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Physiology and conduct of pulmonary function tests

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Learning objectives

By reading this article, you should be able to:

- Describe how pulmonary function tests assess different aspects of respiratory system physiology.
- Explain how the tests are performed and their theoretical basis.
- Recognise physiological factors that affect the results and so their interpretation.

Pulmonary function tests (PFTs) have become the mainstay for evaluating the respiratory system in the perioperative period. It is important to understand how PFTs are performed in order to appreciate fully what the results tell us about a patient, including the limitations of the data presented. The interpretation and clinical use of PFTs will be described in a linked article in this journal.[1]

Lung function tests evaluate three main aspects of the respiratory system: respiratory mechanics, parenchymal lung function, and the interaction of the cardiac and pulmonary systems.

Key points

- Static lung volumes are measured when no gas is flowing and include simple 'bedside' spirometry or complex techniques to include residual volume.
- Dynamic lung volumes involve continuous measurement of inspiratory or expiratory flows against either time or pressure.
- Respiratory system resistance requires simultaneous measurement of both pressure and flow, and different techniques measure various physiological components of resistance.
- Transfer factor is measured by uptake of carbon monoxide and represents lung parenchymal function.
- Tests for assessing the integrated function of the respiratory and cardiovascular systems vary from simple walking tests to complex cardiopulmonary measurements during exercise.

Basic methods for respiratory measurements

Most of the tests described in this section depend on three basic measurements: (i) *Pressure* is measured using transducers within the breathing system that convert the pressure into an electrical signal. With current technology these can be very small and accurate, and have response rates that are easily fast enough for respiratory measurements. (ii) *Flow* is most commonly measured using a pneumotachograph, in which a small resistance is placed in one of the tubes of the breathing system, and the pressure decrease across this resistance relates to flow rate. The resistance offered is too small to be detected by the patient. Mechanical methods are now rare, although handheld peak expiratory flow devices with a variable orifice system are still used for monitoring asthma severity. (iii) *Volume*. Inspired and expired lung volumes may be measured by the following. (a) Spirometers, which may be water-sealed or dry (using bellows), the

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advantage of both types is their low resistance to breathing, though they are bulky machines unsuitable for portable use and now rarely used. (b) Impellers and turbines such as the Wright respirometer, which mechanically converts the turbine movement into a volume reading. (c) Integration of flow measurements with respect to time, usually from a pneumotachograph signal, providing breath-by-breath values without any disturbance to the patient's breathing. This technique is routinely used in anaesthetic machines and artificial ventilators. (d) Body plethysmography, in which the patient sits in an air-tight transparent box of fixed volume and breathes from a breathing system outside of the box: any change in pressure within the box then equates to a change in lung volume. (e) Non-invasive measurement of ventilation may be achieved using belts placed around the chest and abdomen that use electrical impedance to measure the cross-sectional area within the belt. Once calibrated to volume using a spirometer, the impedance changes provide a reasonable measure of tidal volume with no mouthpiece or other equipment. They may then be used even while the subject is sleeping, and if both chest and abdominal belts are used can also detect airway obstruction.

All these techniques measure flow or volume at ambient temperature and pressure at the time of the measurement, and so lung volumes must be converted to the volume they would occupy at body temperature and pressure when saturated with water vapour (BTPS).[2]

Tests of respiratory mechanics

Respiratory mechanics is an ill-defined term describing the mechanical behaviour of the lungs and chest wall as air moves in and out. John Hutchinson coined the word 'spirometer' and first presented his modification of an earlier 'gasometer' in 1846; for many years spirometers became the cornerstone of measuring inspired and expired volumes.

Static lung volumes

These volumes are measured when no air is flowing in or out of the lung, hence 'static' lung volumes. At different levels of inflation and deflation the amount of air in the lungs is represented as the named volumes shown in Figure 1. When two volumes are combined they are referred to as capacities, for example inspiratory reserve volume plus tidal volume is inspiratory capacity.

Static volumes that do not include residual volume (RV) may be measured using any of the techniques described above for measurement of volumes (e.g. a spirometer), many of which are available as bedside or portable devices. Techniques for measurement of the static lung volumes that include RV are discussed in the following subsections.

