes the gas contained in his/her lungs with the spirometer
gas until equilibrium (helium concentration is the same in lungs as it is in the spirometer bell). This usually will occur in less than seven minutes and results in a new helium concentration plateau. If there is a steady fall in the helium concentration with no trend towards equilibrium, check for leaks in the system. The helium concentration should slowly decrease to a stable level.

The data we have to work with is the initial spirometer volume, initial helium concentration and final helium concentration. The fourth factor we require is the final volume of gas in the system. Once that is known, the initial starting volume can be subtracted, leaving the volume of gas contained in the lungs at the start of the test. The start of the test is the point at which the subject begins "rebreathing" the spirometer test gas. This point is usually exactly at FRC or the end of the normal expired tidal breath. It is a stable point that is reasonably reproducible. From the spirometry, the subject's ERV can be calculated, leaving the residual volume value: RV = FRC - ERV

To determine FRC, use the concentration x volume relationship. The starting concentration (C1) multiplied by the starting volume (V1) will equal the final concentration (C2) times the starting volume (V1) plus the additional volume (V
2). This is expressed as: C1V1 = C2(V1+ V2)

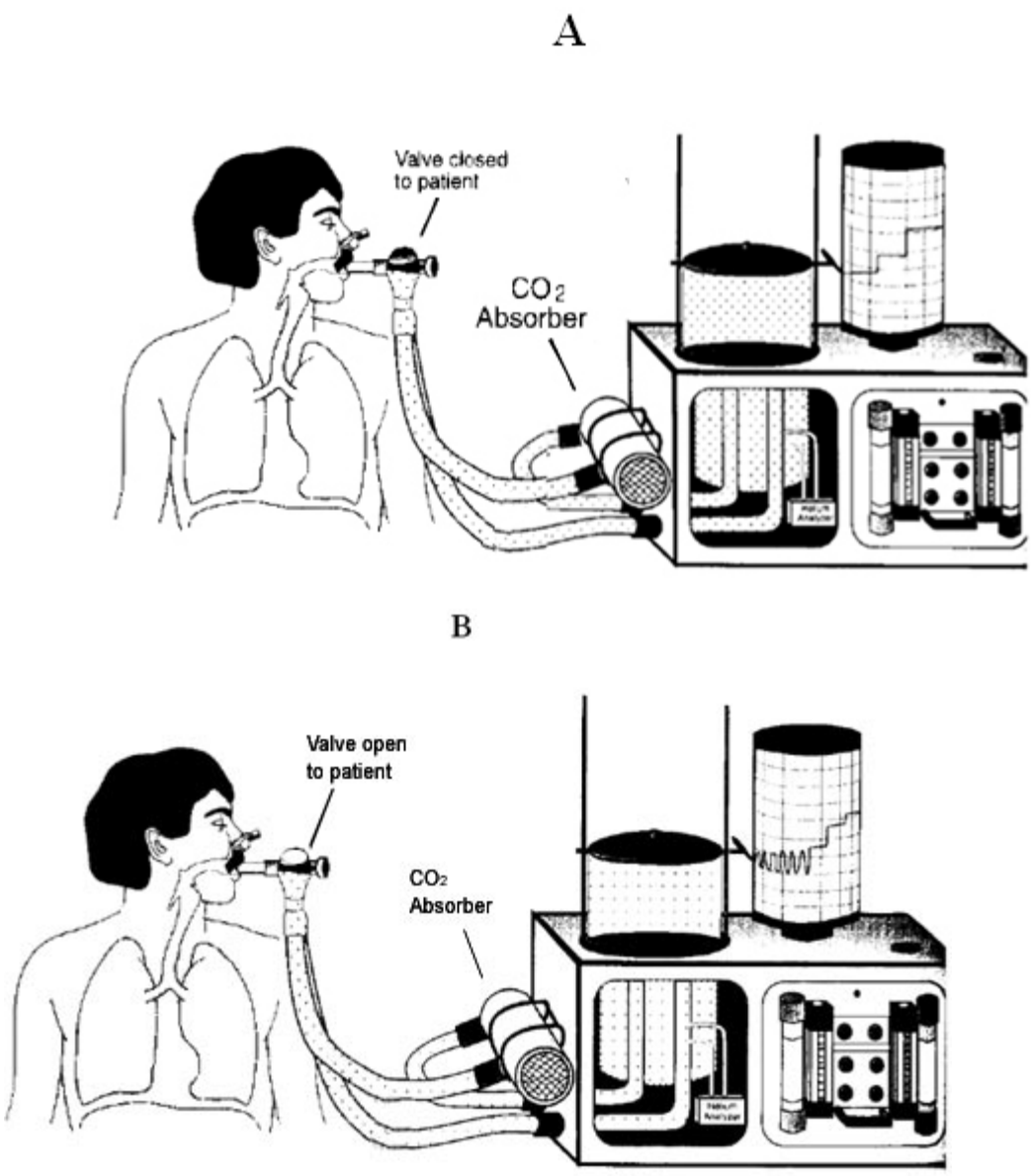


Figure 10
Residual Volume Determination - Closed Circuit Method

Open circuit method

The open circuit method for determining the residual volume value is commonly known as the nitrogen washout technique because the nitrogen contained in the test subject's lungs after breathing room air is "washed out" of the lung by having the subject breathe 100% oxygen until all of the nitrogen has been removed.

This study uses nitrogen as an indicator gas. After breathing room air for a period of time, the subject reaches equilibrium with the room air gases. Nitrogen is the major component of air (approximately 78%). It is easily measured by gas analyzing devices and unlike oxygen, it does not enter into physiological processes under normal conditions. These qualities make nitrogen a very useful indicator gas.

The subject is placed on the spirometer mouthpiece connected to a one-way valve system. The nitrogen percentage contained in the subject's lungs will be different from that of room air. This is due to the presence of carbon dioxide and water vapor in the lungs. Normally, the nitration concentration is lower in the lung, but in certain disease processes, the initial nitrogen concentration in the test subject's lungs may be higher. Therefore it is necessary to actually measure the nitrogen concentration in the subject's lungs by having him/her exhale all the air from the lungs and measuring the nitrogen concentration (indicated by the N2 analyzer) of the breath. This provides the first piece of data, the initial nitrogen concentration in the lung.

The subject is allowed to settle to a normal breathing pattern. When this has occurred, the valving system is switched to allow the subject to breathe 100% oxygen. The switching should be done at the point of end resting exhalation (at the FRC point) just as in the closed circuit or helium dilution technique. The subject will then breathe 100% oxygen with all exhaled gas being captured and analyzed in a collecting device. The subject continues to breathe through this system until all of the nitrogen is "washed out" of the lungs (replaced by oxygen). This continues until the exhaled gases contain less than 1% nitrogen. At this point, the subject can be disconnected from the system and the test terminated.

The volume of gas exhaled from the subjects lungs during the procedure can be measured. This provides two more pieces of data; the final expired nitrogen concentration and the volume of expired gases. The accumulated expired gas is analyzed to determine the nitrogen percentage so that the nitrogen volume can be calculated. The nitrogen volume is the amount of nitrogen contained in the lungs at the beginning of the test (FRC). The nitrogen volume is known to be a percentage (N percentage initial) of the starting volume and gas concentration (%N2) equal the product of the final volume and gas concentration:

V1C1 = V2C21
V1 = FRC

C1 = Initial Nitrogen Concentration
V2 = Accumulated Volume of exhaled gas
C2 = Final Nitrogen Concentration of the exhaled gas

The expression that relates the unknown FRC and the data is:
FRC x %N2 initial = expired volume x %N2 final

This is rearranged to:
FRC = expired volume x %N2 final / %N2 initial

A variation of the nitrogen washout technique involves measure of the nitrogen content breath-by-breath. The breath-by-breath method determines the volume of each breath and the concentration of nitrogen for each breath. From this information, the average nitrogen concentration of the expired breaths can be calculated by an internal computer. During the testing, each breath is individually analyzed and the nitrogen content of all the breaths is summarized to get the total nitrogen content expired. This test usually involves equipment that contained a built-in computer for computation of nitrogen content of each breath and the cumulative nitrogen content. The end results of either nitrogen washout technique are the same. The technique utilized depends upon the type of equipment available for testing.

This method for obtaining the residual volume is commonly called the "body box" method because the test subject sits in a small telephone booth-like chamber not much larger than the subject's body. The body box completely encloses the test subject in an airtight chamber. The subject breathes air from outside the chamber through a series of connecting tubes and shutter valves (Figure 11).

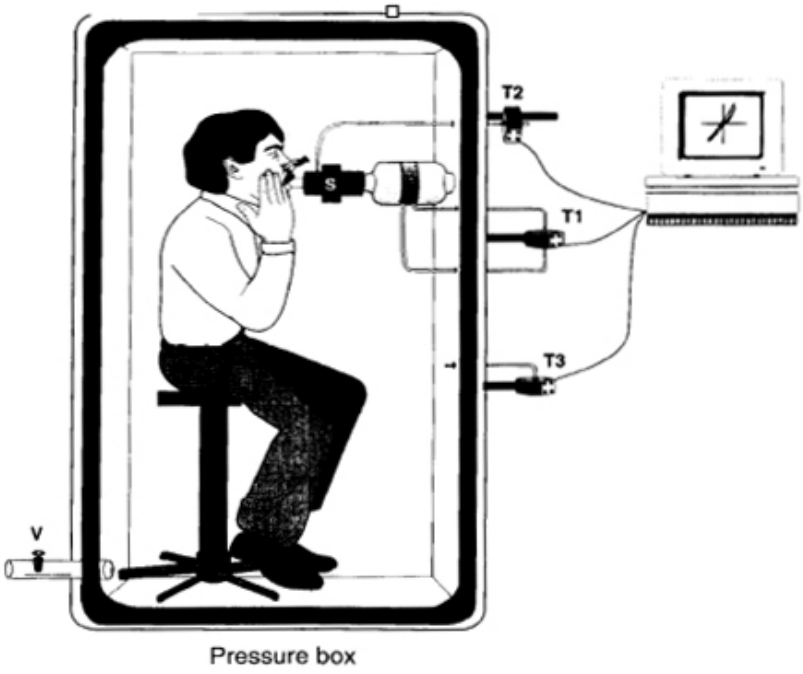


Figure 11 Pressure Plethysmograph

There are two basic types of plethysmographs commonly used in cardiopulmonary departments today. The older models are variable pressure units. They incorporate a pressure transducer in the "body box" to measure pressure changes. The new models are variable volume units. They incorporate a volume transducer rather than a pressure transducer. An advantage of the variable volume units is that the body box need not be sealed quite as efficiently. Both models use Boyle's Law which states that the volume of gas in a container varies inversely with the pressure to which the gas is subjected (temperature is held constant).

When the test subject is initially seated inside the chamber, body heat and humidification cause an immediate increase in pressure within the chamber. However, this temperature equilibrates within four to five minutes. The pressure created by this heating of the boxy must be vented until the pressure drift becomes minimal. As usual, the baseline is the end expiratory level. When end-expiration occurs, the thoracic lung volume can be measured. If a pressure box is used, the end expiration point can be measured. If a pressure box is used, the end expiration point can be identified by closely monitoring pressure changes in the box. When a volume box is used, the spirometer tracing is used to identify end-expiration. Once end-expiration has been reached with the subject breathing outside air, a shutter valve is

activated to close the mouthpiece. This results in a trapped volume of gas
in the lung. The subject is then instructed to perform a panting maneuver against the mouthpiece obstruction. The rate of panting will vary between testing techniques, usually between 60 and 120 times per minute. A rate of 60 per minute is popular.

The expiratory and inspiratory efforts made during the procedure will alternately compress and decompress the air within the lungs. The pressures at the mouthpiece during the panting maneuver are measured, along with the pressure or volume changes that occur in the body box. This is all of the information needed to calculate the volume in the lungs.

Because the end-expiration is used as the point at which the airway is occluded the procedure actually examines the functional residual volume. The actual gas volume being measured is called the thoracic gas volume (VTG), which equals the initial beginning pressure (barometric pressure minus water vapor pressure) multiplied by the ratio of the change in volume over the change in pressure:
VTG = (bp - H2Ovap pres) x change in volume / change in pressure

The change in volume is obtained from either the spirometric tracings (for variable-volume units) or calculated from pressure changes that occurred in the plethysmograph (for variable-pressure units). The changes in the alveolar pressure is obtained by a pressure transducer located at the vicinity of the mouthpiece.

The ratio of volume change to pressure change is a function of the lung volume (FRC). This constant can be obtained from the slope of the ratio displayed on the x-y plotter or oscilloscope display. The ratio can also be determined by directly measuring the peak ratio of the volume and pressure tracings obtained during the procedure. If an x-y plotter or oscilloscopes is used, the mouth pressure is plotted on the vertical axis and the box pressure on the horizontal axis. Changes in these two parameters are graphed continuously and appear as a sloping line (Figure 12).

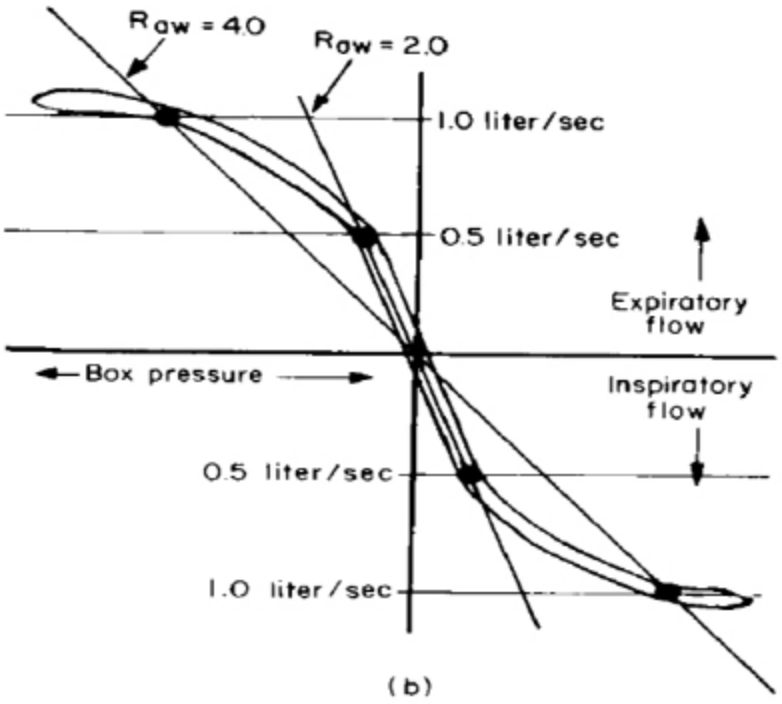


Figure 12
Oscilloscope Output During Plethysmography

The box pressure is an indicator of the volume change occurring in the lungs so that the ratio actually examined is mouth pressure/alveolar volume, or alveolar pressure/alveolar volume since the mouth pressure equals the alveolar pressure when there is no flow.

The thoracic gas volume (VTG) can then be obtained using the following equation:
VTG = ___PB / P/V
VTG = Thoracic Gas Volume
PB = Barometric Pressure - Water Vapor
P/V = Slope of the Oscilloscope Tracing

Note that if the test is initiated at end-expiration, the thoracic gas volume equals the FRC. The plethysmographic method for determining FRC is much more rapid than other methods and is considered to provide a more accurate measurement of FRC in subjects with poorly-ventilated lungs (as in COPD patients).

Radiologic method

The method of determining the residual volume of the lung using chest roentgenograms is called "planimetry." The equipment used to calculate the volume values is called a planimeter. This method involves the calculation of the TLC derived from measurements of both an anterior-posterior and lateral chest roentgenogram done at full inspiration. A set of chest roentgenograms taken at full expiration can give an estimate of residual volume. Normally the TLC determination is sufficient if coupled with spirometry that determines the vital capacity. The residual volume can be determined by subtracting the vital capacity from the total lung capacity.

Essentially, planimetry determines the surface area of the lung as represented on the anterior-posterior and lateral chest roentgenogram. The volume of the lung is calculated using the planimeter. The procedure involves dividing the lung into several segments and determining the volume for each segment. The planimeter is capable of assessing the surface areas of the segment and from these the thoracic gas volume can be determined.

Data obtained using this method is favorable compared to data obtained using the plethysmographic method since both take into account trapped gas volume in the thorax.

- Gas Distribution Procedures

Single Breath Nitrogen Test

The single breath nitrogen test is performed in many pulmonary laboratories. It is performed to assist in evaluating the distribution of ventilation. If the proper equipment is available, it is a relatively easy test to perform. The equipment necessary is a rapid response nitrogen analyzer, a spirometer plotting device capable of plotting nitrogen concentration and exhaled volume, and a valving system that will allow room air breathing and 100% oxygen breathing as desired.

The test is performed by attaching the subject to the appropriate mouth-piece and connecting tubes. The subject is instructed to exhaled until the lungs are empty (residual volume point). The subject then inhales a test gas of 100% oxygen until the lungs are completely fill (total lung capacity). Once the breath of 100% oxygen has been maximally inhaled, the subject is instructed to exhale back to the residual volume point. This is recorded on graph paper. This test

should be performed at resting expired vital capacity. Slow exhalation will aid in obtaining accurate results. A desired exhaled flow rate would be 300 to 700 ml per second. Once the single breath of 100% oxygen has been completely exhaled, the test is completed.

The nitrogen concentration is displayed long the vertical axis of the graph and the volume is displayed along the horizontal axis (Figure 13). The plot of the rise in nitrogen concentration is generally divided into four parts or phases:

Phase I includes the beginning of expiration, when pure oxygen is being exhaled. This is a very short phase.

Phase II is associated with an abrupt rise in the nitrogen concentration, representing the exhalation of mixed bronchial and alveolar gases.

Phase III is a relatively flat portion of the plot, representing the exhalation of alveolar gases.

Phase IV is associated with a noticeable rise in the nitrogen concentration toward the end of exhalation, representing the closure of some airways before others.

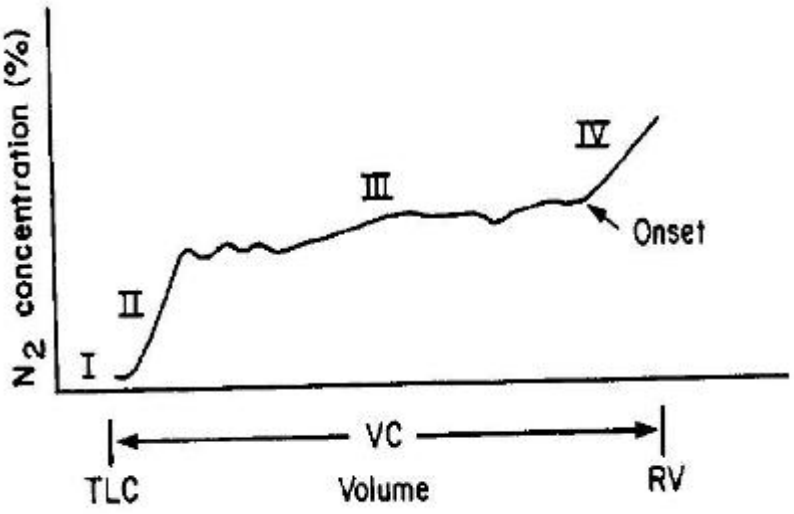


Figure 13
Single-Breath Nitrogen Test

The major portion of the residual volume is concentrated in the upper regions of the lung. The alveoli in the upper regions of the lung will

have a greater volume than the alveoli in the dependent (lower) regions. This also means that the upper regions of the lung will be slightly more compliant than the lower regions, as the opening pressure necessary is not as great in the upper regions. This suggests that the first portion of the inhalation from the residual volume level will first enter the upper region alveoli and then the lower regions. Also, recall that as alveolar volume increases, the compliance becomes less. As a result, the upper regions will fill with less inspired 100% oxygen than the lower regions which started with a smaller alveolar volume. Therefore, the test oxygen will be less dilute in the upper regions than in the lower regions.

During the Phase III portion of exhalation, the nitrogen concentration will be a mixture of gases from all regions of the lung creating a plateau. However, when a certain volume level is reached during exhalation, the airways in the lower dependent regions of the lung will close down, reducing the contribution of gas from this area. As a result, the gases now exhaled will be predominantly from the upper regions, where the higher concentration produces Phase IV and indicates the point at which major airway closure occurs.

- Measurement of Diffusion Capacity

The purpose of studying lung diffusing capacity (DL) is to determine whether or not appropriate volumes of gas are being transferred across the lung-blood gas barriers (Alveolar capillary membrane). There are many techniques for laboratory measurement of lung diffusing capacity. The single breath technique is perhaps the most popular method of DL determinations because of its relative ease and quickness. The values obtained by this method vary somewhat from the steady state method, but the deviations are not clinically important except when comparing values obtained by different methods. Because oxygen and carbon dioxide are difficult to measure and control as indicator gases for diffusion studies, the preferred test gas is carbon monoxide. This gas is used because of its high affinity for hemoglobin and its reasonable similarity to the physiologic gases (oxygen diffusing capacity is 1.23 times greater than carbon monoxide). The high affinity of carbon monoxide has entered the blood, it combines almost completely with hemoglobin and thus exerts no "back pressure" in the capillary to impede molecules from diffusing

g across the alveolar-capillary membrane. This factor allows one to assume that the only significant limiting factor to CO diffusion is the alveolar-capillary membrane.

The single breath (modified Krogh) technique involves instructing the test subject to exhaled all of the gas from the lungs (to residual volume). When all of gas has been expelled from the lungs, the subject is instructed to rapidly inhale as much test gas as possible. At the end a specific breath holding interval (usually 10 seconds) the subject is then instructed to exhale the test gas as completely as possible.

The test gas is a known concentration of gases usually consisting of 21% oxygen, 0.3% carbon monoxide, 10% inert gas (helium) and the balance nitrogen. The initial inspired CO concentration is calculated using the inert gas dilution factor.

The inert gas dilution factor is determined from the following formula:

FeHe / FiHe
FeHe = Exhaled fractional concentration of He measured at end-tidal volume
FiHe = Inspired concentration of He (known)

The end-alveolar concentration of CO is obtained by sampling end-exhalation. Essentially, the amount of CO exhaled is compared to the amount inhaled to determine the amount absorbed. The amount absorbed described the diffusing capacity of carbon dioxide in the lung (DLCO) and is expressed and ml/min/mmHg.

There are many factors affecting DLCO. These include but are not limited to, the alveolar-capillary membrane surface are, distribution of ventilation, distribution of perfusion, red blood cell mass, red blood cell membrane, affinity of the hemoglobin for CO, the thickness of alveolar-capillary membrane, the alveolar PCO2 , and the patient's body position.

In general the single-breath technique is the most popular in laboratories because of its simplicity and non-invasive nature. However, the single-breath technique may not be the most accurate since breath holding is not a physiologic maneuver. Other techniques for evaluating the diffusing capacity include: the Filey steady state, end-tidal steady state, assumed VD steady state, mixed venous PCO2

, rebreathing-equilibration, fractional CO uptake, and membrane diffusion coefficient and capillary blood volume.

The diffusion capacity will be reduced any time there is a malfunction of the alveolar capillary membrane. However, it should be noted that many of the diseases typically classified as diffusion defects may result in decreased diffusion capacities due to a loss of lung volume or capillary bed. Diffusion capacity is also decreased by space-occupying lesions and lung resection which both result in loss of lung volume and capillary bed.

