8 Pulmonary Function Testing

Tarpan Shah

LEARNING OBJECTIVES

At the end of the chapter, the reader will be able to:
- Understand the concepts of pulmonary function testing.
- Describe the various methods of pulmonary function testing available.
- Explain the indications and contraindications of pulmonary function testing.
- Understand the process of interpretation of a pulmonary function testing report.

CHAPTER OUTLINE

- Introduction
- Important Terminologies Related to Pulmonary Function Testing
  - Lung Volumes
  - Lung Capacities
  - Rates of Flow
- Methods of Pulmonary Function Testing
  - Spirometry
  - Closed-circuit Helium Dilution Method
  - Open-circuit Nitrogen Washout Method
  - Body Plethysmography
- Indications for Pulmonary Function Testing
  - Pulmonary Function Testing in Preoperative Evaluation
- Contraindications
- Risks Involved in Pulmonary Function Testing
  - Hazards and Complications
  - Infection Control Measures
- Bedside Pulmonary Function Testing
  - Sabrasez Breath-holding Test
  - Forced Expiratory Time
  - Seberese's Single Breath Count
  - Cough Test
  - Measurement of Lung Volumes
- Pulmonary Function Testing Measurement Instruments/Devices
  - Volume-displacement Spirometer Device
  - Flow Sensor Spirometer
  - Portable Devices
  - Peak Cough Flow
- Graphs In Pulmonary Function Testing
  - Volume–Time Curve
  - Flow–Volume Curve
- Approach to Pulmonary Function Testing Interpretation
  - BODE index
- Case Examples

INTRODUCTION

Pulmonary function tests or lung function tests are noninvasive investigative methods to evaluate the mechanical function of the lungs. The evaluation methods in these tests are based on researched data that takes factors such as age, gender, body composition and ethnicity, and their effects on lung function into consideration.

The main function of the lungs is to do gas exchange. When venous blood passes through pulmonary circulation, the lungs add oxygen and extract carbon dioxide. The capability of gas exchange from lungs depends upon the following:

- Strength of diaphragm and thoracic muscles for expanding thorax and lungs, unobstructed airways to allow gas to flow into the lungs.
- The efficiency of the cardiovascular system to circulate blood through the lungs.
- Diffusion of oxygen and carbon dioxide through the alveolar-capillary membrane.

Definition: Pulmonary function testing (PFT) or lung function testing is a process of having the patient perform specific inhalation and exhalation maneuvers while breathing in and out of tubing attached to the equipment. It measures a variety of variables of pulmonary function and provides a quantitative picture of lung function.

The results of PFT become most meaningful when considered in the context of a complete evaluation.

- The PFT report gives information to a healthcare provider to diagnose patterns of lung diseases (not the lung disease) and decide the treatment for certain lung disorders.

- It is used to screen for the presence of respiratory impairment and to measure the magnitude of respiratory impairment.
- It is widely used in monitoring the progression of lung impairments.

Most of the tests are done in a special pulmonary function laboratory. There are various computerized machines that give results about specific questions of lung function.

There are mainly obstructive, restrictive, and mixed patterns of lung disorders that cause problems with air moving in and out of the lungs.

- *Obstructive*: The problem lies in exhaling air out of the lungs due to airway resistance. This causes a reduced flow of air. The volume of air inside the lungs after full exhalation increases, e.g., chronic obstructive pulmonary disease (COPD), asthma.
- *Restrictive*: There is difficulty in inhaling air due to stiffness of the lung tissue or chest wall cavity, thereby causing a reduction in lung volume. For example, interstitial lung disease, scoliosis, neuromuscular cause, obesity.
- *Mixed pattern*: There is presence of both obstructive and restrictive patterns.

IMPORTANT TERMINOLOGIES RELATED TO PULMONARY FUNCTION TESTING

Mainly three types of information can be obtained from full PFT: (1) lung volumes, (2) lung capacities and flow rates, and (3) diffusion capacities.

- Lung volumes and capacities provide information about the size of the different compartments of the lungs.
- Flow rates are dependent on airway caliber and provide information on the rates of airflow within the airways.
- Diffusion capacity provides information on the ease with which gas flows from the lungs (alveoli) to the capillaries.

Lung Volumes (Fig. 8.1)

This can be remembered using a Mnemonic "*TIER*" (Indian railways 2 TIER and 3 TIER coaches).

- *T = Tidal volume* (*TV*): It is the amount of air inhaled or exhaled during a normal single breath. TV signifies the normal depth of breathing. The normal value is 500 mL.
- *I = Inspiratory reserve volume* (*IRV*): This is the additional amount of air that can be inspired beyond TV. The normal value is 3,300 mL.
- *E = Expiratory reserve volume* (*ERV*): This is the additional amount of air that can be expired out after normal expiration. The normal value is 1,000 mL.
- *R = Residual volume* (*RV*): It is the amount of air left in the lungs after exhaling as much as you can. An abnormal increase in RV is called air trapping. RV increases in obstructive ventilatory disorders because of early airway closure in expiration. The normal value is 1,200 mL.

Lung Capacities

This can be remembered using the Mnemonic "*IVFT*" (IV line and IFT).

- *I = Inspiratory capacity* (IC): This is the maximum volume of air that can be inspired starting from end expiratory position. IC = TV + IRV = 500 + 3,300 = 3,800 mL.
- *V = Vital capacity* (VC): This is the total volume of air that can be exhaled after inhaling as much as possible. VC = IRV + TV + ERV = 3300 + 500 + 1,000 = 4,800 mL.
- *F = Functional residual capacity* (FRC): This is the amount of air remaining in the lungs after exhaling normally. When elastic recoil of the lungs decreases as in emphysema, the FRC increases (hyperinflation); while when the elastic recoil increases as in pulmonary fibrosis, the FRC decreases. FRC is measured by using body plethysmography. FRC = ERV + RV = 1,000 + 1,200 = 2,200 mL.
- *T = Total lung capacity* (TLC): This is the maximum amount of air that remains in the lungs after deep inspiration. TLC = IRV + TV + ERV + RV = 3,300 + 500 + 1,000 + 1,200 = 6,000 mL. It is limited by the elasticity of the thoracic cage and by the strength of the muscles of inspiration affected by the disease. Reduction of TLC is termed "restriction." For example, restrictive ventilatory disorders such as

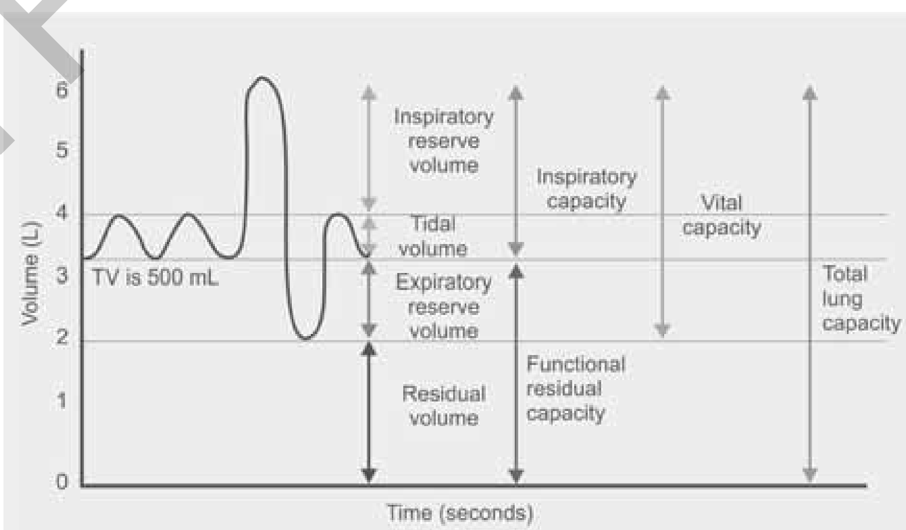


Fig. 8.1: Normal spirogram showing normal lung volumes and capacities.

pulmonary fibrosis, thoracic deformity (e.g., scoliosis), and limitation in the expansion (e.g., ankylosing spondylitis).

