Lecture Seven

Respiratory System, Measurements and Volumes.

INTRODUCTION

The lungs are involved in the exchange of gases between the blood and the atmosphere. Measurement of variables associated with these processes enables the physician to perform two clinically relevant tasks: assess the functional status of the respiratory system (lungs, airways, and chest wall) and intervene in its function.

The objective assessment of respiratory function is performed clinically on two-time scales. One is relatively long, usually in the form of *pulmonary function tests* (PFT), at intervals on the order of days to years. In pulmonary function testing, a subject's parameter values are compared to those expected from specific populations—either normal populations or those with documented diseases.

Tests of pulmonary function are used to (1) screen the general population for disease; (2) serve as part of periodic physical examinations, especially of individuals with chronic pulmonary conditions; (3) evaluate acute changes during episodes of disease; and (4) follow up after treatment.

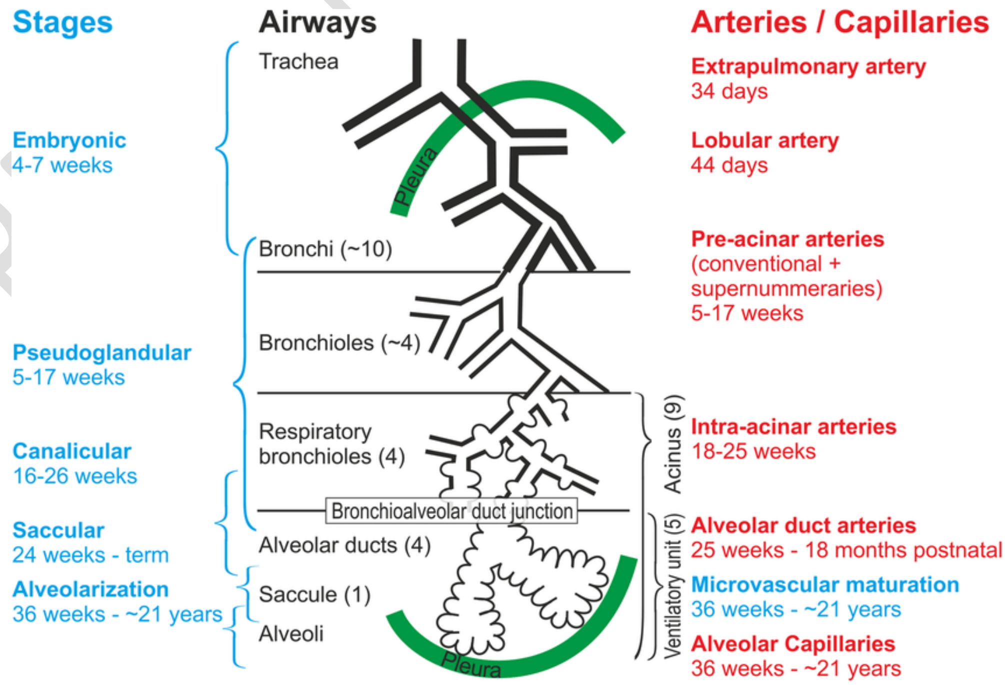
The second time scale on which respiratory function is assessed is very short; observations are made either continuously or at intervals on the order of minutes to hours. This activity comes under the heading of *patient monitoring* and is performed usually in an intensive care unit (ICU). It is warranted in crisis situations such as might result from trauma, drug overdose, or major surgery.

MODELING OF THE RESPIRATORY SYSTEM

It is essential to understand the features of the respiratory system and some approaches to modeling that can be used not only for the respiratory system modeling but also for the devices used to measure the parameters of the respiratory system.

Because it is the respiratory function of living individuals that is to be evaluated, measurements must be minimally invasive, cause minimal discomfort, and be acceptable for use in a clinical environment. This greatly limits the number and types of measurements that can be made and leads to the use of lumped-parameter models. Therefore, it is convenient to divide respiratory function into two categories: (1) gas transport in the lungs (including extrapulmonary airways and pulmonary capillaries) and (2) mechanics of the lungs and chest wall.

The models describing gas transport deal primarily with changes in concentrations of gas species and volume flow of gas, whereas the models dealing with mechanics primarily relate pressure, lung volume, and rate of change of lung volume. These two categories are highly interrelated, and the models and measurements from one complement those from the other.



GAS TRANSPORT

Models of gas transport, both in the gas phase and across the alveolar-capillary membrane into the blood, are developed from mass balances for the pulmonary system depicted as a set of compartments. Figure 1 shows a basic gas-transport unit of the lungs. It consists of a variable-volume alveolar compartment, with its contents well mixed by diffusion; a well-mixed flow through blood compartment that exchanges gases with the alveolar compartment by diffusion; and a constant volume dead space. Gas moves by convection through the dead space, which acts only as a time-delay conduit between its outer opening and its associated alveolar volume. A pair of normal lungs during quiet breathing may be represented satisfactorily by the system shown in Figure 1(a). Lungs undergoing maximal volume changes, subjected to very high (> 1 Hz) ventilatory frequencies, or afflicted with diseases that produce abnormal gas transport may require more complicated models comprising combinations of such units, in parallel or in series or both.

