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Human lung volumes and the mechanisms that set them

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ABSTRACT: Definitions of human lung volumes and the mechanisms that set them are reviewed in the context of pulmonary function testing, with attention to the distinction between functional residual capacity (FRC) and the static relaxation volume of the respiratory system, and to the circumstances in which FRC and residual volume are set by dynamic rather than by static mechanisms. Related terms, conventions, and issues are addressed, including some common semantic and conceptual difficulties, with attention to "gas trapping", "hyperinflation", and "restriction".
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This article reviews definitions of human lung volumes and the mechanisms that set them, in the context of pulmonary function testing. It uses and reconciles existing conventions and terminology [1, 2] and notes some common semantic and conceptual difficulties.

"Lung volume" generally means the volume of gas or of gas-containing spaces in the lung, or one or more of the "lung volume compartments" which they comprise. Gas in the lung is considered to be at body temperature, saturated with water vapour, and (for many purposes) at ambient pressure.

To start, three primary lung volumes, set independently by different mechanisms will be considered: total lung capacity (TLC), residual volume (RV), and functional residual capacity (FRC).

Total lung capacity

TLC in cooperating humans is the greatest lung volume achieved by maximum voluntary inspiration. It is set by a static balance between inspiratory muscle forces and elastic recoil forces arising in the respiratory system. At TLC, these two sets of forces are equal and opposite in sign. Thus, TLC can be thought of as lying at the intersection of the static volume–pressure curves of the relaxed respiratory system and the maximally active inspiratory muscles (fig. 1) [3]. It is the lung, rather than the chest wall,

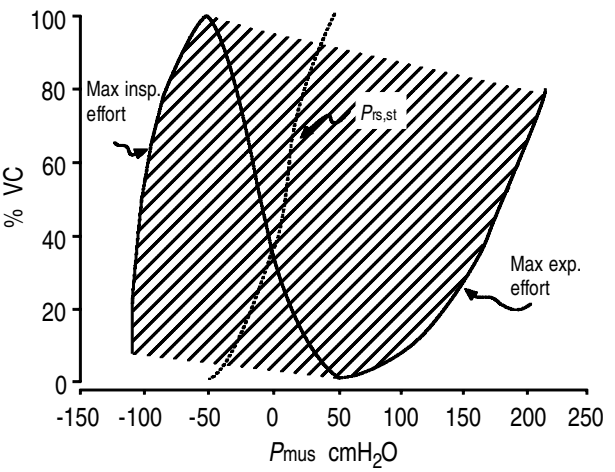

Fig. 1. – Volume–pressure relationships illustrating the range of static pressures available to produce volume change in the respiratory system. The shaded area indicates the range of muscle pressures. VC: vital capacity (%). P_{mus}: pressure generated by muscles (cmH_2O). $P_{rs,st}$: static recoil pressure of relaxed respiratory system. The solid sigmoid line represents pressures equal and opposite to $P_{rs,st}$, *i.e.* the pressures which must be applied to the respiratory system (*e.g.* by the respiratory muscles) to achieve a given volume. Total lung capacity (100% VC) is at the intersection of this line and the line representing maximum inspiratory (Max insp.) effort. Residual volume (0% VC) is at the intersection of the solid sigmoid line and line representing maximum expiratory (Max exp.) effort. (Reproduced with permission from [3].)

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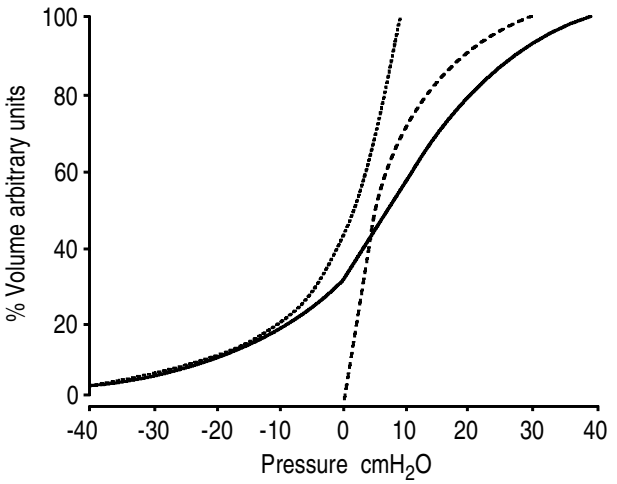