Rates of Flow

- *Forced vital capacity* (*FVC*): Amount of air exhaled forcefully and quickly after inhaling as much as possible.
- *Forced expiratory volume* (*FEV*): The amount of air which can be exhaled forcefully in a given unit of time (after deep inspiration) is called forced expiratory volume.
- FEV_1: Amount of air exhaled forcefully in the first second of expiration (83% of total VC).
- FEV_2: Amount of air exhaled forcefully in the first 2 seconds of expiration (94% of total VC).
- FEV_3: Amount of air exhaled forcefully in the first 3 seconds of expiration (97% of total VC).
- $FEF_{25-75\%}$: It is the forced expiratory flow over the middle one half of the FVC. It is the average flow from the point at which 25% of the FVC has been expired to the point at which 75% of FVC has been expired.
- FEV_1/FVC *ratio*: It is calculated by dividing the patient's largest FEV_1 by the patient's largest FVC and converting to a percentage by multiplying with 100.
- *Peak expiratory flow rate (PEFR)*: It is the fastest rate at which one should force air out of the lungs. The maximum rate at which air can be expired after deep inspiration is known as PEFR. In a normal person, it is 400 L/min. It is measured by using Wright's peak flow meter or a mini peak flow meter. This is useful to differentiate between obstructive and restrictive diseases. PEFR reduction is more significant in obstructive diseases than restrictive diseases. In restrictive diseases, the PEFR is 200 L/min and in obstructive diseases, it is only 100 L/min.

Diffusing capacity of the lungs for carbon monoxide (DLCO): It is the ability of the lungs to transfer gas across the alveolar-capillary membrane. The unit of DLCO is mL/min/mm Hg.

Minute volume (MV): The amount of air moved in and out of the lungs every minute is called MV. It is the product of TV and respiratory rate.

Maximum ventilation volume (MVV): Volume of air exhaled in a specified period during repetitive maximal respiratory efforts is termed MVV. The predicted normal value for MVV is 170 L/min. It reflects the status of respiratory muscles, compliance of thorax-lung complex, and airway resistance.

Maximal inspiratory pressure (MIP): It is a measurement of the strength of inspiratory muscles mainly the diaphragm. This test allows assessment of ventilatory failure, restrictive lung disease, and respiratory muscle strength. This test can be performed extremely fast, it's noninvasive and requires good effort from participants to perform.

Maximum expiratory pressure (MEP): It is the pressure that is generated during maximal expiration against occluded airway. MEP is supra-atmospheric pressure which can be generated with effort of abdominal and intercostal muscles.

Slow vital capacity (SVC): It is one of the spirometry tests that show the volume of gas measured on low complete expiration after a maximal inspiration without forced effort.

METHODS OF PULMONARY FUNCTION TESTING

- Spirometry
- Closed-circuit helium dilution method
- Open-circuit nitrogen washout method
- Body plethysmography

Instructions to be given to patients before PFT:

- Avoid taking any bronchodilator medications 4 hours before the test.
- Avoid smoking for 4 hours before the test.
- Avoid heavy meals few hours before the test.
- Avoid wearing tight clothing as it may restrict full chest and abdomen expansion.
- Instructions regarding the procedure of performing PFT should be given to the subject and they should be asked to inform if they have failed to understand. The examiner should conduct a demonstration if the subject does not comprehend verbal instructions.
- The subject should be informed that it requires effort to perform the test and there is a possibility that they may get tired. In such a case, it is advisable to take rest for a few minutes and then resume.
- In case of feeling dizzy or light-headed, the subject should immediately inform the examiner and test should be discontinued.
- Consuming intoxicants within 8 hours before testing should be avoided.
- Performing vigorous exercises within 1 hour before testing should be avoided.

Spirometry

Spirometry gives a measure of the inhalation and exhalation capacity of an individual as a function of time. It can be presented as a measure of volume or flow. It, generally, should be the clinician's first option, other studies being reserved for specific indications. It is designed to measure only lung volume compartments that exchange gas with the atmosphere. A spirometer with electronic signal outputs also measures flow (volume per unit time), $FEV_{1,}$ and exhaled lung volume (FVC or SVC).

Indications of Spirometry

- *For diagnostic purposes*:
  - To evaluate signs, symptoms, and abnormal findings on laboratory tests
  - To assess preoperative risk
  - To determine the prognosis of a patient
  - To assess the extent and severity of a disease
  - For screening of individuals who are at risk of developing pulmonary disorders
  - As a tool to assess the health risk of an individual before the commencement of a strenuous physical activity

- *For monitoring purposes*:
  - To evaluate the efficacy of the therapeutic intervention program
  - To monitor individuals exposed to intoxicating agents
  - To describe disease course of disorders affecting lung function
- *For disability evaluation*:
  - For insurance evaluation
  - For rehabilitation program
  - For medicolegal purposes
- *For public health*:
  - As part of epidemiological surveys
  - As part of clinical research
  - To derive reference equations

Procedure for Spirometry

- The examiner needs to wash their hands before the procedure.
- *Preparation of the patient*: The subject should sanitize their hands. Confirm demographic details such as name and age.
  - Measuring height and weight without footwear.
  - Getting history of the current and past medications used.
  - Instructions and demonstrations regarding the procedure should be given.
  - Confirm if the patient has properly understood the procedure and is willing to perform the test.
- *Application*: The subject should be asked to assume the correct posture. A nose clip should be used to secure the nose so that breathing occurs only through the mouth. The subject should then be asked to place the mouthpiece in their mouth and seal the lips around it **(Fig. 8.2)**. After a few normal breaths, the subject should be asked to exhale out completely. This is then followed by a maximal inspiration and a maximal expiration, while maintaining an upright posture. This has to be repeated till the examiner has three good efforts from the subject (keeping in mind the criteria for termination).

Residual volume cannot be measured by spirometry; hence, the capacities which include residual volume such as FRC and TLC cannot be measured through it. There are three other techniques that can be used for measuring RV, FRC, and TLC: (1) closed-circuit helium dilution method, (2) open-circuit nitrogen washout method, and (3) body plethysmography.

Fig. 8.2: A subject performing the spirometry test.

Quality Control

A good laboratory practice warrants equipment quality control and calibration. The minimum requirements for a good quality calibrated equipment are as follows:

- Maintenance of a log of calibration results
- Maintenance of records regarding repairs and alterations that return the equipment to an acceptable operation level
- Maintenance of data records regarding software and hardware upgrades
- Repeating quality control procedures and calibration checks in case of relocation or changing of equipment

Equipment quality control measures include the following:

- Daily volume check by calibration check using a 3 L syringe
- Daily leak check by maintaining a 3 cm H_2O constant pressure for 1 minute
- Quarterly volume linearity check by performing 1 L increments using a calibrated syringe measured over the entire volume range
- Weekly flow linearity check by testing at least three different flow rates
- Quarterly time checks using a mechanical recorder with a stopwatch
- Checking of the software with every new installation by performing the test with a known subject

Calibration of Spirometry Equipment

Calibration is the process of establishment of a relationship between the sensor-determined and the actual values of flow or volume. The Association for Respiratory Technology and Physiology (ARTP) recommends calibration of spirometry equipment prior to each clinical session or after every 10th subject, whichever comes first. A device is said to be within calibration limits if it reads ±3% of the true value. The guidelines recommend the use of a certificated 3L calibration syringe and following the manufacturer's recommended procedure.

- The syringe needs to be connected to the spirometer so that there is no leak at the mouthpiece. In the computer software, select the calibration option and start calibrating.
- After starting the calibration process, push the plunger into the syringe. When the plunger is pushed in fully, wait for a second and then pull the plunger out. Try to get a good maneuver.
- After a successful test process, go for the next test process which needs to be at a higher speed and flow rate. The plunger will need to be pushed in and out at a speed higher than the first test process.
- After a successful second test process, go for the third test process which is at an even higher flow rate than the second.
- After completing the third test, go to the calibration test results and check the calibration. If the device is out of

calibration, the technical support team needs to be contacted.

Maneuvers in Spirometry

There are three different maneuvers in spirometry: (1) FVC, (2) SVC, and (3) MVV.

