Measurement of The Respiratory System

- We will deal with the processes in the lungs that are involved in the exchange of gases between the blood and the atmosphere.

- assessment of respiratory function is performed clinically on two time scales.

1) One is relatively long, involving discrete observations, usually in the form of *pulmonary function tests* (PFT), at intervals on the order of days to years.

   - a subject's parameter values are compared to those expected from specific populations— either normal populations or those with documented diseases

2) 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 in a hospital setting, usually in an intensive care unit (ICU)

❑ Modeling the Respiratory System

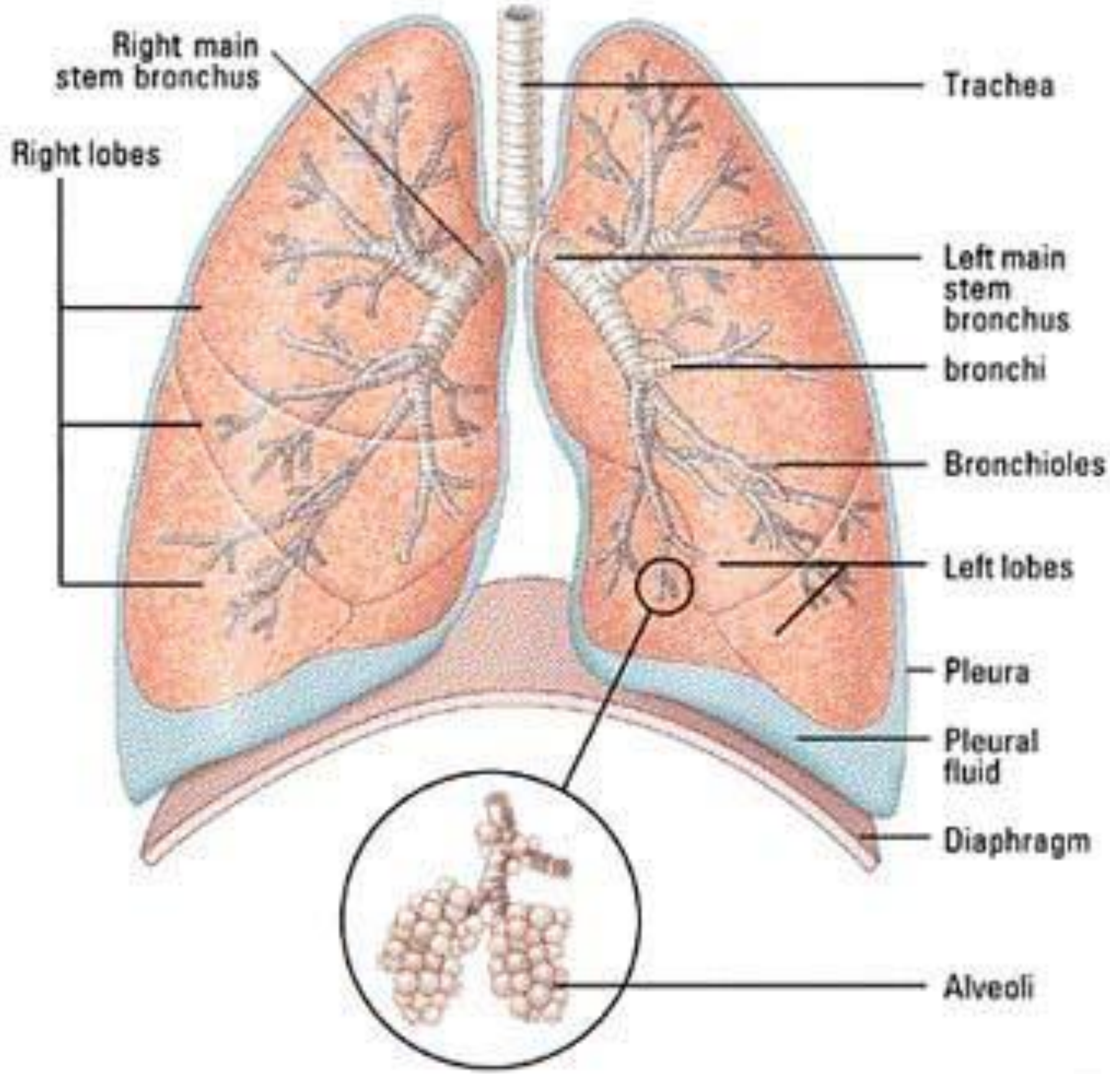
- We may divide respiratory function into two categories:

1. gas transport in the lungs
2. mechanics of the lungs and chest wall.

- The models describing <u>gas transport deal</u> primarily with changes in concentrations of <u>gas species and volume flow of gas,</u> whereas the models <u>dealing with mechanics</u> primarily <u>relate pressure, lung volume, and rate of change of lung volume.</u>

- these two categories are highly interrelated, and the models and measurements from one complement those from the other

Lungs



Right main stem bronchus
Right lobes
Trachea
Left main stem bronchus
bronchi
Bronchioles
Left lobes
Pleura
Pleural fluid
Diaphragm
Alveoli

➢ Gas Transport

- Models of gas transport are developed from mass balances for the pulmonary system depicted as a set of compartments.