Fig. 2. – Volume–pressure curves of the relaxed respiratory system for the lung (P_l; – – –), chest wall (P_{cw}; ·····) and respiratory system (———) in an adult. At total lung capacity in this figure, P_l=30 cmH_2O and P_{cw}=10 cmH_2O. At residual volume, P_l=0 cmH_2O and P_{cw}=-40 cmH_2O. (Reproduced with permission from [4].)

that normally contributes most of the elastic recoil forces of the respiratory system at TLC (fig. 2) [4].

Residual volume

RV in cooperating humans is the lowest lung volume achieved by maximum voluntary expiration. In most healthy young adults it is set by a static balance between expiratory muscle forces and elastic recoil forces arising in the respiratory system. When this static mechanism is operating, these two sets of forces are equal and opposite in sign, and RV can be thought of as lying at the intersection of the static volume–pressure curves of the maximally active expiratory muscles and the relaxed respiratory system (fig. 1) [3]. It is the chest wall, rather than the lung, that normally contributes most of the elastic recoil forces aof the respiratory system at RV (fig. 2) [4].

Dynamic RV

RV is often set, however, by a different mechanism, dynamic rather than static. When maximum expiratory flows are very low near RV, forced expiratory manoeuvres may be interrupted (*e.g.* because of instructions or limited breath-holding ability) before expiration is "complete", *i.e.* while flow is still occurring. This means that RV is greater than the lung volume to which the expiratory muscles could have driven the system, *i.e.* the volume at which a static balance would have been achieved between muscle and elastic recoil forces.

In normal humans over the age of ~35 yrs, it is this dynamic mechanism, rather than the static one described above, that sets RV [5], apparently because of the normal loss of lung elasticity with age and associated decreases in maximum expiratory flow. These presumably account for the progressive increase in RV with further ageing in normal humans [4]. The same dynamic mechanism can also operate to set RV in younger normal subjects who are able to reach very low lung volumes (at which maximum expiratory flows are very low), for example those with unusually strong expiratory muscles or with compliant chest walls (*e.g.* infants).

It is this dynamic mechanism that also usually sets RV in people with obstructive lung diseases. In severe obstruction, maximum expiratory flows are very low throughout forced expiration and, because of limitations on the duration of the manoeuvre, *e.g.* by the expectations of the investigator or by subject discomfort, RV can be increased by several litres. For the same reasons, subjects often reach much lower lung volumes by forced expiration from FRC than from TLC. Therefore, in measuring RV, it is appropriate to specify the starting volume of the manoeuvre. Near RV, with maximum expiratory flows of, say, 40 $mL \cdot s^{-1}$, prolonging the effort by 5 s decreases RV by 200 mL. Such time-dependent variation in RV may be great enough to confuse interpretation of some tests, *e.g.* of bronchodilator effects.

Under these conditions (severe obstructive lung disease), RV can also vary with the intensity of the expiratory effort, which means that this dynamic RV mechanism may explain in part why the forced expiratory vital capacity (FVC) is sometimes less than the slow expiratory vital capacity (VC) in people with dynamically-determined RV. Throughout strongly forced expiratory manoeuvres, intrathoracic pressures are greater and therefore (because of gas compression in the lung) lung volumes and lung recoil forces are lower at all instants than they are during the slow VC manoeuvre. There may also be true negative effort dependence of maximum expiratory flows [6]. For both of these reasons, expiratory flow rates can be less throughout a forced than a slow manoeuvre from the same starting volume, so that in manoeuvres of the same duration, less gas is exhaled in the forced expiration and RV is greater.