FVC maneuver

There are three distinct phases of the FVC maneuver: (1) maximal inspiration, (2) forced maximal expiration, and (3) continued exhalation to the end of the test maneuver. The examiner should follow the below-mentioned protocol:

- Checking the equipment for calibration
- Explaining the test process to the subject
- Preparation of the subject:
  - History-taking
  - Measuring the weight and height of the subject
- Washing hands
- Instruction and demonstration of the test process to the subject:
  - Sitting in a correct posture with slight head elevation
  - Rapid and complete inhalation
  - Positioning the mouthpiece
  - Exhalation with maximal force
- Performance of maneuver by the subject:
  - Assumption of the correct posture by the subject.
  - Placement of the mouthpiece into the mouth of the subject after attaching the nose clip to the nose.
  - Lips should be sealed around the mouthpiece.
  - Complete and rapid inhalation with a pause of <1 second at TLC. Maximal expiration while maintaining an upright posture so that no more air comes out of the lungs.
  - Repetition of instructions if required along with vigorous coaching.
  - Minimum three good maneuvers required [need to exclude the unacceptable patterns **(Fig. 8.3)**]; a maximum of eight maneuvers can be performed at a time.

SVC maneuver

SVC is the volume of air expired with an unforced maneuver. In this maneuver, the subject takes a full breath just like the FVC maneuver but exhales out slowly. In a healthy young adult, SVC and FVC are similar or FVC may be lower than SVC but FVC is comparatively quite higher than SVC in cases of emphysema. With subjects having COPD, the SVC may exceed the FVC by more than 0.5 L.

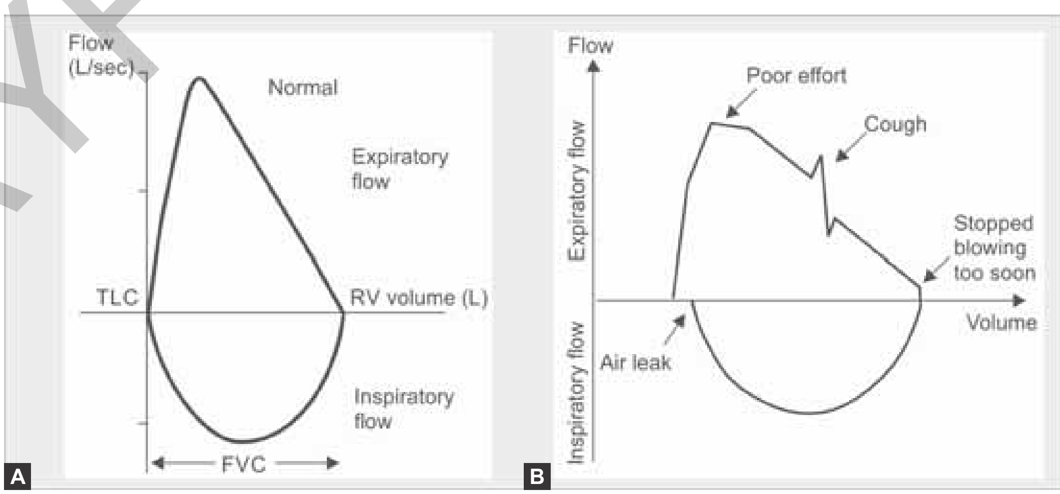
MVV maneuver

MVV is the maximum amount of air breathed in and out of the lungs by an individual in a specified period of time. The time is usually 12 seconds for normal subjects. The procedure for the MVV maneuver is as follows:

- Instruction and demonstration of the procedure by the examiner.
- Seating the subject in a correct upright sitting posture.
- Placement of the mouthpiece into the mouth of the subject with lips sealed around it.
- Ask the subject to breathe at least three resting tidal breaths.
- Ask the subject to breathe as deeply and rapidly as possible.
- Instruct the subject to maintain the teeth and tongue in such a position that they do not obstruct the airflow.
- Vigorous coaching by the examiner to gain an ideal rate of 90–110 breaths/min (may not be possible in individuals with disease).
- TV achieved during the process should be higher than the resting TV.
- The test interval (time interval for which the subject can maintain the rapid and deep breathing) should be reported.
- Report the highest acceptable MVV.

Criteria for acceptance of MVV:

- Obtaining two acceptable maneuvers having values within 10% of each other.
- MVV values should be approximately $35 \times FEV_1$.



Figs. 8.3A and B: Patterns of FVC. (A) Acceptable pattern, (B) Unacceptable pattern.
(FVC: forced vital capacity; RV: residual volume; TLC: total lung capacity)

Bronchodilator Reversibility Test

It is a determination of the degree of improvement of airflow in response to bronchodilator administration as measured by changes in FEV_1 and FVC. It is commonly undertaken as part of spirometry testing and the choice of bronchodilator, dose, and mode of delivery depends on the referring physician's prescription. The main aim of this test is to check whether the patient's spirometric lung function can be improved with a bronchodilator in addition to regular medication.

The American Thoracic Society (ATS) has recommended the following procedure for assessing bronchodilator response:

- Check the baseline lung function. If obstruction is present and FEV_1/FVC ratio is <70%, give four separate doses of 100 µg Salbutamol through the spacer and re-assess lung function after 15 minutes.
- An increase in $FEV_1 \geq 12\%$ above baseline FEV_1 after short-acting β_2 agonist administration shows a positive bronchodilator response.
- Lack of spirometry bronchodilator response does not preclude clinical response of bronchodilator.

Bronchoprovocation Test

It is also called *methacholine challenge test* and is used to help diagnose asthma. Methacholine is an inhaled drug which causes mild narrowing of the airways in the lungs such as in asthma. The test includes a baseline breathing (spirometry) test including FEV_1. The test is considered positive if methacholine causes the lung function (FEV_1) to drop by 20% or more compared to baseline. A negative test nearly rules out a diagnosis of asthma.

Closed-circuit Helium Dilution Method

The closed-circuit helium dilution method **(Figs. 8.4A and B)** is used to measure FRC and RV. Historically, hydrogen gas was used for the technique but it was replaced with helium gas as helium was nontoxic and had no risk of explosion.

In this technique, the patient is connected to a helium–air mixture; helium concentration is slowly diluted by the patient's lung volume.

- The starting point of the test is FRC.
- While wearing nose clips, the patient breathes normally into the circuit.
- Exhaled carbon dioxide is absorbed with soda-lime and oxygen is added at a rate equal to the rate of consumption.
- Until equilibrium of helium concentration is reached, the patient re-breathes into the system.

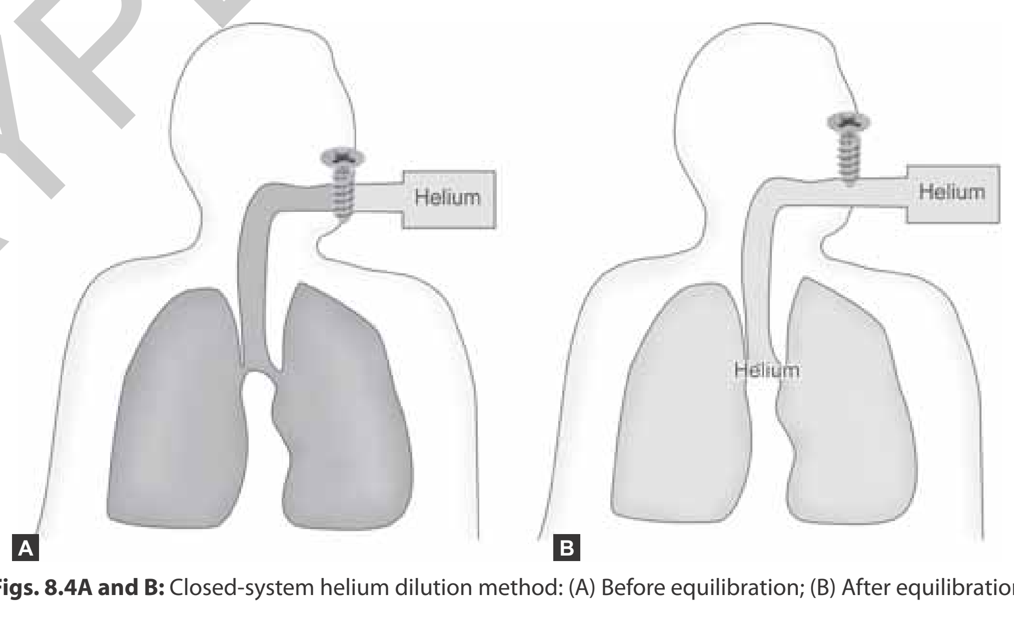
In healthy patients and those with small FRC, equilibration occurs in 2–5 minutes. Patients with obstructive disease may require 20 minutes to equilibrate because of slow mixing in the lungs. Helium dilution time is a gross index of distribution of ventilation.

