

Measurement of Lung Volumes

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Abstract Lung volume measurements always determine total lung capacity (TLC), and most measurement techniques also determine functional residual capacity (FRC) and residual volume (RV). These measurements are needed less often than spirometry-derived values and require somewhat more difficult methods than required by spirometry. As with spirometry, accurate interpretation relies on appropriate reference values, standardized methodology and technically well-performed testing. A reduction in TLC defines chest restriction. Increases in TLC, FRC and RV are often seen in patients with airway obstruction. Patients with mixed restrictive and obstructive disease may have spirometry results that are difficult to interpret, and it is in these patients that lung volume measurements may be especially helpful.

Keywords Lung volumes measurements · Restrictive lung disease · Spirometry

Introduction

Lung volumes measurements determine the total lung capacity (TLC), functional residual capacity (FRC), and residual volume (RV) (see the preceding section on spirometry for full listing and explanations of the four capacities and four volumes of the lung). These measurements are needed less often for clinical decision making than spirometry-derived values. However, accurate measurement

of TLC provides direct evidence of chest restriction that supersedes determinations of chest restriction by measuring FVC. Measurements of RV and TLC by both plethysmographic and gas dilution methods provide evidence of overinflation and trapped gas, respectively, information helpful for understanding the severity of airway obstruction, and information that is not obtainable with spirometry alone.

Because TLC, FRC, and RV are not accessible by measurement of inhaled or exhaled volumes or flows of gases, somewhat more difficult methods than spirometry are required. There are three principal methods to measure lung volumes: gas dilution, body box plethysmography, and a radiographic technique.

Methods of measuring lung volumes

Gas dilution

The most common gas dilution method is the single breath inert gas method. This involves a single maximal inhalation of air containing a small concentration of helium, neon, methane, or another gas that does not cross alveolar walls, a 10-s breath hold, and an exhalation. Exhaled gas is collected, and the space of dilution of the inert tracer gas is measured. The concentration of the tracer gas need not be precisely known as long as the dilution can be measured. Back calculation allows estimation of the TLC (in most cases, an air mixture may be used that also contains a small concentration of carbon monoxide so that the diffusing capacity may be measured at the same time.)

Gas dilution is probably the easiest method of measuring lung volumes because it requires only one additional piece of equipment beyond a simple spirometer. A test subject is asked to exhale to FRC and inhale to TLC a tracer gas such as helium or neon, neither of which are significantly absorbed.

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Exhalation is performed and the exhaled gas is collected and passed through a gas analyzer, and the dilution of the tracer gas is determined by comparing with the inhaled gas. The volume of gas inspired (at ambient temperature, pressure and without water vapor) is multiplied by the dilution factor with a correction to body temperature, pressure, and saturation with water vapor to make an estimate of the TLC. >A further factor of 1.05 is multiplied to the coarse estimate to correct for CO₂ if the gas analyzer requires removal of CO₂ before measuring the concentration of inert gas. The FRC is determined by subtraction of the volume of inhaled tracer gas from TLC, while RV is derived by subtraction of the FVC from TLC. In the current era, this process is entirely automated and physically incorporated into most new spirometers. Equations for the manual derivation of TLC using older equipment are available [1].

Artifacts in lung volume measurement by gas dilution can arise due to technical problems or patient performance issues. Air leaks in the system and inappropriate collection of gas during exhalation of dead space gas both lead to decreased estimates of the dilution factor, leading to a decreased estimate of TLC. Gas meters may fail by having a non-linear response to changes in gas concentration leading to either over- or underestimation of TLC. An inadequate inspiratory effort can lead to a failure to fully inhale, resulting in a decrease in the estimated TLC; this artifact is typically detectable on the accompanying spirogram as an otherwise unexplained decrease in FVC when baseline data are available. Inadequate inter-measurement air breathing time leads to a violation to one of the underlying assumptions of the testing, namely, that the subject's lungs contain no tracer gas before each measurement.

The breath-hold time requirement of 10 s allows tracer gases sufficient time to diffuse into the RV and equilibrate before exhalation in patients with normal TLC. When the 10-s breath hold requirement is not met, it causes an artifactually low estimate of TLC. However, for patients with increased lung volumes due to severe obstructive disease, many more than 10 s may be needed to allow equilibration of gas concentrations throughout the lung. Because the point of measurement is to measure TLC, attempting to adjust the breath hold time to allow for increased TLC for each particular patient is not possible and is quite impractical in any case for patients with the most severe disease who might require breath hold times approaching or even exceeding an entire minute. These last underestimates of TLC are not considered to be artifacts, rather the amount of underestimation, when combined with another method of TLC measurement, allows an additional measurement of the degree of disease known as gas trapping. See below for further discussion. In chronic obstructive pulmonary disease (COPD), there may be poor mixing of the inspired gas into the lung, and the TLC is underestimated.