- Predicted Pulmonary Function Values

Once data is obtained from pulmonary function testing, the interpreter must related the data to lung function. To a large degree, this is done by comparing the values obtained to values that would be expected of a similar subject with no known predisposing lung dysfunction. The values that are being compared to the data obtained from the test subject are loosely called "normals." this term presupposes that what is normal for one person is normal for another. This, of course, does not really apply. The normals we so frequently refer to are more accurately described as "averages." The term "predicted values" may also be used to describe this data.

Predicted values are obtained from a study group of healthy individuals who have not had a history of cardiopulmonary disease. These test subjects represent the pulmonary function of the population as a whole. These selected individuals are considered "normal." All other subjects will have their pulmonary function studies compared to what is expected to be "normal pulmonary function" for a person of that sex, height, weight, age and race.

At this time, there is no single accepted set of "predicted" values available. Many different investigators have conducted studies to establish "normal" predicted values. The data obtained from these various studies does not demonstrate an exact correlation of the values obtained. As a result, each individual laboratory will decide upon a specific investigator's work to arrive at predicted values. These values will vary from laboratory to laboratory. The "predicted" values are usually available for laboratory use in the form of a chart,

nomogram, or formula. Even though there may be variances between predicted values resulting from various studies, all are carefully worked out and are useful in establishing a baseline reference for pulmonary function interpretation.

The chart system of obtaining predicted values usually takes in to account the subject's race and sex. Predicted values are commonly separated into studies for males and females. The charts are then commonly cross-referenced according to age and height, the two most important factors in predicting values. Remember that approximately 2.54 cm equals 1 inch and 1 kilo equals 2.2 pounds. An example of a predicted values chart is given in Figure 14.

Predicted Values Chart On A 25-Year-Old Male

Predicted Values Chart On A 25-Year-Old Male

	Height In Centimeters		
	175	178	180
FVC	5000	5150	5300
$FEV_{0.5}$	3100	3150	3200
FEV_1	4150	4250	4350
FRC	2660	2730	2810
TLC	6350	6550	6750
RV	1450	1530	1550
RV/TLC%	23%	23%	23%
MVV (L/M)	180	183	186

Figure 14

Note:
These values are approximations and are intended for illustrative purposes only.

The second method of obtaining predicted values utilizes a nomogram. This is probably the most popular method where hand calculations are

used. A nomogram is a graphic representation that arranges the various flow and volume parameters along corresponding vertical scales. Separate scales for the height and age are also included. By laying a straight edge across the patient's age and height, values for the various flow volume parameters can be obtained (Figure 15).

Many laboratories have their particular nomogram printed up in tablet form. A line is drawn through the appropriate points for each patient to indicate the values. The nomogram is then included in the subject's folder. Another method involves the use of a single copy of the nomogram for the laboratory which is enlarged and placed in transparent plastic. A wax or water-soluble ink pen is then used to determine the subject's predicted values which can easily be erased to that the nomogram can be used again.

Nomogram for Case Study Patient.

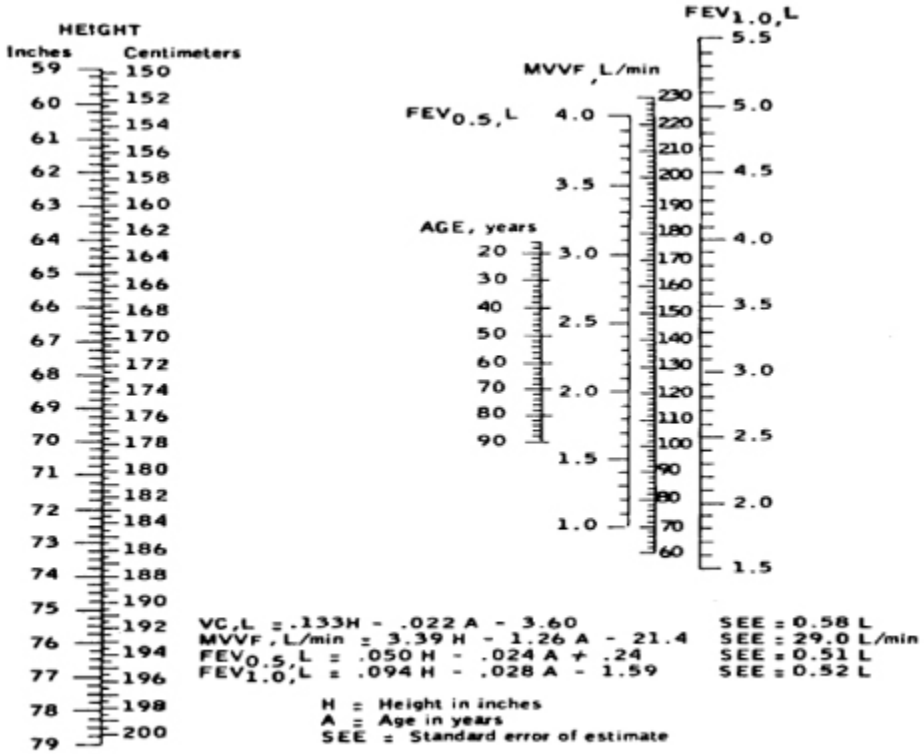


Figure 15 Nomogram

A final method that can be used to determine predicted values involves the use of regression formulas. There will be a separate formula for each value to be predicted. Usually, the formulas are somewhat

lengthy and may become tedious if worked out by hand. Computers have little difficulty using this method to rapidly obtain examples of formulas for predicted values. Each regression formula will use a factor multiplied by the age, added to a factor multiplied by the height. Another factor is added to or subtracted from this total.

value = constant (A) x height - constant (B) x age + constant (C)

Pulmonary Function Interpretation

Pulmonary function interpretation involves evaluating the lung volume subdivisions, airway flow resistance, elastic properties of the lung, distribution of gases within the lung, and gas exchange. When evaluated, these factors may indicate no pulmonary dysfunction or they may indicate the possible presence of disease processes that result in pulmonary dysfunction. The disease processes are classically grouped into categories that are generally described by characteristic alterations in pulmonary function. The two main classifications are obstructive processes and restrictive processes.

Generally, an obstructive disease process will show an increased resistance to air flow, airtrapping and a normal or increased total lung capacity. Classically, restrictive processes are characterized by reduced lung volumes and capacities and flowrates that are normal, increased or reduced in proportion to the reduction in vital capacity.

The above descriptions of restrictive and obstructive processes are provided as only a guideline. Variances of disease processes can occur with each individual patient that are broadly categorized into either the obstructive or restrictive grouping. However, may specific pulmonary disease are classified into these two categories. The following is a listing of disease conditions commonly classified into one of the two categories. This listing is not intended to be all-inclusive, but will include disease states commonly encountered.

Obstructive Pulmonary Disease Mechanisms

1. Secretion or exudate accumulation
2. Mucosal edema
3. Mucosal hyperplasia
4. Spasm of smooth muscles in airways
5. Obliterative bronchiolitis
6. "Check valve" expiratory collapse

Obstructive Pulmonary Diseases

1. Emphysema
2. Chronic bronchitis (extrinsic asthma)
3. Bronchiectasis
4. Cystic fibrosis
5. Asthmatic bronchitis (intrinsic asthma)
6. Tracheobronchialmalacia
7. Bronchial obstruction (tumor or foreign body)

- Restrictive Pulmonary Disease Mechanisms

1. Replacement of ventilating lung tissue by scar tissue, fibrosis, consolidation, tumors, or vascular congestion.
2. Filling of alveoli by edematous fluid, purulent material, infiltrates, or proteinaceous material
3. Restriction of lung expansion by pleural fluid, fibrothorax, or pneumothorax
4. Restriction of chest expansion by chest wall deformities, neuromuscular disorders, pain such as after surgical incision, or anything that prevents downward movement of the diaphragm
5. Loss of lung tissue by surgical removal

Restrictive Pulmonary Disease

1. Intrapulmonic
   a. Interstitial fibrosis
   b. Pulmonary edema
   c. Pneumonia
   d. Vascular congestion
   e. Reduced surfactant
   f. Pneumoconiosis
   g. Sarcoidosis

2. Extrapulmonic
    a. Thoracic
        1) Kyphoscoliosis
        2) Multiple rib fractures
        3) Rheumatoid spondylitis
        4) Thoracic surgery
        5) Pleural effusion
        6) Pneumothorax and/or hemothorax
    b. Abdominal
        1) Abdominal surgery
        2) Peritonitis
        3) Severe obesity
        4) Pregnancy
    c. Neuromuscular defects
        1) Poliomyelitis
        2) Guillain-Barr syndrome
        3) Myasthenia gravis
        4) Tetanus
        5) Drugs (curare and kanamycin)
    d. Respiratory center depression
        1) Narcotics
        2) Barbiturates
        3) Anesthesia
        4) Brainstem damage

It should be noted that several mechanisms may occur simultaneously in the same test subject. A test subject may present with both obstructive and restrictive characteristics. It is also possible for a subject to actually have an obstructive disease when a restrictive process was suspected. It is important not to jump to conclusions until all the data is examined.

Pulmonary function interpretation should proceed in an orderly fashion; first examining the pieces of information individually and then putting the pieces together to form the overall picture. Some information may initially point to one disease category, but additional information may alter this classification. Interpretation should not proceed until all of the data has been analyzed.

- Obstructive Characteristics

In general, the obstructive disease pattern shows a resistance to air flow represented by lower than normal flowrates during forced expiratory maneuvers. The total lung capacity may be increased because of air trapping. This air trapping results in an increase in the residual volume and functional residual capacity (Figure 16). Emphysema is the primary example of a lung disease manifesting the above characteristics.

- Restrictive Characteristics

The primary characteristic of the restrictive process is decreased lung volumes (Figure 16). Flowrates may be normal, increased or reduced. Reduced flowrates do not necessarily indicate an underlying obstructive process. Flowrates will be reduced in proportion to the reduction of lung volume. The normal proportion of FEV1 to FVC will show the FEV1 being approximately 80% of the FVC. With obstructive diseases, FEV1 / FVC is less than 80%. Pure restrictive diseases will demonstration an FEV1 / FVC ratio of approximately 80%. The evaluation of restrictive processes requires careful consideration of flow in relation to lung volumes. The presence of a lower than normal flow rate does not necessarily indicate obstructive disease. An example of a pure restrictive process is interstitial fibrosis.

A summary of the volume and flow characteristics associated with obstructive disease process is given in Table 1.

From this chart a great deal of information can be derived from pulmonary function studies. Once all this information is evaluated, including practitioner impression and spirometric signs, a reasonably complete picture of the subject's lung function can be ascertained. The lung diffusing capacity and blood gas analysis are integral components of lung function evaluation.

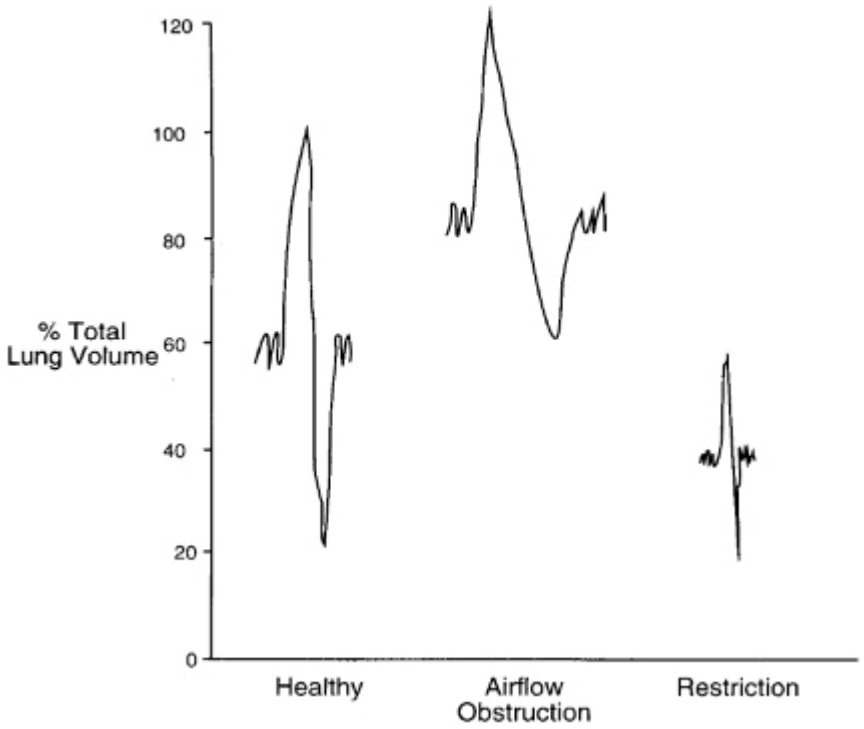


Figure 16
Slow VC Maneuvers For The Normal, Obstructive,
And Restrictive Patient

- Introduction To Testing Equipment

Pulmonary function testing requires diagnostic equipment in order to measure and record a test subject's pulmonary parameters including volume, flow, frequency, pressure and gas analysis. There are many different devices available to measure and record this data. This section will provide a brief description of common types of devices presently in use. The descriptions included are not intended to be specific for particular devices, but are meant to introduce the operation of these devices in the event that the student is not familiar with them. The student must keep in mind that the equipment used for pulmonary function testing will vary significantly from laboratory to laboratory.

Spirometer (Measuring and Recording Devices)

The term spirometer is loosely applied to any device that measures and records volumes of gas moved in and out of a test subject's lungs. This general term is used because the "spirometry" describes the measurement and recording of inhaled and exhaled gas volumes. Generally, these recording and measurement devices operate as volume collecting or flow-sensing devices. The volume collecting devices measure and record the actual volume of gas displaced during inhalation and exhalation. Often, these devices utilize a piston, bellows, or bell for gas collection, though any similar principle may be substituted. The flow-sensing devices operate by sensing the flow of gas generated during exhalation and inhalation. These devices commonly use rotating vanes, rotating cogs, thermal differentials, pressure differentials, or "vortex shedding" to determine flowrates.

Spirometers used to determine lung volumes, capacities, and flowrates and can be divided into the following categories"

1. Water-seal
2. Dry rolling seal
3. Wedge
4. Bellows
5. Wright
6. Electronic

Water-Seal

A water-seal spirometer (Figure 17) consists of a large, hollow bell suspended in a container of water with the closed end above and the open end below the water surface. Two examples of this type of spirometer are the Stead-Wells and Collins spirometers. These are airtight systems that measure gas volume by collection of actual air and displacement of a bell. The bell is connected to a rotating recorder the records a graph that can be used to calculate actual lung volume. Water-seal spirometers are commonly used to determine:

1. Lung volumes/capacities (with gas analyzers)
2. VE and VT measurements
3. Diffusion capacity DLCO (with carbon dioxide analyzer)
4. FVC, FEV1, FEF200-1200, FEV25-75, and MVV

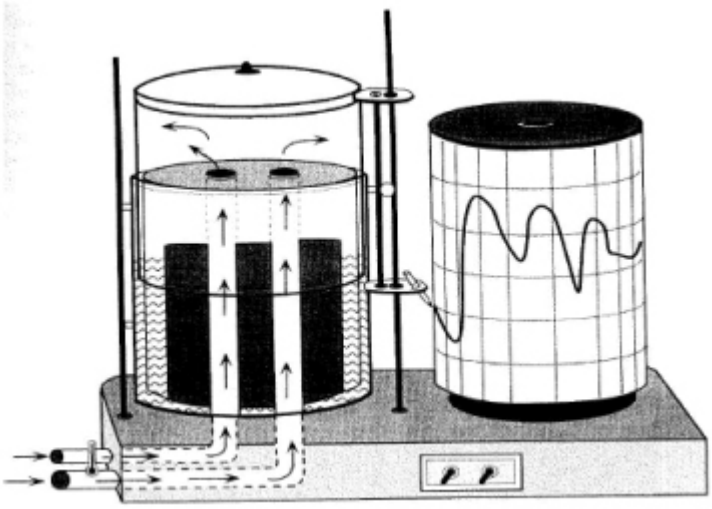


Figure 17
Water-Seal Spirometer

The patient exhales into the spirometer. The exhaled air accumulates in the bell, moving it upward and marking the motion on the revolving recorder with a pen.

Dry rolling seal

The dry rolling seal spirometer (Figure 18) is similar in principle to the water seal spirometer. This type of spirometer is airtight because of a plastic seal that "rolls" on itself rather than sliding. The dry rolling spirometer is capable of performing the same test as the water seal spirometer. Examples of dry rolling spirometers are those manufactured by the Ohio Corporation.

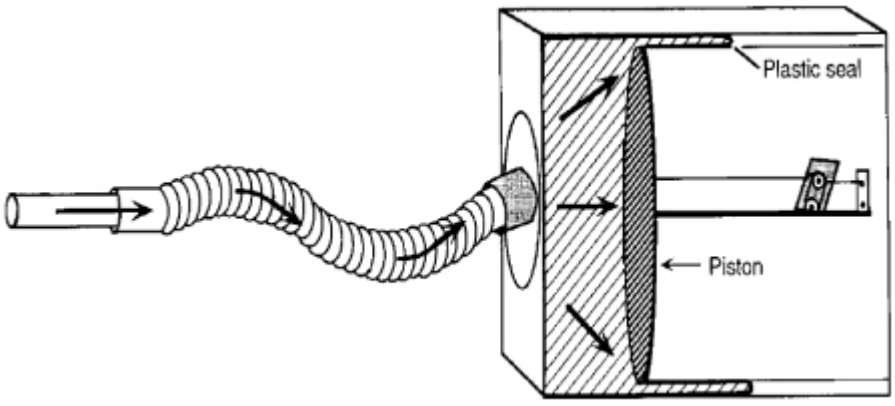


Figure 18
Dry Rolling Spirometer

The patient exhales, driving the piston forward. Motion at the potentiometer is recorded graphically.

Wedge spirometer

Wedge spirometers, also called bellows spirometers, collect exhaled volumes which expand a wedge or bellows. (Refer to the illustration of the wedge spirometer in Figure 19.) An example of a wedge spirometer is the Vitalograph. An example of a bellows spirometer is the MA-1 monitoring spirometer made by Bennett. Figure 20 shows a bellows spirometer.

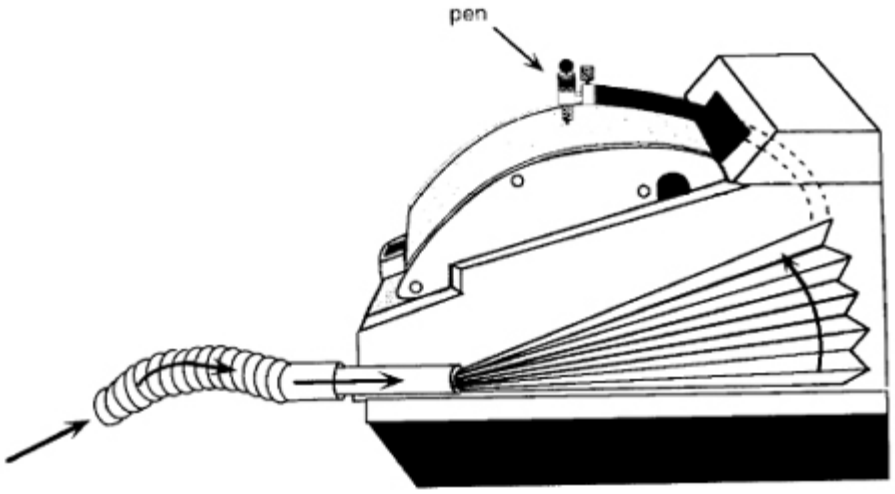


Figure 19
A Wedge Spirometer

The patient exhales, filling the bellows. The movement of the bellows is transmitted to the X-Y recorder so that volumes may be calculated.

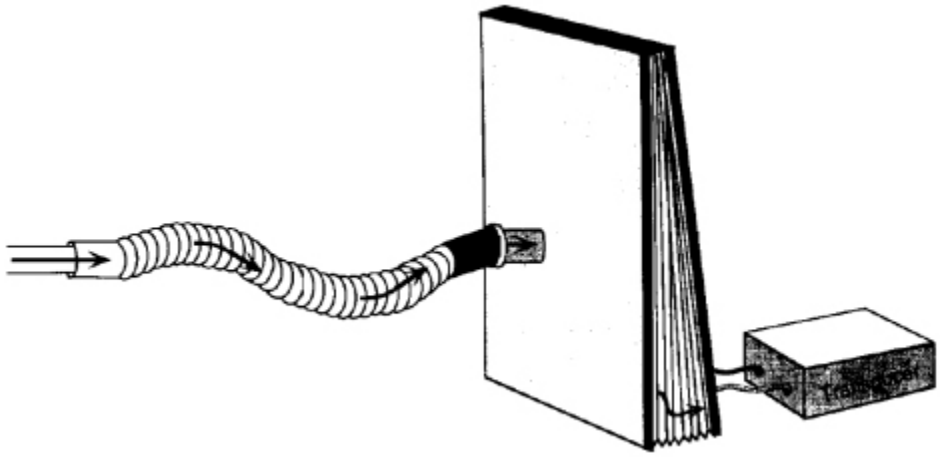


Figure 20
The Bellows Spirometer

The patient exhales, moving the bellows upward. The bellows are placed in a clear, plastic cylinder calibrated to indicate the exhaled volume. This type of bellows is common on mechanical ventilators.

Pneumotachometers

Wright spirometer

Unlike the water-seal, dry rolling, and wedge spirometers, the Wright spirometer directly measures gases passing through it. Low flows (less than 3 lpm) or high flows (greater than 300 lpm) cause inaccurate readings due to van distortion and resistance drag. This type of spirometer is useful in bedside measurement of VT, VE, and VC. FVC measurement may harm the delicate measuring vanes. The Wright spirometer is shown in Figure 21.

Electronic spirometers

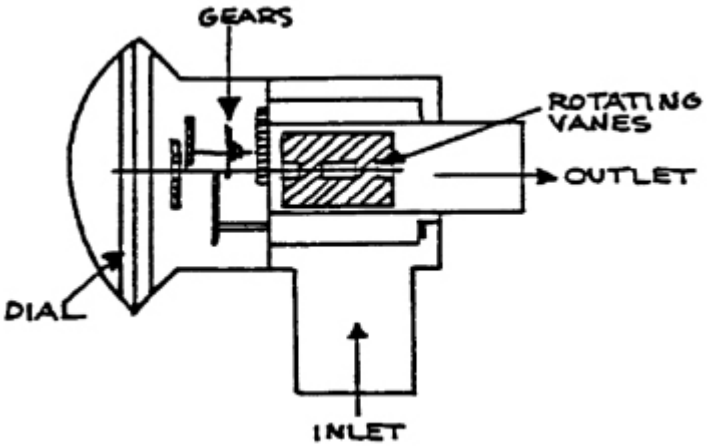
Electronic spirometers, or pneumotachographs, utilize various physical properties to produce an electrical output that is converted to give volumes and flows. The three common types are:

1. Pressure drop pneumotachograph (pneumotach)
2. Temperature drop pneumotach
3. Ultrasonic flow/vortex pneumotach

Pneumotachs actually measure flow. However, the integration of flow over time combined with a recording produces volume determinations. Figure 22 shows three types of pneumotach spirometers.