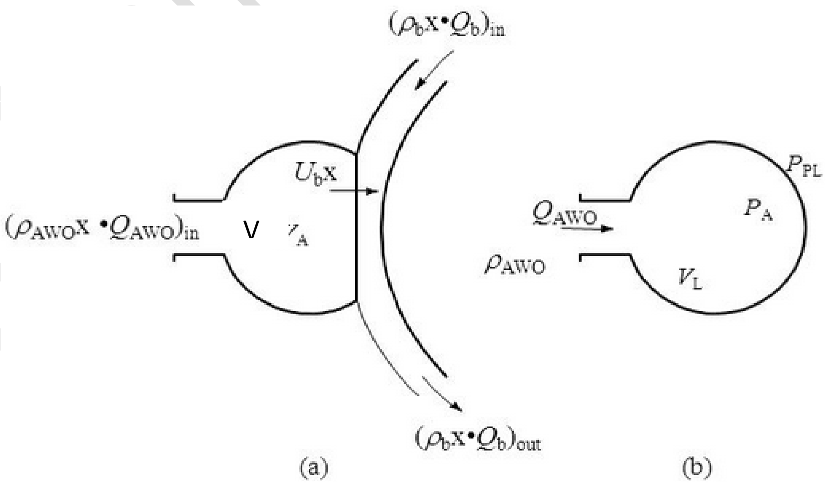


Figure 1 Models of the lungs (a) Basic gas-transport unit of the pulmonary system. Here (ρx.*Q*) is the molar flow of X through the airway opening (AWO) and the pulmonary capillary blood network, b. $U_b x$ is the net rate of molar uptake—that is, the net rate of diffusion of X into the blood. Vd and V_a are the dead-space volume and alveolar volume, respectively. (b) A basic mechanical unit of the pulmonary system. P_A is the pressure inside the lung (in the alveolar compartment). P_{PL} and P_{AWO} are the pressures on the pleural surface of the lungs and at the AWO, respectively. V_L is the volume of the gas space within the lungs, including the airways; Q_{AWO} is the volume flow of gas into the lungs measured at the AWO.

MECHANICS

We can conveniently model the mechanical behavior of the respiratory system as a combination of pneumatic and mechanical elements. Figure 1(b) shows an idealized mechanical unit of the lungs. It consists of a deformable pressure vessel made of a material that exhibits both viscoelastic and plastic behavior and a nonrigid airway that has a variable resistance to convective flow.

Even though each of the millions of alveoli and terminal airways potentially could act as a separate mechanical unit, it has been found that the mechanics of a *pair* of normal lungs during quiet breathing can be represented by the single unit of Figure 1(b).

An additional deformable pressure vessel representing the chest wall surrounding the lungs has been added to the system in Figure 9.2(a). The chest wall includes all extrapulmonary structures, such as ribs, respiratory muscles, and abdominal contents that can undergo motions as a result of breathing. The gap between the lung unit and the chest wall represents the liquid-filled interpleural space.

The mechanics of the respiratory system are described by the relationships between pressure differences across the various subsystems and the changes in volume and flow of gas through them. The subsystems are defined between points in the system at which representative pressures can be computed or measured. Consequently, the difference in pressure across the entire system can be expressed as the algebraic sum of pressure differences across subsystems. Mass balances can be used to follow the path of gas flow through the subsystems, and geometrical constraints determine the distribution of volume changes.

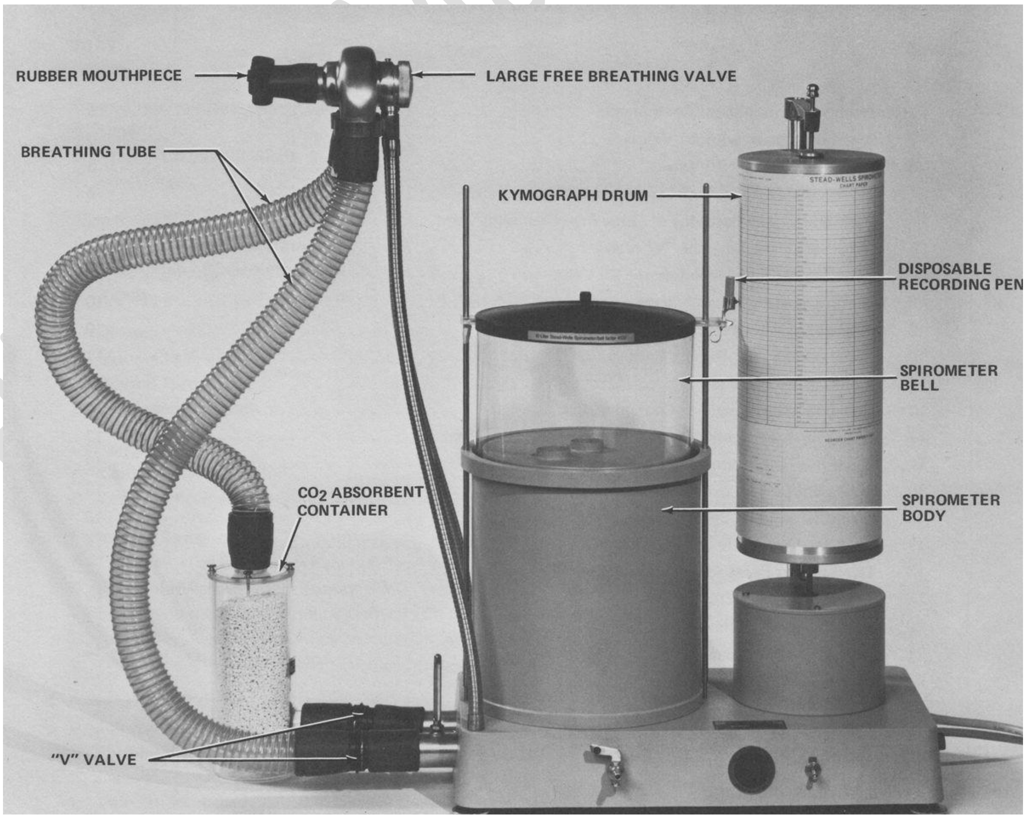
Spirometers

Spirometry is a common office test used to assess how well the lungs work by measuring how much air that a person inhale, exhale and, how quickly exhale. Spirometry is used to diagnose asthma, chronic obstructive pulmonary disease (COPD) and other conditions that affect breathing.