Gas dilution

The closed-circuit gas dilution method for measuring functional residual capacity (FRC) is based on the principle of gas equilibration between a spirometer and the lung. Helium is commonly used as it is inert and mostly insoluble in blood, so it can be assumed that negligible amounts of the gas in the system dissolve in the blood during the measurement. Starting at end-expiration the subject breathes from a closed-circuit spirometer of known volume (V_{spiro}), which contains a known fractional concentration of helium (F_{He1}), and equilibration is allowed to take place with the lung, which has an

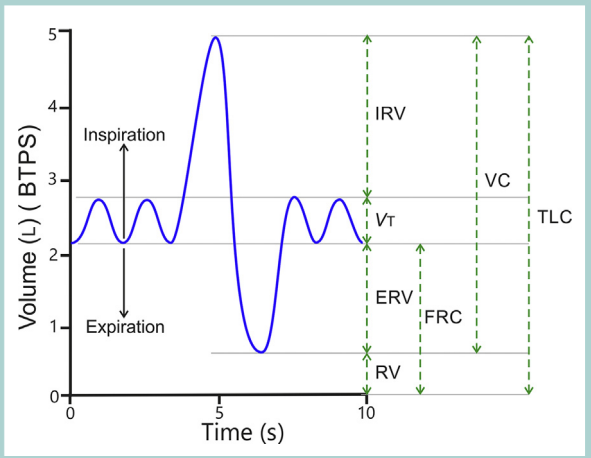

Fig 1 Spirometer trace of a vital capacity manoeuvre in which the subject has breathed in as far as possible before breathing fully out. V_T, tidal volume; IRV, inspiratory reserve volume; ERV, expiratory reserve volume; RV, residual volume; FRC, functional residual capacity; VC, vital capacity; TLC, total lung capacity.

unknown volume (FRC). After equilibration between the two volumes, the helium concentration becomes the same in all parts of this system and the final concentration of helium (F_{He2}) is measured. The total volume of distribution of helium is then calculated using the following equation

$$V_{spiro} \times F_{He1} = (V_{spiro} + FRC) \times F_{He2} \quad (1)$$

which when re-arranged gives

$$FRC = V_{spiro} \times (F_{He1} - F_{He2})/F_{He2} \quad (2)$$

FRC measured by this technique is often referred to as FRC_{He}. If the spirometer is connected to the patient at the end of a maximal exhalation, the volume measured will then be RV, or this can be calculated from the measurement of FRC minus expiratory reserve volume (ERV).

Nitrogen washout

This test is based on the principle that if the volume of exhaled nitrogen is measured then the original volume of gas in the lung (in this case the FRC) can be calculated by dividing this exhaled volume by the initial fractional concentration of nitrogen. For instance, if 2.4 L of nitrogen is exhaled and the fractional concentration is 0.80 the initial lung volume must have been 2.4 ÷ 0.80 or 3 L. Starting at the end of expiration (FRC) the subject breaths 100% oxygen, and the nitrogen contained in the FRC at this time is 'washed out' over a period of approximately 7 min. If all the expired gas is collected and the concentration of nitrogen measured, the amount of nitrogen expired is known. As the end-tidal nitrogen concentration (which equates to alveolar concentration) is measured throughout the washout period then the initial and final alveolar nitrogen concentration is known, allowing the calculation of FRC using the equation:

$$FRC = \frac{(\text{Volume } N_2 \text{ washed out}) - (N_2 \text{ tissue excretion})}{\text{Initial} - \text{Final alveolar } N_2 \text{ concentration}} \quad (3)$$

A very accurate gas analyser is required for this technique and allowance must be made for the nitrogen excreted from tissues (capillary blood and lung tissues) into the alveolus during the washout period: a standard correction factor of 275 ml is normally used.

