

Understanding Pulmonary Function Tests

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Lung volume measurements include vital capacity, inspiratory capacity, expiratory reserve volume, functional residual capacity, residual volume, total lung capacity and tidal volume. Minute ventilation and forced vital capacity help to determine the patient's ability to move air. Other tests measure parameters such as diffusion across the alveolocapillary membrane and gas distribution. Combined with blood gas measurements, these tests are invaluable in the study of dyspneic patients and patients undergoing major surgery, in monitoring of pulmonary disease and in selection of therapy.

The primary function of the lungs is gas exchange: oxygenation of the blood and removal of carbon dioxide. Pulmonary function studies help to evaluate how well the respiratory apparatus is able to accomplish this task. Pulmonary function studies are indicated to determine the presence and/or extent of lung disease, to ascertain the type of lung disease (obstructive, restrictive or diffusion defect), to monitor the course of pulmonary illness, to determine the extent of respiratory disability, including evaluation for surgery, and to aid in the selection of therapy.

Basically, pulmonary function tests measure (1) lung volumes and capacities, (2) the ability to move air (airflow), (3) a combination of volume and flow, (4) diffusion across the pulmonary membrane, (5) gas distribution and (6) ventilation-blood flow effectiveness. Measurements to determine these parameters are listed in Table 1. Normal values of the pulmonary function tests are a function of predicted values that have been determined in large groups of normal individuals; the predicted values are often modified by age, sex and height.

Lung Volumes and Capacities

The various lung volumes and capacities are illustrated in Figure 1. To determine these,

the patient breathes in and out of a spirometer, the bell of which is connected to a recording device so that the inspiratory and expiratory excursions are recorded on calibrated paper. During quiet resting breathing, the excursion represents tidal volume (TV). The patient is then instructed to take as deep a breath as he possibly can, and to exhale maximally. He subsequently resumes normal breathing.

All volumes and capacities can be determined by spirometry except residual volume (RV), functional residual capacity (FRC) and total lung capacity (TLC). Volumes such as inspiratory reserve volume (IRV) are single entities, whereas capacities, such as total lung capacity, are composed of two or more volumes and/or capacities. Changes in vital capacity (VC) and inspiratory capacity (IC)

TABLE 1.

Pulmonary Parameters and
Corresponding Pulmonary Function Test

Lung volumes and capacities
Vital capacity (VC)
Inspiratory capacity (IC)
Expiratory reserve volume (ERV)
Functional residual capacity (FRC)
Residual volume (RV)
Total lung capacity (TLC)
Tidal volume (TV)
Minute ventilation (V _E)
Forced vital capacity (FVC)
Forced expiratory volume in 1 sec (FEV ₁)
Maximum flow rate (ml/min)
Maximum voluntary ventilation (MVV)
Combined flow and volume flow (ml/min)
Peak flow (PF) (ml/min)
Flow rate (FR) (ml/min)
Flow rate (FR) (ml/min)
Flow rate (FR) (ml/min)
Flow rate (FR) (ml/min)
Diffusion capacity (D _{CO})
Gas distribution
Helium equilibration time
Ventilation-blood flow measurement
Arterial blood gases

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usually parallel each other. A decrease in VC to less than 80 percent of the predicted value is considered abnormal; decreases in these measurements are caused by pathologic states which decrease the amount of distensible lung tissue, or interfere with respiratory excursion in any manner. Changes in expiratory reserve volume (ERV) are not usually of diagnostic significance.

FRC, RV and TLC cannot be measured by spirometry because a given amount of air, RV, always remains in the lungs, even at the end of a maximum exhalation. A closed-circuit helium dilution technique is usually applied to determine these three values. A spirometer is filled with a known volume of oxygen to which helium has been added, yielding an approximately 10 percent mixture. The volume and exact concentration of helium are determined before the test begins. Initially, all of the helium is in the spirometer and none is in the patient's lungs. The patient then breathes room air in a normal fashion. A valve is thrown at the end of a normal

expiration to initiate his breathing through the spirometer. Since FRC is the volume of gas in the lungs at the end of a normal expiration, FRC is the capacity determined by this method. The patient continues to rebreathe the gas in the spirometer until the concentration of helium falls to a stable level (equilibrium is reached between the lungs and the spirometer). This is usually accomplished within three minutes. The final helium concentration is measured and recorded.