The spirometer records the amount of air and the rate of air that is breathed in and out over a specified period of time. A Tank-type spirometer works on the same principle as the gasometer. A canister is usually attached to absorb carbon dioxide and a kymograph trace is produced to record changes in total volume gas. From this, vital capacity (VC), tidal volume (TV), breathing rate (BR) and ventilation rate (VR):

$$\mathbf{VR = TV \times BR}$$

From the overall decline on the graph, the oxygen uptake can also be measured.



Common parameters used in spirometry:

1. FVC (forced vital capacity):

This is the total volume of air a patient can exhale after a maximum effort inspiration. Patients with restrictive lung disease (RLD) have a lower FVC than do patients with obstructive lung disease (OLD).

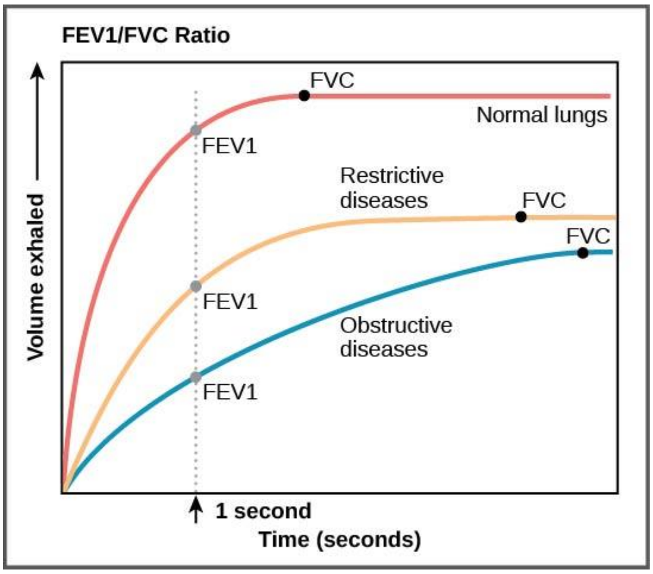
Note: **Obstructive lung diseases** include conditions that make it hard to exhale all the air in the **lungs**. People with **restrictive lung disease** have difficulty fully expanding their **lungs** with air. **Obstructive and restrictive lung disease** share the same main symptom: shortness of breath with exertion.

2. FEV1 (forced expiratory volume in 1 second) (also, FEV1/2):

The volume of air expired in the first second following the beginning of maximum expiratory effort. FEV1 is reduced from normal in both obstructive and restrictive lung diseases, but for different reasons; increased airway resistance in OLD, and decreased vital capacity in RLD.

3. FEV1/FVC:

This ratio is about 0.7 in healthy subjects. It can be as low as 0.2 to 0.3 in patients with OLD. Patients with RLD have near normal ratios.



4. FEF (25-75%): (forced mid-expiratory flow rate):

The average rate of flow during the middle of the FVC maneuver. Reduced in both OLD and RLD.

5. DLCO (diffusion capacity of the lung for carbon monoxide):

The poison gas CO can be used to measure the diffusion capacity of the alveoli. The diffusion capacity of the lung is decreased in parenchymal diseases such as emphysema. It is normal in asthma.

6. FRC (functional residual capacity):

The volume of air remaining in the lungs and trachea after an exhalation in normal breathing.

7. RV (residual volume):

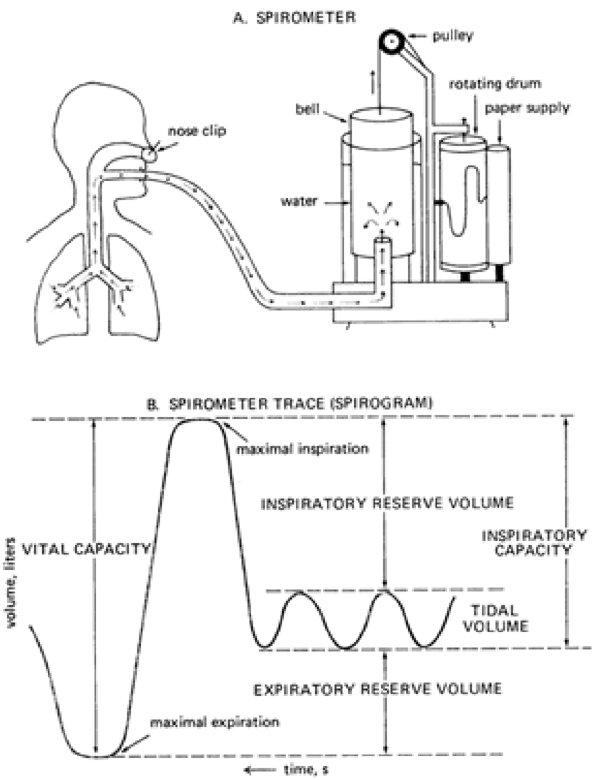
The volume of air left in the lungs after a maximum FVC exhale. It is the "dead space" of the respiratory system, mostly combined trachea and bronchial tube volumes. It cannot be measured directly.

8. TV (tidal volume):

The volume exchanged in normal relaxed breathing.

9. AV (alveolar volume):

Total volume of all the minute alveoli in the lung parenchyma.