There is an interesting sidelight in the concept and definition of RV that is particularly seen in people with severe obstruction. If RV is high and expiratory flows at RV are low, then expiratory muscles may still be able to exert substantial forces at RV, and alveolar pressure (P_A) at RV can be high. The high P_A is associated with alveolar gas compression, which means that the actual lung volume at that instant can be substantially less than it is when the subject relaxes or when the RV is calculated by subtracting the expiratory reserve volume (ERV; measured spirometrically) from the FRC.

Summary

TLC and RV are determined by different sets of muscles, acting predominantly on different structures. Because they are set independently by different mechanisms, they can vary independently of one another. TLC is sensitive to changes in the properties of the inspiratory muscles and the lungs, while RV, when it is set by static mechanisms, is sensitive to changes in the properties of the expiratory muscles and the chest wall. In contrast, when RV is dynamically determined, it is influenced by the mechanisms of expiratory flow limitation.

Near TLC, the volume–pressure curves of lung and inspiratory muscles are relatively flat, and near RV the curves of chest wall and expiratory muscles are relatively flat

(fig. 1); thus, the volume extremes are rather insensitive to changes in muscle or elastic properties alone.

TLC and RV are relatively insensitive to subjects' orientation in gravity, because gravitational forces are small in relation to the larger forces of muscles and elastic recoil that operate at the volume extremes. TLC and RV are also remarkably insensitive to body posture and use of the limbs [7].

Other definitions and mechanisms for TLC and RV

So far, TLC and RV have been considered in subjects who voluntarily achieve lung volume extremes. But how shall we define and reach RV and TLC in subjects unable to cooperate, *e.g.* infants or anaesthetized humans?

Relaxed subjects can be driven to lung volume extremes by application of external pressures to the respiratory system, at the airway opening and/or the body surface. TLC and RV can then be defined as the lung volumes reached by the external application of specified transrespiratory system pressures, *e.g.* ±30 cmH_2O, respectively. The procedures and pressures used, and the relation of the resulting volume extremes to those achieved by voluntary efforts, are not well established. Respiratory muscle activity, if present, may make the results of such procedures uninterpretable. Even modest pressures, *e.g.* 30 cmH_2O, applied at the airway may drive relaxed people with emphysema well above their voluntary TLC [8]. High externally-applied pressures may carry the risk of lung disruption, and both high and low pressures, if sustained, may interfere with gas exchange and the circulation.

TLC and RV can also be defined by maximum and minimum lung volumes achieved during spontaneous activities like sighing, crying, or hyperpnoea. The results may be quite variable and, again, the relation of these to other measures is not well established.

A third mechanism should be noted that can set RV, in addition to the static and dynamic ones already mentioned. When small laboratory animals with compliant chest walls are subjected to negative transrespiratory system pressures, it is possible to reach lung volumes so low that all airways are closed. RV can then be defined as the volume of gas trapped in airspaces behind closed airways. Though this condition (closure of all airways) has not been demonstrated in humans, it probably can occur, *e.g.* in infants subjected to negative transrespiratory system pressures or in adults with severe airway obstruction, especially with bronchoconstriction. Lastly, it is unknown whether closure of some, but not all airways, influences RV set by the static mechanisms discussed above. Incomplete understanding of the physiology of RV impedes interpretation not only of its abnormalities but also of such indices as RV/TLC and the ratio of forced expiratory volume in one second (FEV_1) to FVC (FEV_1/FVC).

Functional residual capacity and relaxation volume and the confusion that exists between them

Functional residual capacity

FRC, by long-established convention [1], means the volume of gas in the lungs at end-expiration, implicitly during tidal breathing, not only at rest, and without reference to the mechanism that sets it. FRC during quiet breathing at rest is the thoracic gas volume most often measured to establish absolute lung volumes. The method used to measure it should be indicated, for example by a subscript: FRC_{He} for measurements based on helium dilution.

Relaxation volume

The relaxation volume (V_r) is the static equilibrium volume of the relaxed respiratory system, the volume at which the elastic recoil pressures of lung and relaxed chest wall are equal and opposite in sign; *i.e.* the net elastic recoil pressure of the total respiratory system ($P_{rs,el}$), is zero (fig. 2).