FRC is calculated from the fact that a known volume of helium was initially in the spirometer but became distributed between the spirometer and the patient's lungs, with an equal concentration in each. Residual volume is determined by subtracting ERV from FRC ($RV = FRC - ERV$). An increase in FRC indicates hyperinflation, which is considered pathologic. Hyperinflation may result from emphysema, asthma or bronchial obstruction of any etiology. FRC and RV usually increase together.

TLC is usually calculated by adding FRC and IC ($TLC = FRC + IC$). TLC is decreased in pulmonary edema, atelectasis, neoplasms, interstitial fibrosis, pulmonary congestion, pneumothorax and thoracic restriction. Because of an increase in FRC in diseases which cause air trapping, TLC may be concomitantly increased.

The RV/TLC ratio is often used. In healthy young adults, this ratio, when expressed as a percentage, may vary from 20 to 35 percent. Values greater than 35 percent in the presence of an increased TLC may be indicative of chronic air trapping.

Airflow

Measurements to determine ability to move air include minute ventilation (V), forced vital capacity (FVC), forced expiratory volume in one second (FEV_1), maximum mid-expiratory flow rate (MMFR) and maximum voluntary ventilation (MVV).

These values also can be determined by use of a spirometer.

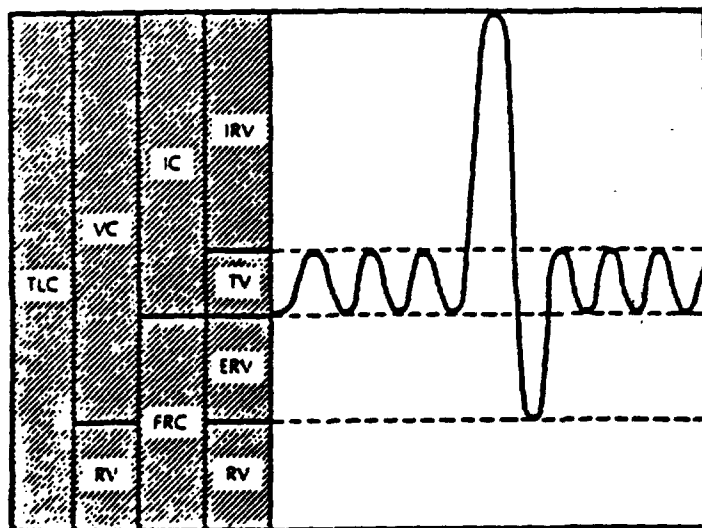


FIGURE 1. Lung volumes and capacities. (TLC=total lung capacity; VC=vital capacity; RV=residual volume; IC=inspiratory capacity; FRC=functional residual capacity; IRV=inspiratory reserve volume; TV=tidal volume; ERV=expiratory reserve volume)

MINUTE VENTILATION

$\dot{V}$ is the amount of air inhaled or exhaled in one minute during quiet breathing. It is determined by multiplying tidal volume (TV) by the average number of breaths per minute as counted from the spirometer tracing. Normal $\dot{V}$ ranges from 5 to 7 L. per minute. It is increased in patients with large dead spaces and by hypoxia, hypertarbia, acidosis and anxiety. It is decreased by severe airway obstruction, hypocarbia, alkalosis and respiratory center depression caused by drugs or CO_2 narcosis. Since $\dot{V}$ is the sum of minute dead space and alveolar ventilation, it is not a measure of effective ventilation for gas exchange. It is of most value when used in conjunction with arterial blood gases.

FORCED VITAL CAPACITY

FVC is the volume of gas that can be expelled as rapidly as possible after a maximum inspiration. False-low values can be obtained in uncooperative patients if maximum effort is not achieved. Normally, FVC is equal to

VC. The forced expiration, however, does cause higher than normal transpulmonary pressures, so that bronchiolar collapse, obstructive lesions and air trapping are exaggerated. Thus, FVC may be smaller than VC in patients with obstructive lung disease such as emphysema and asthma. Both FVC and VC are decreased in restrictive disease such as interstitial fibrosis.