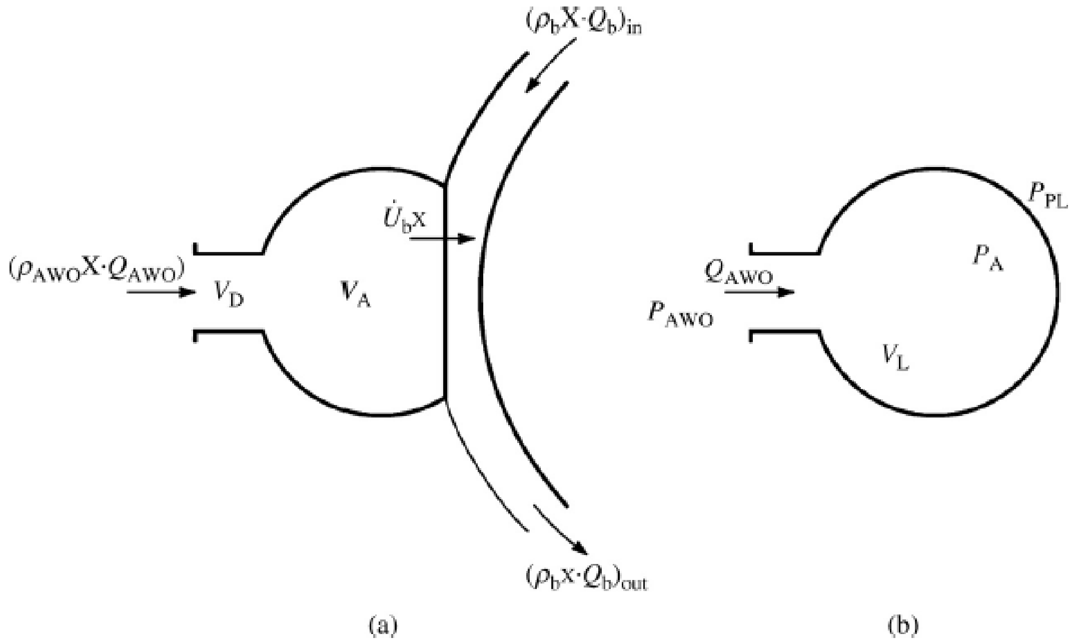


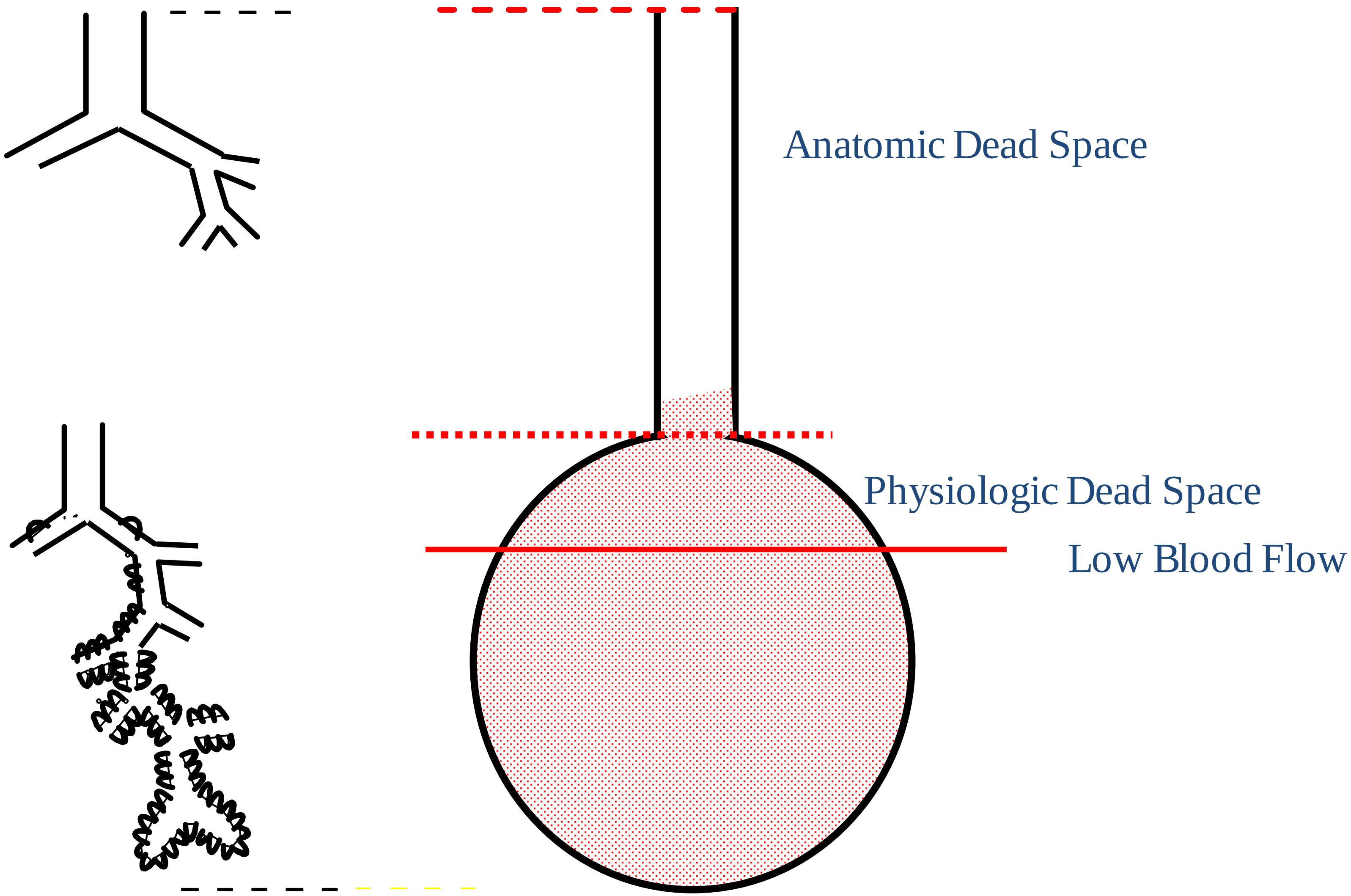
Figure 9.1 Models of the lungs (a) Basic gas-transport unit of the pulmonary system. Here $(\rho x \cdot Q)$ is the molar flow of X through the airway opening (AWO) and the pulmonary capillary blood network, b. $\dot{U}_b x$ is the net rate of molar uptake—that is, the net rate of diffusion of X into the blood. V_D 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—that is, 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.

Definitions of Dead Space

Dead space: no change is happening (nose, pharynx, trachea)

Anatomical dead space: portions where there is no possibility of exchange

Physiological dead space: portions where there is possibility of exchange but is just not happening



- A dynamic mass balance can be written for any chemical species X or set of species in the breathed gas mixture.

- If the production of X by chemical reaction in a system were negligible, a species **mass balance** could be written as

$$\begin{matrix}\text{Rate of mass}\\ \text{accumulation}\\ \text{of X in the}\\ \text{system}\end{matrix} = \sum_{i=1}^{n} \begin{matrix}\text{Rate of mass}\\ \text{convection}\\ \text{of X through}\\ \text{port } i\end{matrix} - \begin{matrix}\text{Net rate of}\\ \text{diffusion out}\\ \text{of the system}\end{matrix}$$

➢ Mechanics

- We can model the mechanical behavior of the respiratory system as a combination of pneumatic and mechanical elements.

- Chest wall surrounding the lungs has been added to the system. The chest wall includes all extrapulmonary structures, such as

    - Ribs
    - respiratory muscles
    - abdominal contents that can undergo motions as a result of breathing.

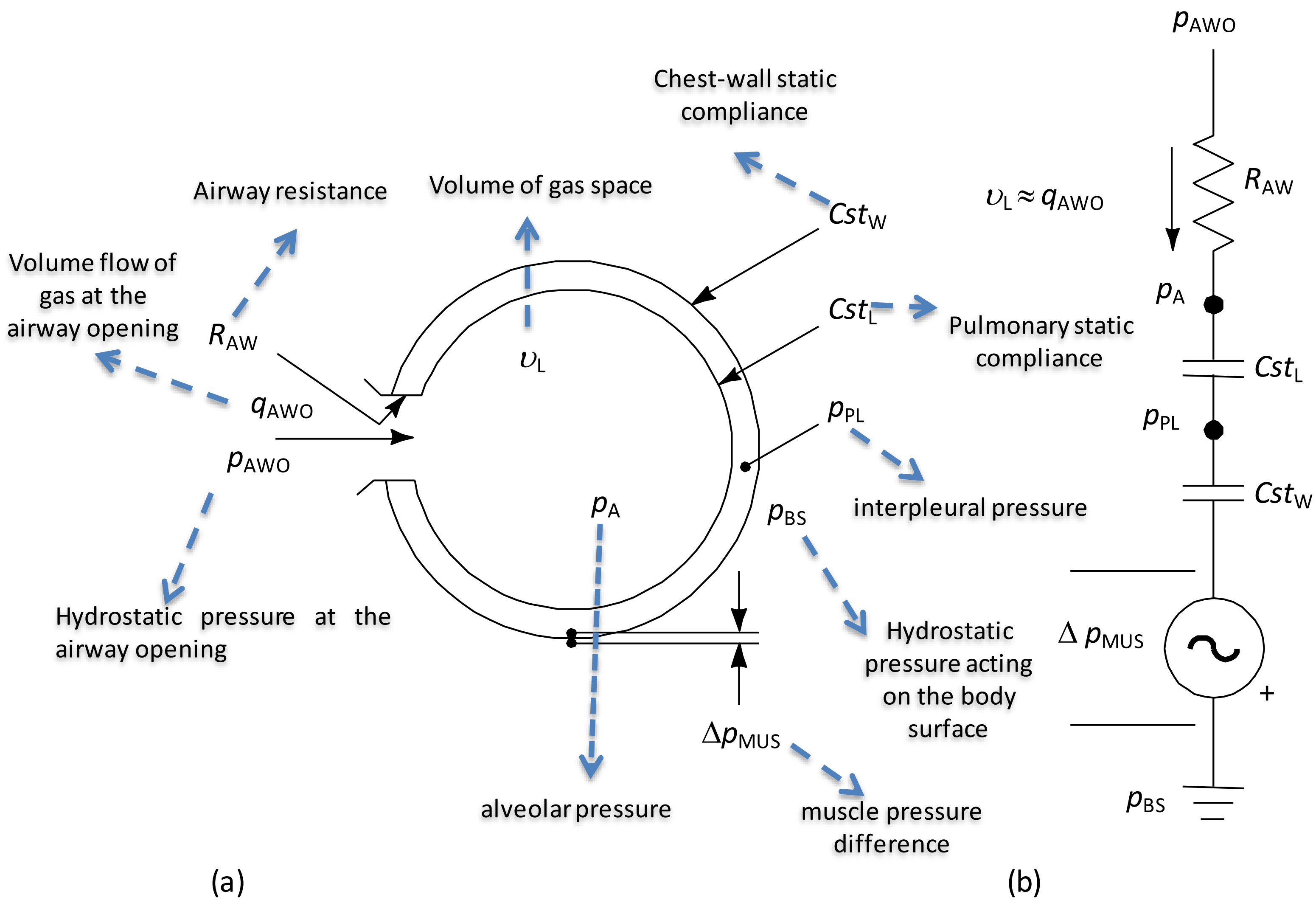


Figure 9.2 Models of normal ventilatory mechanics for small-amplitude, low-frequency (normal lungs, resting) breathing (a) Lung mechanical unit enclosed by chest wall. (b) Equivalent circuit for model in Figure 9.2(a).