Relation between FRC and V_r

During quiet breathing at rest, people may be relaxed or nearly so during expiration. In normal adults, FRC then ordinarily approximates the V_r. FRC and V_r then may vary together, as for example when a subject changes between upright and supine positions.

However, FRC and V_r are not synonymous terms and, while the two volumes are sometimes equal, more often they are not; *i.e.* active or passive mechanisms often operate to make FRC different from V_r. In normal people during exercise, for example, activity of expiratory muscles commonly drives FRC below the V_r [9, 10], although this is not always seen [11]. In obstructive lung diseases, relaxed expiration may still be "incomplete" when it is interrupted by the next inspiration; then FRC exceeds V_r.

V_r is determined by the passive elastic properties of the lung and chest wall, which vary with age. Thus in newborns, the chest wall is very compliant so the V_r is low; FRC then is often maintained above V_r by active mechanisms like inspiratory muscle activity and glottal braking (slowing) of expiration. In adulthood, lung recoil normally decreases with aging but the changes are small, so the static V_r and the resting FRC do not ordinarily increase throughout life.

FRC can increase markedly in obstructive lung diseases. This has sometimes been attributed to an increase in the static V_r due to loss of lung recoil, but the static V_r has seldom, if ever, been measured in these conditions. Furthermore, even if lung recoil were reduced to zero, V_r would increase only to the resting volume of the relaxed chest wall, and would remain sensitive to position (*e.g.* upright *versus* supine). Large increases of FRC in obstructive lung diseases are better explained by dynamic mechanisms (*e.g.* expiratory flow limitation) than by static ones. That is, in advanced chronic obstructive pulmonary disease (COPD), expiratory flow may continue throughout relaxed expirations, to be interrupted by the next inspiration; thus $P_{rs,el}$ at FRC is greater than zero, and FRC exceeds V_r. When FRC is thus increased, the work of inspiration is increased while inspiratory muscles may have to operate at disadvantageous lengths and mechanical arrangements [12, 13]. Gas exchange, alveolar ventilation and circulatory mechanics may be impaired by relatively high intrathoracic pressures persisting throughout expiration [14–16].

In recent years some authors, apparently taking FRC to be synonymous with V_T and needing a term for the end-tidal lung volume without reference to its determinants, have introduced several new terms such as "end-expiratory volume" (EEV) and "end-expiratory lung volume" (EELV). But this is exactly the conventional meaning of FRC. To avoid an undesirable multiplicity of unnecessary terms, we suggest that FRC be retained in its conventional meaning.

Other lung volumes

Tidal volume

Tidal volume (V_T) is the volume exchanged in a single breath. This seems simple enough, but even in a single breath, inspired and expired volumes often differ, and for some purposes the average of several V_T is useful. Thus, it is usually good to specify how V_T was defined and measured.

Lung volumes

Lung volumes defined by reference to TLC, FRC and RV include:

Vital capacity (VC) = TLC - RV
Inspiratory capacity (IC) = TLC - FRC
Expiratory reserve volume (ERV) = FRC - RV
Inspiratory reserve volume (IRV) = TLC - (FRC + V_T)

These four volumes (or "volume compartments") are ordinarily measured directly, *e.g.* spirometrically; *i.e.* they are not calculated from the terms on the right, though the forms of the equations might suggest this. The VC can be measured by full expiration from TLC or by full inspiration from RV (after expiration from FRC). In obstructive diseases particularly these inspiratory (IVC) and expiratory (EVC) VC may differ. Because TLC is a relatively repeatable volume, insensitive to the prior "volume history" of the lungs, the different VC will be associated with different RV, if RV is taken to equal TLC-VC. ERV is best measured directly by full expiration from FRC.

Other terms, conventions and issues

The terms "absolute lung volume" (V_L) and "thoracic gas volume" (TGV) are synonymous and refer to the total volume of gas in the lungs under conditions of interest, which may or may not be named lung volume compartments such as RV, FRC or TLC. V_L can be measured plethysmographically or by gas dilution or radiological techniques (with potential errors not addressed here) but it cannot be measured spirometrically, in contrast to lung volume changes or compartments such as VC and ERV which can.