Figure 21
The Hand-Held Wright Spirometer

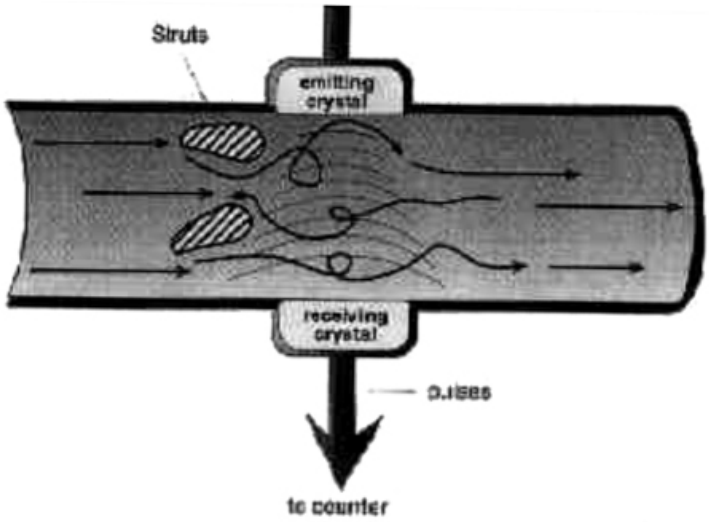
Gas enters the spirometer and rotates the vanes, which rotate the gears, thereby in dicating the volume on the dial.



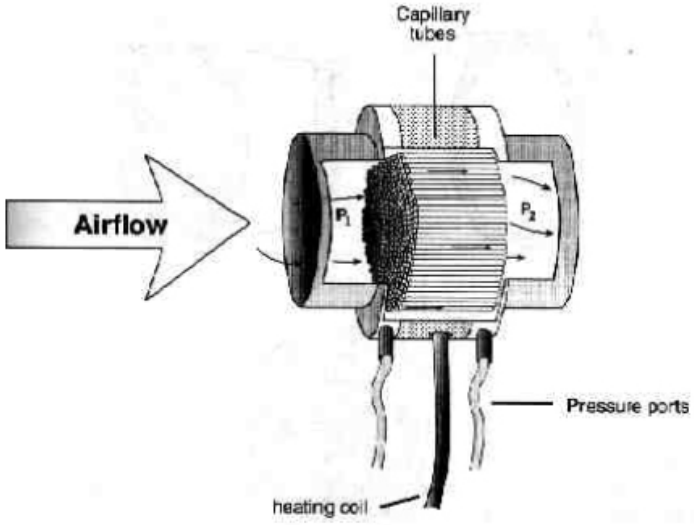
The pressure drop pneumotach (Figure 22A) measure the drop in pressure as gas flows past a resistance. This pressure difference is converted to an electronic signal that indicates flow changes. By measuring the flow and time, volume can be determined.

The temperature drop pneumotach (Figure 22B) measures the drop in temperature as gas flows over and cools a heated wire element. The difference in temperature is converted to an electronic signal from which flow and volume are determined.

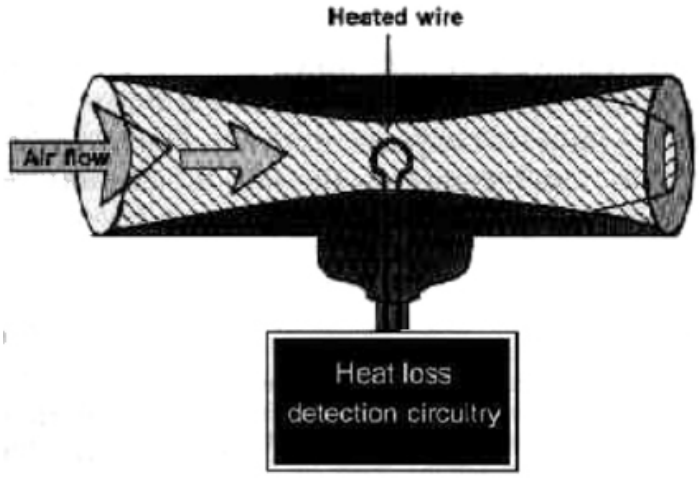
In the ultrasonic flow pneumotach (Figure 22C), struts are placed within the tube to cause turbulence in the flow of gas. This creates vortices (waves) within the flow. At the same time, ultrasonic sound waves are passed vertically through the tube from a transmitter to a receiver. As these waves are hit by the vortices, a change occurs in the intensity of the ultrasonic wave that is pick up by the receiver. These changes in the ultrasonic wave are proportional to the flow of gas. If time is measured simultaneously, the volume can be calculated.



C shows the ultrasonic flow/vortex pneumotach.



B shows the temperature drop pneumotach



C shows the ultrasonic flow/vortex pneumotach

Gas Analyzers

Gas analyzers are very important devices in the pulmonary function laboratory. They are used to determine the concentrations of various gases used in the different pulmonary function tests. The most commonly test gases include:

- oxygen
- carbon dioxide
- carbon monoxide
- helium
- nitrogen

There are many different devices and the descriptions here will be very brief.

Physical (paramagnetic) analyzers

Physical analyzers use specific properties of gases placed in a magnetic field to determine concentration. The gas commonly measured is oxygen. This "paramagnetic" gas is attracted to the strongest portion of the magnetic field distorting that field (Figure 23).

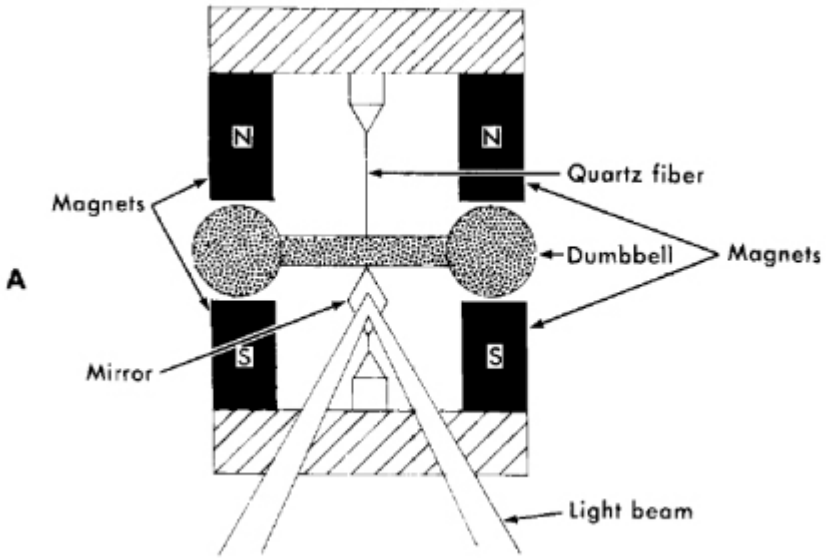


Figure 23
Paramagnetic Analyzer

Electric (thermal conductivity) analyzers

Electric (thermal conductivity) analyzers use the wheatstone bridge principle. This involves heating a sample reference wire or bead. The sample gas is then passed over the sample wire and causes a change in temperature of the sample wire (or bead) according to the gas concentration and molecular weight of the gas.

Chemical analyzers

Chemical analyzers use a method in which specific gas molecules from a gas sample chamber are absorbed by a chemical. The absorbed volume is determined in the chamber by mercury displacement. This method can be extremely accurate, but is not as rapid as many other methods.

Electrochemical analyzers

Electrochemical analyzers use a semipermeable membrane that separates the gas sample from measuring electrodes. The molecules of gas cross the membrane to react chemically in the electrodes solution bath. Representative of this category would be the galvonic fuel cell and the polarographic electrode.

Mass spectrometry

Mass spectrometry is a sophisticated method of measuring gas concentrations. This system utilizes the principle of separating charged gas molecules accorded to their respective charges. The mass spectrometer can measure several gases at the same time. It is accurate, stable and extremely expensive.

Gas chromatography

Gas chromatography is another method of gas analysis based on separation of specific gases according to their properties. The sample gas is passed through a separation column. Molecules of different sizes will pass through the column at different rates. The actual qualitative identification of each gas is passed on its appearance time after the sample is introduced.

Optical transmission

Optical transmission analyzers operate by quantifying light emitted or reflected from the gas sample. The test gas is drawn into an ionization chamber and ionized. The light emitted during this process is transmitted to a photocell which is electronically interfaced to display gas concentration on a calibrated meter. This is a common method used for determining nitrogen concentrations.

- Study Online

I. Introduction

A. There are many reasons for obtaining pulmonary function tests

1. Evaluation of surgical risk
2. Early detection of pulmonary disease
3. Evaluating the effect of occupation on lung function
4. Evaluation of treatment efficacy
5. Differentiating primary causitive abnormalities
6. Evaluation of disability
7. Assessment of degrees of dysfunction
8. Fitness for work or sport

B. PFT involves the evaluation of mechanical movement of gas in ventilation
and gas exchange across the alveolar-capillary membrane

II. Physiology Review

A. Ventilation

1. Is the movement of gas in and out of the lung
2. Minute ventilation is the amount of gas moved over a specific period of time
3. The muscles are diaphragm, external and internal intercostals, abdominal muscles, and accessory muscles
   a. Normal exhalation is passive, but may be forced
4. Gas exchange does not occur in deadspace
   a. Anatomical deadspace is the airways
   b. Physiological deadspace is improperly functioning area
5. Effective ventilation = total expired ventilation - total deadspace
   a. Deeper breaths usually have a lower percentage of dead-space ventilation
6. Elastic recoil of lungs and chest is a function of the architecture and internal surface tension

B. Compliance

1. Define as the volume/pressure relationship of chest wall and lung
   a. Elastance is the ability of an object to return to its original shape
2. 2. Pulmonary surfactant is a phospholipid which lines the alveoli and
   reduces surface tension, preventing collapse

C. Resistance

1. Tissue and chest wall resistance (20% in the normal lung)
   a. Will increase with certain diseases
2. Airway resistance (80% in the normal lung)
   a. Is friction between gas molecules, and between gas and the airway wall
   b. Poiseuille's Law describes gas' internal friction as it relates to tube radius

D. Dynamic airway compression

1. When lung volume decreases resistance increases
   a. Most frequently occurs in forced expiratory efforts

E. Regional ventilation

1. There is greater pleural pressure at the lung base
2. In apical alveoli during normal tidal breathing, the apical segments receive the first gas, then the rest of the gas moves to the basilar segments

F. Work of breathing

1. Optimal breathing frequency is one which requires the least amount of work (normally less than 5% of total resting oxygen consumption goes for the work of breathing)
   a. Oxygen consumption may increase 10 times in severe respiratory disorders
2. Patients with severe respiratory disorders may alter their breathing patterns to reduce work of breathing
   a. Restrictive dysfunctions tend to show small tidal volumes, increased frequencies
   b. Obstructive dysfunctions tend to show larger tidal volumes, decreased frequencies

III. Lung Volume Subdivisions

A. Definitions

1. Inspiratory reserve volume - maximum volume inspired from the inspiratory point of normal tidal volume
2. Tidal volume - average inspired and exhaled volume during normal breathing
3. Expiratory reserve volume - maximum exhaled volume from resting end-expiratory level
4. Residual volume - volume remaining in lungs after maximum exhalation
5. Inspiratory capacity - maximum amount of gas than can be inspired from resting end-expiratory level
6. Vital capacity - maximum amount of gas that can be expired after a
   maximum inspiration
7. Functional residual capacity - the amount of gas than remains in the lungs at the end of a normal exhalation

8. 8. total lung capacity - total volume in lungs after a maximum inspiration

IV. Simple Spirometry

A. Obtaining slow effort volumes

1. A spirometer can be used to measure all lung divisions (except residual volume)
2. 2. The slow vital capacity maneuver avoids production of increased
   intrathoracic pressures which can give a reduced vital capacity measurement in patients with damaged airways
   a. This is particularly true of emphysema

B. Obtaining forced effort volumes

1. Simple spirometry can also be used here
   a. May be performed either standing or sitting in children, is best done standing (produces larger volumes)
   2. Three "acceptable" maneuvers must be collected, varying no more
   than 5%

C. Obtaining flow determinations

1. Flowrates are generally determined from forced maneuvers
2. A restrictive tracing shows smaller than normal volumes
3. An obstructive tracing shows a progressive reduction in volume exhaled

V. Flow-volume Loops

A. This graphic recording can accommodate inspiratory and expiratory vital
capacities during the same test sequence

1. Lacks the ability to calculate time from the graph, but manufacturers have built-in timing markers

B. Common measurements include FEVC, FEV0.5, FEV1, Peak Expiratory
Flow, FEF25%, FEF50%, FEF75%, FIVC, Peak Inspiratory Flow, FIF 25%, FIF50%, and FIF75%

1. Volume measurement is done along the horizontal axis (from left to right side of tracing)

VI. Residual Volume Determinations

A. Gas analysis methods

1. Closed circuit method (helium dilution method)
   a. A known gas volume with a known concentration of a specific indicator gas is rebreathed until equilibrium is reached
2. Open circuit method (nitrogen washout technique)
   a. Nitrogen, the indicator gas, is replaced by 100% O2 until all of the nitrogen in the lungs has been replaced
   b. One variation measures nitrogen content breath by breath

B. Plethysmographic method (body box method)

1. The test subject is enclosed in an airtight chamber
2. As he breathes outside air through a series of hoses, the box measures pressure changes
   a. Based on Boyle's Law
3. This system is a rapid way to determine FRC, and is more accurate
   for subjects with poorly ventilated lungs

C. Radiologic method (planimetry)

1. TLC is calculated from measurements of both an anterior-posterior
   and lateral chest roentgenogram done at full inspiration.

VII. Gas Distribution Procedures

A. Single breath nitrogen test

1. Uses a rapid response nitrogen analyzer, a spirometer plotting device, and a valving system that allows room air breathing and 100% oxygen breathing as desired
2. The plot of the rise in nitrogen concentration is divided into four parts or phases:
   a. Phase I - pure oxygen exhaled (short phase)
   b. Phase II - exhaled mixed bronchial and alveolar gases (abrupt rise)
   c. Phase III - exhaled alveolar gases (flat)

d. Phase IV - end of exhalation; some airways close before others (noticeable rise)

B. Measurement of diffusing capacity

1. Single breath technique is the most popular method because of its ease and quickness
   a. CO is the indicator gas
   b. Factors affecting DLCO
      1) Alveolar-capillary membrane surface area
      2) Distribution of ventilation
      3) Distribution of perfusion
      4) Red blood cell mass
      5) Red blood cell membrane
      6) Affinity of the hemoglobin for CO
      7) Thickness of alveolar-capillary membrane
      8) Alveolar PCO2
      9) The patient's body position
2. Other techniques
   a. Filey steady state
   b. End-tidal steady state
   c. Assumed VD steady state
   d. Mixed venous PCO2
   e. Rebreathing-equilibrium
   f. Fractional CO uptake
   g. Membrane diffusion coefficient and capillary blood volume

VIII. Predicted Pulmonary Function Values

A. Involves comparison of the test data to predicted values (based on an
average of a normal, similar population)

1. The values are usually available in the form of a chart, nomogram
   or formula

IX. Pulmonary Function Interpretation

A. Obstructive disease processes generally show and increased resistance to
air flow, airtrapping and a normal or increased total lung capacity

1. Disease mechanisms
   a. Secretion of exudate accumulation
   b. Mucosal edema
   c. Mucsoal hyperplasia
   d. Spasms of smooth muscles in airways
   e. Obliterative bronchiolitis
   f. "Check valve" expiratory collapse
2. 2. Obstructive pulmonary diseases
   a. Emphysema
   b. Chronic bronchitis (extrinsic asthma)
   c. Bronchiectasis
   d. Cystic fibrosis
   e. Asthmatic bronchitis (intrinsic asthma)
   f. Tracheobronchialmalacia
   g. Bronchial obstruction (tumor or foreign body)

B. Restrictive disease processes generally show reduced lung volumes and
capacities and flowrates that are normal, increased or reduced in proportion to the reduction in vital capacity

1. Disease mechanisms
   a. Replacement of ventilating lung tissue by scar tissue, fibrosis, consolidation, tumors, or vascular congestion
   b. Filling of alveoli by edematous fluid, purulent material, infiltrates, or proteinaceous material
   c. Restriction of lung expansion by pleural fluid, fibrothorax, or pneumothorax
   d. Restriction of chest expansion by chest wall deformities, neuromuscular disorders, pain such as after surgical incision, or anything that prevents downward movement of the diaphragm
   e. Loss of lung tissue by surgical removal
2. Restrictive pulmonary diseases
   a. Intrapulmonic
      1) Interstitial fibrosis
      2) Pulmonary edema
      3) Pneumonia
      4) Vascular congestion
      5) Reduced surfactant
      6) Pneumoconiosis
      7) Sarcoidosis
   b. Extrapulmonic
      1) Thoracic
         a) Kyphoscoliosis

b) Multiple rib fractures
c) Rheumatoid spondylitis
d) Thoracic surgery
e) Pleural effusion
f) Pneumothorax and/or hemothorax

2) Abdominal
a) Abdominal surgery
b) Peritonitis
c) Severe obesity
d) Pregnancy

3) Neuromuscular defects
a) Poliomyelitis
b) Guillain-Barré syndrome
c) Myasthenia gravis
d) Tetanus
e) Drugs (curare and kanamycin)

4) Respiratory center depression
a) Narcotics
b) Barbiturates
c) Anesthesia
d) Brainstem damage

C. Note that several mechanisms may occur in the same object

X. Introduction To Testing Equipment

A. Spirometers
1.Water-Seal
a. A large, hollow bell suspended in a container of water
2. Dry rolling seal
a. An airtight plastic seal "rolls" on itself, rather than sliding
3. Wedge spirometer
a. A wedge or bellows is expanded by the collected gases

B. Pnuemotachometers
1. Wright spirometer
a. Directly measures the gas passing through it
2. Electronic spirometers (pneumotachographs)
a. Measure flow, using various physical properties
1) Pressure drop
2) Temperature drop
3) Ultrasonic flow

C. Gas analyzers
1. Physical analyzers
a. Use specific properties of gases placed in a magnetic field
2. Electric (thermal conductivity) analyzers
a. Use the wheatstone bridge principle
3. Chemical analyzers
a. Absorption of gas by a chemical, measured by mercury displacement
4. Electrochemical analyzers
a. A semipermeable membrane separates gas sample from electrodes
5. Mass spectrometry
6. Gas chromatography
7. Optical transmission
8. Infrared analyzers

- Graphics

FIGURE 1: LUNG VOLUMES AND LUNG CAPACITIES
FIGURE 2: TERMS USED FOR SPIROMETRIC MEASUREMENTS
FIGURE 3: SPIROMETRIC ABNORMALITIES
FIGURE 4: NORMAL PULMONARY FUNCTION VALUES
FIGURE 5: EXAMPLES OF SPIROMETRIC TRACINGS IN DISEASES
FIGURE 6: PREDICTED NORMALS MALES
FIGURE 7: PREDICTED NORMALS FEMALES
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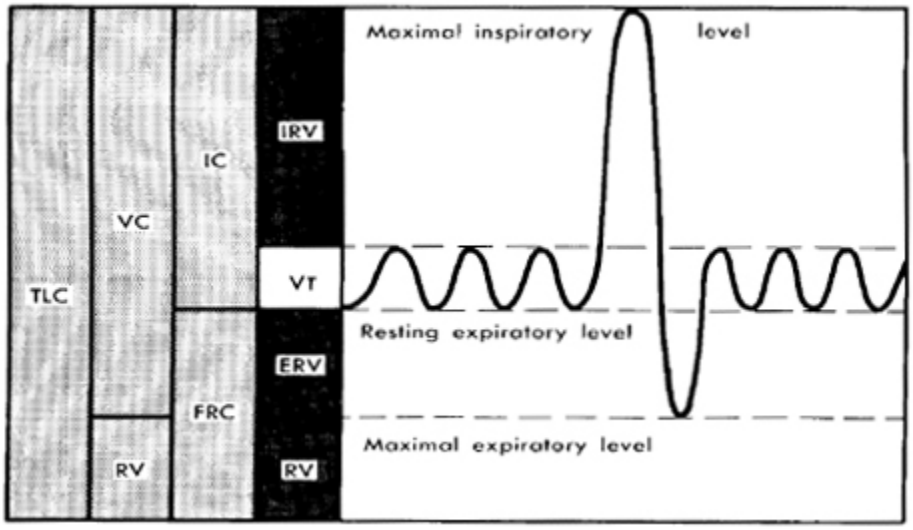
FIGURE 20: PULMONARY FUNCTION SCREENING
FIGURE 21: SPIROMETRY PROCEDURE CHECKLIST
FIGURE 22: A.T.S. STANDARDS
FIGURE 23: TYPES OF LUNG IMPAIRMENT
FIGURE 24: GLOSSARY OF TERMS AND ABBREVIATIONS

FIGURE 1: lung volumes and lung capacities



LUNG CAPACITIES AND VOLUMES

TLC - Total lung capacity - volume of air in the lungs after a maximum inspiration.
VC - Vital Capacity - volume of air which can be expelled from the lungs with maximum effort after a maximal inspiration.
IC - Inspiratory Capacity - maximum volume of air which can be inspired after a normal expiration.
FRC - Functional Residual Capacity - volume of air present in the lungs after a normal expiration.
TV - Tidal volume - volume of air moving in or out of the lungs during each cycle.
IRV - Inspiratory Reserve volume - Maximum volume of air which can be expired following a normal expiration.
ERV - Expiratory Reserve Volume - maximum volume of air which can be expired following a normal expiration.
RV - Residual Volume - volume of air remaining in the lungs after a maximal expiration.
MV - Minute Volume - volume of air passing in or out of the lungs in one minute. (ratge x TV).

FIGURE 2: TERMS USED FOR SPIROMETRIC MEASUREMENTS

Description	Term Used	Symbol	Other Previously Used Terms
The largest volume measured on complete expiration after full inspiration	Vital Capacity	VC	
The vital capacity performed with expiration being as forceful as possible (i.e. forced)	Forced vital capacity	FVC	Timed vital capacity Fast vital capacity
The volume of gas exhaled over a given time interval during the performance of a forced vital capacity	Forced exiratory volume (qualified by subscript indicating the time interval in seconds)	FEV_t (e.g., $FEV_{1.0}$)	Timed vital capacity
FEV_t expressed as percentage of the forced vital capacity i.e. $\frac{FEV_t}{FVC} \times 100$	Percentage expired (in t sec) (e.g., $FEV_{1.0}$)	FEV_t%	Timed vital capacity
The average rate of flow for a specified volume segment of the forced expiratory spirogram. (Most commonly used segment in adults is between 200 and 1200 ml)	Forced expiratory folw qualified by subscript indicating volume segment	FEF_{t1-t2} (e.g., $FEF_{200-1200}$)	Maximal expiratory flow rate
The average rate of flow during the middle two quarter of the volume segment of the forced expiratory spirogram (i.e., from 25-75% of the volume)	Forced mid-expiratory	$FEF_{25-75\%}$	Maximal mid-expiratory flow
The volume of air that a subject can breathe with voluntary maximal ventilatory a given time	Maximal voluntary ventilation	MVV	Maximum breathing capacity

FIGURE 3: SPIROMETRIC ABNORMALITIES

SPIROMETRIC ABNORMALITIES

A. Restrictive

1. Weakness of muscles due to intrinsic muscle disease or neurological defect
2. Decreased compliance of chest cage due to joint changes, parietal pleura thickening, etc.
3. Space-occupying lesions
   a. Pleural effusion, cardiomegaly, masses
   b. Subdiaphragmatic masses
   c. Intrapulmonary masses
4. 4. Decreased compliance of the lungs
   a. Pulmonary fibrosis, congestion
   b. Atelectasis, removal of lung tissue

B. Obstructive (i.e. Asthma, Bronchitis, Emphysema, Bronchiectasis)

1. Endobronchial masses
2. 2. Tracheobronchial wall edema due to inflammation, irritation, allergy, congestive heart failure
3. Endobronchial secretions
4. Bronchial fibrosis and narrowing due to chronic inflammation
5. Loss of bronchial support producing exaggerated expiratory airway closure (i.e. Emphysema)
6. Bronchoconstriction

DEFINITIONS

1. VC - Vital capacity; the maximum volume of air exhaled from the point of maximum inspiration
2. FVC - Forced vital capacity; vital capacity performed with a maximally forced expiratory effort.
3. FETT - Forced expiratory volume (timed). The volume of air exhaled in the specific time during the performance of the Forced Vital Capacity; e.g. FEV1
   for the volume of air exhaled during the first second of the FVC.
4. FEF 200-1200 - Mean forced expiratory flow between 200 ml and 1200 ml of the FVC [formerly called the maximum expiratory flow rate]
5. FEF 25 - 75% - Mean forced expiratory flow during the middle half of the FVC [formerly called the maximum mid-expiratory flow rate]
6. MVVx - Maximum voluntary ventilation. The volume of air expired in specific period during repetitive maximal respiratory effort. The respiratory frequence is indicated by a numerical qualifier; e.g., MVV60 is MVV performed at 60 breaths per minute. If no qualifier is given, an unrestricted frequency is assumed.