Open-circuit Nitrogen Washout Method

The principle of the nitrogen washout method is that the subject inhales 100% oxygen and expires into the spirometer. The amount of nitrogen expired is monitored till there is no nitrogen left in the expired air (nitrogen is washed out).

- FRC is estimated by measuring the amount of gas expired and determining the concentration of nitrogen in it.
- This is done by calculating the volume of gas that would have initially contained the washed-out nitrogen.
- This method, too, has its disadvantages such as inability to estimate volumes of regions with poor ventilation and requires a longer time period.
- Also, the sensitivity of nitrogen volume analysis is quite high so it may not consider any leak that may occur at the mouth.

In this technique, the subject is asked to breathe normally and after the end of the normal expiration the subject inspires pure oxygen through a valve and expires into a Douglas bag. This has to be repeated for 6–7 minutes until nearly all nitrogen is washed out, leaving <2.5% nitrogen in lungs. The nitrogen is collected in the Douglas bag. The time taken for



Figs. 8.4A and B: Closed-system helium dilution method: (A) Before equilibration; (B) After equilibration.

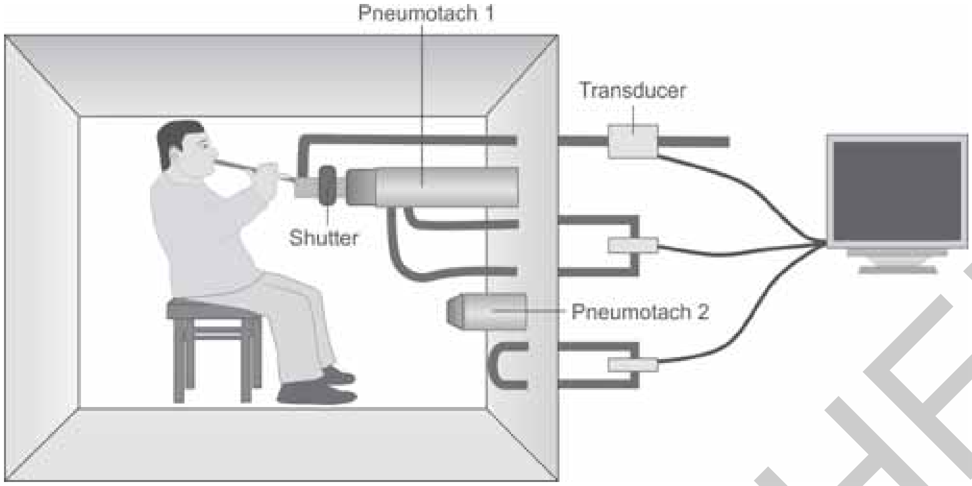


Fig. 8.5: Body plethysmography.

washout is normally 2–5 minutes in healthy subjects and longer in obstructive disease.

Body Plethysmography

Body plethysmography **(Fig. 8.5)** helps in assessing:

- FRC
- Specific airway resistance
- TLC
- RV

Airway resistance can be calculated based on the specific airway resistance and FRC. Body plethysmography is based on the principle that generation of volume requires generation of pressure. One of the disadvantages of body plethysmography is the high cost of the body box. Dilution methods are less costly and simpler. An advantage of body plethysmography over spirometry is the maneuver which is done at rest and is not forced.

This method is used only in hospitals and research facilities but is more accurate than dilution methods. This method is not indicated for patients with known air trapping conditions.

INDICATIONS FOR PULMONARY FUNCTION TESTING

Pulmonary function testing is mainly used for diagnostic, monitoring, and impairment evaluations of respiratory disease and disorders. **Box 8.1** presents the indications of PFT.

Box 8.1: Indications for pulmonary function testing.

Assessment and monitoring of disease severity:

- To evaluate patients with signs and symptoms that suggest pulmonary disease, e.g., cough, wheeze, breathlessness, crackles, abnormal chest X-ray
- Monitoring patients with a known pulmonary disease for progression and response to treatment, e.g., chronic obstructive pulmonary disease, asthma, interstitial fibrosis
- To evaluate patients with diseases that may have respiratory complications, e.g., connective tissue disorders, neuromuscular diseases
- To assess the progression of impairments
- To assess preoperative risk
- To assess response to therapeutic intervention as part of the rehabilitation program
- To measure the effect of disease or disorder on physiological parameters
- To find out individuals at risk of having a pulmonary disease
- For epidemiological surveys
- For pre-employment screening of at-risk occupations
- To check for adverse reaction of drugs

Pulmonary Function Testing in Preoperative Evaluation

Preoperatively PFT should be done to know individuals with known or suspected respiratory disease. Preoperative PFT is done to identify patients at risk, evaluating risk. The American College of Chest Physicians (ACCP) has recommended preoperative PFT in two groups:

1. Patients undergoing coronary bypass or upper abdominal surgery with a history of smoking or dyspnea.
2. Patients undergoing head and neck, lower abdominal, orthopedic surgery with unexplained dyspnea or pulmonary symptoms.

Patients with severe COPD, classified as high-risk by spirometry, can undergo surgery with an acceptable risk of pulmonary complications. The results of the PFT should be interpreted in relevance with the clinical situation and not be the main reason to withhold necessary surgery.

There is a higher risk of postoperative pulmonary complications in patients with FEV_1 or FVC of <70% predicted or FEV_1/FVC ratio of <65% predicted.

CONTRAINDICATIONS

Boxes 8.2 and 8.3 mention the absolute and relative contraindications of PFT respectively.

RISKS INVOLVED IN PULMONARY FUNCTION TESTING

There are several risks involved in the PFT procedure. These risks include dizziness, shortness of breath, coughing, and asthmatic attack.

Box 8.2: Absolute contraindications for pulmonary function testing.

- Myocardial infarction in the last 1 month
- Unstable angina
- Recent thoracoabdominal surgery
- Recent ophthalmic surgery
- Current pneumothorax
- Severe hypotension/hypertension
- Significant atrial or ventricular arrhythmia
- Corpulmonale
- Unstable pulmonary embolism
- Cerebral aneurysm
- Infection control issues: Active tuberculosis or active infection

Box 8.3: Relative contraindications for pulmonary function testing.

- Mental confusion
- Large meal taken before the test
- Smoking within 24 hours of test administration
- Hemoptysis of unknown origin
- Pneumothorax
- Unstable vital parameters
- Presence of an acute disease that affects test performance, e.g., nausea, vomiting

Hazards and Complications

Complications while performing PFT include the following:

- Pneumothorax
- Increased intracranial pressure (ICP)
- Syncope, dizziness, lightheadedness
- Chest pain
- Paroxysmal coughing
- Oxygen desaturation
- Bronchospasm

Infection Control Measures

The PFT procedure warrants certain infection control measures to be taken as there are high chances of the spread of infection through the equipment.

- The examiner should always use disposable mouthpieces to avoid cross-contamination between patients.
- Use of a filter should also be considered as using a filter has the advantage of protecting sensors and internal surfaces of the spirometer from damage.

BEDSIDE PULMONARY FUNCTION TESTING

Bedside PFT **(Fig. 8.6)** can be used to identify acute respiratory problems and quantify risk. Bedside PFT includes:

- Ventilatory frequency
- Pulse oximetry
- Cough strength and effectiveness
- Arterial blood gas analysis
- Measurement of lung volumes

Fig. 8.6: Portable pulmonary function testing machine.

Bedside PFT can be done using the below-mentioned procedures:

Sabrasez Breath-holding Test

- The subject is asked to rest for 5 minutes and then take a deep breath and hold it.
- The time for which the subject is able to hold the breath is noted in seconds.