$$R = \frac{\partial(\Delta P)}{\partial Q}$$

$$Cst = \frac{\partial V}{\partial(\Delta P)}$$

$$R_{\mathrm{AW}} = \frac{\partial(P_{\mathrm{AWO}} - P_{\mathrm{A}})}{\partial Q_{\mathrm{AWO}}}$$

$$Cst_{\mathrm{L}} = \frac{V_{\mathrm{L}}(t_2) - V_{\mathrm{L}}(t_1)}{\Delta P_{\mathrm{L}}(t_2) - \Delta P_{\mathrm{L}}(t_1)}$$

$$\Delta P_{\mathrm{L}} = (P_{\mathrm{AWO}} - P_{\mathrm{PL}})$$

$$\Delta P_{\mathrm{W}} = P_{\mathrm{PL}} - P_{\mathrm{BS}}$$

$$Cst_{\mathrm{W}} = \frac{V_{\mathrm{L}}(t_4) - V_{\mathrm{L}}(t_3)}{\Delta P_{\mathrm{W}}(t_4) - \Delta P_{\mathrm{W}}(t_3)}$$

$$P_{\mathrm{AWO}} - P_{\mathrm{PL}} = \frac{1}{Cst_{\mathrm{L}}} v_{\mathrm{L}} + R_{\mathrm{AW}} \dot{v}_{\mathrm{L}}$$

$$\Delta P_{\mathrm{L}} = (\Delta P_{\mathrm{L}})\mathrm{st} + (\Delta P_{\mathrm{L}})\mathrm{dyn}$$

- When the flows, changes of volume, or their respective time derivatives are large, the equations describing the mechanical behavior of the respiratory system are highly nonlinear.

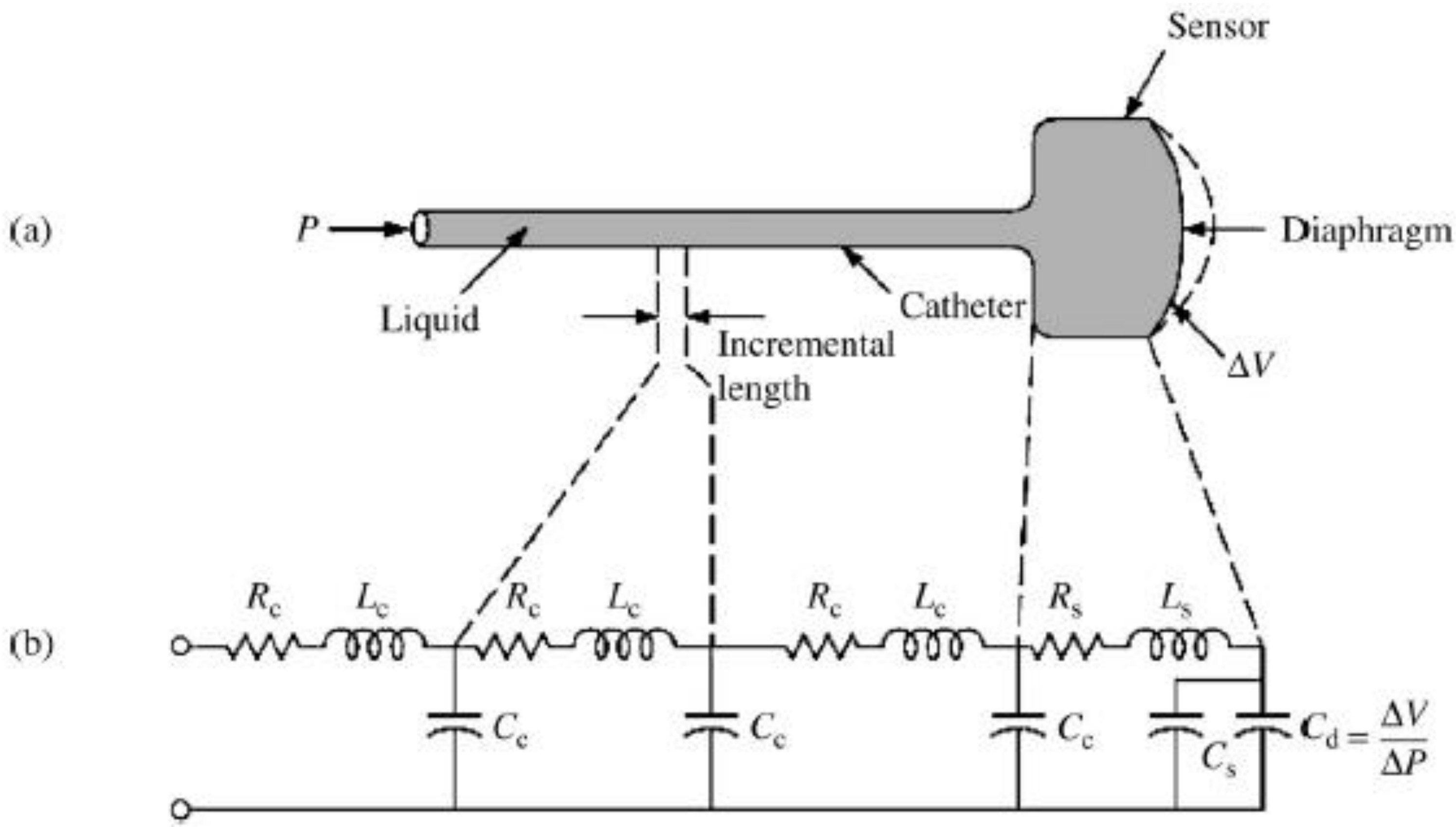
- However, for small flows and changes of volume such as those that occur during resting breathing, linear approximations adequately describe the respiratory system.

MEASURABLE VARIABLES IN THE RESPIRATORY SYSTEM

- volume flow of gas through the mouth and nose
- pressure at the mouth, nose and body surface
- partial pressures or concentrations of various gases in gas mixtures passing through the mouth and nose
- discrete samples of blood *in vitro*; and temperature, including body-core temperature

❑ Measurement of Pressure

- We can conveniently perform dynamic measurements of respiratory pressures using an electronic strain-gage pressure sensor with a tube or catheter as a probe