FIGURE 4: NORMAL PULMONARY FUNCTION VALUES

(25 years old, 150 lbs., healthy, adult, white, male)

VC	4800 cc
Vt	500 cc
IRV	3100 cc
ERV	1200 cc
IC	3600 cc
FRC	2400 cc
RV	1200 cc
TLC	6000 cc
RV/TLC	20 %
$FEV_{0.5}$	64 %
$FEV_{1.0}$	83 %
$FEV_{2.0}$	94 %
$FEV_{3.0}$	97 %
MEFR	420 – 672 L/m (mean: 546 L/m)
MMF	148 – 414 L/m (mean: 282 L/m)
Peak Flow	416 – 820 L/m (mean: 618 L/m)
MVV	170 L/m
Compliance	0.1 L/cm H_2O Pressure
Airway Resistance	0.6 – 2.4 cm H_2O /liters/sec. @ 0.5 liters/sec. Flow (mean: 1.6 cm H_2O/liter/sec.)

FIGURE 5: EXAMPLES OF SPIROMETRIC TRACINGS IN DISEASE

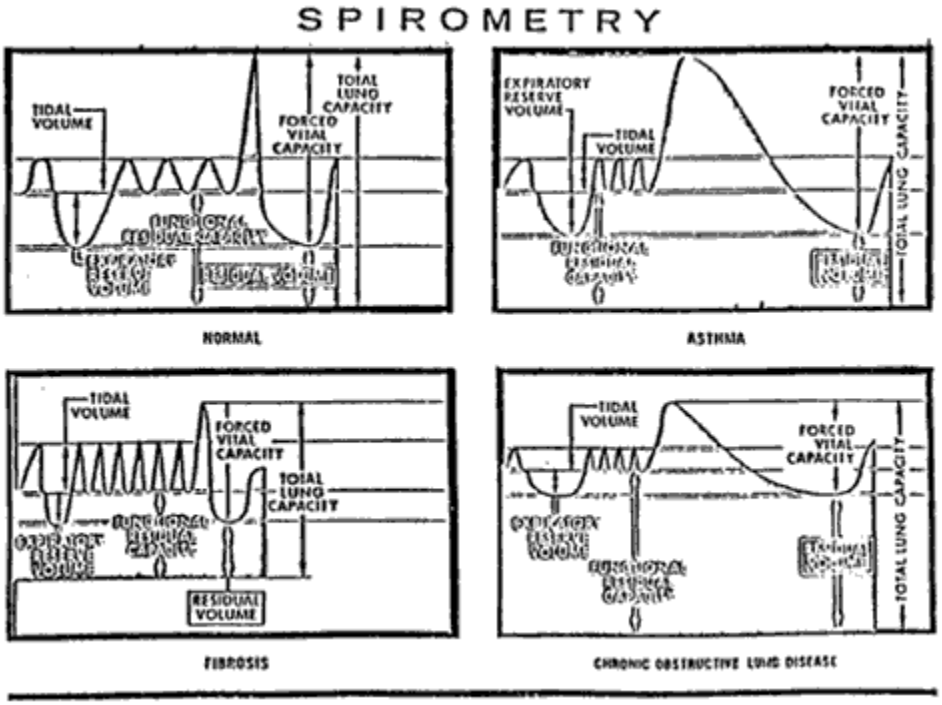


FIGURE 6: PREDICTED NORMALS – MALES

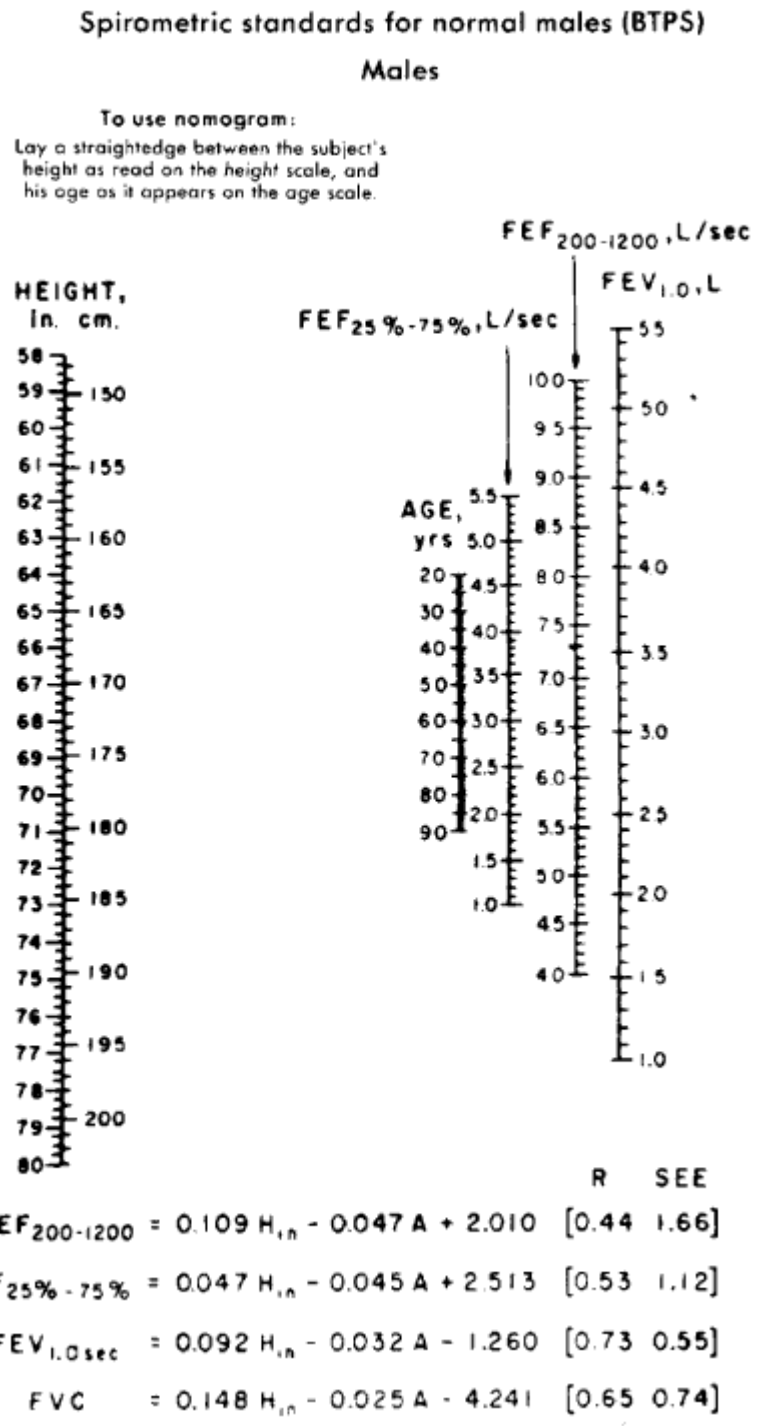


FIGURE 7: PREDICTED NORMAL – FEMALE

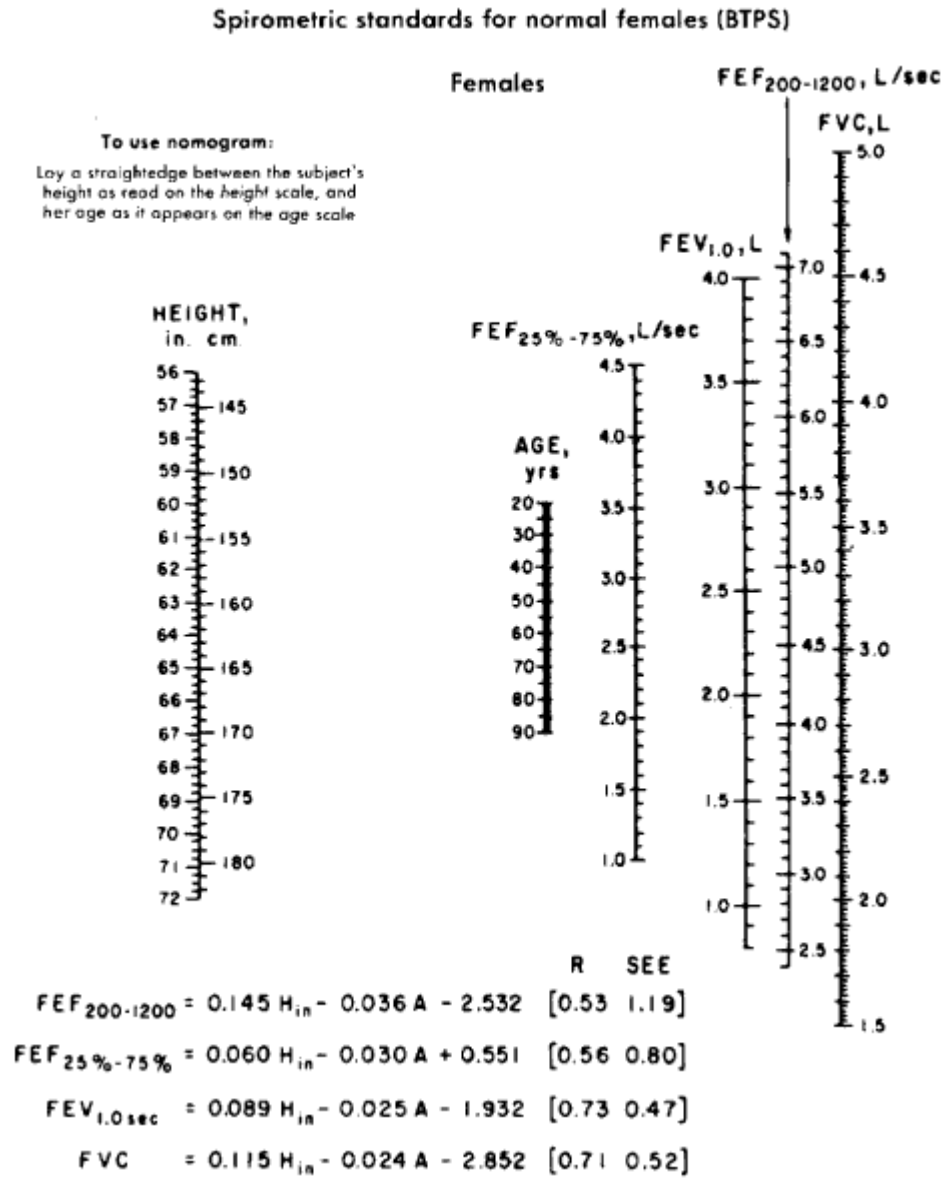


FIGURE 8: SPIROMETRIC TRACING – F.E.V.

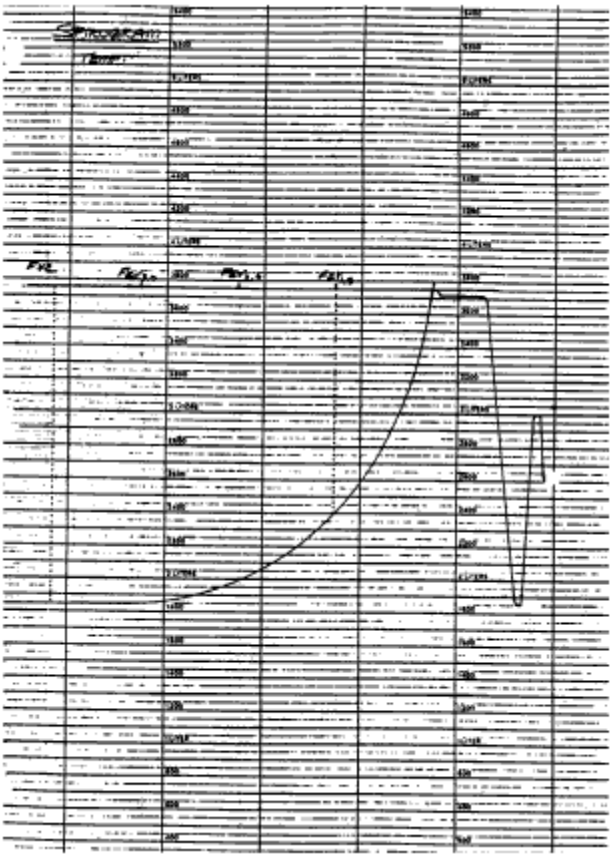


FIGURE 9: TRACING F.E.F. 200-1200

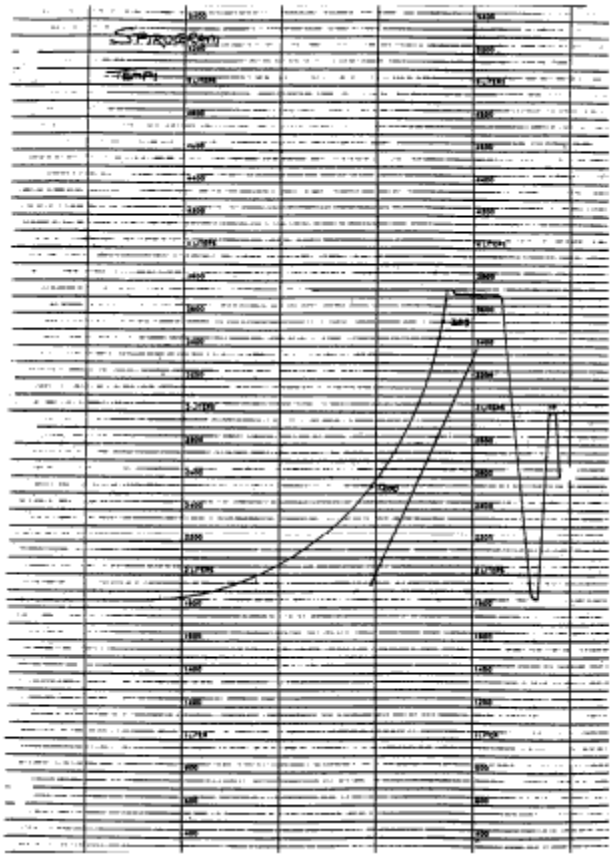


FIGURE 10: TRACING F.E.F. 25% - 75%

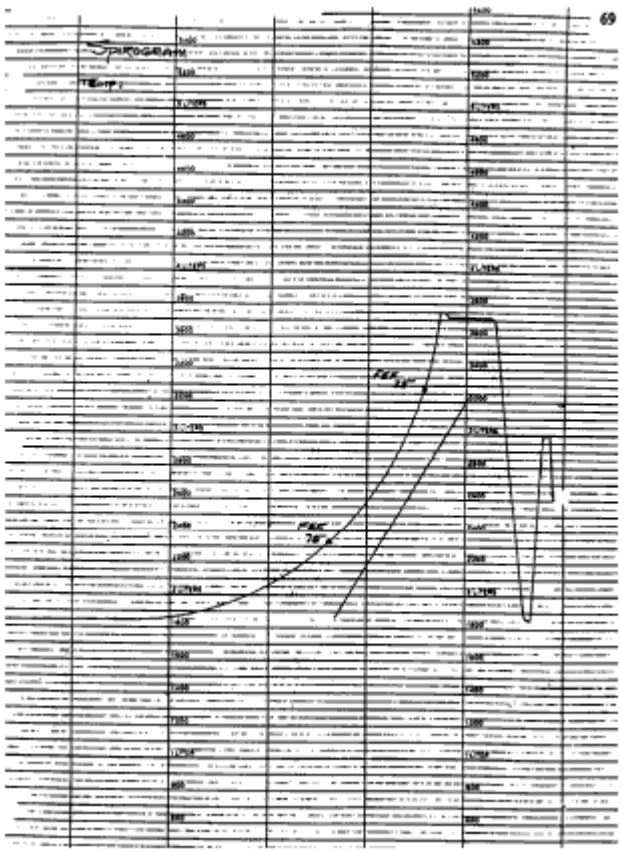


FIGURE 11: CONVERTING FROM A.T.P.S. TO B.T.P.S.

FACTORS FOR CONVERTING GAS VOLUMES FROM ROOM TEMPERATURE TO BTPS

$$\text{Volume (BTPS)} = \text{Volume (ATPS)} \times \frac{P_B - P_{H_2O}}{P_B - 47} \times \frac{310}{273 + T}$$

where

P_B = Barometric pressure, mm Hg
P_{H_2O} = Vapor pressure of water at spirometer temperature
T = Temperature centigrade
47 = Vapor pressure of water at 37° C
310 = Absolute body temperature

Most of the factors of this equation can be combined to give an approximate value for a conversion factor; local P_B causes slight differences.

Conversion factor	Gas temperature (centigrade)
1.114	18
1.111	19
1.102	20
1.096	21
1.091	22
1.085	23
1.080	24
1.075	25
1.068	26
1.063	27
1.057	28
1.051	29
1.045	30
1.039	31
1.032	32
1.026	33
1.020	34
1.014	35
1.007	36
1.000	37

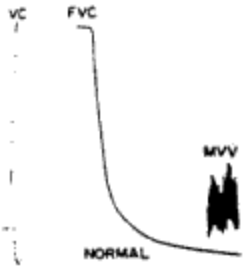
Factors to Convert Gas Volumes from Room Temperature, Saturated, to 37 C, Saturated (9)

Factor to Convert Vol. to 37 C Sat.	When Gas Temperature (C) Is	With Water Vapor Pressure (Mm Hg)* of
1.102	20	17.5
1.096	21	18.7
1.091	22	19.8
1.085	23	21.1
1.080	24	22.4
1.075	25	23.8
1.068	26	25.2
1.063	27	26.7
1.057	28	28.3
1.051	29	30.0
1.045	30	31.8
1.039	31	33.7
1.032	32	35.7
1.026	33	37.7
1.020	34	39.9
1.014	35	42.2
1.007	36	44.6
1.000	37	47.0

*H_2O vapor pressures from Handbook of Chemistry and Physics (23th ed., Cleveland: Chemical Rubber Publishing Co., 1944), p. 1802.

Note:—These factors have been calculated for barometric pressure of 760 mm Hg. Since factors at 22 C, for example, are 1.0904, 1.0910 and 1.0915, respectively, at barometric pressures 770, 760 and 750 mm Hg, it is unnecessary to correct for small deviations

FIGURE 12: TRACING IN DISEASE STATES



Interpretation: Normal
Ventilatory Study

	Predicted Normal	Performed	Percent of Predicted
VC	4.52 L	4.89	108
FVC	4.52 L	4.89	108
$FEV_{0.5}$	2.60 L	2.67	103
$FEV_{0.5}$ (%FVC)	50%	55%	
$FEV_{1.0}$	3.55 L	3.82	108
$FEV_{1.0}$ (%FVC)	75%	78%	
$FEF_{25-75\%}$	4.3 L/sec	4.11	
MVV	152 L/min		

Normal spirogram. Age, 47; sex, M; height, 173 cm.

Interpretation: Mild Restrictive
Ventilatory Defect

	Predicted Normal	Performed	Percent of Predicted
VC	3.72 L	2.84	76
FVC	3.72 L	2.84	76
$FEV_{0.5}$	2.21 L	2.28	103
$FEV_{0.5}$ (%FVC)	50%	80%	
$FEV_{1.0}$	2.92 L	2.50	86
$FEV_{1.0}$ (%FVC)	75%	88%	
$FEF_{25-75\%}$	3.6 L/sec	4.33	
MVV	129 L/min		

Restrictive ventilatory pattern. Age, 51; sex, M; height, 159 cm.

Interpretation: Very Severe Obstructive
Ventilatory Defect

	Predicted Normal	Performed	Percent of Predicted
VC	4.60 L	2.33	51
FVC	4.60 L	2.33	51
$FEV_{0.5}$	2.70 L	0.54	20
$FEV_{0.5}$ (%FVC)	50%	23	
$FEV_{1.0}$	3.68 L	0.85	23
$FEV_{1.0}$ (%FVC)	75%	36	
$FEF_{25-75\%}$	4.3 L/sec	0.39	
MVV	158 L/min		

Obstructive ventilatory pattern. Age, 41; sex, M; height, 171 cm.