FORCED EXPIRATORY VOLUME IN ONE SECOND

FEV_1 is the volume of air expelled in the first second of an FVC maneuver (Figure 2). It is an indication of the degree of airway obstruction. FEV_1 is most useful when it is expressed as a percent of FVC ($\text{FEV}_1/\text{FVC} \times 100$). A normal individual should be able to expel at least 80 percent of his FVC in one second. A patient who has obstructive disease usually shows a reduced FEV_1 value, whereas a patient with restrictive disease has a normal value despite having a lower than normal FVC.

MAXIMUM MID-EXPIRATORY FLOW RATE

The MMFR, also known as forced expiratory flow 25 to 75 percent ($\text{FEF}_{25-75\%}$), is a measurement of airflow during the middle portion of an FVC maneuver. It is determined according to Figure 3. An abnormal MMFR is indicative of disease in small to medium-sized airways. It is usually decreased in obstructive lung disease. The MMFR complements the FEV_1 ; normal values for healthy young men average 4.5 L. per second.

MAXIMUM VOLUNTARY VENTILATION

The MVV is the largest volume per minute that can be breathed by voluntary effort. It is measured by having the patient breathe as deeply and rapidly as possible for 12 seconds. The volume breathed in this period is multiplied by five to give MVV in liters per minute. MVV measures the status of the respiratory muscles, the compliance of the lungs and thorax and the resistance of the airways and tissues. Healthy young men may average 170

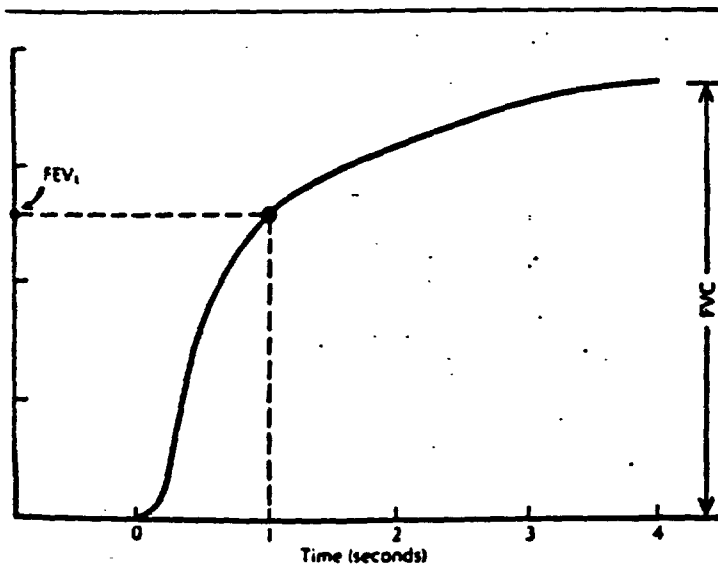


FIGURE 2. Determination of FEV_1 .

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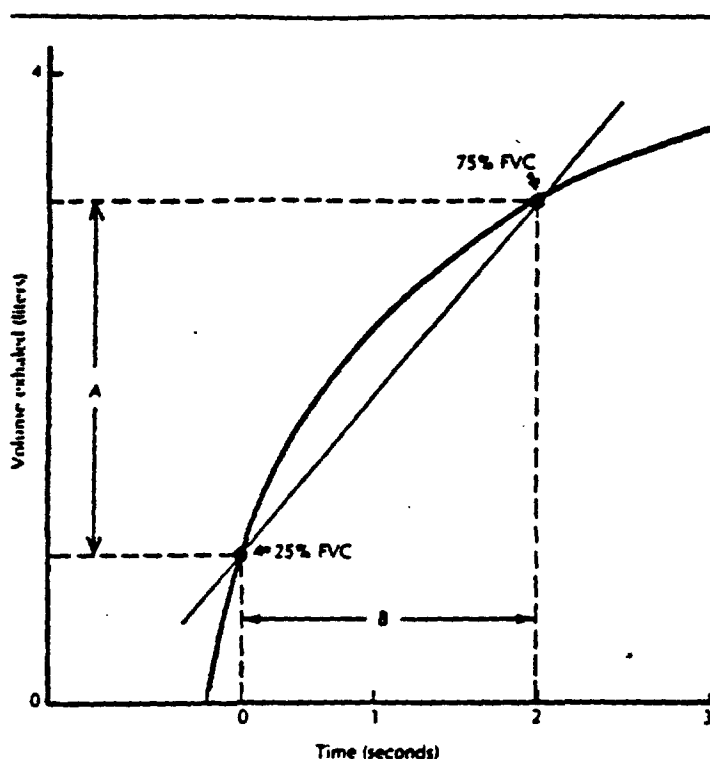