Respiratory volumes:

Minute Volume (MV): The volume of gas exchanged per minute during quiet breathing. It is equal to the tidal volume multiplied by the breathing rate.

Alveolar Ventilation (AV): The volume of fresh air entering the alveoli with each breath.

Alveolar Ventilation = (Breathing rate) X (Tidal volume - Dead space).

Inspiratory Reserve Volume (IRV): The volume of gas, which can be inspired from a normal end tidal volume.

$$IRV = VC - (TV + FRC)$$

Expiratory Reserve Volume (ERV): The volume of gas remaining after a normal expiration less the volume remaining after a forced expiration.

$$ERV = FRC - RV$$

Residual Volume (RV): The volume of gas remaining in the lungs after a forced expiration.

Respiratory Capacity:

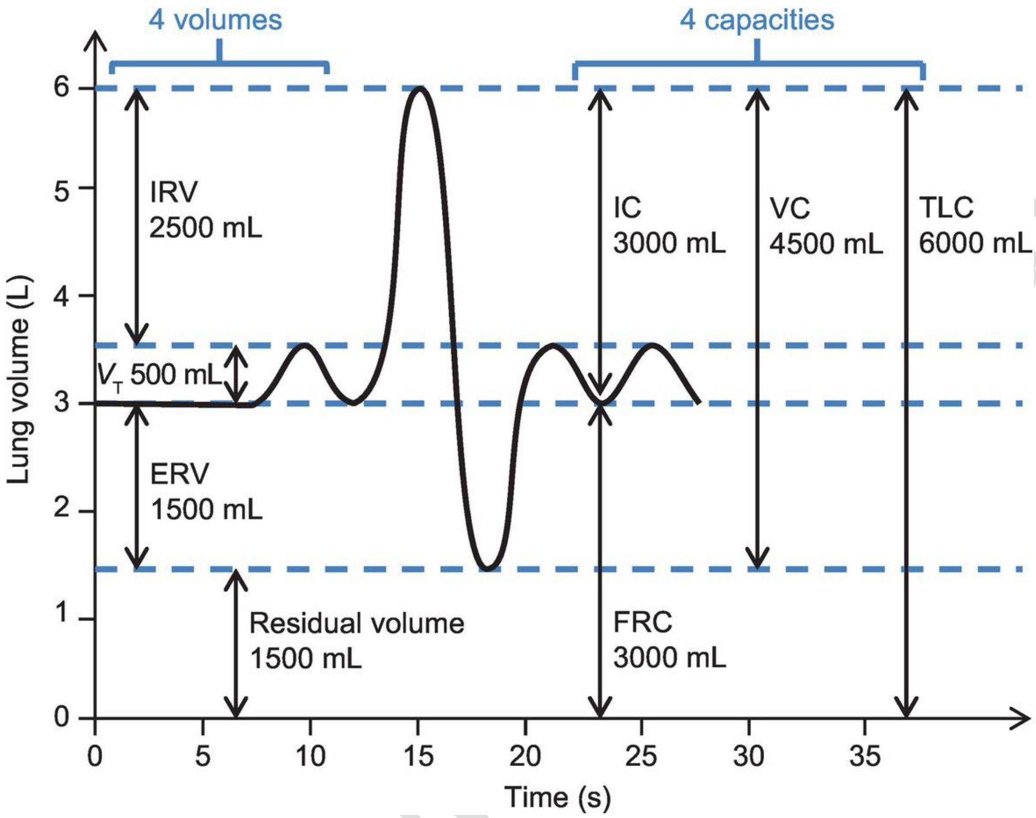
Functional Residual Capacity (FRC): The volume of gas remaining in the lungs after normal expiration.

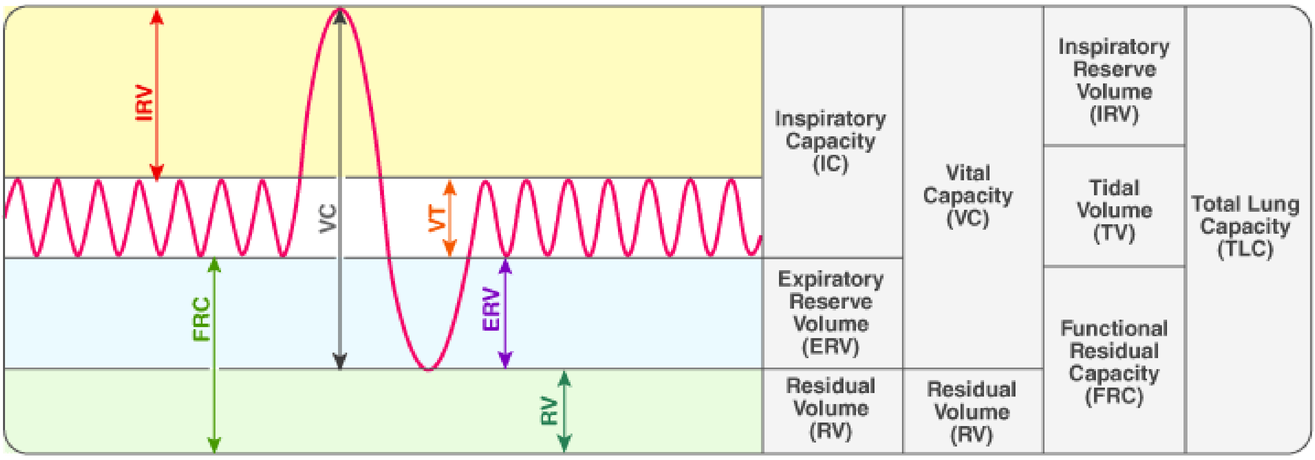
Total Lung Capacity (TLC): The volume of gas in the lungs at the point of maximal inspiration. $TLC = VC + RV$

Vital Capacity (VC): The greatest volume of gas that can be inspired by voluntary effort after maximum expiration, irrespective of time.