An alternative method is to have the patient re-breathe the mixture of gases until a meter demonstrates that the concentration of the test gas has reached an equilibrium. However, most modern pulmonary function testing equipment is designed to measure the gas dilution TLC using the 10-s breath hold method, and this is done simultaneously with the measurement of the diffusing capacity (see the following section on measuring the pulmonary diffusing capacity).

For completeness, there is also a nitrogen washout method of measuring the TLC, but now, this is rarely, if ever, used. With this method, nitrogen is washed out of the lung and collected as the patient breathes 100% oxygen. Since the gas in the lung is 79% nitrogen, measuring the amount of exhaled nitrogen and the percent of residual nitrogen in the lung allows for calculating the TLC. With this method, there is also a correction factor for the nitrogen washed out of the blood during the test.

Body plethysmography

Gas at a constant temperature obeys Boyle's Law, which states that a quantity of gas (with a constant mass) has a constant product of pressure and volume, or $P_1V_1=P_2V_2$. This physical law forms the underlying basis for measurement of thoracic gas volume in a body plethysmograph. A patient is asked to breathe through a valve connecting the air within the plethysmograph with the atmosphere. The body plethysmograph is otherwise isolated from the atmosphere. After sufficient quiet breathing, to be confident that the patient is starting breaths from FRC, the resting position of the chest and lung, the patient is warned, the valve is occluded, and the patient is asked to pant against the closed valve. As the patient pants, the change in pressure within the body box (surrounding the patient) and the pressure in the patient's airway are measured. Because the body box is a constant known volume, the change in volume surrounding the patient in the body box due to expansion and contraction of the patient's chest during panting is linearly related to the accompanying change in pressure and can be calculated using a calibration factor associated with the particular body box. Once this is known, the patient's FRC is calculated. To derive TLC, the patient is asked to inhale to TLC from FRC via the valve, and the volume inhaled is added to FRC. To derive RV, FVC is measured and subtracted from the TLC.

This method assumes that alveolar pressure is equal to the pressure measured at the mouth. In severe airway obstruction, there may be insufficient time for alveolar pressure to equilibrate with mouth pressure, and this can lead to an overestimation of TLC. More modern body plethysmographs allow for slower rates of panting, allowing for pressures measured at the mouth to represent alveolar gas pressure. See the manual for the specific body

plethysmograph being utilized for details of the methodology and for techniques for calibration.

Radiographic TLC

Because plane film radiographs of the chest are obtained while a patient performs a breath hold at full inspiration, measurement of the TLC may be accomplished by making measurements of the air spaces imaged in the chest. On a PA radiographic projection, measurements of the right to left distance of the thoracic cavity are taken at four different levels along with longest axis of the heart and the perpendicular axis to the heart. On a lateral radiograph, the AP diameter of the thorax is measured at the same four levels along with the AP diameter of the heart and diaphragms. The thoracic volume is assumed to be a stack of elliptical cylinders; the heart is assumed to be an ellipsoid, and the hemi-diaphragms are assumed to be hemi-ellipsoids. Using the volume formulas for the various shapes and the measurements taken from the radiographs, the TLC is calculated as the difference between the thoracic volume and the sum of the heart and hemidiaphragm volumes with a further subtraction accounting for lung tissue and blood volumes [2]. This procedure is somewhat laborious but is of interest for two reasons. First, there is no need for a spirometer, gas concentration analyzer, or body box plethysmograph so that TLC can be measured at any clinic with the ability to perform radiography—a much more common ability worldwide than spirometry, gas dilution lung volumes, or body plethysmography. Second, TLC measurement may be made anytime after a chest radiograph is made so that historical changes in TLC can potentially be tracked in a retrospective fashion provided that old chest radiographs are available. This method has the disadvantage, however, that FRC and RV cannot be derived without simultaneous spirometry.

Quality control

TLC measurement made by gas dilution must be performed at least twice, and the values obtained should be within 5% of each other. Plethysmographic measurements must be performed a minimum of three times, and at least two of the measurements should be 5% of each other. It is important to remember that repeated measurements using either method can be exhausting and lead to artifacts in measurement. Patients with claustrophobia may not tolerate being in the body plethysmograph.