Intraesophageal Pressure

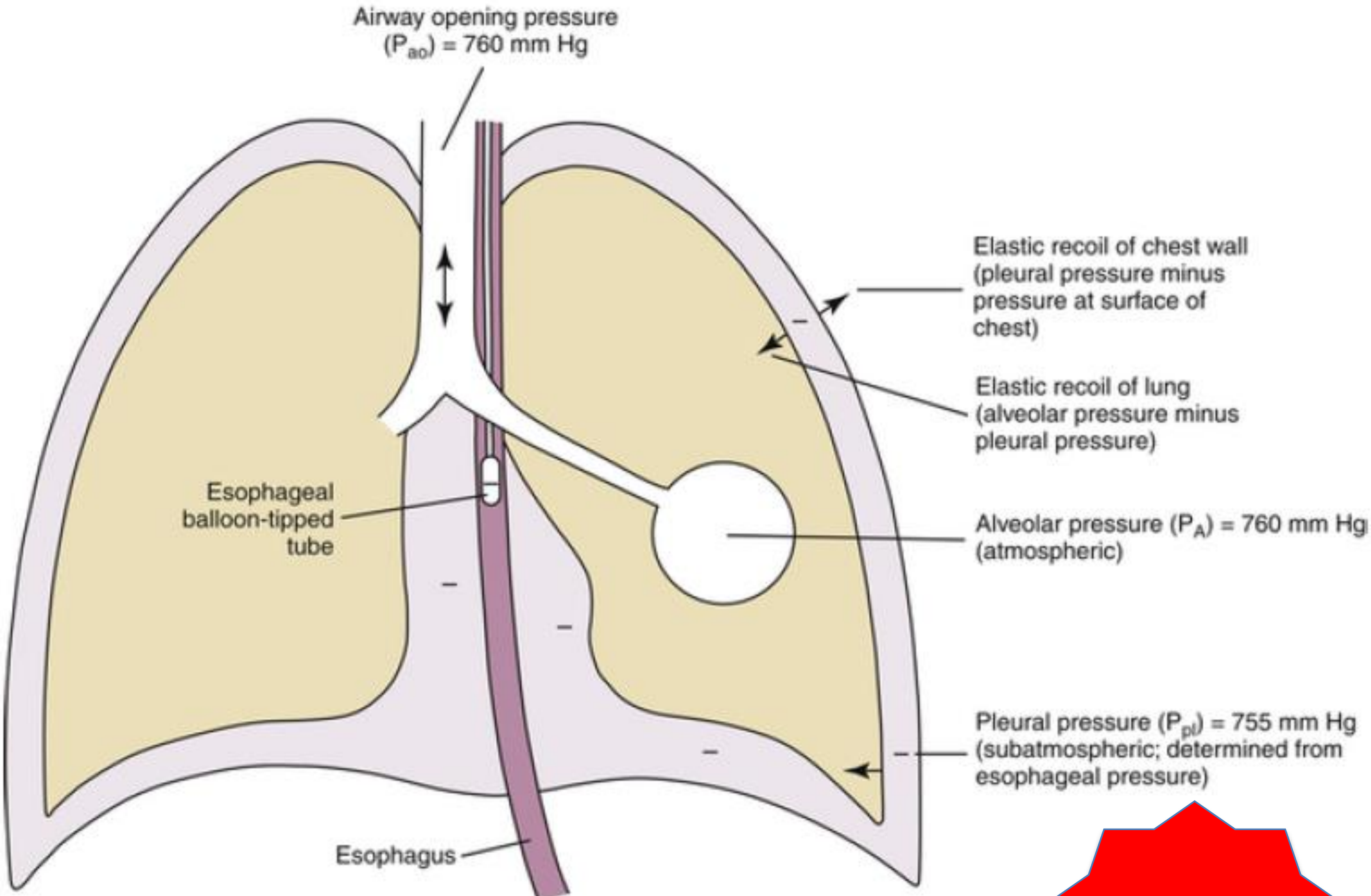
- Computing pulmonary mechanical properties requires a measure of the averaged pressure acting on the pleural surfaces

- Direct measurements of the pressure on the visceral pleural surface made by puncturing the thoracic wall and introducing a catheter into the interpleural space are not clinically applicable.

- The most commonly used technique involves passing an air-filled catheter with a small latex balloon on its end through the nose into the esophagus

- The esophagus which is normally a flaccid, collapsed tube, is subjected to the pressure in the interpleural space (acting through the parietal pleura) and to the weight of other thoracic structures, primarily the heart.

- The pressure in the air trapped in a small balloon situated within the thoracic esophagus depends on the compression or expansion caused by these sources.



Watch
movie # R3

❑ Measurement of Gas Flow

- When the lungs change volume during breathing, a mass of gas is transported through the airway opening by convective flow.

- Measurement of variables associated with the movement of this gas is of major importance in studies of the respiratory system.

- The instruments used to measure volume flow are referred to as ***volume flowmeters.***

- Commonly used respiratory volume flowmeters fall into one of four categories:

①rotating-vane :turbine in the flow path> rotation of the turbine >volume flow of gas

② ultrasonic :measures the effect of the flowing gas on the transit time of the ultrasonic signal

③thermal-convection: measures the electrical resistances of which change with temperature depending on the volume of gas.

④differential pressure flowmeters: Convective flow occurs as a result of a difference in pressure between two points. From the relationship between pressure difference and volume flow through a system, measurement of the difference in pressure yields an estimate of flow. (Pneumotachometers, Pitot Tubes)

Pneumotachometers:

- In general, the term pneumotachometer is synonymous with *gas volume flowmeter.*
- utilizes flow resistors with approximately linear pressure–flow relationships.
- Flow-resistance pneumotachometers have sufficient accuracy, sensitivity, linearity, and frequency response for most clinical applications

- those **most commonly** used **flow-resistance elements** consist of either one or more **fine mesh screens** [Figure 9.3(a)] placed perpendicular to flow, or a tightly packed **bundle of capillary tubes or channels** [Figure 9.3(b)] with its axis parallel to flow.

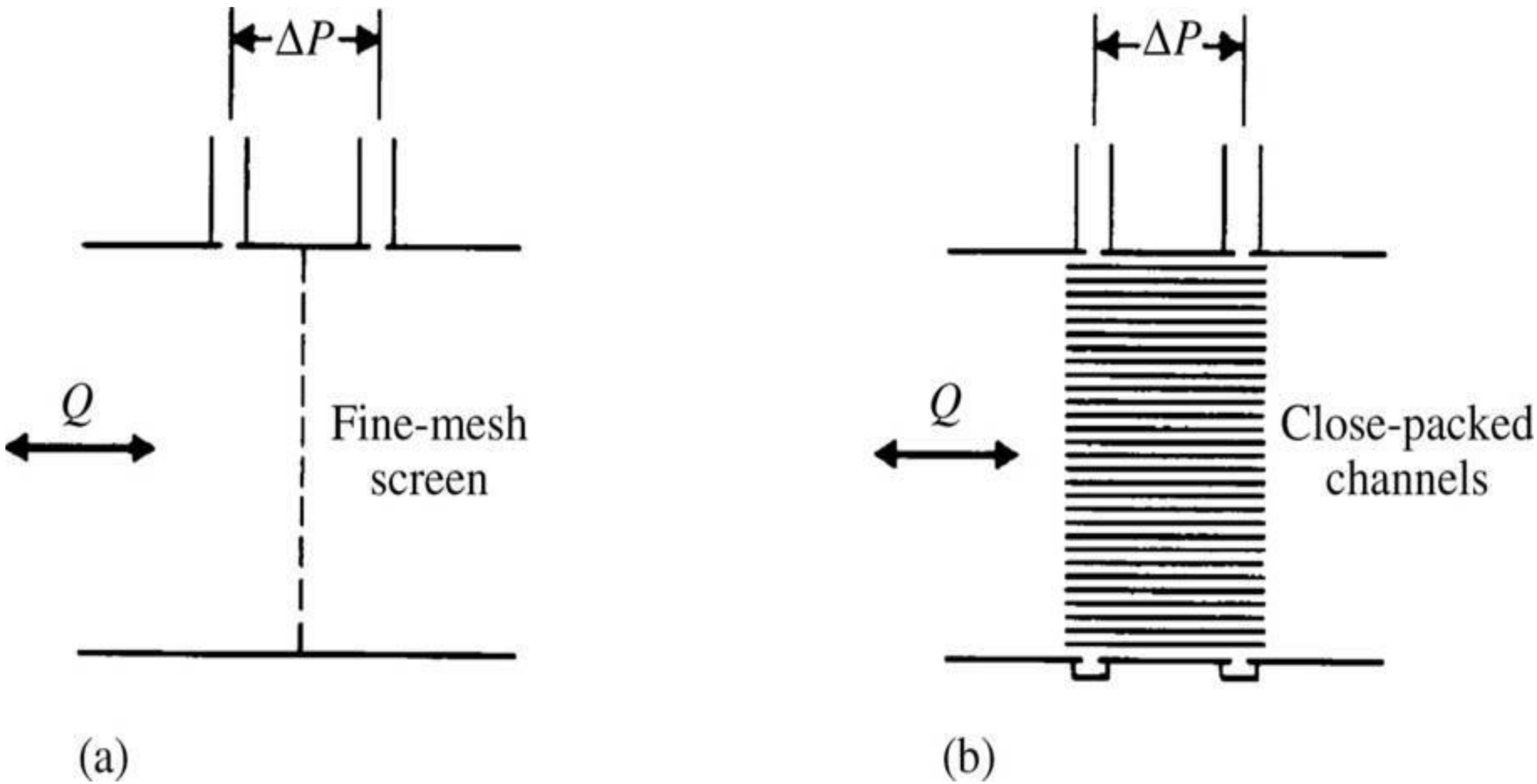


Figure 9.3 Pneumotachometer flow-resistance elements: (a) Screen. (b) Capillary tubes or channels.