Body plethysmography

In a closed system at constant temperature the volume (V) of an ideal gas is indirectly proportional to the pressure (P) in the system, that is the product of P and V is a constant. This Boyle–Mariotte law is the basis for plethysmographic measurements of lung volumes, as first described by Dubois and colleagues in 1956.[3] The subject sits in the box, much like a shower cubicle, and is attached to a mouthpiece while wearing a nose clip so all respiratory effort is through the mouth. After a period of tidal breathing and at the end of expiration (FRC), a shutter is closed at the mouthpiece by remote control and the patient is asked to make respiratory efforts, a bit like panting, with the glottis open. This varies the pressure and volume of gas present in the lungs. Two calculations are done: the first determines the change in volume (ΔV) in the box by applying Boyle's law to the cubicle before and after shutter closure:

$$P_1 \times V_1 = P_2 \times (V_1 - \Delta V), \quad (4)$$

where P_1 and P_2 are the pressures in the box before and after shutter closure, respectively, and V_1 is the initial volume in the box (volume of the box minus volume of the patient) before shutter closure. This is measured by injecting a small known volume of air into the box once the patient is inside and recording the pressure change. ΔV can then be calculated by solving equation (4).

The second calculation applies Boyle's law to the gas in the lung V_2:

$$P_3 \times V_2 = P_4 \times (V_2 + \Delta V), \quad (5)$$

where P_3 and P_4 are the mouth pressures before and after shutter closure, respectively. This equates to alveolar pressure. Solving the equation for V_2 gives the volume of the lung at the point of shutter closure or airflow occlusion. If this point was at the end of normal expiration, then V_2 is FRC, usually referred to as FRC_{pleth}.

FRC_{pleth} is the only measuring technique that also includes gas in the FRC trapped distal to closed small airways, so different results may be obtained for FRC_{He} and FRC_{pleth} in patients with airway disease.

Dynamic lung volumes

As the name suggests, some of these volumes are measured while inspiration or expiration are occurring. Forced vital capacity (FVC) is the volume of air exhaled with a forced effort from a maximal inspiration to total lung capacity (TLC), that is vital capacity (VC) performed with a maximal expiratory effort. This differs slightly from VC, which is a slower expiration from TLC to RV: FVC is usually less than VC, the difference reflecting to the amount of small airway closure during the forced expiration. Forced expiratory volume in 1 s (FEV_1) is the volume of air exhaled in the first second of the forced expiration. These tests are also easily performed at the bedside. Examples of measurements of dynamic lung volumes are shown in Figure 2.

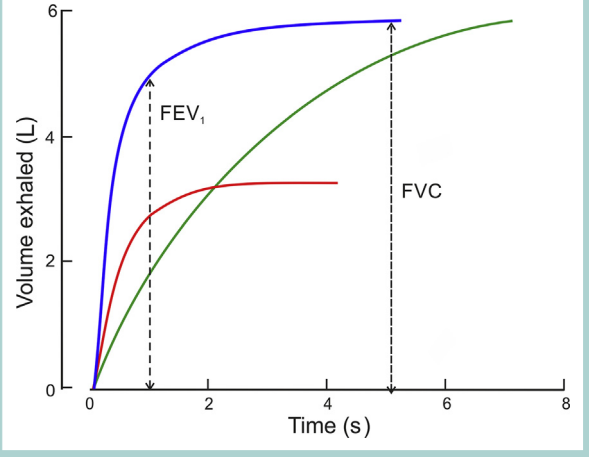

Fig 2 Idealised forced expiratory spirograms (volume–time curves) of a healthy subject (blue line) and patients with airflow obstruction (green line) and restrictive lung disease (red line). In the obstructive pattern expiration is prolonged but theoretically reaches a normal forced vital capacity (FVC) although this is rare in practice. In the restrictive pattern, a normal vital capacity is not achieved. Note also that forced expiratory volume in 1 s (FEV_1) is reduced irrespective of the abnormality so is a good screening tool for lung disease.

Other indices such as $FEV_{0.50}$ or $FEV_{0.75}$ can also be used and are self-explanatory. Peak expiratory flow rate (PEFR) is the maximal *flow* achieved during an FVC manoeuvre. Finally, FEV_1 % is $FEV_1/FVC \times 100$ and as a ratio has the advantage of being nearly independent of lung size, stature, or height.

Dynamic tests such as FVC and FEV_1 are dependent on many factors at the time of performing the test, including patient effort; and the staff performing the test will comment on these in the PFT report if they consider them to have had an impact on the test result.