Inspiratory Capacity (IC): The maximum volume that can be inspired from the resting end-expiratory position.

Dead Space: Dead Space is the functional volume of the lung that does not participate in gas exchange.





Compliance and related Pressures:

Compliance (C): Change in volume resulting from unit change in pressure. Units are l/cm H_2O.

Lung Compliance (CL): Change in lung volume resulting from unit change in trans-pulmonary pressure (P_L).

Chest-Wall Compliance (Ccw): Change in volume across the chest wall resulting from unit change in trans-chest wall pressure.

Static Compliance (CST): Compliance measured at point-of-zero airflow by interruption or breath-hold technique.

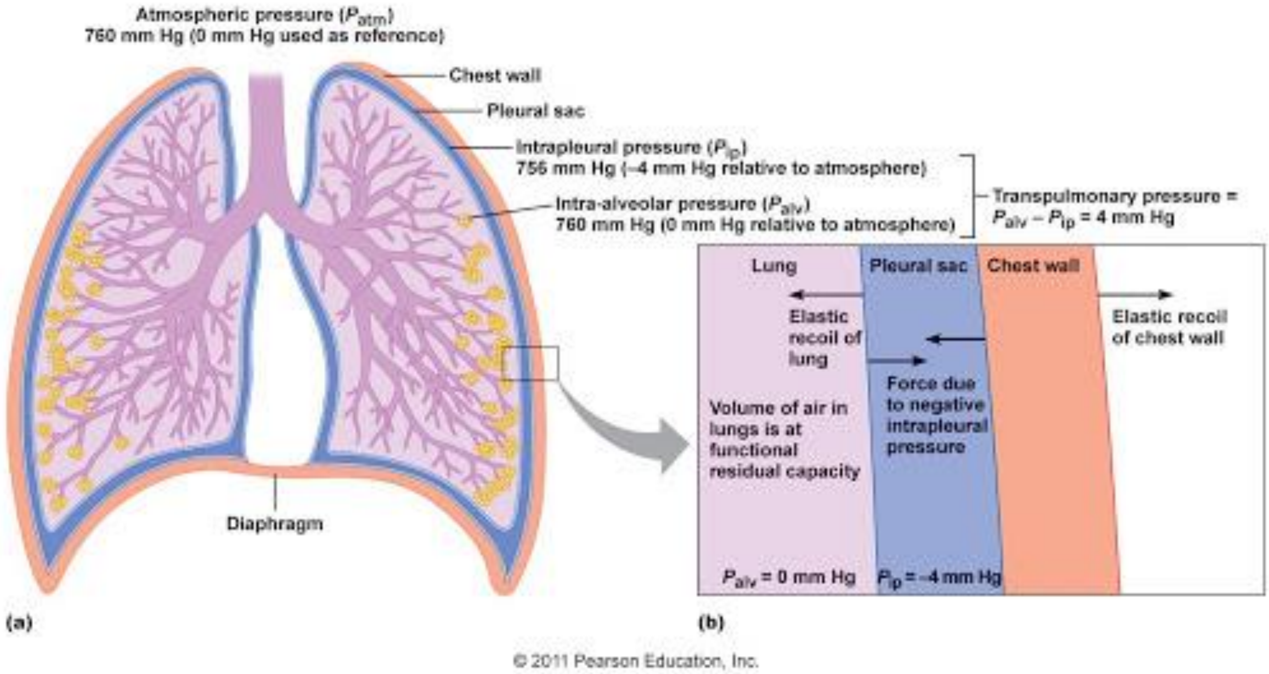
Elastance (E): Reciprocal of compliance. Units are cmH_2O/liter.

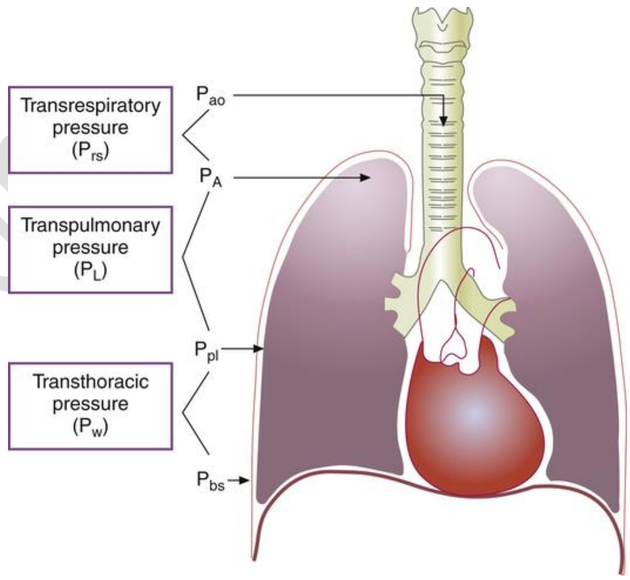
Transpulmonary Pressure (P_L): Pressure gradient developed across mouth (Pao) and pleural surface at lung (P_{PL}).

Transalveolar Pressure (P_{EL}): Pressure gradient developed between alveolar wall (P_{ALV}- P_{AL}).

Transairway Pressure (P_{RES}): Pressure gradient developed between alveoli and mouth.

Static Elastic Recoil Pressure ($P_{ST(L)}$): Pressure developed in elastic fibers of the lung by expansion.