- The ΔP–Q relationship may be **more linear for steady flow** when there is a **large axial separation** between pressure ports than when there is a **smaller separation**.

- **In order to avoid excessive formation of vortices at high flow rates, the cross-sectional area of the conduit at the flow-resistance element must be large enough to reduce the velocity through the element.** This area may be several times that of the mouth of the subject from which the gas originates, requiring an adapter or diffuser between the mouthpiece and the resistance element.

- The volume within the adapters and conduit represents **a dead space for cyclic breathing**.

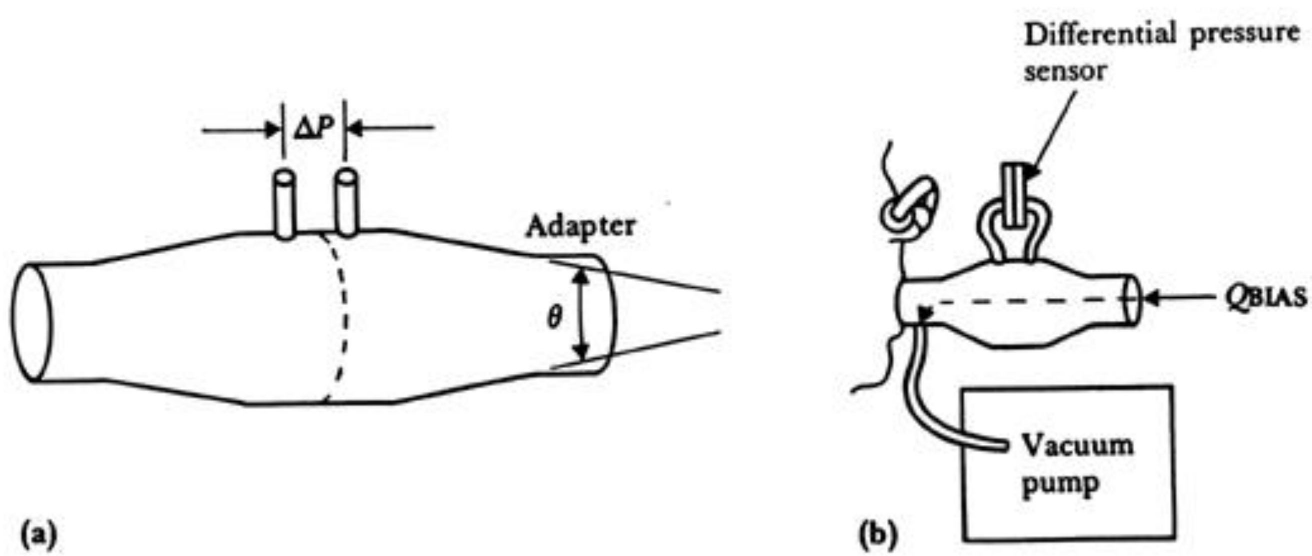


Figure 9.4 Pneumotachometer for measurements at the mouth (a) Diameter adapter that acts as a diffuser. (b) An application in which a constant flow is used to clear the dead space.

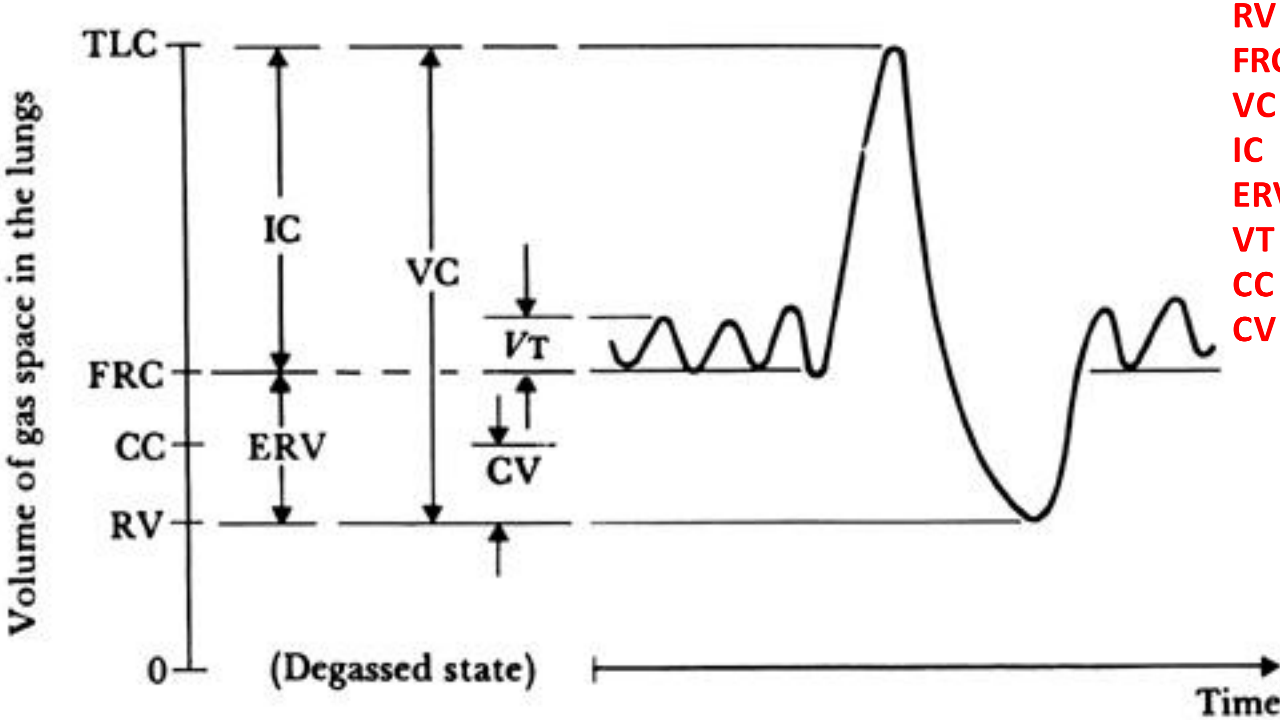
EXAMPLE 9.2 A Fleisch pneumotachometer has 100 capillary tubes, each with a diameter of 1 mm and a length of 5 cm. What pressure drop occurs for a flow of 1 liter/s?

ANSWER A flow of 1 liter/s through 100 tubes is 0.00001 m^3/s through one tube. In SI units, using (7.1) and (7.2),

$$\Delta P = RF = \frac{8\eta LF}{\pi r^4} = \frac{8(0.000018)(0.05)(0.00001)}{\pi(0.0005)^4} = 367\,\mathrm{Pa} = 3.74\,\mathrm{cm\,H_2O}$$

❑ Measurement of the Lung Volume

- The most commonly used indices of the mechanical status of the ventilatory system are the absolute volume and changes of volume of the gas space in the lungs achieved during various breathing maneuvers.



TLC	: Total lung capacity
RV	:Residual volume
FRC	:Functional Residual Capacity
VC	: Vital capacity (TLC - RV)
IC	: Inspiratory capacity (TLC-FRC)
ERV	: Expiratory reserve volume (FRC-RV)
VT	: Tidal Volume
CC	: Closing capacity
CV	:Closing volume

Figure 9.5 Volume ranges of the intact ventilatory system (with no external loads applied). TLC, FRC, and RV are measured as absolute volumes. CV, IC, ERV and *V*T are volume changes. Closing volume (CV) and closing capacity (CC) are obtained from a single-breath washout experiment.

- **Total lung capacity (TLC) :** the largest volume to which the subject's lungs can be voluntarily expanded.

- **residual volume (RV):** The smallest volume to which the subject can slowly deflate his or her lungs.