FIGURE 13: COMMON RESTRICTIVE AND OBSTRUCTIVE DEFECTS

Common Causes of Restrictive Ventilatory Defect

- Interstitial lung diseases
  - Interstitial pneumonitis
  - Fibrosis
  - Pneumoconiosis
  - Granulomatosis
  - Edema
- Space-occupying lesions
  - Tumors
  - Cysts
- Pleural diseases
  - Pneumothorax
  - Hemothorax
  - Pleural effusion, empyema
  - Fibrothorax
- Chest-wall diseases
  - Injury
  - Kyphoscoliosis
  - Spondylitis
  - Neuromuscular disease
- Extrathoracic conditions
  - Obesity
  - Peritonitis
  - Ascites
  - Pregnancy
- Upper abdominal surgery

Common Causes of Obstructive Ventilatory Defect

- Upper airway disease
  - Pharyngeal and laryngeal tumors, edema, infections
  - Foreign bodies
  - Tumors, collapse, and stenosis of trachea
- Peripheral airway disease
  - Bronchitis
  - Bronchiectasis
  - Bronchiolitis
  - Bronchial asthma
- Pulmonary parenchymal disease (loss of airway support and of elastic recoil)
  - Emphysema

The Restrictive Pattern

- Characteristics of restrictive ventilatory defect
  - Decreased vital capacity
  - Relatively normal expiratory flow rates
  - Relatively normal maximal voluntary ventilation
- Supplementary data confirming restriction
  - Decreased total lung capacity

The Obstructive Pattern

- Characteristics of obstructive ventilatory defect
  - Normal or decreased vital capacity
  - Decreased maximum expiratory flow rates
  - Decreased MVV
- Supplementary data confirming obstruction
  - Increased residual volume
  - Increased airway resistance

Criteria for Severity of Ventilatory Defect

- Tests utilized to reflect overall severity of ventilatory defect
  - Forced expiratory volume at 0.5 sec
  - Forced expiratory volume at 1.0 sec
- Degree of severity
  - Mild: 65–79% of predicted value
  - Moderate: 50–64% of predicted value
  - Severe: 35–49% of predicted value
  - Very severe: below 35% of predicted value

Criteria for Reversibility of Airways Obstruction

- Significant improvement in two of these three parameters indicates reversibility
  - Forced vital capacity
  - Forced expiratory volume at 1 sec
  - Forced expiratory flow rate from 25–75% of forced vital capacity
- Degree of reversibility
  - Slight: 15–25% change
  - Moderate: 25–50% change
  - Marked: greater than 50% change

(Adapted from data in Snider GL, Kory RC, Lyons HA: Grading of pulmonary function impairment by means of pulmonary function tests. Recommendations of the Committee on Pulmonary Physiology, American College of Chest Physicians. Dis Chest 52:270, 1967)

FIGURE 14: ALTERATIONS IN PATIENT EFFORT

"Poor-Effort" Pattern

Characteristics of "poor-effort" ventilatory defect
- Decreased vital capacity
- Relatively normal expiratory flow rates
- Decreased maximum voluntary ventilation

Supplementary data confirming invalid test results
- Uneven, slurred, or notched curve on direct examination
- Poor reproducibility on repeated testing

Mixed or Indeterminate Pattern

Characteristics of Mixed Ventilatory Defect
- Decreased vital capacity
- Decreased expiratory flow rates
- Decreased maximal voluntary ventilation
- Lack of predominance of obstruction or restriction

Supplementary tests
- Lung volume determination
- Repeat tests after bronchodilator administration
- Diffusing capacity
- Compliance
- Airways resistance

Methods for Measurement of Subdivisions of Lung Volume

Methods that underestimate lung volume in obstructive disease and bullous disease
- Nitrogen washout[78]
- Helium dilution[80]

Methods that accurately measure lung volume in obstructive disease and bullous disease
- Plethysmography[75]
- Planimetry of chest roentgenograms[82–86]

Some Factors That May Limit Exercise Tolerance in Disease

- Decreased ventilatory reserve
- Hypoxemia, anemia, carboxyhemoglobin
- Cardiovascular disease: angina, limited cardiac output, arrhythmias, peripheral vascular disease
- Musculoskeletal disorders
- Dyspnea in absence of objective ventilatory impairment
- Malingering

Methods of Measuring Air-Flow Resistance

Techniques used to measure total pulmonary resistance
- Transpulmonary pressure (esophageal balloon)[100]
- Forced oscillations[101]

Techniques used to measure only airways resistance
- Estimation of alveolar pressure by momentary flow interruption[102]
- Panting technique with plethysmography and sustained shutter closure[103]

$$\text{airway resistance (cm } H_2O\text{/L/sec)} = \frac{\text{alveolar pressure (cm } H_2O) - \text{mouth pressure (cm } H_2O)}{\text{flow (L/sec)}}$$

FIGURE 15: FLOW – VOLUME LOOP

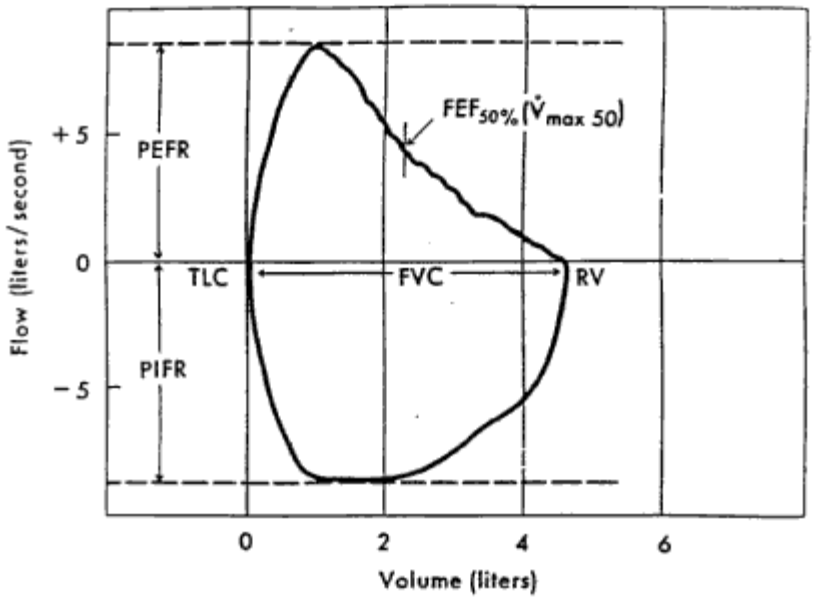


FIGURE 16: GRAPHIC ANALYSIS OF FLOWRATES

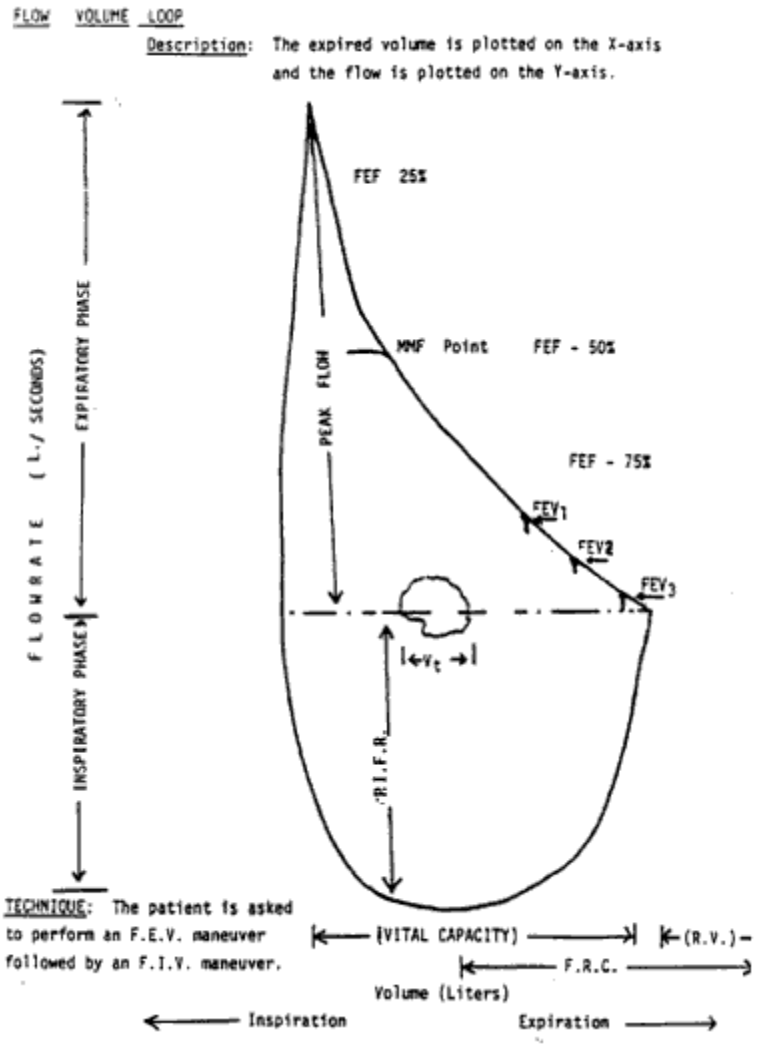
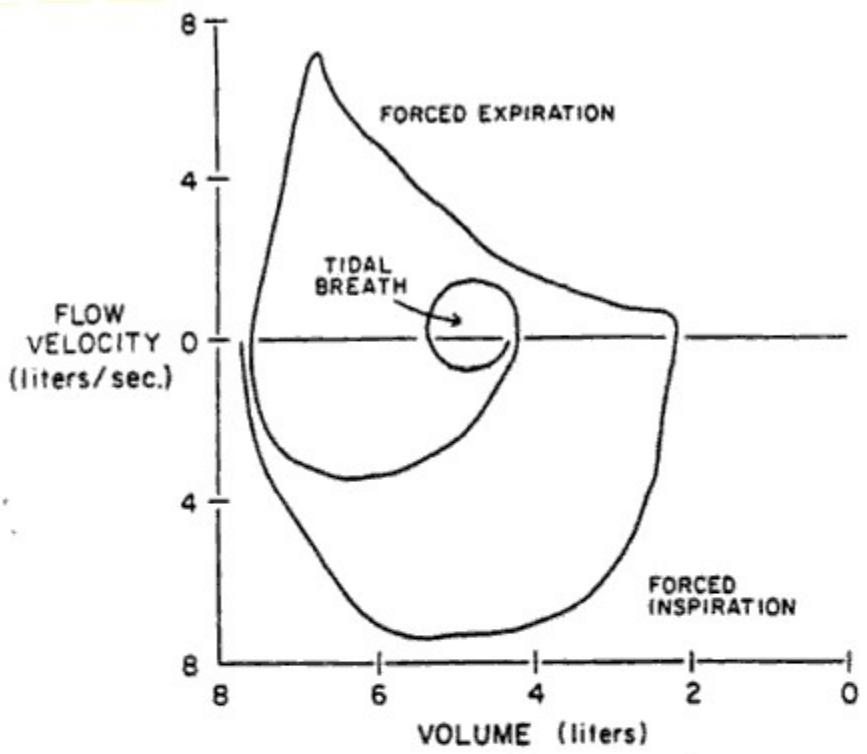


FIGURE 17: NORMAL FLOW – VOLUME LOOP



—Flow-volume loop of a normal subject. This plot indicates total lung volume on the abscissa and flow measured at the mouth (with a flowmeter) on the ordinate, expiratory flow upwards and inspiratory flow downwards. Total lung volume was calculated from the FRC (measured separately) and the inspired or expired lung volume. Tidal breathing is indicated by the small loop with its origin at FRC (4.2 L). The subject slowly inspired to TLC, then forcibly exhaled to RV followed by a forcible inspiration to TLC. These maneuvers generated forced expiratory and forced inspiratory flow-volume loops. Note that peak expiratory flow occurs early in expiration and is followed by rapidly decreasing flow indicating dynamic compression of the airways. Peak inspiratory flow slightly exceeds peak expiratory flow and is maintained for a longer period since the airways remain patent during inspiration. The respiratory maneuvers depicted are analogous to those depicted by the more conventional spirometric representation of volume versus time

FIGURE 18: EXAMPLES OF OBSTRUCTIVE AND RESTRICTIVE DISEASE

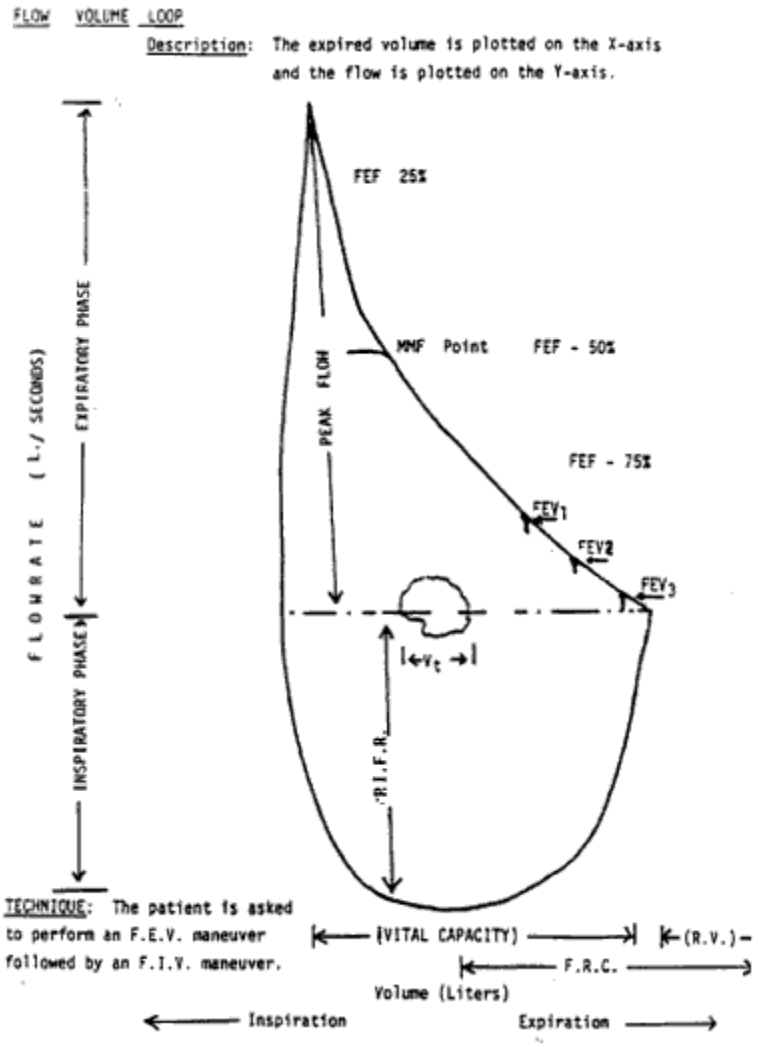
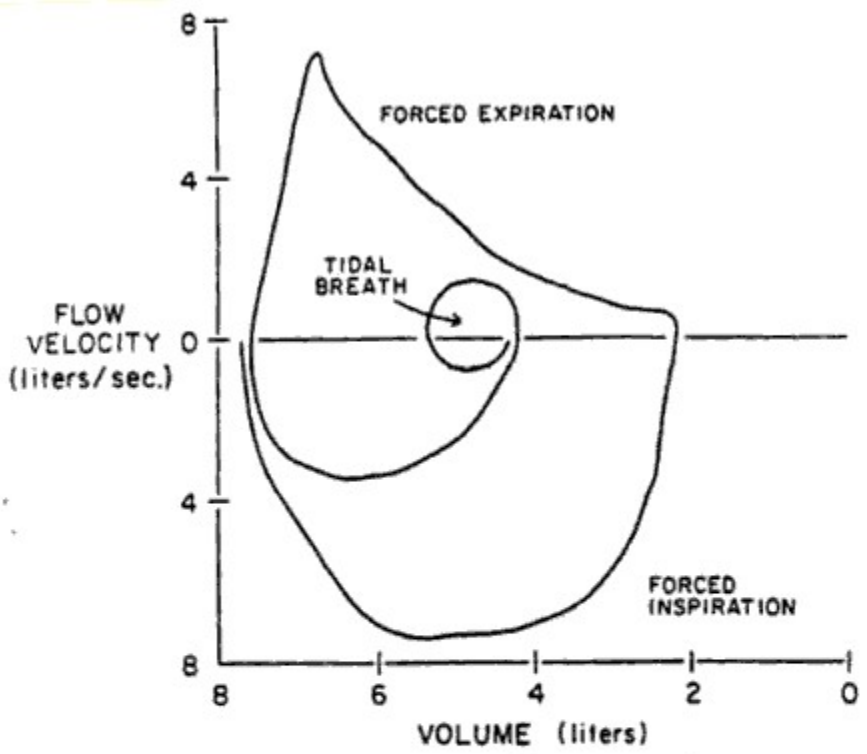
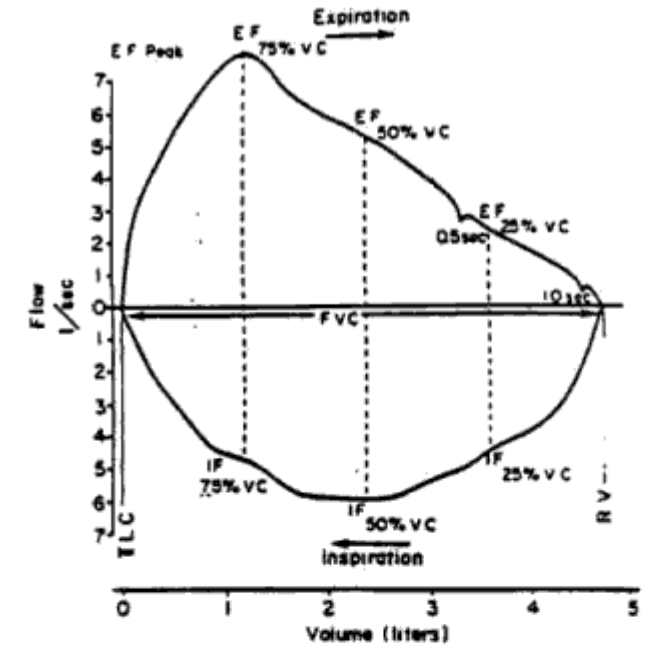


FIGURE 19: SPIROMETRIC INTERPRETATION



—Flow-volume loop of a normal subject. This plot indicates total lung volume on the abscissa and flow measured at the mouth (with a flowmeter) on the ordinate, expiratory flow upwards and inspiratory flow downwards. Total lung volume was calculated from the FRC (measured separately) and the inspired or expired lung volume. Tidal breathing is indicated by the small loop with its origin at FRC (4.2 L). The subject slowly inspired to TLC, then forcibly exhaled to RV followed by a forcible inspiration to TLC. These maneuvers generated forced expiratory and forced inspiratory flow-volume loops. Note that peak expiratory flow occurs early in expiration and is followed by rapidly decreasing flow indicating dynamic compression of the airways. Peak inspiratory flow slightly exceeds peak expiratory flow and is maintained for a longer period since the airways remain patent during inspiration. The respiratory maneuvers depicted are analogous to those depicted by the more conventional spirometric representation of volume versus time

FIGURE 20: PULMONARY FUNCTION SCREENING



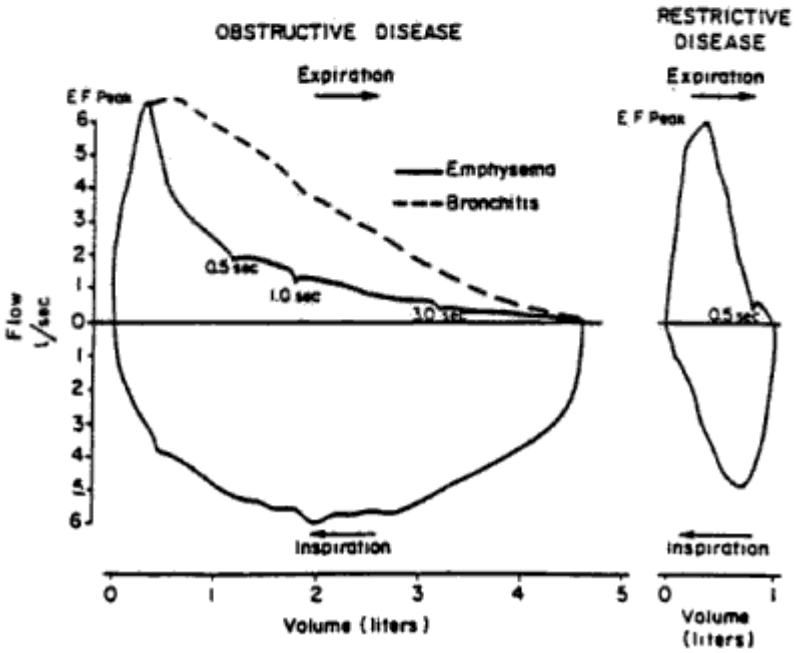


FIGURE 21: SPIROMETRY PROCEDURE CHECKLIST

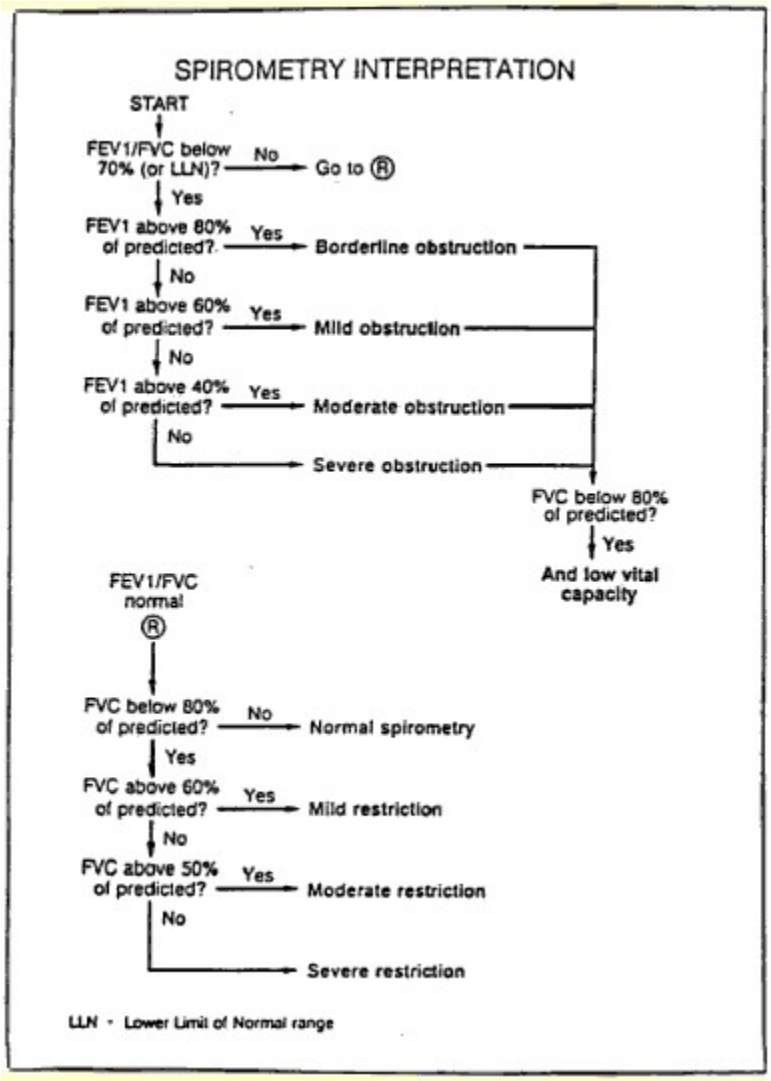


FIGURE 22: A.T.S. STANDARDS

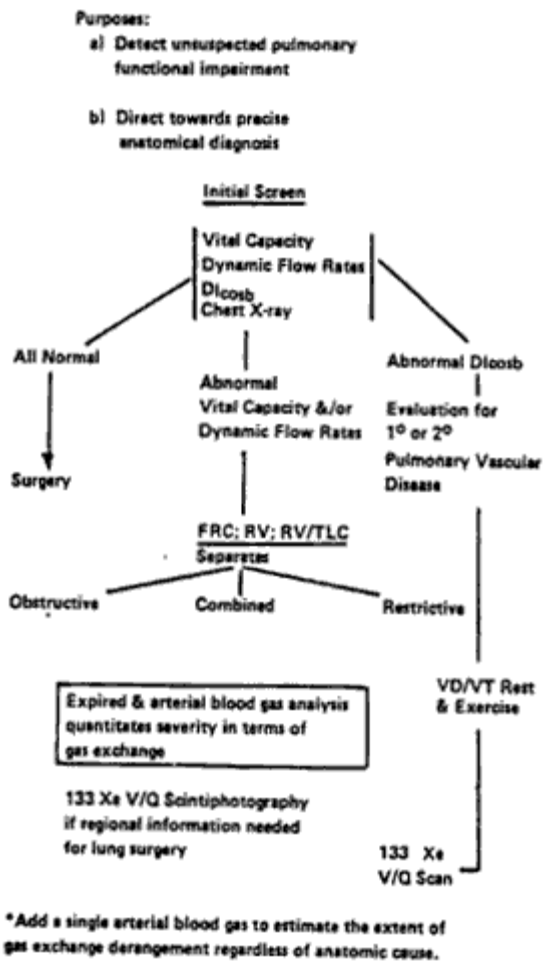


FIGURE 23: TYPES OF LUNG IMPAIRMENT

APPENDIX A

SPIROMETRY PROCEDURE CHECKLIST

1. Briefly explain purpose of spirometry — "I want to test how hard, how fast and how long you can breathe."
2. Ask appropriate questions to determine if spirometry should be postponed:
   a. "How are you feeling today?"
   b. "Have you smoked a cigarette, used an aerosolized bronchodilator, or had a heavy meal in the past hour?"
   c. "Have you had pneumonia, bronchitis, influenza or a severe cold in the past three weeks?"
3. Position the subject comfortably, requesting that he either stand or sit.
4. Instruct him to loosen tight clothing, remove dentures and extend his chin slightly.
5. Apply noseclips securely.
6. Instruct the subject in proper performance of the forced expiratory maneuver— "Whenever you are ready, take the deepest possible breath, place your mouth firmly around the mouthpiece and without further hesitation, blow into the spirometer as hard, fast and completely as possible."
7. Place recorder pen in the appropriate position on the chart paper.
8. Start the chart paper moving at least one second before the subject blows into the mouthpiece.
9. Coach actively throughout the entire forced expiratory effort until a plateau occurs in the tracing.
10. Examine the tracing and re-instruct if necessary.
11. Continue testing until three acceptable tracings have been obtained. The two largest forced vital capacities (FVC's) should not vary by more than 5% or 100 mL, whichever is greater.