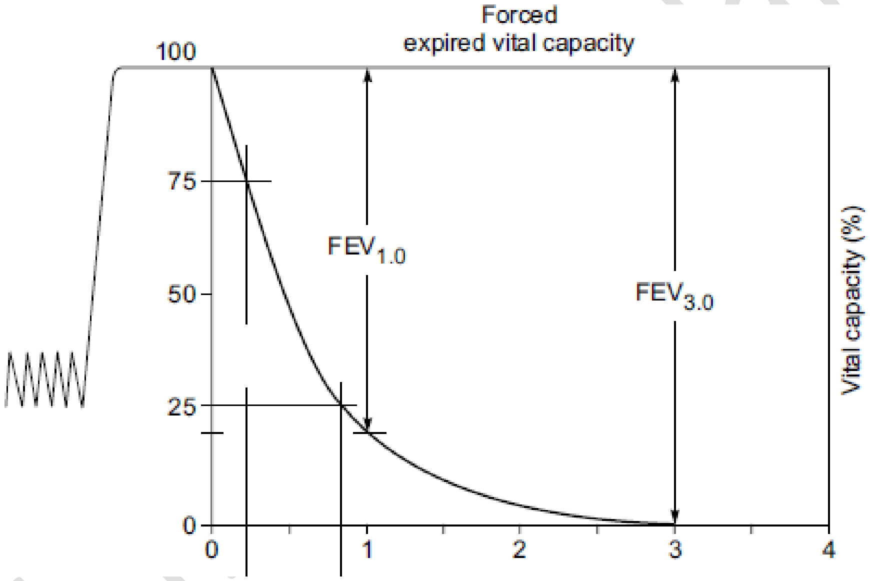
Dynamic Respiratory Parameters:

A number of forced breathing tests are carried out to assess the muscle power associated with breathing and the resistance of the airway. Among these are:

Forced Vital Capacity (FVC): This is the total amount of air that can be forcibly expired as quickly as possible after taking the deepest possible breath.

Forced Expiratory Volume (FEV): The percentage of the VC that can be forced out of the lungs in a given period with 'maximal exertion'. This is written as FEVT where T is usually in seconds.

Maximum Mid-Expiratory Flow (MMEF or MMF) or Maximum Mid-Flow Rate (MMFR): The maximum rate of flow of air during the middle half of the FEV spirogram. One half VC is obtained from the volume indicated by the curve between 25 and 75% VC. This is illustrated in next figure.



Mid-Expiratory Time (MET): It is the time in seconds over which this volume is forcibly exhaled. The MMEF is calculated from:

$$MMEF = (1/2\ VC)\ X\ (1/MET)$$

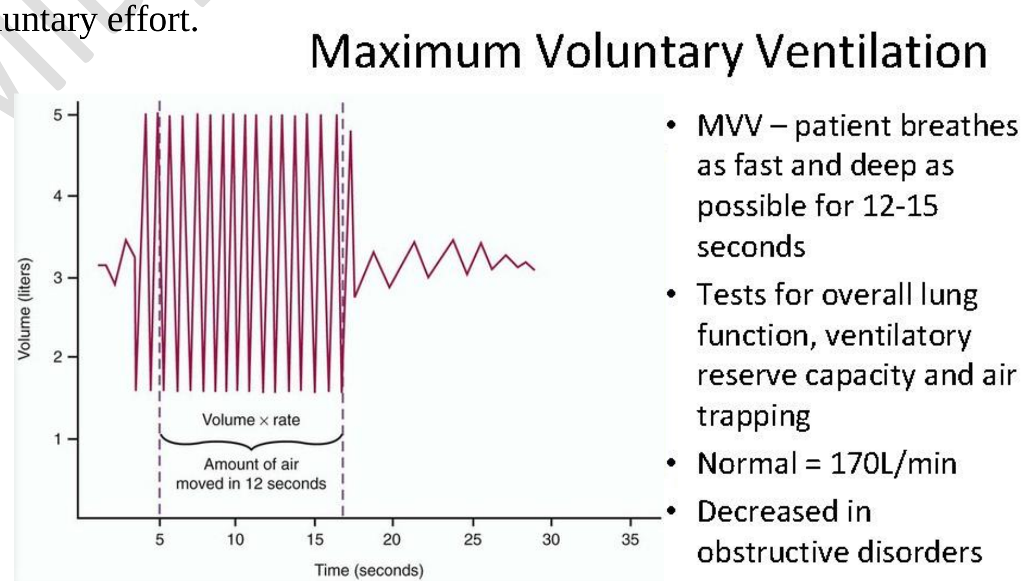
Notes:

Normal values for each of these volumes and capacities have been calculated. They have been found to vary with Gender, height and age. All pulmonary volumes and capacities are about 20 to 25 % less in females than in males. A particular pattern of abnormal lung volume may occur in a particular form of lung disease and such a pattern is useful confirmatory evidence of a diagnosis made on clinical grounds.

Further, serial lung function testing is of use in demonstrating progressive deterioration in function or in confirming a satisfactory response to therapy. For example, if the ratio (FEV1)/(FVC) of the volume of gas that can be exhaled forcibly in one second from maximum inspiration (FEV1) to the forced vital capacity (FVC) is less than 70%, airway obstruction as in chronic bronchitis is likely to be present. If the FEV1/FVC is greater than 85%, a so called 'restrictive' defect may be present. This is seen in cases of diffuse pulmonary fibrosis.

Pulmonary function tests are performed for the assessment of the lung's ability to act as a mechanical pump for air and the ability of the air to flow with minimum impedance through the conducting airways. These tests are classified into two groups: single-breath tests and multiple-breath tests.