By convention, lung "capacities" consist of two or more "volumes". Thus, four lung volumes are used here to make up four capacities:

Function residual capacity (FRC) = RV + ERV
Inspiratory capacity (IC) = V_T + IRV
Total lung capacity (TLC) = RV + ERV + V_T + IRV
Vital capacity (VC) = ERV + V_T + IRV

This is a simple and useful convention, but it also presents conceptual traps often reflected in the literature. FRC is written, for example, as FRC = RV + ERV. This is true by definition, but the form of the equation suggests to some that RV and ERV are independent variables and FRC a dependent variable, so that, for example, if the FRC is abnormally high, the cause must be sought and understood in terms of high RV or ERV or both. But that is untrue; the answers lie in the mechanisms that determine FRC directly, as reviewed above.

As a second example, TLC is written as TLC = RV + ERV + V_T + IRV. Again, this is true by definition, but again, abnormalities of this "capacity" are not to be explained by examining its four component volume compartments; biologically, it is not dependent on them. Instead, the answers lie in abnormalities of the muscle and elastic recoil forces that set static limits to maximum inspiration, *i.e.* that directly determine TLC as a biologically independent variable.

"Gas trapping" has several meanings, so the term should be defined when it is used. Gas may be "trapped" behind closed airways in the lung periphery, no longer in communication or exchanging normally with respired gas. Gas may also be "trapped" in the whole lung, or in lung regions, by dynamic mechanisms not involving airway closure, for example, when they empty slowly in relation to the time available for expiration. This can lead not only to abnormalities of gas exchange but also to dynamic increases in local or overall RV and FRC, and to such phenomena as "dynamic hyperinflation" or "auto positive end-expiratory pressure (PEEP)" [12–15, 17, 18]. These two forms of "gas trapping" (*i.e.* with closed and with open airways) may coexist.

"Hyperinflation" also has several meanings, which should be made explicit when the term is used. In general it means that the volume of the lung, or of a lung region, is greater than normal, expected, or predicted, *e.g.* at RV, FRC or TLC. Thus, when the term "hyperinflation" is used, the volume or region in question should be specified, *e.g.* hyperinflation at TLC, RV, left lower lobe. The mechanisms are many, including local and general airway obstruction, loss of lung recoil, increased ventilation, and both muscular and skeletal adaptations in the chest wall. Clinical or physiological criteria may be used, or radiographic ones; actual volumes are often unknown and indeed the evidence for abnormality uncertain.

"Restriction" also has several meanings, which should be made clear when the term is used. The 1975 American College of Chest Physician (ACCP)-American Thoracic Society (ATS) joint committee gave this definition: "Restrictive Pattern (restrictive ventilatory defect): Reduction of vital capacity not explainable by airways obstruction". Some find this definition unsatisfactory, and substitute the criterion that there must be a reduction in TLC before a "restrictive pattern" is said to exist. In this view, reduced VC unaccompanied by reduced maximal flows can suggest, but does not by itself demonstrate, "restriction", because TLC could still be normal or high, *e.g.* with bullous or cystic disease.

Note that the term "restriction" as it is used in chest medicine implies nothing about mechanism, *e.g.* whether abnormalities exist in the lung (such as pulmonary fibrosis) or the chest wall (such as stiffness or muscle weakness) or even in the nervous system. In everyday use, however, "restriction" implies being held back, hindered, confined by external constraints; and so for clarity we think it desirable to specify neural or muscular abnormalities when they are responsible for low TLC and to reserve the term "restriction" for conditions in which the lungs and/or chest wall are abnormally stiff. Progressive reduction in TLC over months or years, even if all values lie within the predicted normal range, is accepted by some clinicians as evidence that a restrictive process, and perhaps a restrictive deficit, exists. For reductions in FRC alone (such as may occur in obesity and pregnancy) the term "restriction" should not be used.

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