Flow-volume loops

A flow-volume loop plots inspiratory and expiratory flow on the ordinate (y-axis) against the inspiratory or expiratory volume on the abscissa (x-axis). This may be done during tidal ventilation when the pattern is almost circular, but for diagnostic purposes the patient usually performs an FVC manoeuvre (Fig. 3). The inspiratory part of the curve is saddle shaped with flow rising steadily to a plateau before falling again. As the patient begins to forcibly exhale there is a steep rapid increase in the curve to PEFR. This is quickly followed by a linear decrease in flow until the end of expiration as lung volume decreases to RV. This part of the curve in normal subjects is linear to almost convex in shape and demonstrates closure of small airways during forced expiration. Most current anaesthetic machines and ventilators display real-time flow-volume loops during tidal ventilation and calculate compliance from them.

Characteristic flow-volume loop patterns are associated with certain types of obstructive and restrictive conditions and can help with their localisation (Fig. 3).

Respiratory system resistance

In healthy individuals the resistance to movement of air in and out of the lung is approximately equally distributed

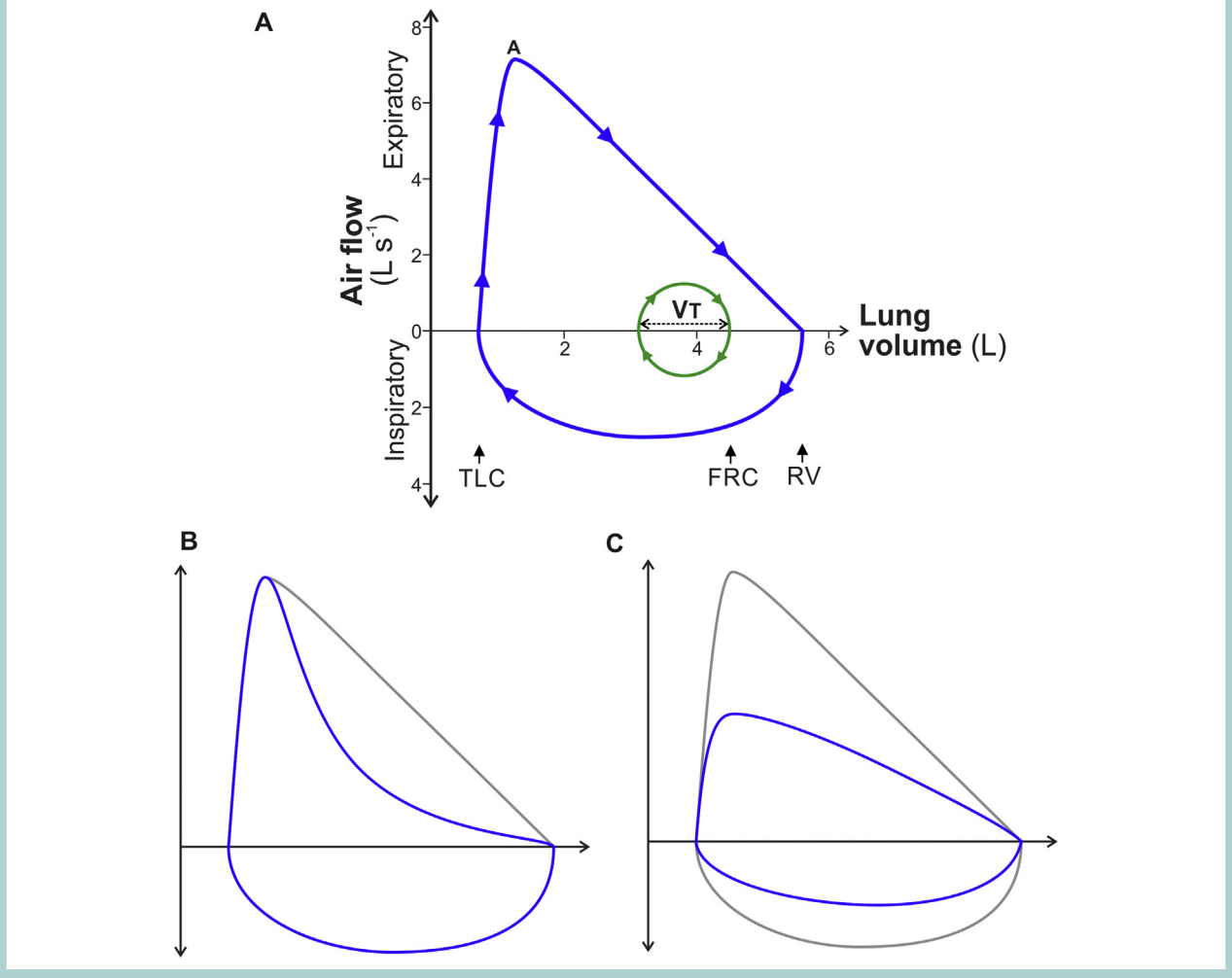

Fig 3 Flow-volume curves. A, normal tidal volume curve (green line) from functional residual capacity (FRC) and a vital capacity manoeuvre (blue line) in which the subject exhales to residual volume (RV), breathes in fully to total lung capacity (TLC) and then exhales forcibly back to RV. (A) Peak expiratory flow rate, after which closure of small airways limits expiratory flow rate. (B) Abnormal curves because of airway obstructive airway diseases such as asthma or chronic obstructive pulmonary disease (COPD) with a concave expiratory phase caused by increased intrathoracic airway closure early in expiration (normal curve shown in grey). (C) Fixed large airway obstruction, either intra- or extrathoracic, causing poor flow in both respiratory phases.