There are three types of tests under the single-breath category. These are: A: tests that measure expired volume only. B: tests that measure expired volume in a unit time. C: tests that measure expired volume/time. In the class of multiple-breath test measurements is the Maximal Voluntary Ventilation (MVV) which is defined as the maximum amount of air that can be moved in a given time period. Here, the patient breathes in and out for 15 sec as hard and as fast as he or she can do. The total volume of the gas moved by the lungs is recorded. The value is multiplied by 4 to produce the maximum volume that the patient breathed per minute by voluntary effort.



A resting person inspires about 0.5 litre of air with each breath, with the normal breathing rate of 12 to 20 breaths per minute. With exercise, the volume may increase 8 to 10 times and the breathing rate may reach 40 to 45 breaths per minute. A respiratory disease may be suspected if these volumes, capacities or rates are not in the normal range.

Volume measurement

One method is to integrate the flow rate electronically and record the resulting signals. The flow rate is measured as the pressure change across a pneumotachograph head with a micromanometer whose output is a voltage proportional to the pressure difference at the manometer input, i.e.

$$V_1 = K(P_1 - P_2)$$

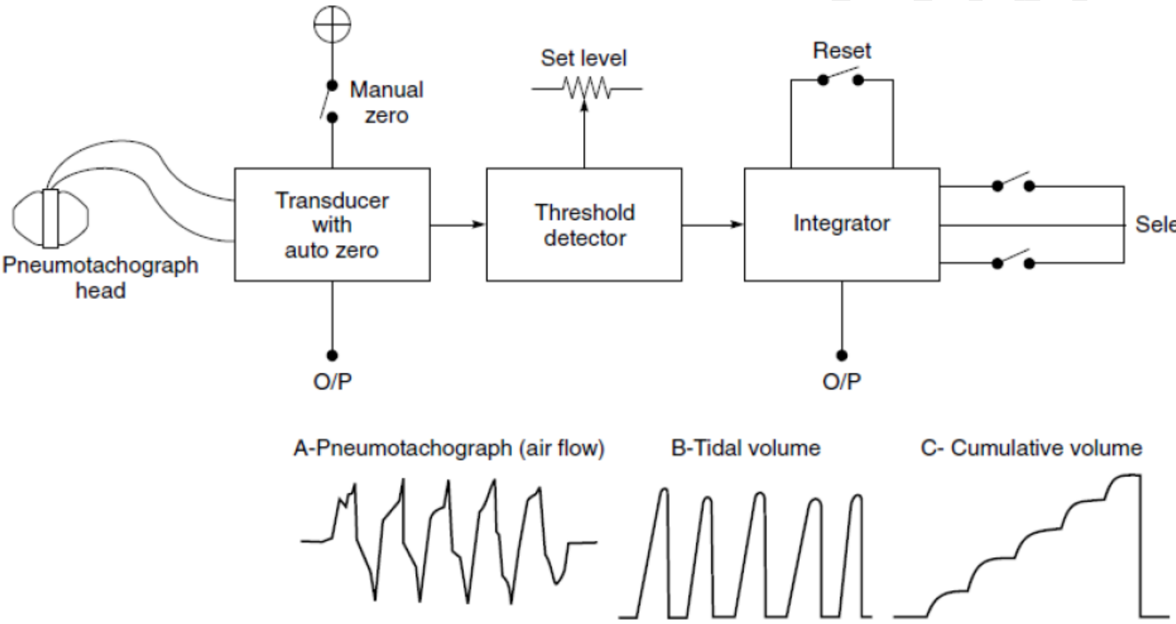
where K is a constant.

The output from the integrator is a voltage V_o such that:

$$V_o = \frac{1}{RC}\int_{t_1}^{t_2} V_i d_t$$

A simplified integrator set up is shown in the next figure for flow and volume measurement. It consists of an 'autozero' flowmeter together with a threshold detector and an integrator. The threshold detector selects which portion of the flow signal is to be integrated and this is normally set to switch on when the flow signal moves past zero in a positive direction, and off again when the flow signal returns to zero. This means either inspiration or expiration can be measured depending on how the flowhead is connected.