FIGURE 3. Determination of MMFR. (MMFR = A/B)

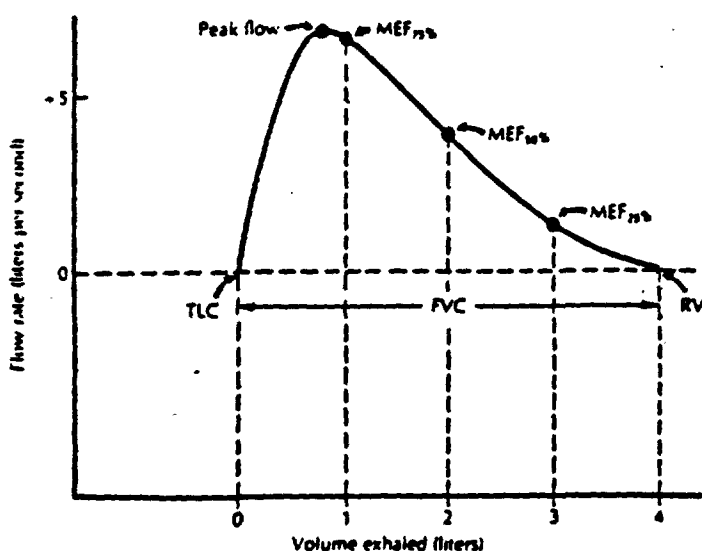


FIGURE 4. The expiratory portion of the flow-volume loop.

L. per minute. Values less than 80 percent of predicted values are considered abnormal. MVV is reduced greatly in patients with obstructive disease, but may be within normal limits for patients with restrictive disease. The MVV maneuver depends considerably on patient effort.

Combined Flow and Volume (Flow-Volume Loop)

The flow-volume loop is a graphic recording of volume versus its first derivative, air-flow, during a forced expiratory maneuver followed by a forced inspiratory maneuver. This type of recording requires a special spirometer capable of generating an electrical signal from which volume and flow can be determined. In actuality, only the expiratory portion of the loop is used, as illustrated in Figure 4. The excursion, in terms of lung volumes, goes from TLC to RV. FVC can be determined from the tracing as shown. Other parameters obtained from the flow-volume loop are peak flow (PF) and flow rates at specific expired volumes (MEF_{75%}, MEF_{50%}, MEF_{25%}).

PEAK FLOW

PF is the maximum flow rate obtained during an FVC maneuver (Figure 4). In healthy young men, PF may exceed 10 L. per second. Peak flow rates, however, are of limited value. Patients with obstructive disease, for instance, may develop an initially high flow rate before airway closure occurs. The value obtained is also dependent on patient effort.

FLOW RATES AT SPECIFIC EXPIRED VOLUMES

Flow rates at specific expired volumes have been shown to be more sensitive measurements of airway resistance than peak flow. MEF_{75%} is the flow rate at 75 percent of FVC, MEF_{50%} is the flow rate at 50 percent of FVC and MEF_{25%} is the flow rate at 25 percent of FVC (Figure 4). Because the pressures exerted on the alveoli and the small airways become equal during a forced expiration,

MEF_{25%} and MEF_{75%} are independent of patient effort. Normal values of MEF_{75%}, MEF_{50%} and MEF_{25%} for healthy young men average about 8.5, 6.5 and 3.5 L. per second, respectively.

Examples of flow-volume patterns with normal function, upper airway obstruction and small airway obstruction are illustrated in Figure 5. It is evident that PF, MEF_{75%},

MEF_{50%} and MEF_{25%} will vary in these conditions.