between the reluctance of the thoracic cage and lung tissue to change shape (tissue resistance) and the resistance to gas flow through the airways (airway resistance, R_{aw}). R_{aw} itself results mainly from the resistance of the larger airways, including the mouth, nasal passages, and the larynx, as their total cross-sectional area is small compared with the total cross-sectional area of the large number of smaller airways. Thus, with all other factors remaining mostly constant it is the changes in calibre of the small airways that determines R_{aw}. Gas flow through airways is turbulent in the upper airway and large airways, and tends to become more laminar as the flow velocity decreases in the small airways.

Airway diameter, and thus resistance, varies with lung volume, resistance being lower at larger lung volume when the airways are expanded and higher as lung volume approaches RV (Fig. 4). This inverse relationship of R_{aw} to lung volume is hyperbolic such that the reciprocal of R_{aw} (airway conductance, G_{aw}) increases linearly with lung volume. Furthermore, if conductance is divided by thoracic gas volume 'specific conductance' (sG_{aw}) is obtained, which is independent of lung volume and so is a good marker of bronchomotor tone.

Determination of respiratory system resistance requires measuring the pressure difference across the airways and dividing this by the air flow, as analogous to Ohm's law for electrical resistance.[4] Airway resistance (R_{aw}) requires measurement of the driving pressure between the mouth and the alveoli, lung tissue resistance the pressure between the pleura and alveoli, and chest wall tissue resistance the difference between the pleural and ambient pressures. Pleural pressure may be measured with an oesophageal balloon, but this is rarely done outside of research studies. The various clinical techniques for measuring resistance therefore all measure slightly different combinations of the components of overall respiratory system resistance, as shown in Table 1.

Methods for measuring respiratory system resistance

Whole body plethysmography. The measurement is made using a constant volume plethysmograph as described above

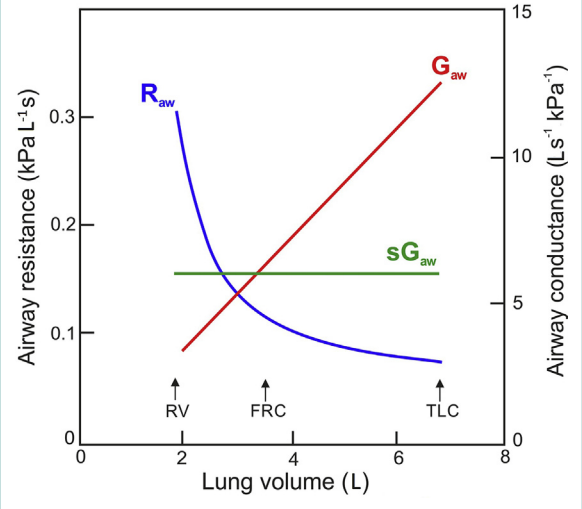

Fig 4 Relationship between airway resistance (R_{aw}, blue line) and lung volume. The reciprocal of R_{aw} is airway conductance (G_{aw}, red line), and G_{aw} divided by thoracic gas volume is specific airway conductance (sG_{aw}, green line). Note that only sG_{aw} is independent of lung volume. RV, residual volume; FRC, functional residual capacity; TLC, total lung capacity.