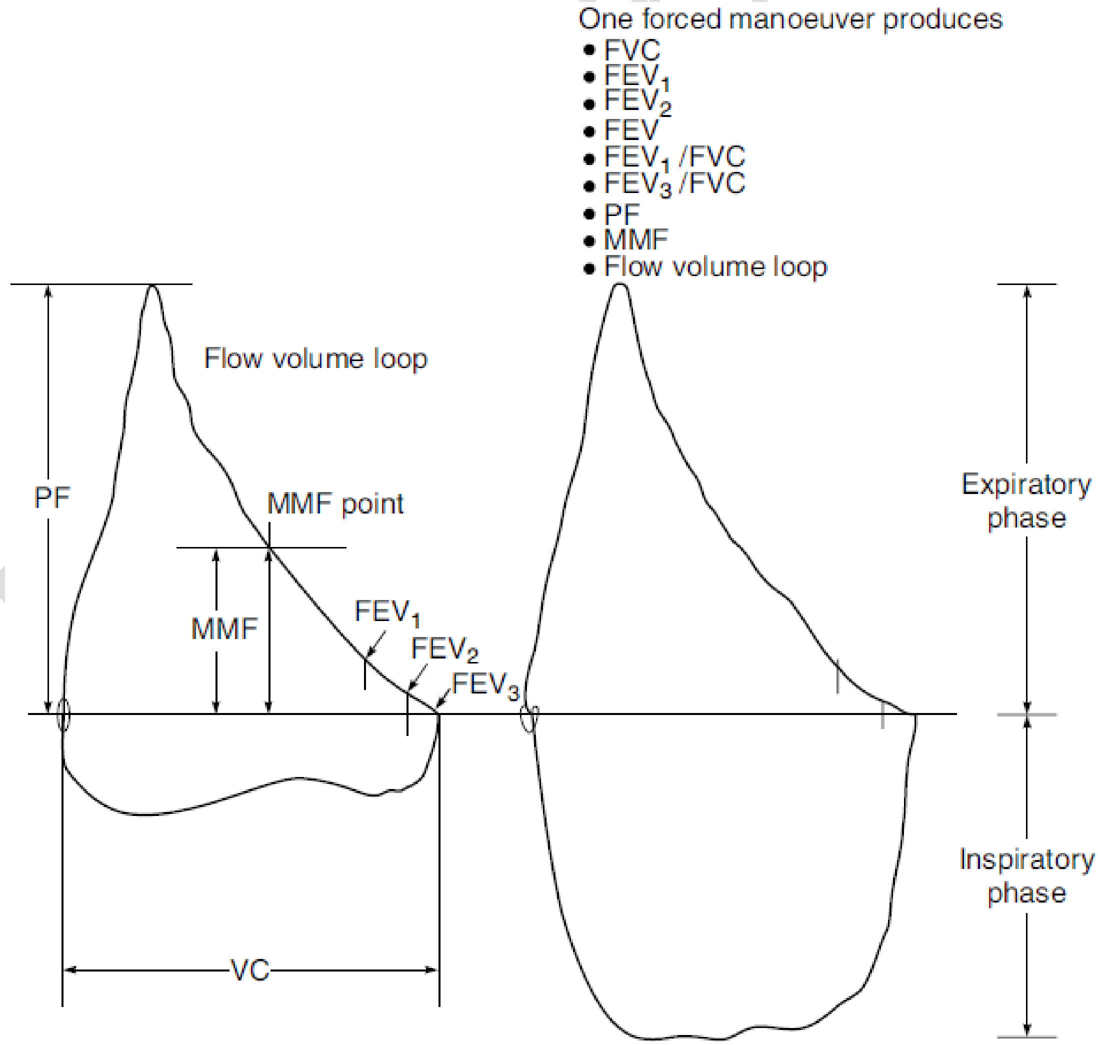
When it is intended to measure tidal volume, the flow signal moves positive and continues until the flow output returns to zero, when the integrator output is reset. The display shows the size of each breath which is referred to as constant baseline. In case cumulative volume is to be measured the volume displayed after each breath is held up. The next breath integrated is added to its predecessor, thus producing a staircase pattern. The pattern can be recorded on a chart paper. Unless extremely high quality amplifiers are used, the integrator circuit will drift and give false readings. Drift can be minimized by starting each volume from a fixed baseline on the record.



Flow - Volume Curve:

This is a plot of instantaneous maximum expiratory flow rate versus volume. The shape of the flow-volume curve does not vary much between normal subjects of different age, size and gender, although absolute values of flow rate and volume may vary considerably. In patients with obstructive airway disease, the shape of this curve is drastically altered. For this reason, the flow-volume curve is a good early indication of abnormality.

Typical MEFV curves are shown in next figure. There are various methods of producing the flow-volume curve. The method which has been very common in the past was to record it on the storage oscilloscope and then make a permanent record by photographing it with a polaroid camera. This procedure, obviously, is time consuming and expensive. General purpose X-Y recorders are not fast enough to follow the rapid changes encountered in the signals while recording flow-volume curves. Therefore, special recorders have been designed to meet this requirement. For example, in the H.P. Pulmonary Function Analyzer, the recorder used has an acceleration of 76.2 m/s^2 and a slewing speed of over 0.762 m/s will result in approximately a 7.5 cm deflection. The recorder will thus be able to accurately plot a MEFV curve in which the subject reaches a



peak flow of 10 l/s in less than one-tenth of a second.

A plot of the inspiratory flow-volume curve is also found to be useful in the detection of certain lung abnormalities, though it does not yield as much information about the lung mechanics as does the expiratory flow-volume curve. A useful indicator of the relative degrees of inspiratory and expiratory obstruction is the MEF 50% / MIF 50% ratio, MIF 50% is maximum inspiratory flow at 50% of vital capacity. A microcomputer is incorporated in the modern equipment to calculate the maximum spirometer value stored; FVC, the FEVI and the ratio FEVI/FVC.

Besides these, some other indices were also evaluated. For example, the average flow over the middle portion of the spirogram has been the most widely accepted parameter for the early detection of increased airway resistance.A microcomputer based system facilitates automating many of such indices which are under investigation.

Area of the Flow-Volume:

The area under the maximum expiratory flow-volume curve (AFV) is a sensitive indicator of lung function impairment. This is because within the scope of a single measurement, maximum flow at all lung volumes, the vital capacity and FEV1 are all accessible. It has been found that AFV is the only variable capable of detecting significant inter and intra-individual differences in respect of both the immediate and the delayed asthmatic responses. The area under the flow-volume curve can be easily computed by using a square-and- intgerating circuit. In the derivation of are, the following equation is used:

$$A = \int_0^{Vt} F dV$$

Where dV = Fdt and therefore

$$A = \int_0^T F^2 dt$$

Where V_t= total volume exhaled during the time.

T is a time greater than the period taken to complete the respiratory manoeuvre. A multiplier module can be used to square the flow rate signal and then integrate it with respect to time to obtain the area.