The breath-holding test is an accurate measure of blood and tissue chemistry and vitality and endurance of the subject. The normal breath holding time is around 30–35 seconds. The VC is measured by multiplying the breath-holding time with 100 cc. A breath-holding time of 20 seconds or lower is suggestive of acidemia and a breath-holding time of <10 seconds suggests acidosis.

Forced Expiratory Time

This test is usually done for subjects with obstructive disorders.

- The subject is asked to take a full deep breath inside and exhale as forcibly and completely through the mouth as possible.

In a normal subject, this takes about 3 seconds, but may take longer in a subject with obstructive disorder. The severity of the disease can be noted by the degree of prolongation.

Seberese's Single Breath Count

A count of >30 is suggestive of normal cardiopulmonary reserve, whereas a lower count suggests abnormality.

Cough Test

The normal cough production in a day is around 30 cc. In this test, the subject is asked to cough. A dry cough is considered to be normal. A wet productive cough suggests postoperative complications.

Measurement of Lung Volumes

This is done using a *portable spirometer.* The steps of the procedure are the same as clinical spirometry.

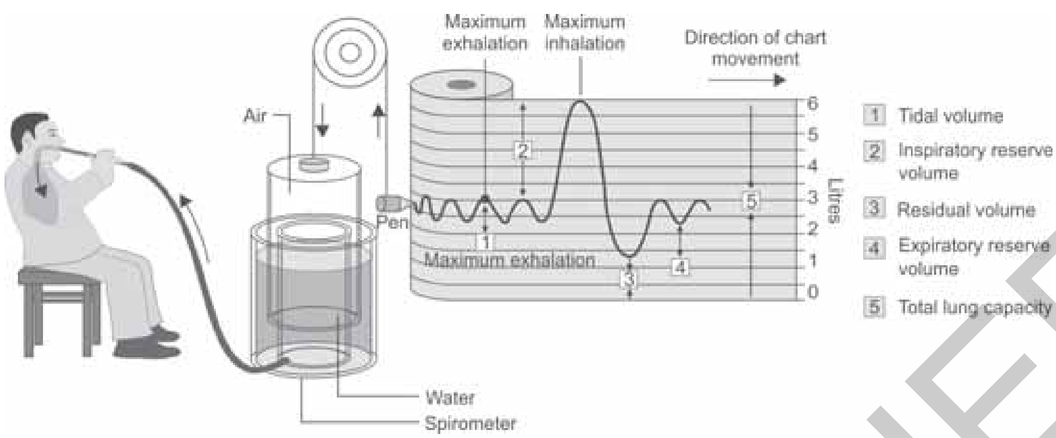


Fig. 8.7: Volume displacement spirometer device.

PULMONARY FUNCTION TESTING MEASUREMENT INSTRUMENTS/DEVICES

The commonly used devices are volume displacement and flow sensing spirometers for use in the clinic and portable (easy to carry) devices for individual use.

Volume-displacement Spirometer Device

It is a traditional spirometer **(Fig. 8.7)** which gives an idea about the direct measure of inspired volume from: Displacement of a bell (water-sealed), piston (rolling seal), or bellows (e.g., wedge bellows).

The findings are normally shown as a graphic display of exhaled volume against time (spirogram).

- Parameters such as FVC are generally calculated manually from the spirogram by the person who performed the test.
- Volume type spirometer is time consuming due to the cleaning process required and less convenient for daily use by the physician.
- However, volume spirometers are easy to use and require less maintenance and provide a clear record of the test, but these are less portable than flow spirometers.

Flow Sensor Spirometer

The recent advances in the field of electronics and microprocessors have led to the development of small portable spirometers. The flow sensor spirometer uses a sensor to measure flow as a primary signal and calculate volume by the digital flow of signal.

Widely used flow sensors **(Fig. 8.8)** check and measure flow in three ways:

1. Measuring the pressure drop across a resistance (e.g., pneumotach)
2. Measuring it on cooling of a heated wire (anemometer)
3. Electronically counting the rotation of a turbine blade

Family physicians use this instrument very commonly.

- It is portable, self-calculates a range of ventilatory indices, and checks the acceptability of each blow of air.
- Patient reports can be stored, and comparison with standard reference values can also be done.

Fig. 8.8: Flow sensor spirometer.

- These benefits along with easy maintenance (cleaning and sterilization) have resulted in ease of use with flow-based spirometers.
- Few flow spirometers have disposable sensors that can be replaced between patients and which remove the need for cleaning and disinfection, but the accuracy of new sensors needs to be established.
- Such spirometers also need to be calibrated regularly.

Portable Devices

A peak flow meter is a mechanical device which needs to be expired into **(Fig. 8.9)**. A built-in indicator is pushed with the force of expiration. The farther the indicator moves, the higher is the flow rate. The maximum expiratory airflow can be measured by it.

- The subject, here, is asked to take a deep inspiration and then blow out into the peak flow meter as strongly and fast as they can.
- Values can be compared with predicted values or the subject's personal values.
- PEFR is effort dependent and also depends on the age, gender, ethnicity, and height of the subject. PEFR is

Fig. 8.9: Peak flow meter.

normally ≥500 L/min. It is a sensitive indicator of early airway obstruction.

Peak flow meters have been available since many decades for frequent monitoring of lung function and have been found especially useful in the management of bronchial asthma. The most commonly used peak flow meter is Wright's peak flow meter.

- Peak flow meters give reproducible results which are a must for serial monitoring.
- But they have limited accuracy and limited use in the initial examination of respiratory diseases.

Peak expiratory flow rate values are decreased in diseases that cause airway obstruction. PEFR monitoring is needed to check the response to treatment and identify trigger factors in bronchial asthma.

At present, there are many portable peak flow meters available that are reliable tools to self-monitor the patients for their own airway function. Presently, many small, cost-effective, and accurate battery-operated devices are available. Some of these can store data that can be downloaded or taken into the computer for review and statistical analysis.

Clinical Pointer

Points to consider while choosing a spirometer

A spirometer device should:
- Be easy to use
- Provide simple calibration checking and allow adjustments by the person who operates it
- Be reliable and should have low maintenance requirement
- Give graphical display of the maneuver performed
- Use standard predicted values
- Be economical in purchase

Peak Cough Flow

- Peak cough flow (PCF) is used to show the effectiveness of cough.
- The normal values of PCF in an adult range from 400 to 1,200 L/min.
- Patients with neuromuscular disorder, where the respiratory muscles are affected, can have a reduction in PCF values.
- When the values are <260 L/min, cough augmentation techniques should be delivered to prevent accumulation of secretion.
- This maneuver can also be performed preoperatively to predict the development of postoperative pulmonary complications.

GRAPHS IN PULMONARY FUNCTION TESTING

Volume–Time Curve (Fig. 8.10)

It can be examined by:
- Observing the duration of the curve (should be at least 6 seconds to meet ATS criteria)
- In obstructive disorder, the curve is less steep than the predicted value.
- In restrictive disorder, the curve has a normal shape but with reduced total volume than the predicted curve.

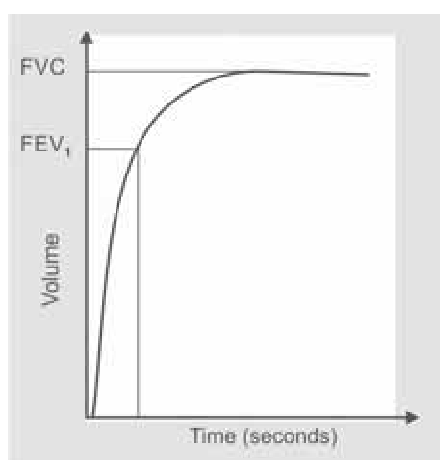


Fig. 8.10: Normal volume–time curve.
(FEV_1: forced expiratory volume in the first second; FVC: forced vital capacity)

Flow–Volume Curve

The curve shows the relationship between lung volume and maximal airflow as lung volume changes during forced expiration.