with the subject connected to a pneumotachograph measuring flow via a mouthpiece with a shutter mechanism. Mouth pressure (equal to alveolar pressure when there is no flow) and box pressure are recorded when the subject either pants against the closed shutter or during quiet breathing. The compression and expansion of air within the plethysmograph during the respiratory cycle changes the pressure in the box and lungs and the greater the airway resistance the greater the pressure swings. The plethysmographic method for lung resistance measurement also measures thoracic gas volume; this is necessary for interpreting resistance measurements.

The interrupter method. This measures alveolar pressure, which is equal to mouth pressure when there is no flow, during a brief (<100 ms) interruption in inspiration with a shutter. Resistance is then calculated using inspiratory flow rate (measured before interruption), mouth pressure (measured before interruption), and alveolar pressure (measured at the end of the interruption). This method of measuring resistance is non-invasive, quick, and requires no special respiratory manoeuvres, so it can be used in children.

Pressure-flow method. This is an invasive method using a manometer in the oesophagus to reflect pressure in the pleural space along with flow and pressure recordings at the mouth. A pressure flow curve is produced from which lung resistance (i.e. all components except the chest wall) may be calculated.

Forced oscillation method. Forced oscillations generated by a pump connected to the mouthpiece induce a back pressure that is a function of the amplitude of the oscillations and the total respiratory impedance. The term resistance mostly refers to the degree of impairment of constant flow, as occurs with normal breathing, whereas impedance is usually used to describe the impairment of an oscillating flow, as used by this technique. The total respiratory impedance has three components: resistance (including airway and tissue components), respiratory system compliance, and inertance. The last of these is the energy required to overcome the inertia of gas molecules as they change flow direction, which is negligible during normal breathing but becomes significant with oscillatory air movement. There is a resonant frequency at which the compliance and the inertance components cancel out each other and the resultant impedance of the lungs is attributable entirely to the resistive component. In practice, the subject breaths through a pneumotachograph connected to a sinewave pump or loudspeaker, and pressure and flow are displayed on a screen.

Tests of lung parenchymal function

From the alveolar gas, oxygen diffuses down its partial pressure gradient across the alveolar epithelial cells, interstitial space, basement membrane, capillary endothelial cell, through the plasma, and then across the red blood cell membrane before combining with haemoglobin. The rate constant for this complex process is usually referred to as lung diffusing capacity (D_L), but is more accurately called the transfer factor (T_L) as its final stage (the reaction with haemoglobin) is unrelated to diffusion. In addition, the measurement is made at rest, so it is not a 'capacity' measurement that normally suggests 'best achieved' value. When referring to carbon monoxide (see below), the term T_{LCO} is used by the European respiratory community and is expressed in mmol min^{-1} kPa^{-1}, whereas the term D_{LCO} is used in North America, and is expressed in ml min^{-1} mm Hg^{-1}. The European Respiratory Society (ERS) and the American Thoracic Society (ATS) task force in 2005 agreed to use the term D_{LCO} for uniformity and because of its historical use.[5,6]

Transfer factor can be measured for oxygen, carbon monoxide, or nitric oxide. Oxyhaemoglobin dissociates

Table 1 Components of respiratory system resistance. Shaded areas indicate which components contribute to each form of resistance, whereas the text in the shaded boxes states the methodology used to measure each form of resistance

	Mouth and pharynx	Larynx and large airways	Small airways <3 mm diameter	Alveoli and lung tissue	Chest wall	Total
Contribution (kPa L^{-1} s)	0.05	0.05	0.02	0.02	0.12	0.26
Airway resistance	Body plethysmograph or interrupter technique					0.12
Pulmonary resistance	Pressure flow technique					0.14
Respiratory system resistance	Forced oscillation technique					0.26

readily with the ensuing partial pressure of oxygen in the plasma rising along the pulmonary capillaries, which can only be determined indirectly. In particular, the P_{O_2} at the end of a pulmonary capillary varies between different lung regions and cannot be measured, so it must be calculated from knowledge of the kinetics of the reaction between haemoglobin and oxygen. Thus, T_{LO_2} is rarely considered.