2007 UPDATE INFORMATION:

Pulmonary Function Tests

Spirometry

Description

Spirometry (Current Procedural Terminology [CPT] code 94010 [spirometry], 94060 [spirometry before and after bronchodilators]) measures the mechanical function of the lung, chest wall, and respiratory muscles by assessing the total volume of air exhaled from a full lung (total lung capacity [TLC]) to an empty lung (residual volume). This volume, the forced vital capacity (FVC) and the forced expiratory volume in the first second of the forceful exhalation (FEV_1), should be reproducible to within 0.15 L upon repeat efforts unless the largest value for either parameter is less than 1 L. In this case, the expected reproducibility is to within 0.1 L of the largest value.

The patient is instructed to inhale as much as possible and then exhale rapidly and forcefully for as long as flow can be maintained.

Reduction in the amount of air exhaled forcefully in the first second of the forced exhalation (FEV_1) may reflect reduction in the maximum inflation of the lungs (TLC), obstruction of the airways, loss of lung elastic recoil, or respiratory muscle weakness. Airway obstruction is the most common cause of reduction in FEV_1. Response of FEV_1 to inhaled bronchodilators is used to assess the reversibility of airway obstruction.

Indications

Spirometry is used to establish baseline lung function, evaluate dyspnea, detect pulmonary disease, monitor effects of therapies used to treat respiratory disease, evaluate respiratory impairment, evaluate operative risk, and perform surveillance for occupational-related lung disease.

Contraindications

Relative contraindications for spirometry include hemoptysis of unknown origin, pneumothorax, unstable angina pectoris, recent myocardial infarction, thoracic aneurysms, abdominal aneurysms, cerebral aneurysms, recent eye surgery (increased intraocular pressure during forced expiration), recent abdominal or thoracic surgical procedures, and patients with a history of syncope associated with forced exhalation.

Patient care/preparations

Two choices are available with respect to bronchodilator and medication use prior to testing. Patients may withhold oral and inhaled bronchodilators to establish baseline lung function and evaluate maximum bronchodilator response, or they may continue taking medication as prescribed. If medications are withheld, a risk of exacerbation of bronchial spasm exists.

Interpretation

Interpretation of spirometry results should begin with an assessment of test quality. Failure to meet performance standards can result in unreliable test results (see Image 1). The American Thoracic Society (ATS) defines acceptable spirometry as an expiratory effort that shows (1) minimal hesitation at the start of the forced expiration (extrapolated volume (EV) $\leq$5% of the FVC or 0.15 L, whichever is larger), (2) no cough in the first second of forced exhalation, and (3) meets 1 of 3 criteria that define a valid end-of-test: (a) smooth curvilinear rise of the volume-time tracing to a plateau of at least 1-second duration; (b) if a test fails to exhibit an expiratory plateau, a forced expiratory time (FET) of 15 seconds; or (c) when the patient cannot or should not continue forced exhalation for valid medical reasons.

Additionally, the 2 largest values for FVC and the 2 largest values for FEV_1 should vary by no more than 0.15 L (0.1 L if the largest value is <1 L). A recent study has shown start-of-test problems (affecting FEV_1 measurements) to be relatively uncommon (2% prevalence in one series) and end-of-test problems (affecting FVC quality) being very common (61-84% prevalence). Allowing the patient to relax and push gently after 3-4 seconds of forced exhalation has been shown to greatly enhance the ability of patients with airflow obstruction to satisfy end-of-test criteria.

Inspection of the volume-time tracing aids in identification of early termination of expiration by evaluating the presence of an expiratory plateau. In the absence of an expiratory plateau, a 12- to 15-second expiratory time ensures the quality of the FVC. Inspection of the start of the volume-time tracing can identify a hesitant start, which can result in a falsely low FEV_1. Reproducibility of the FVC and the FEV_1 helps ensure that the results truly represent the patient's lung function. Attention should be focused on 3 key parameters: FVC, FEV_1, and the FEV_1-to-FVC ratio.

In the United States, normal values and lower limits of normal defined by Hankinson et al (the National Health and Nutrition Examination Survey [NHANES] III predicted set) should be used. These provide specific equations for whites, African Americans and Mexican Americans. If the patient belongs to another ethnic group, the predicted values and lower limits of normal provided for Caucasians by Hankinson et al should be reduced by 12% by multiplying by 0.88 before comparison with the patient's results.

Abnormalities can be classified by the physiologic patterns outlined below.

Obstructive defects

Disproportionate reduction in the FEV_1 as compared to the FVC (and therefore the FEV_1-to-FVC ratio, also called FEV_1%) is the hallmark of obstructive lung diseases. This physiologic category of lung diseases includes but is not limited to asthma, acute and chronic bronchitis, emphysema, bronchiectasis, cystic fibrosis, pneumonia, alpha1-antitrypsin deficiency, and bronchiolitis. The expiratory flow at any given expiratory volume is reduced. The mechanism responsible for the reduction in airflow can be bronchial spasm, airway inflammation, increased intraluminal secretions, and/or reduction in parenchymal support of the airways due to loss of lung elastic recoil.

Assessment of reversibility of airway obstruction

When airway obstruction is identified on spirometry, assessing response to inhaled bronchodilators is useful. The ATS has recommended that the threshold for significant response be demonstration of an increase of at least 12% and 0.2 L in either FVC or FEV_1 on a spirogram performed 10-15 minutes after inhalation of a therapeutic dose of a bronchodilating agent. New standards recommend the use of 4 inhalations (100 mcg each, 400 mcg total dose) of albuterol administered through a valved spacer device. When concern about tremor or heart rate exists, lower doses may be used. Response to an anticholinergic drug may be assessed 30 minutes after 4 inhalations (40 mcg each, 160

mcg total dose) of ipratropium bromide. Failure to respond to bronchodilator challenge does not preclude clinical benefit from bronchodilators. A positive response to the bronchodilators may correlate with response to steroid therapy.

Restrictive defects

Reduction in the FVC with a normal or elevated FEV_1-to-FVC ratio defines the classification of restrictive lung diseases as assessed by spirometry. Because the FEV_1 is a fraction of the FVC, it also is reduced, but the FEV_1-to-FVC ratio is preserved at a normal or elevated level. Measuring the TLC and residual volume (RV) can confirm restriction suggested by spirometry (see Image 2).

Quantification of impairment by spirometry

In normal spirometry, FVC, FEV_1, and FEV_1-to-FVC ratio are above the lower limit of normal. The lower limit of normal is defined as the result of the mean predicted value (based on the patient's sex, age, and height) minus 1.64 times the standard error of the estimate from the population study on which the reference equation is based. If the lower limit of normal is not available, the FVC and FEV_1 should be greater than or equal to 80% of predicted, and the FEV_1-to-FVC ratio should be no more than 8-9 absolute percentage points below the predicted ratio. The ATS has recommended the use of lower limits of normal instead of the 80% of predicted for setting the threshold that defines abnormal test results.

A reduced FVC on spirometry in the absence of a reduced FEV_1-to-FVC ratio suggests a restrictive ventilatory problem. An inappropriately shortened exhalation during spirometry can (and often does) result in a reduced FVC. Causes of restriction on spirometry include obesity, cardiomegaly, ascites, pregnancy, pleural effusion, pleural tumors, kyphoscoliosis, pulmonary fibrosis, neuromuscular disease, diaphragm weakness or paralysis, space-occupying lesions, lung resection, congestive heart failure, inadequate inspiration or expiration secondary to pain, and severe obstructive lung disease. The severity of reductions in the FVC and/or the FEV_1 can be characterized by the following scheme:

- Mild - 70-79% of predicted
- Moderate - 60-69% of predicted
- Moderately severe - 50-59%
- Severe - 35-49% of predicted
- Very severe - Less than 35% of predicted

Note that small airway obstruction may be present even when the FEV_1/FVC% is above the lower limit of normal. The mid-flow rate or forced expiratory flow occurring in the middle 50% of the patient's exhaled volume ($FEF_{25-75\%}$) may fall below its lower limit of normal even when the FVC, FEV_1, and FEV_1/FVC% are all normal. The lower limit of normal for the $FEF_{25-75\%}$ can be less than 50% of the mean predicted value, making it important to use the lower limit of normal defined by the 95% confidence limit of the

mean predicted value rather than a threshold defined by a fixed percentage of the predicted value. The $FEF_{25-75\%}$ is also very dependent on expiratory time. If expiratory times of spirometry efforts vary by more than 10%, comparisons before and after bronchodilator challenge are difficult. Early termination of expiration shifts the middle 50% of the exhaled volume toward the start of the exhalation, artifactually raising the $FEF_{25-75\%}$.

Special assessments

Sitting versus supine vital capacity: Evaluation of diaphragm strength can be accomplished by measuring the vital capacity in an upright or sitting position followed by a measurement made in the supine position. A reduction in the vital capacity to less than 90% of the upright vital capacity suggests diaphragm weakness or paralysis. Interpreting an increased reduction in vital capacity in the supine position as diaphragm dysfunction should be made cautiously if the patient is obese. Studies reporting the normal reduction of the vital capacity of less than 10% from upright to supine were conducted with individuals who were not obese. Slightly greater reductions in obese individuals in a supine position may not indicate diaphragm dysfunction, but rather an increase in the resistance to diaphragm descent.

Upper airway obstructions: The configuration of the flow-volume curve of a properly performed spirometry test can be used to demonstrate various abnormalities of the larger central airways (larynx, trachea, right and left mainstem bronchi). Three patterns of flow-volume abnormalities can be detected: (1) variable intrathoracic obstructions, (2) variable extrathoracic obstructions, and (3) fixed upper airway obstructions. Reproducing these findings on every effort is important because spurious nonreproducible reductions in inspiratory flow are not uncommon after completion of forced expirations in subjects without upper airway obstruction. Examples of variable intrathoracic obstruction include localized tumors of the lower trachea or mainstem bronchus, tracheomalacia, and airway changes associated with polychondritis (see Image 3).

Variable upper airway obstructions demonstrate flow reductions that vary with the phase of forced respirations. Variable intrathoracic obstructions demonstrate reduction of airflow during forced expirations with preservation of a normal inspiratory flow configuration. This is observed as a plateau across a broad volume range on the expired flow limb of the flow-volume curve. The reduction in airflow results from a narrowing of the airway inside the thorax, in part because of a narrowing or collapse of the airway secondary to extraluminal pressures exceeding intraluminal pressures during expiration.

Variable extrathoracic obstructions demonstrate reduction of inspired flows during forced inspirations with preservation of expiratory flows. Again, the major cause of the reduced flow during inspiration is airway narrowing secondary to extraluminal pressures exceeding intraluminal pressures during inspiration. Causes of this type of upper airway obstruction include unilateral and bilateral vocal cord paralysis, vocal cord adhesions, vocal cord constriction, laryngeal edema, and upper airway narrowing associated with obstructive sleep apnea.

Fixed upper airway obstructions demonstrate plateaus of flow during both forced inspiration and forced expiration. Causes of fixed upper airway obstruction include goiters, endotracheal neoplasms, stenosis of both main bronchi, postintubation stenosis, and performance of the test through a tracheostomy tube or other fixed orifice device.

Assessment of operative risk

While no single test can effectively predict intraoperative and postoperative morbidity and mortality from pulmonary complications, the FEV_1 obtained from good quality spirometry is a useful tool. When the FEV_1 is greater than 2 L or 50% of predicted, major complications are rare.

Operative risk is heavily dependent on the surgical site, with chest surgery having the highest risk for postoperative complications, followed by upper and lower abdominal sites. Patient-related factors associated with increased operative risk for pulmonary complications include preexisting pulmonary disease, cardiovascular disease, pulmonary hypertension, dyspnea upon exertion, heavy smoking history, respiratory infection, cough (particularly productive cough), advanced age (>70 y), malnutrition, general debilitation, obesity, and prolonged surgery.

Assessment for lung surgery typically involves prediction of a postoperative FEV_1 by using the preoperative FEV_1. In a borderline case, consideration of the contribution of the remaining portions can be assessed by a perfusion scan. The relative percentage of perfusion (Q) of the remaining lung or lung segments usually is proportional to its contribution to ventilation and can be used to estimate postoperative function as shown in the following equation:

$$\text{Postoperative } FEV_1 = \text{Preoperative } FEV_1 \times Q\% \text{ of the remaining lung}$$

For example, if the preoperative FEV_1 is 1.6 L and the lung to be resected demonstrates 40% perfusion, the postoperative FEV_1 would be $1.6 \times 0.6 = 0.96$ L. An estimated postoperative FEV_1 of less than 0.8 L often is associated with chronic respiratory failure and may indicate an unacceptable degree of operative risk. Arterial blood gases (ABGs) and cardiopulmonary exercise testing may help evaluate operative risk in patients who have a preoperative FEV_1 below 2 L or 50% of predicted.

The algorithm for clearance of candidates for lung resection proposed by Bolinger and Perruchoud has been successfully evaluated in 137 consecutive patients who were referred for resection by Wyser et al with an overall mortality rate of 1.5% and is detailed in Cardiopulmonary Stress Testing. Patients with a negative cardiac history and ECG that demonstrate an FEV_1 and a diffusing capacity of lung for carbon monoxide (DLCO) that are greater than 80% of predicted are judged to be able to undergo pneumonectomy safely.

Technical considerations

The ATS has published guidelines for a standardized technique that includes spirometer performance standards. A reasonable end-point for the maneuver in the absence of true flow cessation (i.e., airway obstruction is present) is 15 seconds. Patients often discontinue the forced exhalation prematurely because of the discomfort of prolonged forced exhalation. A modified technique in which the patient exhales with maximum force for 3 seconds followed by continued relaxed exhalation has been shown to enhance the patient's ability to sustain expiration, thereby yielding a larger FVC in patients with airflow obstruction.

Office spirometry

Recently, the National Lung Health and Education Program (NLHEP) has proposed an initiative to identify approximately 13 million Americans with undiagnosed chronic obstructive pulmonary disease (COPD) by performing spirometry on 2 groups of patients, i.e., (1) those aged 45 years or older who are actively smoking or who have quit within the last year and (2) those aged 25 years or older who have respiratory symptoms (e.g., cough, dyspnea, wheezing), regardless of smoking history. Based on the last NHANES survey, approximately 50-60 million Americans fall into one of these groups.

The proposal suggests that every primary care practitioner, internist and general practitioner should have the capability of administering a form of spirometry test that would presumably be easier to administer than the standard spirometry test. This test, called "office spirometry" would differ from standard spirometry in both instrumentation and procedure. Office spirometry exhalations would automatically terminate at 6 seconds rather than continuing to an expiratory plateau. The forced expiratory volume at 6 seconds (FEV_6) would act as a surrogate for the FVC. Likewise, the FEV_1/FEV_6% would act as a surrogate for the FEV_1/FVC%. Normal values for both the FEV_6 and the FEV_1/FEV_6% are provided by Hankinson et al (NHANES III predicted set).

A recent study suggests that the sensitivity for detecting obstruction using the FEV_1/FEV_6% is greater than 95%. The NLHEP recommends that abnormalities detected by office spirometry be confirmed by diagnostic spirometry (using the FVC and the FEV_1/FVC%) and lung volumes, if necessary.

Lung Volumes Determination

Synonyms

Functional reserve capacity (FRC), helium dilution lung volumes, nitrogen washout lung volumes, static lung volumes, lung subdivisions

Indications

Lung volumes determinations (CPT code 94240 [FRC or RV], 94260 [thoracic gas volume by body plethysmography]) are used in the evaluation of suspected restrictive lung disease and the evaluation of hyperinflation.

Contraindications

Inability to follow instructions is a contraindication. Patients with claustrophobia may not tolerate being closed into a confined space (body plethysmograph).

Patient care/preparations

Use of supplemental oxygen just prior to a nitrogen washout test may cause underestimation of FRC unless the initial exhaled nitrogen is considered in the calculations. Duplicate measurements of FRC by either gas dilution technique should be delayed until a post-test interval is equivalent to 1.5 times the equilibration time to eliminate the effects of residual oxygen or helium.

Test

Lung volumes provide useful information that confirms the presence of restrictive lung disease suggested by a low vital capacity on a spirometry test. Hyperinflation, elevation of the RV and TLC can be demonstrated by this test. The test is dependent first on an accurate measurement of the volume of gas in the lungs at a resting end-expiration, known as the FRC, which represents the balance of the elastic recoil properties of the lung and the chest wall.

FRC can be measured by 1 of 3 techniques, inert gas dilution, nitrogen washout, or whole-body plethysmography. Both gas dilution techniques are subject to error by leak at the mouthpiece or nose clip or, occasionally, even small leaks from the eardrum. When measured by whole-body plethysmography, resting end-expiratory volume is known as the intrathoracic gas volume (ITGV) and will include the volume of gas contained in noncommunicating spaces such as blebs or bullae that the FRC measured by gas dilution techniques will not measure. In addition to this advantage, body plethysmography allows multiple determinations of lung volumes to be made rapidly.

When measured by inert gas dilution or nitrogen washout, premature termination of the procedure before adequate demonstration of equilibrium or washout results in underestimation of FRC, RV, and TLC. Repeat measurements should allow a recovery period of 1.5-times the wash-in or wash-out time to prevent residual helium or oxygen from affecting the new measurement. Body plethysmography is performed rapidly, allowing multiple determinations in minutes. Ideally, each measurement of lung subdivisions should be linked to each FRC or ITGV measurement (patient should remain on the mouthpiece).

Results

FRC or ITGV is expressed in liters. This is the volume of gas in the lungs at the end of an average resting expiration. It is comprised of the expiratory reserve volume (ERV), the volume of gas that can be voluntarily exhaled beyond the FRC or ITGV, and the RV. The TLC then can be calculated by adding the RV to the vital capacity (VC). RV also is expressed as a fraction of the TLC, the RV-to-TLC ratio (see Image 2).

Interpretation

Obstructive lung diseases, particularly emphysema, result in an increase in the RV and RV-to-TLC ratio. In severe emphysema, particularly bullous emphysema, the TLC can show a marked increase. Bronchial spasm, airway inflammation, excessive secretions in the airway, and loss of elastic recoil increase the airway's resistance and result in an insidious progressive increase in the end-expiratory lung volume that results in chronic hyperinflation (elevated RV, TLC, and RV-to-TLC ratio). Other pulmonary causes of increased RV include pulmonary vascular congestion and mitral stenosis. Extrapulmonic causes of increased RV include expiratory muscle weakness as observed in spinal cord injuries and myopathies.

A reduced TLC is the hallmark of restrictive lung disease. An isolated reduction of the residual volume may be an early sign of restrictive lung disease. Pulmonary processes that can reduce the TLC include interstitial lung disease, atelectasis, pneumothorax, pneumonectomy, consolidation, edema, and fibrosis. Extrapulmonary causes of restriction include obesity, respiratory muscle weakness, thoracic deformities, and disease of the pleura.

DIFFUSING CAPACITY OF THE LUNG FOR CARBON MONOXIDE

Synonyms

Transfer factor (TL, mmol/min/kilopascal, Europe); DLCO; diffusing capacity of lung (DL, mL/min/mmHg); diffusing capacity of lung/alveolar volume (DL/VA); rate of carbon monoxide (CO) uptake (KCO), which is equivalent to the DL/VA; and alveolar volume (VA, L), which is the single-breath estimate of the TLC determined by the dilution of the helium concentration

Contraindications

Inability to follow instructions is a contraindication to a DLCO test (CPT code 94070). Patients should be alert, oriented, able to exhale completely and inhale to total lung

capacity, able to maintain an airtight seal on a mouthpiece, and able to hold a large breath for 10 seconds.

Patient care/preparations

Refrain from smoking for several hours before the test. Alcohol vapors can affect the accuracy of some fuel cell types of CO analyzers, and alcoholic beverages should be withheld for 8 hours.

Test

DLCO, also known as the transfer factor of the lung for CO (TLCO), is a measurement of the ease of transfer for CO molecules from alveolar gas to the hemoglobin of the red blood cells in the pulmonary circulation. It often is helpful for evaluating the presence of possible parenchymal lung disease when spirometry and/or lung volume determinations suggest a reduced vital capacity, RV, and/or TLC.

Most pulmonary laboratories in the United States perform this test by the single-breath technique (DLCO SB) because it is quicker to perform and more reproducible than other techniques. Other techniques, such as the rebreathing technique, are not commonly available and are not described here. In the single-breath technique, the subject exhales to RV and then inspires the test gas (10% helium, 0.3% CO, 21% oxygen, and balance nitrogen) briskly to TLC. This vital capacity size breath is held for 10 seconds and then exhaled into a sample bag after an initial discard of 0.5-0.75 L to account for dead space.

The grab sample (0.5-1 L) then is analyzed for helium and CO. The helium dilution of the vital capacity breath of test gas by the patient's RV provides both a means to estimate the initial alveolar concentration of CO and to estimate the patient's TLC. The rate of diffusion of the CO can be estimated by the change from this initial alveolar level to that of the expired grab sample. This change in the CO concentration is then multiplied by the single-breath estimate of TLC to calculate the diffusing capacity. Abnormal hemoglobin (Hb) levels can affect the diffusing capacity and, if known, should be used to mathematically correct the measured diffusing capacity to normal Hb.

> Adjusted DLCO (adolescent males and men): Hb adjusted DLCO (DLCOc) = measured DLCO ([10.22 + Hb g/dL]/[1.7 Hb])
> Hb adjusted DLCO (children <15 y and women): Hb adjusted DLCO (DLCOc) = measured DLCO ([9.38 + Hb g/dL]/[1.7 Hb])

The measured DLCO also can be adjusted for elevated levels of carboxyhemoglobin, as follows:

> Carboxyhemoglobin-adjusted DLCO (DLCOc) = measured DLCO (1 + [%CO Hb/100])

The diffusing capacity is a measure of the conductance of the CO molecule from the alveolar gas to Hb in the pulmonary capillary blood. The transfer of the CO molecule is limited by both perfusion and diffusion. CO (and oxygen) must pass through the alveolar epithelium, tissue interstitium, capillary endothelium, blood plasma, and red cell membrane and cytoplasm before attaching to the Hb molecule.

Results

Reported parameters typically include the DLCO (mL/min/mm Hg) and the DL/VA, the average inspiratory vital capacity (IVC) of 2 reproducible measurements and the average calculated alveolar volume (VA), and Hb-corrected and carboxyhemoglobin-corrected values.