The flow–volume curve is recorded by patient performing maximal expiratory maneuver followed by maximal inspiratory effort. A graph is plotted with a positive expiratory limb and a negative inspiratory limb **(Fig. 8.11)**. The maximal flow rate during exhalation can be documented as PEFR. Useful information can be obtained from the curve in patients suspected of pulmonary disease.

Patients with obstructive lung diseases due to reduced expiratory flow from the peripheral airways will have a reduction in PEFR, concave appearance of the descending portion of the expiratory limb (reduced $FEF_{25-75\%}$) rather than a straight line in a normal flow–volume loop. The volume–time curve will show a significant reduction in FEV_1 value compared to the value in the normal predicted curve **(Figs. 8.12 and 8.13)**.

In restrictive lung diseases, in the flow–volume curve, the expiratory limb has a convex appearance because flow rates (PEFR, $FEF_{25-75\%}$) are preserved and the problem is seen as reduced lung volume (reduced FVC seen as a small loop). The volume–time curve will show a significant reduction in lung volume (FVC reduction) **(Figs. 8.14 and 8.15)**.

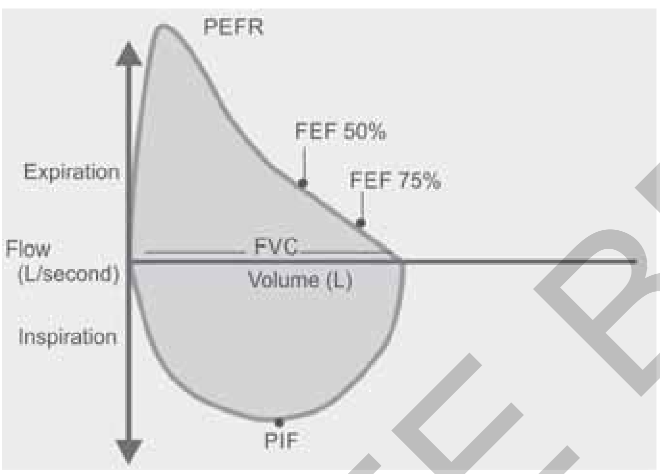


Fig. 8.11: Normal flow–volume curve.
(FEF: forced expiratory flow; FVC: forced vital capacity; PEFR: peak expiratory flow rate)

APPROACH TO PULMONARY FUNCTION TESTING INTERPRETATION

Clinical data:

- A patient's demographics such as age, gender, height, weight, and race also provide important information, e.g., patient's weight (obesity can lead to a restrictive pattern).
- The technician's comment also gives an idea about the quality of the study and the patient's effort.

Simple steps for interpretation:

Step 1: Look at flow–volume loop and volume–time loop.
Step 2: Look at FEV_1 (≥80% predicted).
Step 3: Look at FVC (≥80%).
Step 4: Look at the FEV_1/FVC ratio (≥70%).
Step 5: Look at $FEF_{25-75\%}$ (≥80%).
Step 6: Examine the lung volumes.
Step 7: Examine the gas transfer study.
Step 8: Compare the current findings with previous one, if available.

Approach to the volume–time curve:

- Observe the duration of the curve—it should be at least 6 seconds to meet ATS criteria.
- In obstructive disorder, the curve is less steep than the predicted curve.
- In restrictive disorder, the curve is in normal shape but there is decreased total volume than the predicted curve.

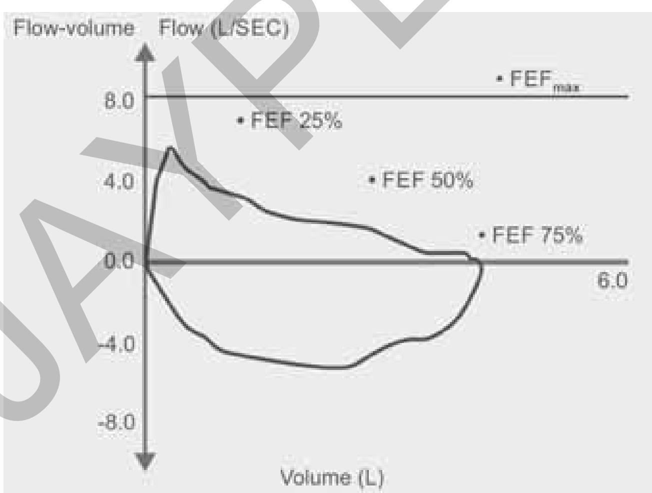


Fig. 8.12: Flow–volume curve in obstructive lung diseases.
(FEF: forced expiratory flow)

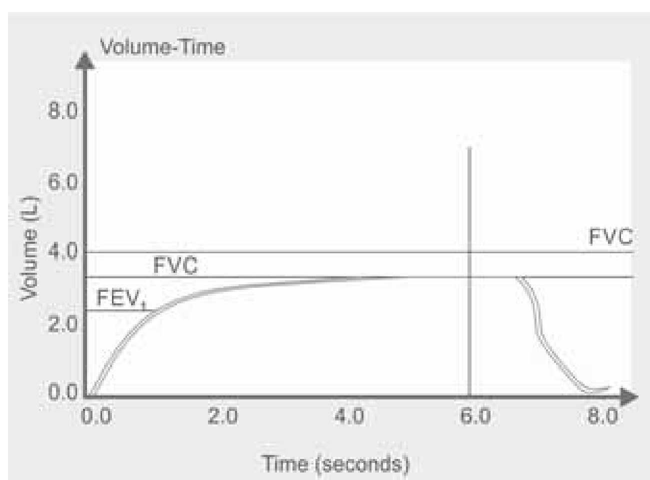


Fig. 8.13: Volume–time curve in obstructive lung diseases.
(FEV_1: forced expiratory volume in the first second; FVC: forced vital capacity)

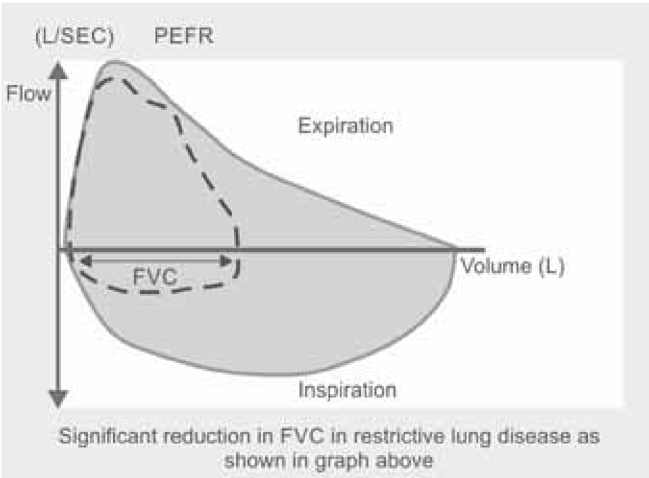


Fig. 8.14: Flow–volume curve in restrictive lung diseases.
(FVC: forced vital capacity; PEFR: peak expiratory flow rate)

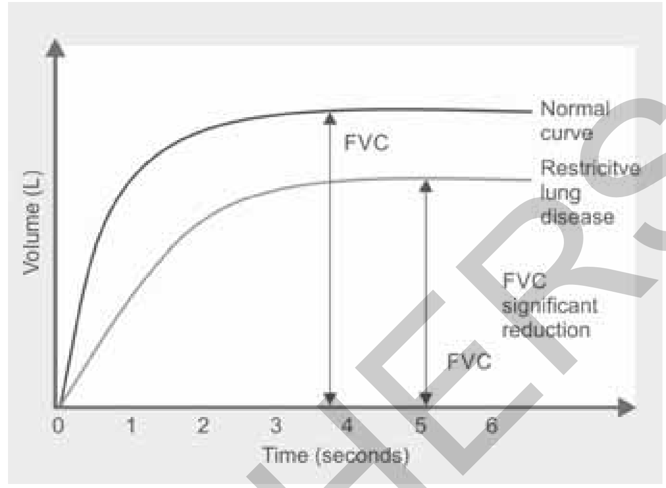


Fig. 8.15: Volume–time curve in restrictive lung diseases.
(FVC: forced vital capacity)

- FVC (the height of the curve) and FEV_1 help to distinguish restrictive from obstructive abnormalities.
- In suspected patients with obstructive disorders, a postbronchodilator spirometry with the volume–time curve should be done and repeated.
- Improvement in the shape and slope of the curve compared to the original indicates response to bronchodilator.