- **functional residual capacity (FRC)**: The volume of the lungs at the end of a quiet expiration when the respiratory muscles are relaxed.

- **vital capacity (VC)**: The difference between TLC and RV which defines the maximal change in volume the lungs can undergo during voluntary maneuvers. The vital capacity can be divided into the inspiratory capacity . (IC) and the expiratory reserve volume ERV

- The peak-to-peak volume change during a quiet breath is the **tidal volume (VT)**.

❑ Changes in Lung Volume: Spirometry (measurement of the gas passing through the airway opening)

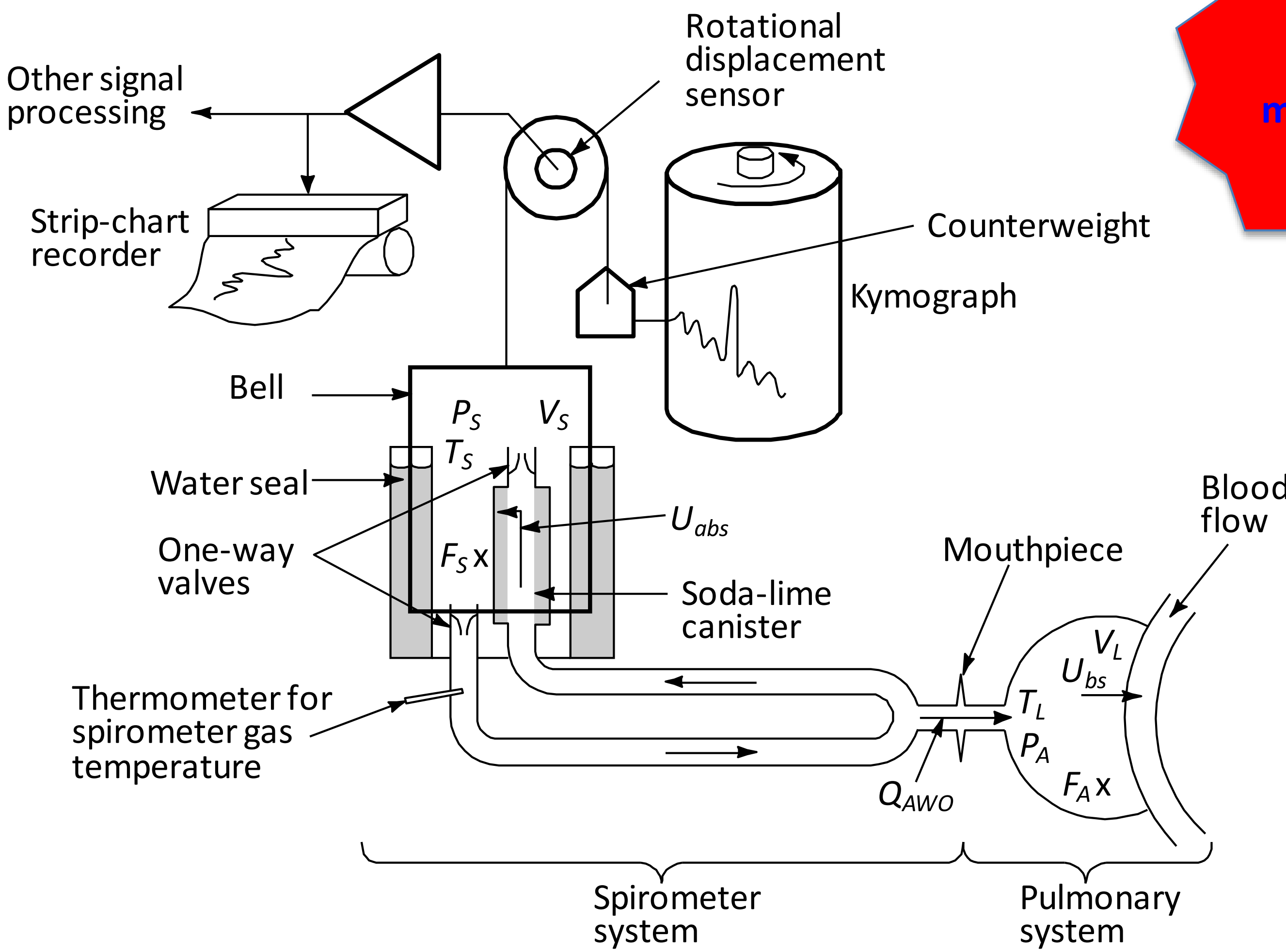


Figure 9.6 A water-sealed spirometer set up to measure slow lung-volume changes. The soda-lime and one-way-valve arrangement prevent buildup of CO_2 during rebreathing.

➢ Nitrogen-washout Estimate Of Lung Volume

- The subject inhales only an N_2-free gas mixture (ex O_2)because of the one-way valves, but she/he exhales N_2,O_2,CO_2 and water vapor.

- He or she is allowed to breathe the N_2 -free mixture in a relaxed manner around FRC with relatively constant tidal volumes for a fixed period of time (7 to 10 min) or until the N_2 molar fraction in the expirate is sufficiently near zero (< 2%)

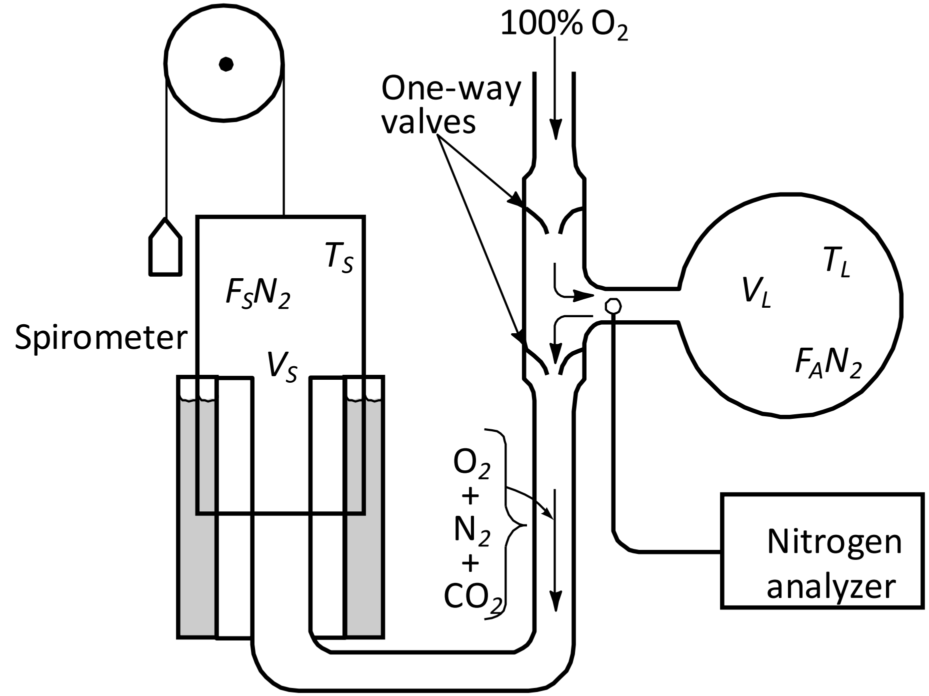
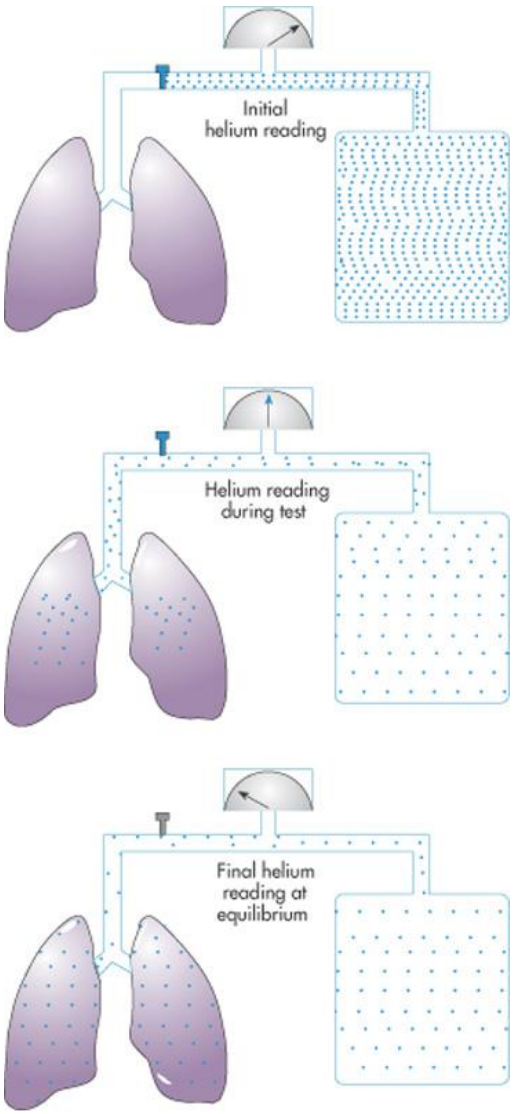