Obstructive vs. Restrictive Disease

Pulmonary function studies allow the physician to distinguish between obstructive and restrictive lung disease (Table 2). Obstructive diseases, in general, reduce the ability to move air; lung volumes and capacities are either normal or increased. Obstructive diseases include emphysema, chronic bronchitis and asthma. Restrictive diseases, in general, reduce volumes and capacities without interfering with airflow. Restrictive diseases include atelectasis, neoplasms, pneumothorax, surgical excision and pulmonary fibrosis. A restrictive pattern may also be seen in certain conditions not related to the lungs, such as respiratory center depression, neuromuscular disease, limitation of diaphragm movement by pregnancy or ascites and limitation of thoracic movement by kyphosis or pain.

TABLE 2

Capacities and Flows in Obstructive and Restrictive Disease

Pulmonary Function	Obstructive Disease	Restrictive Disease
VC	Normal or increased	Decreased
FRC	Increased	Decreased
TLC	Normal or increased	Decreased
FEV ₁	Decreased	Normal or increased
MMFR	Decreased	Normal or increased
MMV	Decreased	Normal or increased

* - May be decreased in severe restrictive disease.

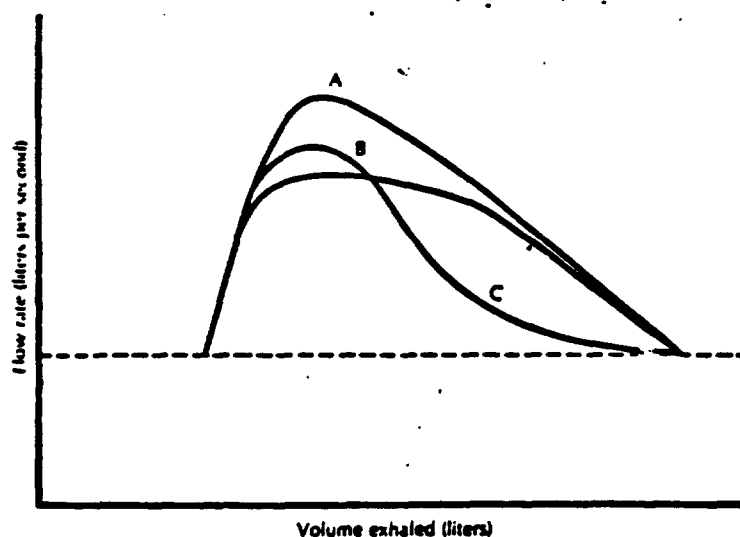


FIGURE 5. Typical flow-volume curves for (A) a normal individual, (B) upper airway obstruction such as tracheal stenosis and (C) small airway obstruction, such as occurs with chronic obstructive pulmonary disease.

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Determination of Therapy

Pulmonary function studies aid in the determination of therapy, particularly in diseases which have an obstructive component. After determination of baseline volumes, capacities and flow rates, a bronchodilator challenge (usually inhaled isoproterenol) is administered and the volumes, capacities and flows are redetermined. Significant reduction in FRC and increases in FEV₁, MMFR, MVV and other flow parameters suggest that use of oral bronchodilators will be beneficial, whereas lack of response or minimal changes suggest that chronic oral bronchodilation will be of no value. An increase in TLC of greater than 15 percent in restrictive disease indicates improvement will occur with the use of oral bronchodilators.

Diffusion Tests

The ability of gases to diffuse across the pulmonary membrane is expressed as the diffusing capacity for carbon monoxide

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(DLco). Carbon monoxide is used because of its tremendous affinity for hemoglobin, thus reducing the partial pressure of carbon monoxide in the blood of alveolar capillaries to essentially zero. The principle of determination for the steady-state technique is as follows: in the steady state, the rate of uptake by mouth of a low concentration of carbon dioxide (0.3 percent) is equal to the rate of its diffusion across the pulmonary membrane. The rate of diffusion across the pulmonary membrane is proportional to the difference in partial pressure of carbon monoxide in alveolar gas and alveolar capillary blood. Hence:

$$\text{Rate of uptake at mouth} = K (P_A - P_c)$$

P_A is the partial pressure of carbon monoxide in alveolar gas, P_c is its partial pressure in alveolar capillary blood and K is a proportionality constant equivalent to DLco. Since P_c is approximately zero, rearranging the equation yields:

$$DLco = \text{Rate of uptake at mouth} / P_A$$

The rate of uptake of carbon monoxide at the mouth can be measured, and alveolar carbon monoxide partial pressure can be approximated from end-tidal samples; DLco can then be calculated. Normal values for DLco average about 21 mL. per minute per mm. Hg. Diffusing capacity is decreased in emphysema, interstitial fibrosis, sarcoidosis, the

pneumoconioses, oxygen toxicity and pulmonary edema, states that are usually categorized as "diffusion defects." A diffusion defect is suspected when DLco is less than 75 percent of the predicted value. DLco is also decreased by anemia.