Approach to the flow–volume curve:
- A normal size and shape indicate normal study.
- A small and concave expiratory limb suggests an obstructive disorder.
- A small and parallel slope to the predicted curve is seen in chest wall restriction.
- Height (PEF) and slope (FEF 25–75%), if low, suggest an obstructive disorder.
- The width of FVC is smaller than the predicted curve which suggests a restrictive defect.
- If the FEV_1/FVC ratio is low, it suggests obstruction.

Approach to spirometry:
- Examine FVC, FEV_1, and FEV_1/FVC ratio.
- *Normal*: When all values are normal.
- *Obstructive*: When there is a decrease in the FEV_1/FVC ratio (as FEV_1 is mostly decreased and FVC is usually normal or relatively preserved). The FEV_1 level (%pred) determines the severity.
- *Restrictive*: Decrease in FVC and normal or increased in the FEV_1/FVC ratio. TLC value is low.
- Postbronchodilator values of FVC, FEV_1, and FEV_1/FVC ratio can be concluded as a significant response to bronchodilator if there is a 12% and 200 mL increase in FEV_1 and FVC, respectively.
- PEF decreases with poor effort and in obstruction.

Approach to lung volume study:
- Examine TLC and RV.
- High volumes suggest obstruction.

Table 8.1: Characteristics of obstructive and restrictive disorders.

	Obstructive	*Restrictive*
FEV_1	Decreased	Decreased or normal
FVC	Decreased or normal	Decreased
FEV_1/FVC%	Decreased	Increased or normal
RV	Increased	Normal or decreased
TLC	Increased	Decreased
FRC	Increased	Decreased

(FEV_1: forced expiratory volume in 1 second; FRC: functional residual capacity; FVC: forced vital capacity; RV: residual volume; TLC: total lung capacity)

- A decrease in TLC suggests the restrictive pattern of lung diseases.
- An increase in TLC indicates hyperinflation.
- An increase in RV indicates air trapping.

ATS grading of severity of any spirometric abnormality based on FEV_1: After determining the pattern to be obstructive, restrictive, or mixed **(Table 8.1)**, FEV_1 is used to grade the severity of a postbronchodilator.
- *Mild*: FEV_1 > 70 (%pred)
- *Moderate*: 60–69
- *Moderately severe*: 50–59
- *Severe*: 35–49
- *Very severe*: <35
- *TLC*: Increases in COPD, mainly emphysema. High in swimmers due to large lungs and decreased in restrictive disorders.
- *RV*: Increased (air trapping) in obstructive disorders, e.g., COPD, asthma. Decreased in parenchyma restriction.
- *FRC*: Increased (hyperinflation) in obstructive disorders, mainly in emphysema due to loss of lung elastic recoil. Decreased in restrictive disorders and obesity.
- $FEF_{25-75\%}$: Decreased in obstructive disorders.

Reduction in $FEF_{25-75\%}$ may be the earliest sign of airway obstruction.

BODE Index

The Body mass index (B), airflow Obstruction (O), Dyspnea (D) and Exercise capacity (E) index (BODE index) is a composite instrument used for a more global evaluation of COPD.

- Body mass index is calculated from the height and weight of the subject.
- Airflow obstruction is measured by postbronchodilator FEV_1.
- Dyspnea is graded using the Modified Medical Research Council (MMRC) grading.
- Exercise capacity is measured using the 6-minute test.

The BODE index score ranges from 0 to 10; a higher score gives a higher probability of death. Each variable gets a score from 0 to 3 with the body mass index (BMI) getting a score of 0 or 1.

Summary

Ventilatory function measurement should be included as a part of routine assessment of patients with respiratory diseases. Pulmonary function tests are an especially important tool in the assessment of patients with suspected pulmonary disease and are also required to be performed prior to any major surgery. For interpretation of PFT, one needs to have knowledge about normal values and curves/graphs, and it must be clinically correlated with the patient's history and assessment.

REVIEW QUESTIONS

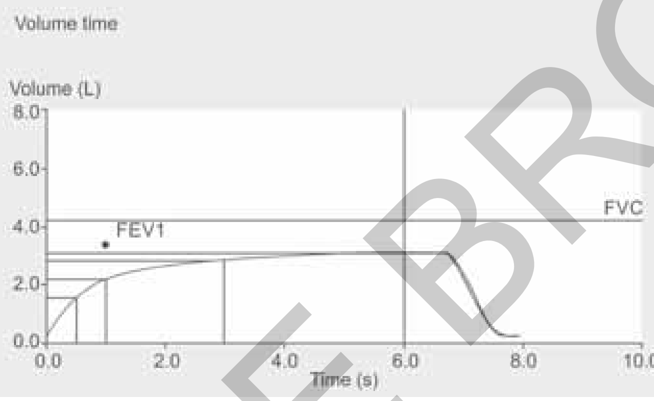
1. What is pulmonary function testing?
2. What are the uses of pulmonary function testing?
3. What are the lung volumes and lung capacities? Mention in detail about the same.
4. What is forced vital capacity?
5. What is forced expiratory volume?
6. What is FEV_1?
7. What is peak expiratory flow rate (PEFR)?
8. What are the different methods of pulmonary function testing?
9. Mention different indications of spirometry.
10. What are instructions to be given to the patient before PFT?
11. Describe in detail about different maneuvers in spirometry.
12. Explain closed-circuit helium dilution method.
13. What is the open-circuit nitrogen washout method?
14. What is body plethysmography?
15. What is the bronchodilator reversibility test?
16. What are the contraindications of PFT?
17. What is flow volume curve in PFT?
18. Write in detail about approach to PFT interpretation.

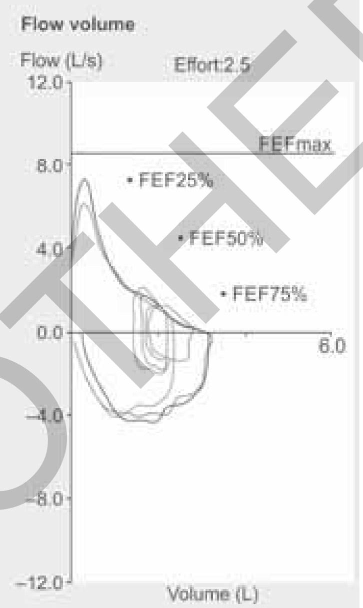
CLINICAL EXAMPLES

Example 1:

FVC Test

	Predicted (Favor mean)	Pre-drug (Reported)	Pre-drug % predicted	Post-drug reported	Post-drug % predicted	% Change
FVC	4.22	3.13	74	3.16	75	1
FEV.5		1.58		1.64		4
FEV_1	3.40	2.16	63	2.27	67	5
FEV_6		3.10		3.13		1
FEV_1/FVC	77.85	68.83	88	71.64	92	4
FEF25-75%	3.80	1.37	36	1.54	41	13
PEF	8.47	6.18	73	7.30	86	18
FEF25%	7.41	3.67	49	3.91	53	7
FEF50%	4.56	1.61	35	1.89	41	17
FEF75%	1.80	0.51	28	0.57	31	11
FET		6.69		6.60		–1
FIVC	4.39	3.06	70	2.95	67	–4
PIFR		4.08		4.38		7
FIF50%		4.03		4.25		6
MVV	118.93.	90.80	76	80.96	68	–11



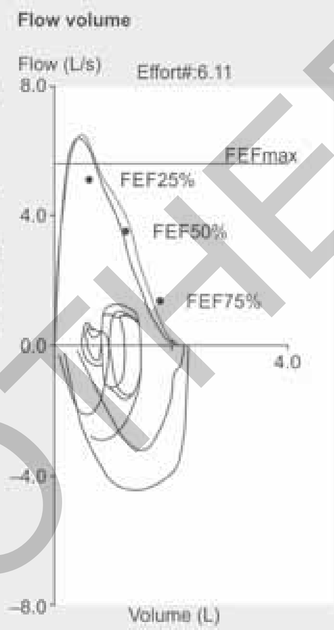


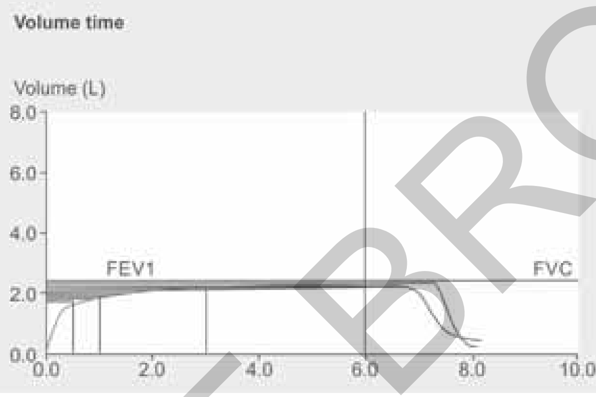
Here, FEV_1 is <80% of predicted (63%) but the FEV_1/FVC ratio (88%) is >70% so there is no obvious airway obstruction but FEF25%, FEF50%, and FEF75% (49%, 35%, and 28% of predicted values, respectively) show significant reduction suggesting mid airway obstruction.