Figure 9.7 Diagram of an N_2 washout experiment The expired gas can be collected in a spirometer, as shown here, or in a rubberized-canvas or plastic Douglas bag. N_2 content is then determined off-line. An alternative is to measure expiratory flow and nitrogen concentration continuously to determine the volume flow of expired nitrogen, which can be integrated to yield an estimate of the volume of nitrogen expired.

➢ Helium-Dilution Estimate Of Lung Volume

- add a measured amount of a nontoxic, insoluble tracer gas to the inspirate, and—after it is uniformly distributed in the lungs—determine its concentration and compute lung volume.

    - Closed system
    - Known volume and concentration of He added and it will be diluted in proportion to the size of the lung volume



(From Wilkins RL, Stoller JK, Scanlan CL: *Egan's fundamentals of respiratory care*, ed 8, St Louis, 2003, Mosby.)

- Helium is often used as the tracer gas for this experiment, though argon and neon are also acceptable.

➢ total-body plethysmography

- The total-body plethysmograph (TBP) is a rigid, constant-volume box in which the subject is completely enclosed.

- Clinically it is used primarily to evaluate the absolute volume of the lungs, and to provide a continuous estimate of alveolar pressure, from which airway resistance R_{AW} can be computed.

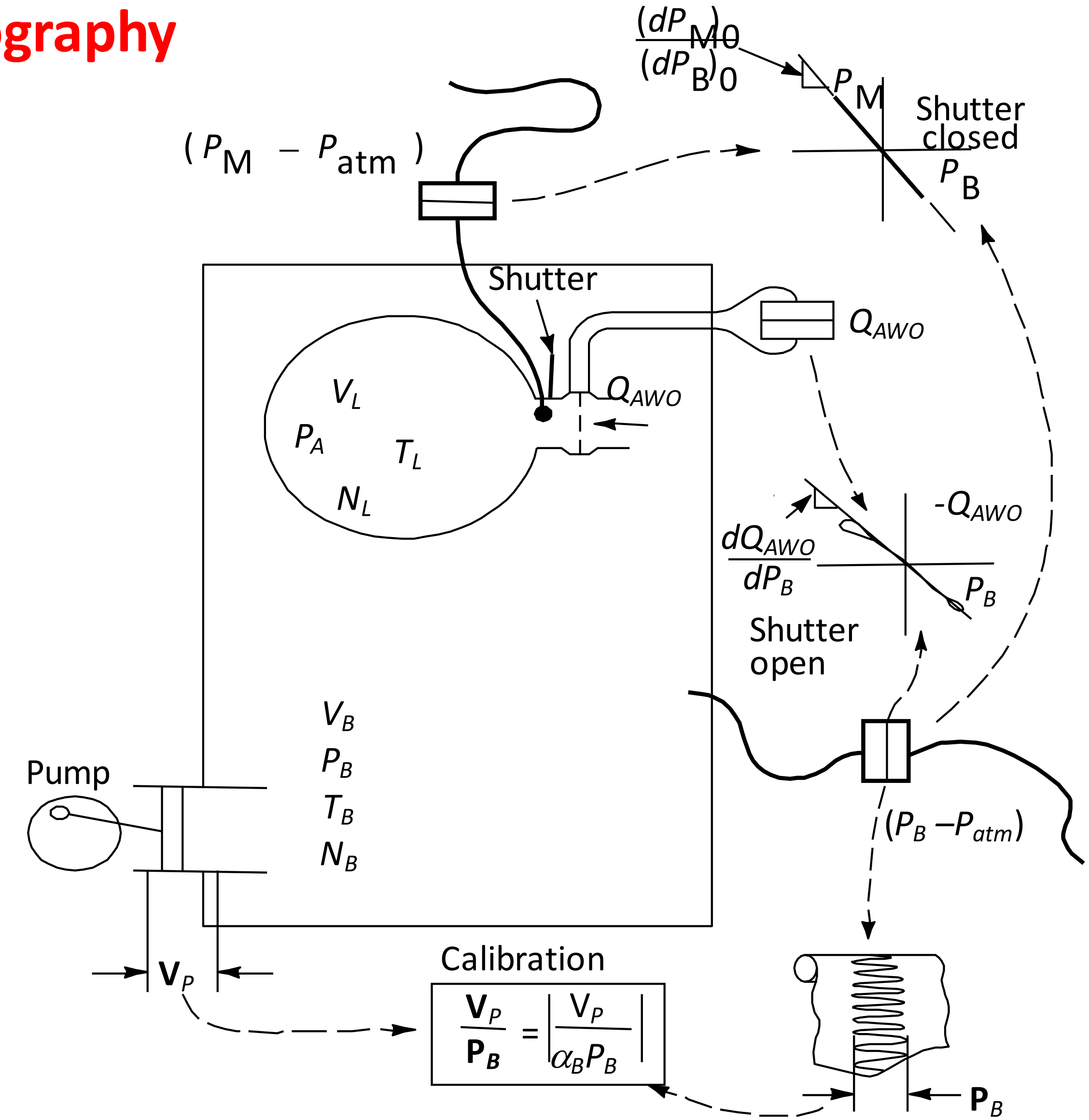
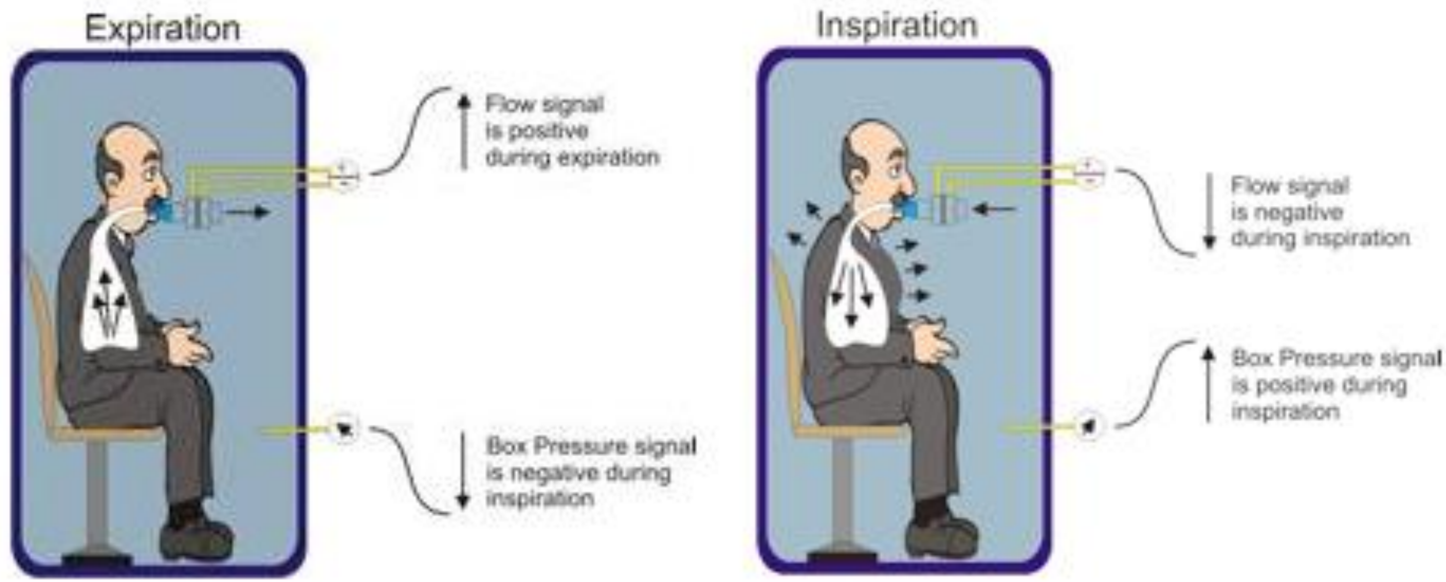
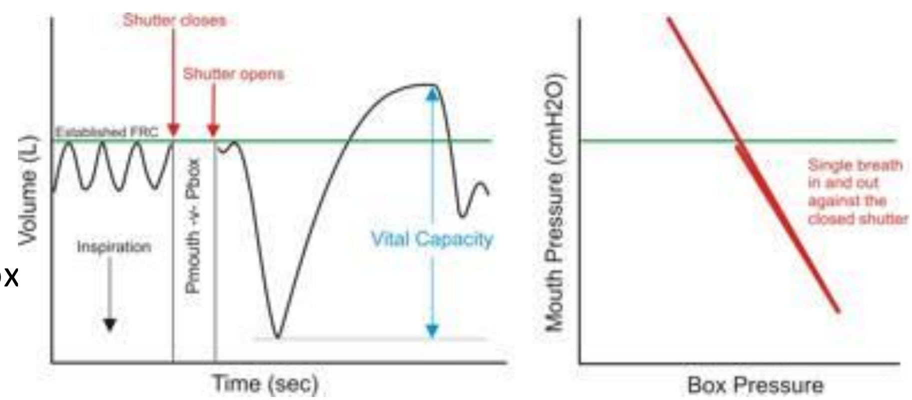