Interpretation

Because the DLCO is directly proportional to VA (the single-breath dilutional estimate of TLC), nonpulmonary processes that reduce the TLC cause reductions in the DLCO. If VA can be assessed accurately, these reductions produce a normal or elevated DL-to-VA ratio. Examples of this include lung resection, thoracic cage abnormalities (e.g., kyphoscoliosis), and small lungs. DLCO is reduced in pulmonary emphysema; however, because of the poor distribution of the inspired test gas, the VA may grossly underestimate the TLC, and the resultant DL/VA may be normal. A reduced DLCO and a reduced DL-to-VA ratio suggest a true interstitial disease such as pulmonary fibrosis or pulmonary vascular disease. Recent work has shown that, in normal patients, the DL/VA is increased to above normal levels when the DLCO test is performed at volumes less than the TLC. This suggests that a low DLCO and a normal DL/VA may be a function of an inappropriately low predicted value for DL/VA when TLC is reduced.

The pattern of a low DLCO and a normal DL/VA may not be sufficient to rule out the presence of parenchymal disease. The recent works of Johnson and Chinn et al advocate the volume correction of the predicted value for DLCO by using the measured VA to "correct" the predicted DLCO for low or high lung volumes. Further work is warranted, but studies demonstrating the nonlinearity of the relationship between lung volume and DLCO are sufficiently convincing that the practice of interpreting a low DLCO and a normal DL/VA as normal should not be performed. The degree of severity of reduction in the diffusing capacity can be assigned according to the following scheme: less than the lower limit of normal (LLN) but greater than 60% of predicted is mild, between 40 and 60% of predicted is moderate, and less than 40% is severe.

Nonperfusion of ventilated alveoli, such as in pulmonary vascular disease, produces reduction of both the DLCO and the DL/VA. Anemia produces a virtual reduction in pulmonary capillary blood volume that causes a reduction in DLCO that can be adjusted mathematically for the reduced Hb. The DLCO may be reduced temporarily in a variety of disorders such as pneumonia, interstitial infiltrative disorders, and alveolar proteinosis. The importance of obtaining an inspiratory vital capacity (IVC) greater than 90% of the best measured VC from the day of the test cannot be overemphasized. Inability to achieve

an IVC of greater than or equal to 90% of the largest VC measured that day must be noted on the report.

ASSESSMENT OF RESPIRATORY MUSCLE STRENGTH

Synonyms

Maximum inspiratory pressures (MIP), maximum expiratory pressures (MEP), negative inspiratory force (NIF), respiratory pressures, maximum respiratory pressures

Indications

Assessing respiratory muscle strength allows for assessment ventilatory failure, restrictive lung disease, and respiratory muscle strength.

Contraindications

No contraindications exist.

Patient care/preparations

Patients must be able to follow directions.

Test

Determinations of respiratory muscle pressures are a quick and noninvasive means of assessing respiratory muscle strength.

MIP: Patients breathe through a flanged mouthpiece with nose clips in place. Patients are instructed to exhale to RV. At RV, a valve or shutter is closed and the patient is coached to inhale as forcefully as possible. Maximum pull should be maintained for 1-2 seconds. A standardized leak must be present in the measurement system to eliminate significant overstatement of MIP by allowing the cheek muscles to contribute to the measured pressures. Initial maximum negative pressures that cannot be maintained for 1 full second are ignored.

MEP: Patients breathe through a flanged mouthpiece with nose clips in place. Patients are instructed to inhale to TLC. At TLC, a valve or shutter is closed and the patient is coached to exhale as forcefully as possible. Maximum push should be maintained for 1-2 seconds. Initial maximum positive pressures that cannot be maintained for 1 full second are ignored.

A new procedure, measurement of sniff nasal-inspiratory force (SNIF) has recently been shown to have promising utility in predicting mortality in patients with amyotrophic lateral sclerosis (ALS). A standardized device is not commercially available. A polyethylene catheter ending in a plug is attached to a pressure transducer, and the plug end is inserted into a nostril. The contralateral nostril is occluded, and the patient is instructed to exhale to FRC, then close the mouth and take a deep sniff or a maximal inspiratory effort. Both nostrils are tested, and the highest of 6 recorded pressures sustained for at least 1 second is reported.

Results

Maximal inspiratory mouth pressure (PImax), maximal expiratory mouth pressure (PEmax), and SNIF are reported in centimeters of water pressure.

Interpretation

As many as 10 efforts are needed before consistency (2 measurements within 10% of the highest measured pressure) is achieved in some patients. When respiratory muscle fatigue or neuromuscular disease is present, fatigue may set in before consistency is achieved. Adequate rest between efforts is important.

The range of normal values is broad, suggesting wide variations in respiratory muscle strength among normal values. This makes interpretation of low values difficult. Initial values should be compared to the lower limit of normal values for the patient's age.

In general, a PImax of less than -80 cm water pressure and a PEmax of greater than +80 cm water pressure excludes important weakness of the respiratory muscles. Patients with a PEmax less than 50 cm water pressure may have difficulty generating sufficient cough to clear respiratory secretions.

In patients with ALS, a SNIF pressure less than 40 cmH_2O was associated with a hazard risk for death of 9.1 (confidence interval [CI], 4-20.8) and the median mortality was 6 ± 0.3 months (95% CI, 2.5-8.5 mo).

Technical considerations

All tests are dependent on effort and technique. Good instruction, vigorous coaching, and adequate rest between efforts are essential. Maximum values should be reproducible within the greater of 10% or 5 cm water pressure. A controlled leak (1 mm diameter, 15 mm length) must be part of the system to prevent erroneously high MIP readings resulting from the use of cheek muscles. This leak is not needed for MEP or SNIF pressure measurements.

PULSE OXIMETRY

Synonyms

Oximetry, oxygen saturation check, oxygen sat check, exercise oximetry, oxygen titration by oximetry, oxygen saturation measured using pulse oxymetry (SpO_2), oxygen desaturation test

Contraindications

No contraindications exist.

Patient care/preparations

Standard pulse oximeter probes may be placed on fingers or earlobes of ambulatory patients. Some oximeters offer reflectance probes that can be placed on the forehead. Fingernail polish should be removed, and peripheral circulation should be maximized by warming or by applying vasodilating cream, if necessary.

Test

Although widely used, the practice of assessing oxygen desaturation by pulse oximetry is poorly standardized. The principle of oximetry measurement by spectrophotometry, although improving, is not as reliable as many practitioners believe. One side of the oximeter probe acts as a light-emitting source, and the other side acts as a photodetector. The probe is placed on a finger or earlobe. A forehead reflectance probe may also be used. The relative absorption of red (absorbed by oxygenated blood) and infrared (absorbed by deoxygenated blood) light of the pulsatile (systolic) component of the absorption waveform correlates to arterial blood oxygen saturation.

Resting readings should be for at least 5 minutes, and the stability of the reading should be characterized by the report. If a finger probe is used, the hand should be placed on the chest at the level of the heart to minimize venous pulsation, which can falsely lower the reading. Correlation of the heart rate displayed on the oximeter with an ECG rate or a manually palpated pulse can help characterize the quality of the signal. Agreement within 5 or more beats per minute generally rules out significant motion artifact. Ideally, correlation of pulse oximetry saturation should be made with a measured oxygen saturation by multiple wavelength spectrophotometry on a simultaneously obtained arterial blood gas sample.

Results

Documentation of the type of pulse oximeter used, probe type, and probe site should be included on each report. The heart rate and SpO_2 readings at rest should be reported.

When obtaining pulse oximetry readings during exercise, the type and intensity of exercise (e.g., walking speed, duration of activity) along with the heart rate and SpO_2 at the end of the activity should be reported. When desaturation is detected, the activity should be repeated with supplemental oxygen in place to demonstrate improvement in SpO_2 values.

Pulse oximetry is often performed (though optional) in the setting of the 6-minute walk test, a standardized measure of functional exercise capacity. This test is a measure of the maximum distance the patient is able to walk in a hallway with a minimum of 100 feet marked in 5-foot increments. The patient is permitted to slow down or even stop, if required; however, the elapsed time counter continues during rest periods. This test should be performed while exercise oxygen needs are being adequately met with portable oxygen delivery. Borg dyspnea and fatigue scores are collected immediately after completion of the walk.

Interpretation

Interpretation of oximetry studies, while seemingly simple, generally is not possible without characterizing oximeter accuracy by correlating SpO_2 with at least one simultaneously obtained arterial oxygen saturation (SaO_2). Laboratories should characterize the average oximeter bias (SpO_2 - SaO_2) through pooled data to better understand the limitations of using the oximeter, but this does not eliminate the possibility that oximeter readings on individual patients may exhibit larger biases. While SpO_2 readings greater than 95% make the probability of clinically significant hypoxemia unlikely, clinical suspicion of hypoxemia should initiate the examination of ABGs. The goal of titration of supplemental oxygen should be a stable SpO_2 reading of 93% or higher. Arterial desaturation can be considered present when the pulse oximeter saturation falls more than 4% below the baseline reading.

The role of pulse oximetry in the Medicare guidelines for reimbursement for continuous supplemental oxygen therapy are demonstration of one of the following while at rest and breathing room air: PaO_2 less than or equal to 55 mm Hg, SaO_2 less than or equal to 88%, or SpO_2 less than or equal to 88%.

If supplemental oxygen is prescribed at a flow rate of greater than 4 liters per minute (LPM), the results of a PaO_2 or oxygen saturation (SaO_2 or SpO_2) taken on 4 LPM supplemental oxygen must be provided.

Patients may qualify for supplemental oxygen therapy reimbursement even if the PaO_2 is greater than 55 mm Hg and the SaO_2 or SpO_2 is greater than 88% if one of the following conditions is met: (1) dependent edema due to congestive heart failure; (2) cor pulmonale

documented by P pulmonale on an ECG or by an echocardiogram, gated blood pool scan, or direct pulmonary artery pressure measurement, and (3) hematocrit greater than 56%.

Technical considerations

Carboxyhemoglobin (CoHb) and methemoglobin (metHb) absorb light at the same wavelength as deoxyhemoglobin, causing a very significant overestimation of SaO_2 when these are elevated. Pulse oximetry has other shortcomings. It does not provide information about the oxygen content of the arterial blood. Tissue hypoxia can exist when SpO_2 is normal when anemia is present. Elevated levels of dysfunctional hemoglobins (CoHb, metHb) can cause significant overestimation of the actual SaO_2.

Additionally, pulse oximetry does not address the adequacy of ventilation, which can be assessed only by evaluation of the partial pressure of carbon dioxide in arterial gas ($PaCO_2$). Motion of the finger within the probe can cause a motion artifact secondary to equal rhythmic absorption of red and infrared light that most oximeters interpret as an SpO_2 reading of 85%. Disposable finger probes fixed to the probe site with adhesive and fixed positioning of the probe site during walking can minimize this.

Pulse oximetry tends to overestimate SaO_2. One reason for this is the fact that pulse oximetry expresses the percentage of oxyhemoglobin without consideration for CoHb or metHb.

$$SpO_2 = \text{oxyhemoglobin}/(\text{oxyhemoglobin} + \text{reduced hemoglobin [rHb]})$$

In contrast, spectrophotometrically determined oxygen saturation from an ABG sample expresses oxygen saturation as the percentage of the sum of reduced hemoglobin, oxyhemoglobin, CoHb, and MetHb.

$$SaO_2 = \text{oxyhemoglobin}/(\text{oxyhemoglobin} + \text{rHb} + \text{CoHb} + \text{metHb})$$

This significant difference generally results in pulse oximeters reporting an oxyhemoglobin value that is 2-3% higher than the spectrophotometrically determined oxygen saturation, even when the pulse oximeter is functioning perfectly.

While the accuracy of pulse oximetry generally is good in population studies (SaO_2 - SpO_2 <2%), SpO_2 values in individual patients may show a much greater bias, even when dysfunctional Hb levels are normal. Anemia and polycythemia can cause greater oximeter overestimation. SaO_2 from simultaneously obtained ABG determinations should be used to characterize oximeter bias in individual patients, although this is not commonly performed.

ABG determinations should be considered whenever the clinical suspicion of hypoxemia exists, even when the oximeter displays a value over the threshold of 88%. Finally, the shape of the oxygen dissociation curve causes the pulse oximeter to be inherently

insensitive to mild hypoxemia because relatively large changes in PaO_2 in the flat upper portion of the curve cause very small changes in blood SaO_2.

Advantages of pulse oximetry include that it is noninvasive, simple, and can be used to evaluate trends (evaluation of oxygenation during exercise, sleep, during procedures).

Disadvantages of pulse oximetry include that it cannot be used to assess oxygen delivery (anemia) or adequacy of ventilation ($PaCO_2$) and that accuracy is lessened in the presence of elevated dysfunctional hemoglobin levels (CoHb, metHb), with a tendency to overestimate SaO_2 by an average of 2-3%.

Factors that influence the accuracy of pulse oximetry readings

Overestimation of SaO_2 is possible with bright sunlight on the probe, fluorescent lights, operating room lights, infrared heat lamps, elevated CoHb, elevated metHb, anemia, and motion artifact if the actual SaO_2 is less than 85%.

Underestimation of SaO_2 is possible because intravascular dyes, such as methylene blue and indocyanine green, produce transient reductions in SpO_2. Fingernail polish, increased venous pressures, and motion artifact if the actual SaO_2 is greater than 85% also can cause underestimation of the SaO_2.

METHACHOLINE CHALLENGE TESTING

Synonyms

Mecholyl challenge, bronchial provocation test

Indications

Diagnose asthma, confirm diagnosis of asthma, document severity of hyperresponsiveness, and follow changes in hyperresponsiveness

Contraindications

Absolute contraindications include FEV_1 less than 1.5 L in adults, less than 1 L in children, recent severe acute asthma, myocardial infarction or cerebral vascular accident within 3 months, and arterial aneurysm.

Relative contraindications include moderate baseline airway obstruction, spirometry-induced bronchoconstriction, recent upper respiratory tract infection (URI), exacerbation of asthma, hypertension, pregnancy, and epilepsy.

Patient care/preparations

The following medications are withdrawn before a methacholine challenge test for the specified period:

- Short-acting beta agonists (6 h)
- Long-acting beta agonists (36 h)
- Oral beta agonists (24 h)
- Short-acting methylxanthines (12 h)
- Long-acting methylxanthines (48 h)
- Anticholinergics (6 h)
- Cromolyn sodium (24 h)
- Antihistamines (72 h)
- The withholding of oral or inhaled steroids before methacholine has not been shown to be necessary but may have an impact. The appropriateness of the methacholine challenge test in a patient who requires oral steroids should be considered (see Contraindications).

Test

The following list shows the most common schedule of methacholine dosing in use in the United States today. Some labs begin with the lowest strength methacholine solution immediately after baseline; others advocate the use of a diluent stage between baseline and methacholine. This allows identification of a small percentage of individuals who exhibit significant bronchoconstriction in response to the diluent itself, suggestion, or repeated spirometry efforts. Abbreviated protocols that start with higher concentrations of methacholine should be used cautiously, if at all.

Methacholine challenge schedule: After establishing baseline spirometry measurements, the patient inhales 5 breaths of saline or diluent aerosol and then 5 breaths of each of the following strengths of aerosolized methacholine in solution: 0.0625 mg/mL, 0.25 mg/mL, 1 mg/mL, 4 mg/mL, and 16 mg/mL.

An alternative longer (10-stage) dosing schedule that may yield a more precise assessment of airway hyperreactivity calls for the patient to inhale 5 breaths of methacholine aerosol in the following strengths: 0.031 mg/mL, 0.0625 mg/mL, 0.125 mg/mL, 0.25 mg/mL, 0.5 mg/mL, 1 mg/mL, 2 mg/mL, 4 mg/mL, 8 mg/mL, and 16 mg/mL.

The following dosing schedule is approved by the US Food and Drug Administration and also may be used, although the ATS guidelines for methacholine challenge testing recommend 1 of the 2 schedules outlined above because the dosing steps are more even: 0.025 mg/mL, 0.25 mg/mL, 2.5 mg/mL, 10 mg/mL, and 25 mg/mL.

Methacholine aerosol is delivered in a standardized fashion by using a dosimeter, a device that applies a 0.6-second burst of compressed air to the nebulizer at the start of the

inhalation from FRC to TLC. Subjects should hold their breath for 5 seconds. Spirometry is performed 30-90 seconds after the end of the last breath of each stage of the challenge. Symptoms volunteered by the subject are recorded. The challenge is discontinued when a fall in FEV_1 of greater than 20% is observed upon repeat efforts or a final cumulative dose of 188.64 cumulative dose units is received. Administration of a bronchodilator should immediately follow the final postmethacholine assessment.

Results

Results are presented as both a table of spirometry parameters for each stage of the challenge and as a dose-response curve plotting the fall in FEV_1 against the methacholine concentration. The reporting of the PC20 (provocative concentration in mg/mL causing a 20% fall in FEV_1 from baseline) is the usual method of expressing the results of a positive test.

Interpretation

A 20% fall in FEV_1 generally is considered a positive test. One scheme for using the PC20 FEV_1 to characterize the severity of clinical hyperreactivity has been used by Hargreave et al. PC20 FEV_1 severity is assessed as follows: 0.03-0.124 is considered severe, 0.125-1.99 is considered moderate, 2.00-7.99 is considered mild, and 8-25 is considered an increased hyperresponsive reaction (however, clinically significant disease is not common).

Technical considerations

Spurious nonreproducible falls should not be considered valid. Continuation of the challenge beyond 25 mg/mL has little clinical value because responses of some healthy patients who are nonasthmatic begin at this level.

Failure to demonstrate bronchial hyperreactivity does not totally exclude asthma, particularly asthma triggered by occupational exposure to chemicals (e.g., methylene diisocyanate, toluene diisocyanate).

Nonspecific bronchial hyperreactivity is characteristic of asthma but can persist for some months after a viral respiratory illness.

Nonspecific bronchial hyperreactivity also can be found in chronic obstructive pulmonary disease, cystic fibrosis, and bronchiectasis.

CARDIOPULMONARY STRESS TESTING

Synonyms

Cardiopulmonary exercise (CPX) test

Indications

CPX test is used for evaluation of dyspnea that is out of proportion to findings on static pulmonary function tests, preoperative evaluation of operative risk when lung function is compromised or removal of lung segments is contemplated, evaluation of disability, identification of exercise-induced asthma, and evaluation of therapy.

Contraindications

Absolute contraindications include unstable angina, aortic stenosis, uncontrolled hypertension, uncontrolled asthma, hypoxemia (SaO_2 <85% at rest), and febrile illness.

Relative contraindications include hypertension, cardiac disease, epilepsy, and locomotor disorder (inability to exercise).

Patient care/preparations

Perform calibration of the volume-measuring device and gas analyzers. Patients should avoid eating a heavy meal 1-2 hours before the test. Patients should wear loose comfortable clothing and athletic shoes. If exercise-induced bronchoconstriction is considered, withhold medications as with the methacholine challenge. ECG electrodes/leads are applied. Adjustment of the seat height on a bicycle ergometer is made to permit near-full leg extension when one pedal is at its lowest position (slight bend at knee). Airtight fitting of a low dead-space mask or mouthpiece/nose clips is applied. Apply and correctly position a blood pressure cuff. A pulse oximeter probe is applied securely. Insertion of an indwelling arterial canula for arterial blood sampling is optional.

Test

The cardiopulmonary exercise test is a means of measuring the integrated response of the pulmonary, cardiovascular, and muscular systems to a steadily increasing workload. The test may be performed on a bicycle ergometer or treadmill. Resting measurements are made for 3-5 minutes. Three minutes of unloaded cycling is performed as a warmup period. The workload is incremented at a rate designed to allow reaching maximum work capacity in 8-12 minutes. The test continues to a point of symptom limitation (severe dyspnea, chest pain, faintness, pallor, inability to continue pedaling or walking) or discontinuation by medical staff for one of the following conditions: significant ECG abnormalities, fall in systolic or diastolic blood pressure (BP) greater than 20 mm Hg

below resting value, rise in systolic BP to greater than 250 mm Hg, rise in diastolic BP to greater than 120 mm Hg, severe oxygen desaturation (<80%), or achievement of maximum predicted heart rate.

Determining the proper rate of workload incrementation: The workload incrementation rate should be chosen to produce a test of 8-12 minutes in length. If the workload incrementation is too high, the test will be too brief. In this circumstance, the patient should be allowed to recover and should be retested. If the workload incrementation is too small, fatigue may prevent a valid second test. Below is Wasserman's method for estimating the workload increment size for cycle ergometry:

- Estimate the unloaded oxygen consumption per minute (VO_2): Unloaded VO_2 (mL/min) = 150 + (6 x weight [kg])
- Estimate the peak VO_2: Peak VO_2 (mL/min) = (height [cm] – age [y]) x 20 for sedentary men or peak VO_2 (mL/min) = (height [cm] – age [y]) x 14 for sedentary women
- Estimate the work rate increment: Work rate increment (watts/min) = (peak VO_2 (mL/min) – unloaded VO_2 (mL/min)/100

Patients with significant reductions in the predicted VEmax (FEV_1 below 50% of predicted) should use an increment of 10 watts/min or less. Patients with severe obstruction resulting in a preexercise maximum voluntary ventilation (MVV) of less than 40 L/min should use a 5-watt/min incrementation rate.

Results

The following parameters are measured or calculated on a breath-by-breath basis: minute ventilation (V_E, LPM), tidal volume (V_T, mL/breath), respiratory rate (RR, mL/breath), oxygen uptake (VO_2, mL/min and mL/min/kg), carbon dioxide production (VCO_2, mL/min), respiratory exchange ratio (RER, VCO_2-to-VO_2), SpO_2, heart rate (HR, beats/min), oxygen pulse (mL VO_2/min/heartbeat), and BP (mm Hg). If ABG determinations are obtained, discrete values for the ratio of dead space to tidal volume (VD-to-V_T) and alveolar to arterial oxygen gradient (A-a-to-O_2) can be calculated for that interval of exercise.

Interpretation

The assessment of a normal work capacity is made by evaluation of the peak oxygen uptake (VO_2 peak). The normal value for oxygen uptake is based on sex, age, and weight.

The predicted peak VO_2 is determined by the patient's age and sex. This value can be further refined for sedentary individuals by a 3-step process (see below) that adjusts the predicted value up or down based on a comparison of the patient's weight and their ideal body weight.

- Sedentary men: Calculate the cycle factor, i.e., cycle factor = 50.72 – (0.372 x age).
    - Step 1: Measure the man's weight (W [kg]) and height (H [cm]) in light clothes and without shoes, and record his age (A [y]).
    - Step 2: Calculate his normal (predicted) W in kg, i.e., normal (predicted) W = (0.79 x H) – 60.7.
    - Step 3A: If his actual W equals his normal W, the formula is predicted peak VO_2 (mL/min) = actual W x cycle factor.
    - Step 3B: If his actual W is less than his normal W, the formula is predicted peak VO_2 (mL/min) = [(normal W + actual W)/2] x cycle factor.
    - Step 3C: If his actual W exceeds his normal W, the formula is predicted peak VO_2 (mL/min) = (normal W x cycle factor) + [6 x (actual W – normal W)].
    - Step 4: If a treadmill is used rather than cycle, multiply predicted VO_2 by 1.11.
- Sedentary women: Calculate the cycle factor, i.e., cycle factor = 22.78 – (0.17 x age)
    - Step 1: Measure her weight (W [kg]) and height (H [cm]) in light clothes and without shoes, and record age (A [y]).
    - Step 2: Calculate her normal (predicted) W in kg, i.e., normal (predicted) W = (0.65 x H) – 42.8.
    - Step 3A: If her actual W equals her normal W, the formula is predicted peak VO_2 (mL/min) = (actual W + 43) x cycle factor.
    - Step 3B: If her actual W is less than her normal W, the formula is predicted peak VO_2 (mL/min) = [(normal W + actual W + 86)/2] x cycle factor.
    - Step 3C: If her actual W exceeds her normal W, the formula is predicted peak VO_2 (mL/min) = [(normal W + 43) x cycle factor] + [6 x (actual W – normal W)].
    - Step 4: If a treadmill is used rather than a cycle, multiply her predicted VO_2 by 1.11.