Gas Distribution

Helium equilibration time is determined during the closed-circuit measurement of FRC. The unevenness of ventilation determines the slope of the equilibration curve. If distribution is uniform, the curve is exponential. If ventilation is uneven, the slope is decreased, especially after the initial dilution of well-ventilated areas. A helium equilibration time of more than three minutes is abnormal.

Ventilation-Blood Flow Effectiveness

Ventilation-blood flow effectiveness can be determined by several methods, including radionuclide ventilation-perfusion scanning. The only indicator of ventilation-blood flow effectiveness used as part of routine pulmonary function studies is arterial blood gases (*American Family Physician*, March 1980).

Body Plethysmography

The body plethysmograph is not routinely used in small community hospitals, but is commonly used in larger institutions. It measures thoracic gas volume, airway resistance and specific conductance. To make the measurements, the patient sits inside an airtight box and breathes through a flowmeter. Calculations are based on the relationship between lung volume and the pressure within the box.

THORACIC GAS VOLUME

Body plethysmography measures all of the gas in the thorax, not just the portion freely exchangeable with the atmosphere. Therefore, in a patient with large noncommunicating bullae or cysts, the thoracic gas volume (TCV) would be larger than its counterpart, the FRC.



The Author

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TABLE 3.

Candidates for Preoperative Evaluation of Pulmonary Function

Patients scheduled for upper abdominal surgery
Patients with a history of heart, smoking and cough
Obese patients
Patients greater than 70 years of age
Patients with pulmonary disease

AIRWAY RESISTANCE

Airway resistance (R_{AW}) is defined as the pressure difference between the mouth and the alveoli, divided by the flow rate. Alveolar pressure, however, can only be measured indirectly; the body plethysmograph is one method of obtaining this measurement. Since airway resistance varies inversely with lung volume, reported values of R_{AW} must be accompanied by the values of TGV at which the measurements were made. R_{AW} is normally less than 2 cm. H_2O per L. per second.

SPECIFIC CONDUCTANCE

Specific conductance (SC) is an indicator of how easily air flows in and out of the lungs. It is determined by dividing the reciprocal of R_{AW} by the TGV at which it is measured:

$$SC = (1/R_{AW})/TGV$$

Normal values range between 0.14 and 0.35.

All community hospitals that have a body plethysmograph do not use it routinely. Its application may be based on criteria determined from routine pulmonary function studies. For instance, plethysmography may be used only if FVC is less than 80 percent of the predicted value, if FEV_1 is less than 70 percent of the predicted value or if MMFR is less than 50 percent of its predicted value.

Evaluating Surgical Patients

Pulmonary function studies are valuable in evaluating patients with shortness of breath and in patients undergoing major surgery.

Measurement of lung volumes, capacities and flow rates allows separation of lung disease into restrictive and obstructive types. Distribution of ventilation tests indicates asynchrony in filling and emptying of lung units; they are, therefore, helpful in the evaluation of cysts and bullae in patients undergoing lung surgery. Diffusion tests aid in evaluating the amount of functioning pulmonary capillary bed. Arterial blood gases allow an overall assessment of pulmonary gas exchange from the atmosphere to the blood.

Preoperative evaluation of pulmonary function is used to identify patients at increased risk for morbidity and mortality. Several pulmonary functions do, however, change postoperatively. Total lung capacity and each of its subdivisions decrease after abdominal surgery, but not after operations on extremities. This decrease is greater for upper than for lower abdominal surgery; VC, for instance, may decrease as much as 50 percent following upper abdominal surgery. Pao_2 may also decrease significantly following abdominal surgery, consistent with intrapulmonary shunting. Risk factors predisposing patients to postoperative pulmonary complications are listed in Table 3. Patients with these risk factors are generally considered candidates for preoperative pulmonary function studies.

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