Example 2:

FVC Test

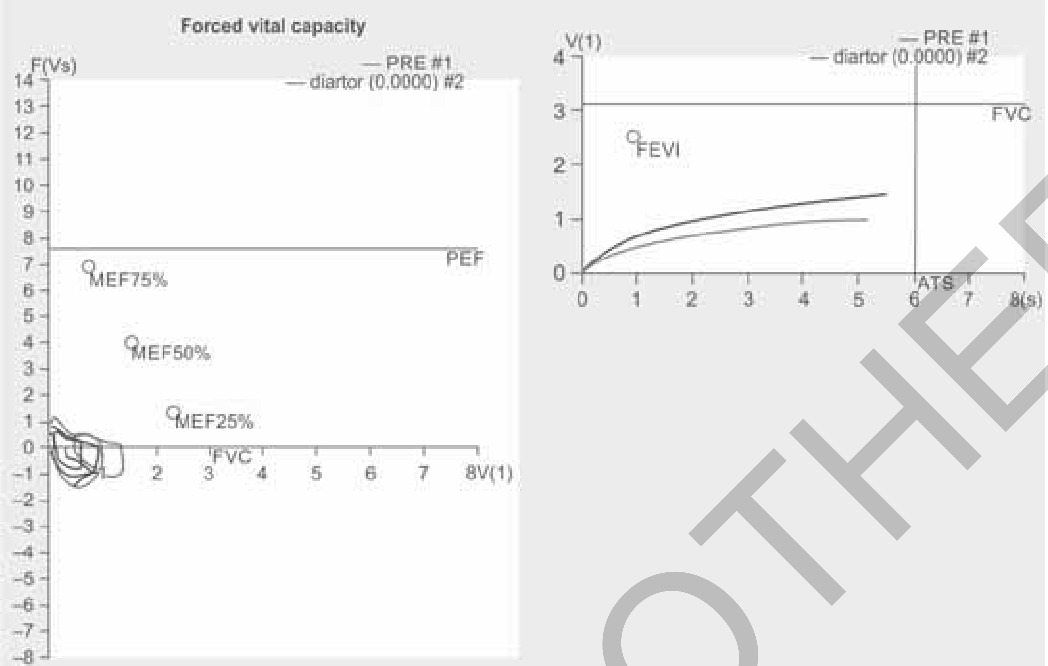
	Predicted (Favor mean)	Pre-drug Reported	Pre-drug % predicted	Post-drug reported	Post-drug %predicted	%Change
FVC	2.41	2.20	91	2.29	95	4
FEV.5		1.66		1.77		6
FEV_1	2.03	1.91	94	1.98	98	4
FEV_6		2.19		2.27		4
FEV1/FVC	78.65	86.72	110	86.83	110	0
FEF25-75%	2.95	2.82	95	3.31	112	18
PEF	5.60	6.40	114	6.51	116	2
FEF25%	5.12	6.26	122	6.31	123	1
FEF50%	3.51	3.89	111	4.20	120	8
FEF75%	1.33	0.95	72	1.17	88	23
FET		6.66		7.25		9
FIVC	2.48	1.81	73	2.10	85	16
PIFR		3.20		4.43		38
FIF50%		3.07		4.37		42
MVV	71.01	64.11	90	92.18	130	44





All parameters are >80% which suggest a normal PFT report.

Example 3:



Parmeter	UM	Pred.	Pre#1	%Pred.	Post#2	%Pred.	%Pre#1
Best FVC	1(btps)	3.10	0.95	30.6	1.39	44.8	+46.3
Best FEV_1	1(btps)	2.42	0.46	19.0	0.67	27.7	+45.7
FEV_1/FVC%	%	75.3	48.4	64.3	46.0	61.1	–4.9.
Best PEF	1/sec	7.57	0.80	10.6	1.18	15.6	+47.5
FEF25–75%	1/sec	3.10	0.23	7.4	0.32	10.3	+39.1
MEF25%	1/sec	1.30	0.16	12.3	0.18	13.8	+12.5
MEF50%	1/sec	3.93	0.26	6.6	0.36	9.2	+38.5
MEF75%	1/sec	6.73	0.47	7.0	0.62	9.2	+31.9

Here, the values of FEV_1 (19%), PEFR (10.6%), and FEF25–75% (74%) show significant reduction suggesting severe airflow obstruction and the significant reduction in the value of FVC (30.6%) suggests a restrictive pattern of disease. So, it can be interpreted that this patient has a mixed pattern of pulmonary disease.

BIBLIOGRAPHY

1. Altalag A, Road J. Pulmonary Function Testing in Clinical Practice, 2nd edition, Switzerland: Springer; 2018.
2. Graham BL, Steenbruggen I, Miller MR, Barjaktarevic IZ, Cooper BG, Hall GL, et al. Standardization of Spirometry 2019 Update. An Official American Thoracic Society and European Respiratory Society Technical Statement. Am J Respir Crit Care Med. 2019;200(8). https://doi.org/10.1164/rccm.201908-1590ST.
3. Gupta B, Gupta L. Pulmonary function tests-relevance to anesthesiologists. Anaesth Crit Care Med J. 2018;3(1):000131.
4. International Association of Fire Fighters. Pulmonary Function Tests. [online] Available from https://www.iaff.org/pulmonary-function-tests/ [Last accessed May, 2021]
5. Johns Hopkins Medicine. [online] Available from www.hopkinsmedicine.com [Last accessed May, 2021]
6. Kacmarek RM, Stoller JK, Heuer AJ. Egan's Fundamentals of Respiratory Care, 11th edition. Philadelphia: Elsevier; 2019.
7. Khan MA, Hussain SF. Review article pre-operative pulmonary evaluation section of pulmonary and critical care medicine. Karachi J Ayub Med Coll Abbottabad. 2005;17(4):82-6.
8. Miller MR, Hankinson J, Brusasco V, Burgos F, Casaburi R, Coates A, et al. Standardisation of spirometry. Eur Respir J. 2005;26: 319-38.
9. Moore VC. Spirometry step by step. Breathe. 2012;8(3):232-40.
10. NICE Guideline, No. 80.1. Asthma: diagnosis and monitoring of asthma in adults, children and young people. London: National Institute for Health and Care Excellence; 2017. [online] Available from https://www.ncbi.nlm.nih.gov/books/NBK536615/ [Last accessed April 2021]
11. Pulmonology Advisor. [online] Available from www.pulmonologyadvisor.com [Last accessed May, 2021]
12. Ranu H, Wilde M, Madden B. Pulmonary function tests. Ulster Med J. 2011;80(2):84-90.
13. Sembulingam K. Essentials of Medical Physiology. New Delhi: Jaypee Brothers Medical Publishers.
14. Shah SN (Ed). API Textbook of Medicine, 7th edition. Mesh Publishing House; 2003.
15. Stanford Medicine. Managing CF. [online] Available from https://med.stanford.edu/cfcenter/education/english/ManagingCF.html [Last accessed May, 2021]
16. Web Medicine. [online] Available from www.webmed.com [Last accessed May, 2021]