Radiographic TLC requires care while making the measurements needed for the calculations and equal care for the actual calculations. Repeated measurements are typically not performed, as the chest radiograph is static. While not immediately obvious, because the chest film may

have been taken at some distant time in the past, this test also depends on the subject's inspiratory effort at the time of the radiographic study.

Uses of lung volume measurements

Chest restriction

Most diagnoses of chest restriction are based on observed reductions in FVC because spirometric measures are more easily obtained. Nevertheless, chest restriction is defined by a reduction in TLC. Reduction in TLC may be due to increased stiffness of the chest wall such as found in kyphoscoliosis, stiffness in the lung itself as found in pulmonary fibrosis, or reduced muscular strength to expand chest and lungs of normal stiffness as in muscular dystrophy or other neuromuscular disorders. The difference in etiology makes little difference for spontaneous breathing, but it may somewhat influence ventilator management for those patients unfortunate enough to require mechanical ventilation.

The most reliable measurement methods for TLC are body plethysmography and the radiographic method. Body plethysmography estimates total body gas at full inspiration. It is thus subject to errors due to the presence of extrapulmonary gas, primarily in the gastrointestinal tract. The radiographic method is not subject to errors due to extrapulmonary gas; however, manual measurement requires taking several assumptions based on estimates of cardiac volume, hemidiaphragm sizes, and volume of lung tissues and vessels. Gas dilution methods can be reliable for defining the degree of restriction, but only if there is no concomitant airway obstruction. In patients with moderate to severe airway obstruction, mixing of inhaled gases with RV gases may be incomplete leading to an underestimate of TLC.

Airway obstruction

Airway obstruction is defined as the reduction in the ratio of forced expiratory volume in 1 s/forced vital capacity (FEV_1/FVC), and the degree of obstruction is determined by the magnitude of reduction in FEV_1 . Lung volume measurements can provide confirmatory information to supplement spirometric information. TLC is often increased in airway obstruction as are FRC and RV. An increase in TLC is termed overinflation, and the degree of overinflation is defined by the amount of increase in TLC compared to reference values. The ratio of RV/TLC is often increased in airway obstruction. Detection of an increased RV/TLC ratio requires a measurement of RV, making it difficult to use the radiographic technique for TLC determination [2] as part of the evaluation.

The method of lung volume measurement must be considered when looking for information to supplement spirometric determination of airway obstruction. While both plethysmography and radiographic TLC measurements are usually unaffected in sensitivity by airway obstruction and are able to report the actual amount of gas present, single breath lung volume measurements may be underestimated because of the failure of inhaled gases to fully mix with residual gases in the lung, leading to an underdilution of tracer gas and an underestimate of TLC. However, the vulnerability in the method, as it is known, can be used to provide additional supplementary information supportive of a diagnosis of airway obstruction. Simultaneous TLC by body box or radiographic can be used as a reference, and the ratio of TLC by body plethysmography or the radiographic method to the TLC measured by gas dilution can be used to determine the presence and degree of gas trapping [1]. This derived result is essentially a reflection of the volume of gas that has poor ability to exchange with inhaled gases and represents

intrapulmonary dead space. The inverse of the ratio gives the fraction of gas in the chest that is in good communication with inhaled gases. The larger the fraction of lung that is not in good communication, the more likely that poor gas exchange will lead to both hypoxemia and retention of CO₂. Gas trapping thus can provide an additional measure of the severity of airway obstruction.

TLC measurements by body plethysmography allow the simultaneous measurement of airway resistance (Raw) and its reciprocal, airway conductance (Gaw). The specific airway conductance, SGaw, is the airway conductance divided by the thoracic gas volume used to measure the Gaw. In patients with bronchoconstriction, the Raw may be acutely increased and the Gaw and SGaw decreased without a change in TLC. These measurements may be more sensitive to airway obstruction than the spirometry-derived FEV₁ and can be helpful in diagnosing asthma in selected patients whose spirometry is otherwise normal. Their increased sensitivity to changes in larger airways may result in an increased ability to detect