A normal CPX test demonstrates a normal peak VO_2, the peak HR at or below the predicted maximum HR, and demonstration of ventilatory reserve (peak ventilation/predicted maximum ventilation <65-70%). When the VO_2 peak is low, the peak HR is compared to the predicted maximum HR to determine cardiovascular reserve. A ratio of HR peak to HR predicted maximum that approaches or exceeds 1 indicates a clear cardiovascular limitation to exercise.

Likewise, the peak expired volume (minute ventilation, V_E) is compared to the larger of a pretest MVV or FEV_1 multiplied by 40 to determine the pulmonary reserve. A ratio of V_E peak to V_E predicted maximum that approaches or exceeds 1 is a clear indication of pulmonary limitation. A VO_2 peak below 15 mL/min/kg often is used as an indication of disability. Pulmonary limitation also may cause significant oxygen desaturation due to the reduction of the transit time of the pulmonary capillary blood to a point where diffusion limitation can occur. In the absence of cardiovascular or pulmonary limitation,

peripheral circulatory or skeletal muscle limitation may exist. This must be distinguished from poor effort or malingering.

The anaerobic threshold is defined as the workload (expressed as VO_2) in which blood lactate levels rise significantly, indicating that a significant fraction of the work is being accomplished by anaerobic metabolic sources. The establishment of the anaerobic threshold may have clinical importance, particularly when the evaluation seeks to determine the presence of an occupational disability.

Identifying the anaerobic threshold noninvasively: The noninvasive determination of the anaerobic threshold can be accomplished by analyzing time averaged (20- to 30-s intervals) plots of parameters measured or calculated during the CPX test. Two methods can be used, the V-slope method and the ventilatory equivalent method. Both methods allow determination of the same physiologic event, the increased production of carbon dioxide by isocapnic buffering of lactic acid produced by anaerobic metabolism and yield comparable estimations.

V-slope method: The V-slope method of determining the anaerobic threshold makes use of the fact that carbon dioxide production (VCO_2) plotted against oxygen consumption (VO_2) shows a slope of slightly less than 1 for work below the anaerobic threshold. A line of best fit for points obtained from the start of exercise is drawn through this plot to obtain the initial slope (S1). When this slope changes to a steeper slope (S2), it indicates an increase in carbon dioxide production from the isocapnic buffering of lactic acid. The intersection of S1 and S2 mark the anaerobic threshold, typically reported as either the absolute value of the oxygen uptake (VO_2, mL/min) at that point or as the percentage of the predicted peak VO_2.

Ventilatory equivalent method: The ventilatory equivalent method of determining the anaerobic threshold makes use of the derived values known as the ventilatory equivalents for oxygen and carbon dioxide. Carbon dioxide production (VCO_2) and oxygen consumption (VO_2) divided into the minute ventilation (V_E, L/min) are known as the ventilatory equivalents for carbon dioxide (V_E/VCO_2) and oxygen (V_E/VO_2). When time averaged (20- to 30-s intervals) plots of V_E/VO_2 and V_E/VCO_2 are plotted against time, the point at which the V_E/VO_2 is seen to increase without a simultaneous increase in the V_E/VCO_2 marks the anaerobic threshold.

Case examples

Normal male: This 46-year-old man who previously smoked (smoking history of 30 pack-years) is evaluated as a biological control in the authors' laboratory. He has no health complaints.

Table 1A. Lung Function

Parameter	Predicted	Measured

Age		46
Sex		Male
Height (cm)		188
Weight (kg)		104
Hemoglobin		15.4
VC (L)	5.65	6.5
TLC (L)	7.76	9.02
RV (L)	2.17	2
FEV_1 (L)	4.47	5.01
FEV_1/FEV (%)	79	76
MVV (L/min)	170	212
DLCO (mL/min/mm Hg)	31.6	32.4

Table 1B. Exercise

Parameter	Predicted	Measured
Peak VO_2 (L/min)	3.05	3.03
Maximum HR (beats/min)	174	182
Maximum O_2 pulse (mL/beat)	17.5	16.6
AT (L/min)	>1.34	1.5
BP (mm Hg) (rest, maximum)		120/68, 188/85
Maximum V_E (L/min)		129
Ventilatory reserve (L/min)	>15	83
SpO_2 (%) (rest, maximum)		98, 98

The patient stopped the exercise test citing leg fatigue and dyspnea as the reasons for terminating the test. The results reveal a normal oxygen uptake with a normal cardiovascular limitation to exercise (predicted maximum HR was exceeded). Significant ventilatory reserve existed at the end of exercise.

Ventilatory limitation: A 55-year-old man with a smoking history of 35 pack-years and a diagnosis of emphysema was referred for cardiopulmonary exercise testing to evaluate the complaint of dyspnea upon exertion. The patient uses an inhaled beta-agonist as needed.

Table 2A. Lung Function

Parameter	Predicted	Measured
Age		55
Sex		Male
Height (cm)		173
Weight (kg)		80
Hemoglobin		15.6
VC (L)	4.55	4.32
TLC (L)	6.6	7.31
RV (L)	2.04	3.56
FEV_1 (L)	3.63	2.68
FEV_1/FEV (%)	80	62
MVV (L/min)	134	99
DLCO (mL/min/mm Hg)	23.8	16.7

Table 2B. Exercise

Parameter	Predicted	Measured

Peak VO_2 (L/min)	2.32	1.39
Maximum HR (beats/min)	165	122
Maximum O_2 pulse (mL/beat)	14.1	11.4
AT (L/min)	>1.04	1
BP (mm Hg) (rest, maximum)		117/85, 170/102
Maximum V_E (L/min)		93
Ventilatory reserve (L/min)	>15	6
SpO_2 (%) (rest, maximum)		95/91

The patient terminated the procedure citing dyspnea as the sole reason for stopping the test. The results show moderate impairment of the peak oxygen consumption with a clear ventilatory limitation to exercise. Significant cardiovascular reserve existed at the end of exercise, and the ventilatory reserve was below normal. Pulse oximetry readings are suggestive of exercise desaturation.

Cardiac limitation: This 48-year-old woman was referred for a cardiopulmonary exercise testing to evaluate her shortness of breath upon exertion over the last 6 months. Pulmonary function tests reveal a mild restrictive ventilatory defect with a normal DLCO, suggesting no active parenchymal disease.

Table 3A. Lung Function

Parameter	Parameter Predicted	Measured
Age		48
Sex		Female
Height (cm)		158
Weight (kg)		55
Hemoglobin		13.4
VC (L)	3.13	2.1

TLC (L)	4.79	3.57
RV (L)	2.04	3.56
FEV_1(L)	2.6	1.79
FEV_1/FEV (%)	83	85
MVV (L/min)	98	85
DLCO (mL/min/mm Hg)	18.9	20.6

Table 3B. Exercise

Parameter	Predicted	Measured
Peak VO_2 (L/min)	1.47	0.79
Maximum HR (beats/min)	172	184
Maximum O_2 pulse (mL/beat)	8.5	4.3
AT (L/min)	>0.69	0.62
BP (mm Hg) (rest, maximum)		115/89, 165/88
Maximum V_E (L/min)		49
Ventilatory reserve (L/min)	>15	26
SpO_2 (%) (rest, maximum)		96, 94

The patient terminated the exercise test citing shortness of breath. The results reveal a moderately reduced oxygen consumption with a cardiovascular limitation (HR maximum exceeded the predicted maximum HR) and adequate ventilatory reserve. The oxygen pulse did not increase normally during the study, with near-peak values observed during unloaded cycling and very little increase during the work phase of the study. Cardiac function studies demonstrated left ventricular failure secondary to mitral insufficiency.

Preoperative evaluation for pneumonectomy

VO_2 maximum values greater than 20/mL/kg/min or 75% of predicted indicate the ability to withstand pneumonectomy when the cardiac history is negative.

A VO_2 maximum between 10 and 20 mL/kg/min and 40-75% of predicted require prediction of postoperative FEV_1, DLCO, and VO_2. Prediction of postoperative function is calculated by multiplying the preoperative value by the fraction of total perfusion ascribed to the remaining lung, as follows:

> Predicted postoperative (PPO) (FEV_1, DLCO, or VO_2) = preoperative (FEV_1, DLCO, or VO_2) x Q% of the remaining lung

When the FEV_1 PPO and DLCO PPO are greater than 40% and the VO_2 PPO is greater than 10 mL/kg/min and 35% of predicted, resection up to the calculated extent is feasible.

A VO_2 maximum of less than 40% or 10 mL/kg/min or VO_2 maximum PPO of less than 35% or 10 mL/kg/min strongly suggest inoperability for lung resection candidates.

Technical considerations

Because motion artifact typically causes an estimation of SpO_2 of 85%, care should be taken to differentiate oxygen desaturation from motion artifact, particularly if circulation to the oximeter probe site is compromised by pressure on a treadmill handrail or ergometer handgrip. If arterial blood is sampled at peak exercise, it should be obtained while exercising because PaO_2 values can recover in as little as 15-30 seconds after cessation of exercise.

ARTERIAL BLOOD GASES

Synonyms

ABGs

Indications

ABGs are used in the evaluation of ventilation, oxygenation, and acid-base status.

Contraindications

No contraindications exist, although some sampling sites may be deemed unsuitable for use secondary to peripheral circulatory disorders.

Patient care/preparations

Assess collateral circulation. If a baseline room air oxygen level is desired, patients should discontinue use of supplemental oxygen for 20 minutes. If the patient is receiving anticoagulant therapy, extra care must be taken to continue pressure on the sampling site until bleeding has stopped. Personnel obtaining and/or analyzing the sample should don rubber gloves and take appropriate infection control measures.

Test

The sampling site of choice is the radial artery, unless tests of collateral circulation indicate otherwise. Samples also may be obtained from the brachial and femoral arteries.

Results

Measured: pH, $PaCO_2$ (mm Hg or kilopascal), PaO_2 (mm Hg or kilopascal), and, if hemoximetry is performed, total hemoglobin (tHb, g/dL), oxyhemoglobin (O_2Hb [%]), and metHb (%)

Calculated: Total bicarbonate (HCO_3 [mEq/L]), base excess or deficit (mEq/L), oxygen content (CO_2 [mL] O_2/dL or volume%)

Interpretation

ABGs provide 3 assessments of the function of the respiratory system: evaluation of oxygenation (PaO_2 [mm Hg] and A-a oxygen gradient PO_2), evaluation of the adequacy of ventilation ($PaCO_2$ [mm Hg]), and evaluation of the lung's role in acid-base balance of the arterial blood (pH, $PaCO_2$).

Oxygenation

In healthy subjects breathing room air at sea level, the normal PaO_2 (mm Hg) is affected by age, body mass index (BMI), $PaCO_2$ (mm Hg), and posture (upright vs. supine). An average decline in PaO_2 of 10 mm Hg occurs for each decade of life up to approximately 75 years.

Normal PaO_2 can be predicted by the following equation:

$$\text{Normal resting, room air } PaO_2 = 104 - (0.27 \times \text{age}) + 7 \text{ mm Hg}$$

Low levels of arterial oxygen can be attributed to 1 or more of 5 categories, as follows: (1) ventilation/perfusion (V/Q) mismatching, (2) alveolar-capillary diffusion limitation, (3) hypoventilation, (4) anatomic right-to-left shunts, and (5) low inspired oxygen partial pressures (e.g., altitude).

Evaluation of hypoventilation as a cause for a reduced PaO_2 can be made using the ideal alveolar air equation, which allows computation of an alveolar oxygen tension and calculation of an A-a oxygen gradient.

The simplified ideal alveolar gas equation is as follows:

$$PaO_2 = PIO_2 – (PaCO_2/R)$$

PaO_2 is the ideal alveolar oxygen tension, PIO_2 is partial pressure of inspired oxygen, $PaCO_2$ is partial pressure of arterial carbon dioxide, and R is the ratio of carbon dioxide production to oxygen consumption (generally assumed to be 0.8 at rest).

The measured partial pressure of oxygen in the arterial blood is subtracted from the ideal alveolar oxygen tension to calculate the A-a PO_2 gradient. This gradient can be compared to a normal age-adjusted gradient (normal resting, room air A-a oxygen gradient = (age + 4)/4) to determine the effects of hypoventilation and hyperventilation. Reduced arterial oxygen tension secondary to pure hypoventilation exhibits a normal A-a PO_2 gradient.

Determination of right-to-left shunt by blood gases: The fraction of the cardiac output that bypasses normal circulatory pathways can be estimated by obtaining an ABG sample after 20 minutes of breathing 100% oxygen from a large reservoir bag. This period of oxygen breathing should wash out all of the nitrogen from all ventilated alveoli. This makes the measured oxygen gradient (A-a PO_2) independent of V/Q inequalities. While the true shunt requires a measurement of a mixed venous oxygen level, this often is not practical, and an estimated arterial-to-mixed venous oxygen content difference of 5 volume percent often is assumed, as shown.

$$Qs/Qt = (0.0031 \text{ X } [A\text{-}a]PO_2)/(0.0031 \text{ X } [A\text{-}a]PO_2 + 5)$$

Qs/Qt is the calculated right-to-left shunt fraction, 0.0031 is the solubility coefficient of oxygen in blood, (A-a) PO_2 is the gradient of alveolar to arterial oxygen partial pressure after 20 minutes of breathing 100% oxygen, and 5 is the assumed difference in resting arterial-to-mixed venous oxygen content. States of low and high cardiac output may invalidate the assumed arteriovenous oxygen (A-VO_2) difference and cause significant error in the calculated shunt fraction.

Causes of increased right-to-left shunting may be intrapulmonary, such as pulmonary arteriovenous malformations, dilated capillaries in hepatopulmonary syndrome, lobar collapse or consolidation, or extrapulmonary conditions (e.g., right-to-left intracardiac shunts, bronchial artery-to-pulmonary vein connections.

Technical considerations

Samples must be mixed with an anticoagulant, preferably heparin (if liquid, dead space volume of syringe and needle should be filled before sampling with 1000 U/mL heparin) to avoid clotting before or during analysis. If analysis is not performed immediately, samples should be placed in an ice-water solution.

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PULMONARY FUNCTION TESTING
EXAM

1. Dynamic airway compression can occur in which of the following situations?
A. When the intrapleural pressure exceeds the airway pressure
B. when there is an increased surfactant production
C. During forced expiration
D. when the compliance of the lungs is reduced
E. When the airway pressure is below atmospheric pressure

2. The normal resting individual will consume less than _____ % of the total resting oxygen consumption for the work of breathing.
A. 2
B. 5
C. 8
D. 10
E. 15

3. Which of the following is a definition of the expiratory reserve volume?
A. The maximum volume of gas that can be exhaled from the lungs after a maximum inspiration
B. The maximum volume of gas that can be exhaled from the lungs after a normal inspiration
C. The volume of gas that remains in the lungs after a normal exhalation
D. The volume of gas that remains in the lungs after a normal exhalation
E. The maximum volume of gas that can be exhaled from the resting end-expiratory level

4. If a patient has an FRC of 3000 ml, a V of 600 ml, a VC of 4400 ml, and an ERV of 1400 ml, the TLC would be:
A. 3600 ml
B. 5200 ml
C. 5800 ml
D. 6000 ml
E. 7400 ml

5. In the closed circuit method of determining residual volume, which gas is used for the indicator gas?
A. Carbon monoxide
B. Helium
C. Nitrogen
D. Oxygen
E. Carbon Dioxide

6. Which of the following methods for determining the residual volume account for air trapping?
A. Closed circuit method
B. Open circuit method
C. Single breath method
D. Plethysmographic method
E. Carbon dioxide diffusion method

7. Which phase of the single breath nitrogen test represent exhalation of alveolar gases throughout the lungs?
A. Phase I
B. Phase II
C. Phase III
D. Phase IV
E. Phase V

8. In the "Measurement of Diffusing Capacity" the test gas is a known concentration of gases usually consistant of _____ % oxygen.
A. 10
B. 11
C. 20
D. 21
E. 30

9. Which of the following are typical of obstructive pulmonary diseases?
A. Emphysema
B. Chronic bronchitis
C. Cystic fibrosis
D. All of the above
E. None of the above

10. The most common gas measured by paramagnetic analyzers is:
A. Oxygen
B. Carbon dioxide
C. Carbon monoxide

11. The minimal number of acceptable spirometric FVC maneuvers to be preformed is:
A. 1
B. 2
C. 3
D. 4
E. 5

12. A decrease in peak expiratory flow rates are indicative of:
A. Obstructive disease
B. Pulmonary embole
C. Restrictive Disease
D. Atelectasis

13. The normal FRC for a young adult male is:
A. 1000 ml
B. 1500 ml
C. 2400 ml
D. 3600 ml
E. 4000 ml

14. Which of the following techniques is the most accurate to measure the effect of a Bronchodilator?
A. Wright peak flow meter
B. Wright respirometer
C. Collins spirometer
D. Schwartz rebreathing tube

15. In preparing to perform a radial arterial puncture, a modified Allen's test is used to determine the presence of:
A. Raynaud's phenomenon
B. Collateral Circulation
C. Clubbing
D. Pulsus paradoxus

16. The normal range for FVC1 sec. In an adult is:
A. 55% to 65%
B. 75% to 85%
C. 85% to 95%
D. Greater than 95%

17. The normal range for FVC2 sec. In an adult is:
A. 55% to 65%
B. 75% to 85%
C. 85% to 95%
D. Greater than 95%

18. The normal range for FVC3 sec. In an adult is:

A. 55% to 65%
B. 75% to 85%
C. 85% to 95%
D. Greater than 95%

19. Residual volume is the volume of gas:
A. That can be maximally exhaled
B. Remaining in the lungs at the end of a normal expiration
C. Remaining in the lungs at the end of a maximum expiration
D. In the lungs following a maximum inspiration
E. In the lungs following a normal inspiration

20. The vital capacity is defined as the:
A. Volume of air that can be completely exhaled after a maximum inspiration
B. Total volume of air that the lungs contain
C. Maximum capacity of ventilation for 1 minute
D. Volume of air that can be exhaled after a normal inspiration
E. Volume of air that can be inhaled following a normal inspiration

21. The components of the vital capacity include:
A. Inspiration reserve volume, expiratory reserve volume and functional residual capacity
B. Inspiration reserve volume, expiratory reserve volume and tidal volume
C. Inspiratory capacity, expiratory reserve volume and residual volume
D. Inspiratory capacity, expiratory capacity and residual volume
E. Inspiratory capacity and residual volume

22. When an aerosolized bronchodilator is administered, the most important parameter to monitor is the patient's:
A. Skin color
B. Respiratory rate
C. Blood pressure
D. Heart rate

23. In the industrial screening situation which of the following test is regarded as the most useful indicator of airway obstruction:
A. Maximum voluntary ventilation (MVV)
B. Forced expiratory flow between 200 and 1200 ml. of the vital capacity
C. Peak expiratory flow rates
D. Forced expiratory volume in one second expressed as a percent of the total FVC (FEV1/FVC%)
E. Forced Vital Capacity (FVC)

24. All of the following are important instrument A.T.S. minimal standards except:
A. Volume of at least 7 liters a BTPS
B. Accuracy of 50 ml or to within 3% of reading, whichever is greatest
C. Digital readouts of results
D. Provisions of a written tracing
E. Capability of being calibrated in the field

25. The FEV1 is:
A. The first fixed expiratory volume
B. The volume of air forcibly exhaled during the first second of expiration
C. The final exhaled volume at one minute
D. The volume of air exhaled during the last second of exhalation

26. Under normal circumstances, the spirometry can be performed:
I Sitting
II Standing
III Prone
IV Supine

A. I only
B. I and III
C. I and II
D. I and IV

27. A decreased FVC is frequently seen in:
I Asthma
II Pleural effusion
III Atelectasis
IV Bronchitis

A. I only
B. I and II
C. I and III
D. I and IV

28. Spirometer is an instrument for measuring:
I flow rates
II residual volume
III lung volumes
IV functional residual capacity

A. I and II only
B. I and III only
C. II and IV only
D. III and IV only

29. In the calculation of the FEV1/FVC%, the largest FEC1 and FVC should be used:
I only if they are from the same curves
II only on the first curve
III even though they come from different curves
IV as long as the two best curves do not vary more than +/- 5%

A. I and II only
B. I and III only
C. II and IV only
D. III and IV only

30. Which of the following can be an important source of variable effort:
I early termination
II cough
III inconsistent effort
IV decreased vital capacity

A. I only
B. I and II only
C. I, II, and III only
D. I, II, III and IV

31. During a pulmonary function test, a patient has a V.C. of 3.8 liters and an F.V.C. of 3.4 liters, her predicted F.V.C. is 3.9 liters. Based on these values, which of the following conclusions can be made:
A. The patient's lung function is normal
B. The patient has a restirictive dysfunction
C. The equipment is not properly calibrated
D. The patient has some Bronchiole collapse
E. The patient has a restrictive and obstructive dysfunction

32. A patient with reduced flow rates and an increased total lun capacity and residual volume has which of the following conditions?
A. Restrictive disease
B. Obstructive disease
C. Restrictive and obstructive disease
D. There is not enough information to make a diagnosis

33. The pneumotachograph measures flow by measuring:
A. The number of air swirls
B. Volume change
C. Pressure difference across a fixed resistance
D. The current required to heat a small wire

34. The term “restrictive process" usually refers to:
A. Reduced airflow
B. Increased obstruction
C. Reduced lung volumes
D. Reduced FEV1/FVC ratio

35. In a patient with severe emphysema the FRC determined by multiple breath closed-circuit helium dilution will be:
A. Greater then the FRC determined by N2 washout
B. Greater then the FRC determined by body plethysmograph
C. Less than the FRC determined by chest x-ray
D. Less than the FRC determined by body plethysmograph

36. If the IRV = 2.0 liters, the Vt = 0.5 liters, the FRC = 2.9 liters, and the VC = 4.4 liters,
the TLC is:
A. 4.90 liters
B. 4.50 liters
C. 5.4 liters
D. 6.40 liters

MEDEDSYS

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How to Complete Your Test and Print Your Certificate Online

If you chose to receive your order by postal mail, you have been mailed the printed course material(s) and the printed test(s). To take a test, simply complete the mailed test and send it back. Upon successful completion of a test, a certificate will be mailed or faxed to you. If you don't wish to mail the test back, customers who chose to have the course material(s) mailed may also follow the steps below to complete a test and print a certificate online.

INSTRUCTIONS

1. Go to www.mededsys.com

2. Login and go to "My Account".

3. On the page that opens, select an option from the "My Courses" menu.

4. Select the test you wish to complete.

5. After completion of test, print your certificate online by clicking on the "Continue" button. Alternatively, you may return to the "My Courses" section and select the option to print a certificate.