Nitric oxide has more affinity for haemoglobin than oxygen or carbon monoxide and reflects the properties of the alveolar–capillary membrane much better than the more commonly measured T_{LCO}. It holds promise for the future.

Carbon monoxide (CO) is used as a surrogate for oxygen to measure the gas exchanging properties of the lung as it has several advantages. It is a foreign gas not normally present in appreciable amounts in the body so venous blood contains negligible CO, and its chemical reaction with Hb is so rapid and slow to reverse that pulmonary end-capillary blood P_{CO} can be assumed as zero. Thus, one needs only to measure CO uptake and the alveolar concentration of CO.

CO uptake in the lung is composed of two processes: membrane conductance (D_m), where D reflects the diffusion of CO across the available membrane, and reactive conductance, which reflects the rate constant for the combination of CO with haemoglobin. This can be presented as the product of the CO–Hb chemical reaction rate (θ) and the volume of Hb in alveolar capillary blood (V_c).

These two processes occur in series and are thus added as reciprocals.

$$T_{LCO} = \frac{1}{D_m} + \frac{1}{\theta \times V_c} \quad (6)$$

Measuring T_{LCO}

Relevant terms

CO leaves the lung exponentially, and when expressed logarithmically k_{CO} (lower case k), the rate constant, is the measured rate of change in CO concentration (in mmol L^{-1}) per minute. K_{CO} (capital K) is k_{CO} corrected for barometric pressure and so represents the rate of uptake of CO measured as the decrease in alveolar CO concentration per unit time per unit CO driving pressure (P_{ACO}) (units of mmol L^{-1} min^{-1} kPa^{-1}). In equation form,

$$K_{CO} = \Delta CO/\Delta t/P_{ACO}, \quad (7)$$

where T_{LCO} is the total uptake of CO by the lung per unit of time per unit driving pressure and is the product of K_{CO} (the transfer coefficient) and V_A (the alveolar volume containing CO):

$$T_{LCO} = K_{CO} \times V_A, \quad (8)$$

where V_A is the alveolar volume measured by helium dilution during the single breath T_{LCO} measuring technique (see below). The SI unit for T_{LCO} is therefore mmol min^{-1} kPa^{-1}.[6]

Techniques for measurement of T_{LCO}

There are numerous methods of measuring T_{LCO}, all of which involve breathing small concentrations of CO either in a steady state or within a single breath. The single breath method is the most widely used technique and is standardised by the ERS.[5,6] The subject exhales to RV then inhales a gas mixture of CO (0.3%) and an inert gas not normally present in the body (helium) to near TLC, and then holds their breath for 8–10 s. During exhalation back to RV, a sample of alveolar gas is obtained after about 750 ml of gas has been expired (dead space washout) and then analysed. Measuring the dilution of the helium from the alveolar gas sample allows calculation of the initial concentration of CO assuming CO is diluted to the same extent. The inert gas helium is used to calculate VA using a method almost identical to that described above for measuring FRC.

The indices obtained are the initial and final alveolar concentrations of CO, the time for breath holding, and V_A during breath holding, and these may be used to calculate transfer factor.

Interpretation of T_{LCO}

T_{LCO} varies with the patient's age, sex, height, ethnicity, and various other physiological factors including haemoglobin concentration, lung volume, carboxyhaemoglobin (e.g. as a result of smoking), inspired oxygen concentration (e.g. if at altitude or breathing supplemental oxygen), and body position (the supine position increases T_{LCO}). These must all be taken into consideration and adjustments made for interpretation of a result. For instance, anaemia reduces the CO carrying capacity of blood leading to a low T_{LCO}. Consequently, laboratories are required to give both the actual T_{LCO} result and an adjusted T_{LCO} result that assumes the patient was transfused to a haemoglobin level of 146 g L^{-1} in males and 134 g L^{-1} in females and children younger than 15 yr.[5] It is important to note that the primary measurements are K_{CO} and V_A from which T_{LCO} is derived.

As the same value for T_{LCO} is obtained with different combinations of K_{CO} and V_A, it can be seen that more information can be gleaned from the individual components than from their product.