Table 1 Reference equations for lung volume studies

Reference	Year published	Number of subjects	Population studied
Harris et al. [2]	1971	102, gender not specified	42 healthy, 60 with COPD and other lung diseases
Crapo et al. [6]	1982	123 M 122 F	Non-smoking Caucasians
Massey et al. [7]	1986	59 M 59 F	Japanese-Americans aged 20–80
Withers et al. [8]	1988	162 M	South Australian men including smokers
Petersen and Hodous [9]	1988	African American 286 M 297 F Caucasian 337 M 291 F	Smoking and non-smoking African-Americans and Caucasians from the food, synthetic textile and electrical equipment and supplies industries in North Carolina
Withers and Lemmey [10]	1989	161 F	South Australian never-smoking women
Kilburn et al. [11]	1992	357 M 315 F	Smoking and non-smoking Caucasian adults randomly chosen by phone numbers from Michigan, USA
Rosenthal et al. [12]	1993	455 M 317 F	Caucasian children and teenagers from London
McCoy et al. [13]	1995	14 M 13 F	Infants aged 4 weeks to 26 months studied under chloral hydrate sedation
Chin et al. [14]	1997	Chinese 60 M 115 F Malay 37 M 58 F Indian 49 M 87 F	Chinese, Malaysian and Indian never smoking adults without history of lung disease, Singapore
Corzo-Alvarez et al. [15]	1998	50 M	Healthy adult males from Maracaibo, Venezuela (Spanish Language)
Roca et al. [16]	1998	300 M 182 F	Non-smoking healthy adult volunteers from Barcelona, Spain
Cordero et al. [17]	1999	305 M 286 F	Non-smoking healthy adults from Valencia, Spain
Neder et al. [18]	1999	50 M 50 F	Non-smoking adults randomly chosen from among 8,226 non-student and non-medical Brazilians associated with the Federal University of Sao Paolo
Ip et al. [19]	2000	219 M 332 F	Non-smoking, native-born Chinese children 7–19 years old with no history of lung disease from 7 schools in Hong Kong
Cotes et al. [20]	2001	383 M 97 F	All non-smokers except 22 female ex-smokers from the UK
Zheng and Zhong [21]	2002	2,560 M 2,213 F	Healthy Chinese volunteers from 6 parts of China
Marsh et al. [22]	2006	110 M 102 F	Never smoking New Zealanders of European descent
Piirilä [23]	2007	9 M 1 F	Never smoking Finnish adults
Caussade et al. [24]	2008	122 M 123 F	Healthy Chilean children and adolescents

responses to bronchodilators. Unfortunately, increased sensitivity is accompanied by decreased specificity. Additionally, in a patient with acute bronchoconstriction and dyspnea, claustrophobia may make the use of the body box plethysmograph impractical. Furthermore, the body plethysmograph is a much more expensive instrument than a spirometer and thus is less often used in smaller pulmonary function laboratories.

Mixed airway obstruction and restriction

Because airway obstruction is defined as a reduction in FEV₁/FVC ratio and because the spirometric determination of restriction depends upon reduction in FVC, mixed disease can be quite difficult to determine from spirometry alone. Even with supplementary information from lung volume determinations, a fully satisfactory diagnosis may not always be possible.

In airway obstruction, TLC, FRC, and RV may all be elevated. Typically, the ratio of RV/TLC is elevated. In chest restriction, TLC is reduced by definition so that an increase in TLC essentially rules out the presence of restriction. Thus, in mixed disease, one might see a near-normal or clearly reduced TLC but with an elevated RV/TLC ratio. There may also be overinflation when simultaneous measurements of TLC are taken by body box plethysmography or radiographic plethysmography and gas dilution TLC measurement. Combining spirometry as a measure of airway obstruction with body plethysmography as a measure of restriction can allow for a diagnosis of mixed abnormal lung physiology.

Interpretation

As with spirometry, measurements of lung volume must be interpreted using appropriate normalization or reference equations [3]. There are far fewer published sets of reference values and equations for lung volume measurements than for spirometry. This reflects the decreased frequency of lung volume measurements and the decreased need for reference values. Most laboratories in the USA and Europe use reference equations published by the American Thoracic and European Respiratory Societies [4, 5]. A non-exhaustive list of papers that present lung volume reference values are shown in Table 1.

Summary

Lung volume measurements are less commonly obtained than spirometry. Decreased TLC defines restrictive lung disease. Airway obstruction is defined by dynamic spirometric

measurements; however, lung volume measurements can be a valuable adjunct for patients with difficult to detect or characterize airway obstruction. It can be useful in assessing patients with severe chronic obstructive pulmonary disease for lung volume reduction surgery. Finally, for patients with mixed restrictive and airway obstruction, lung volume measurements may provide the information needed for full understanding of the nature and degree of lung disease.

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