Tests that evaluate the interplay of the cardiac and pulmonary systems

In its simplest form the ability to climb a number of flights of stairs was used historically as a functional assessment of a subject's cardiopulmonary status. It has been shown that perioperative mortality and complications both correlate with an inability to climb steps.[7]

Functional walking tests

Three walking tests have now been standardised.[8] They are easy to perform and require little equipment. (i) *A 6 min walk test* is a self-paced test of walking capacity with the distance walked in 6 min reported in metres as the primary outcome: the 6 min walk distance (6MWD). Oxygen saturation, heart rate, recovery time, symptoms of dyspnoea and fatigue (e.g. Borg scales), and 6 min walk work (6MWD × body weight) are secondary data. (ii) *The incremental shuttle walk test* (ISWT) is an externally paced walking test in which the subject shuttles between two cones 10 m apart, increasing their pace every 1 min in response to an audio signal. There are 12 levels of increasing pace, and the test is terminated if the subject cannot keep up the pace between the cones. The primary outcome is the distance walked, measured as the number of completed shuttles. (iii) *Endurance shuttle walk test* requires an initial ISWT to be performed to determine the pace at which the subject will initially shuttle between the 10 m cones,

which is usually around 85% of maximal ISWT pace, and the subject then walks as long as possible at this pace, with duration as the primary outcome.

Reference equations using globally accepted standardised functional walking tests from healthy populations are not yet available. Most healthy subjects have a 6MWD of between 400 and 700 m. An ISWT distance of greater than 400 m has been linked to a maximum oxygen uptake ($\dot{V}O_{2max}$) of $\geq$15 ml kg^{-1} min^{-1}.[9]

Cardiopulmonary exercise testing

This requires more complex resources compared with a functional walking test but cardiopulmonary exercise testing (CPET) is now considered the gold standard as a test of the combined function of the cardiopulmonary and circulatory systems. CPET records a huge number of physiological variables, but the most widely used measurements for clinical use are discussed in the following subsections.

Peak $\dot{V}O_2$

A spirometric method is used to measure $\dot{V}O_2$ during exercise by recording the oxygen concentration in inspiratory and expiratory gas and the minute ventilation, thus allowing consumption to be calculated. The maximum value achieved just before exhaustion is recorded as peak $\dot{V}O_2$. Clearly peak $\dot{V}O_2$ is related to the subject's fitness, but also to how motivated the subject is to carry on exercising. This is different from $\dot{V}O_{2max}$, of $\geq$15 ml kg^{-1} min^{-1}, which is difficult to define except in trained athletes who can sustain maximal exertion for the period of time required for its measurement.

Peak $\dot{V}O_2$ is normalised for body weight and reported in ml of oxygen per kg of body weight per minute (ml kg^{-1} min^{-1}) to allow for standardisation and comparison of individuals. An adult at rest consumes about 3.5 ml kg^{-1} min^{-1}, also known as one metabolic equivalent or MET.

Anaerobic threshold

The same measurement of minute ventilation used for $\dot{V}O_2$ can also be combined with measured mixed expired CO_2 to derive the CO_2 production per minute $\dot{V}CO_2$. The anaerobic threshold (AT) is marked by a disproportionate increase in $\dot{V}CO_2$ relative to $\dot{V}O_2$ because of the buffering of lactic acid in muscle cells. AT is believed to represent the point at which oxygen delivery to muscle becomes inadequate and anaerobic metabolism occurs, though this is an oversimplification of a complex physiological situation.[10] Most patients will pass their AT as it occurs at around half of their peak $\dot{V}O_2$, and like peak $\dot{V}O_2$, fitter people have a higher AT but the AT has the advantage of being less dependent on a subject's motivation.

Ventilatory equivalent for CO_2 ($\dot{V}E/\dot{V}CO_2$)

This is the volume of ventilation required to eliminate a volume of CO_2. This can be measured at any time point, but the value is usually taken at AT. This is a good measure of the lungs' ability to respond to the increased needs of exercise and relates to the ventilation perfusion relationships of the lungs, including dead space. Lower values indicate better lung health.

Declaration of interest

The authors declare that they have no conflict of interest.

MCQs

The associated MCQs (to support CME/CPD activity) will be accessible at www.bjaed.org/cme/home by subscribers to *BJA Education*.

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