Figure 9.8 A pressure-type total-body plethysmography is used with the shutter closed to determine lung volume and with the shutter open to determine changes in alveolar pressure. Airway resistance can also be computed if volume flow of gas is measured at the airway opening. Because atmospheric pressure is constant, changes in the pressures of interest can be obtained from measurements made relative to atmospheric pressure.



- the patient sits inside an airtight box, inhales or exhales to a particular volume (usually FRC), and then a shutter drops across their breathing valve.
- The subject makes respiratory efforts against the closed shutter causing their chest volume to expand and decompressing the air in their lungs.
- The increase in their chest volume slightly reduces the box volume and thus increases the pressure in the box.
- This method of measuring FRC actually measures all the conducting pathways including abdominal gas; the actual measurement made is VTG (Volume of Thoracic gas).



❑ Some tests for respiratory mechanics

- One of the ultimate objectives of mechanics tests is to determine whether the defect(s) that produce abnormal pressure–volume–flow relationships can be identified as intrinsic to

    - the airways (lumen and/or walls)
    - the lung parenchyma surrounding and supporting the airways
    - extrapulmonary structures.

- A **distinction** is often made between obstructive and restrictive disease processes.

- **Obstruction** stands for dynamic mechanics, being associated with <u>abnormal rates of change of volume or gas flows</u> in the lungs during breathing movements (For example; expiratory flow is below normal).

- **Restriction** stands for abnormal static mechanics. It is <u>used to refer not only to the lungs but also to extrapulmonary structures</u> (such as the chest wall, muscles, and the abdominal contents).

    - This condition is indicated when the volume attained by the ventilatory system is inappropriate for the difference in pressure applied or when the differences in pressure that the respiratory muscles are capable of producing are abnormally low (For lung volumes are reduced).

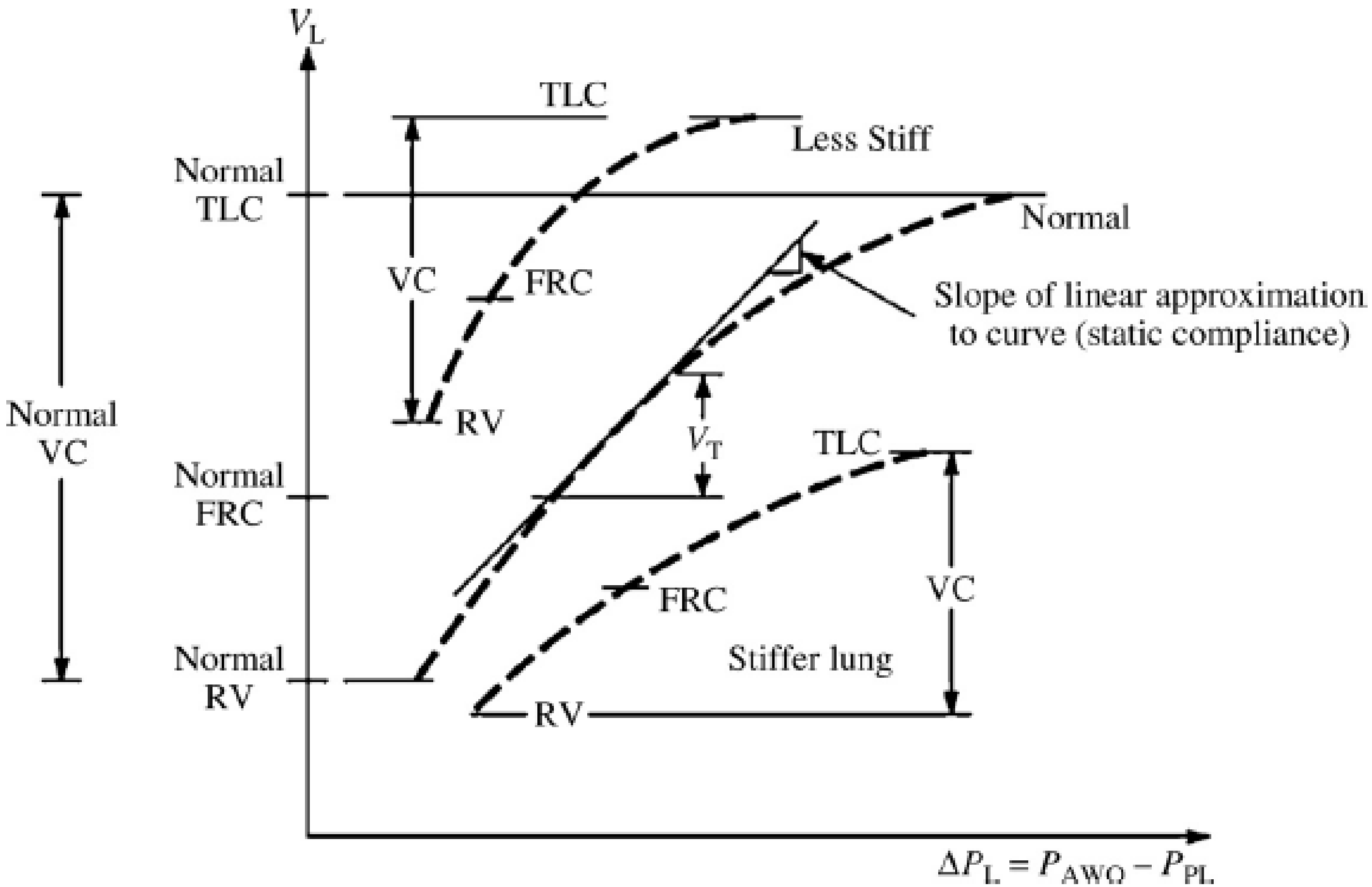
Static Mechanics

- the static mechanical characteristics of the lungs can be **obtained by measuring simultaneously the lung volume and the transpulmonary pressure difference**, at various lung volumes.

Static compliance

- to produce an expiratory ΔP-V curve, the subject is instructed to inspire to TLC and then to exhale to successively smaller volumes, holding each volume while the pressure in an esophageal balloon is measured relative to pressure at the airway opening. This pressure difference is used as an estimate of *transpulmonary pressure.*

- Figure shows a facsimile of statically determined expiratory ΔP-V curves for a normal subject, for a subject who has restricted, or stiff, and for a subject who has very distensible lungs.



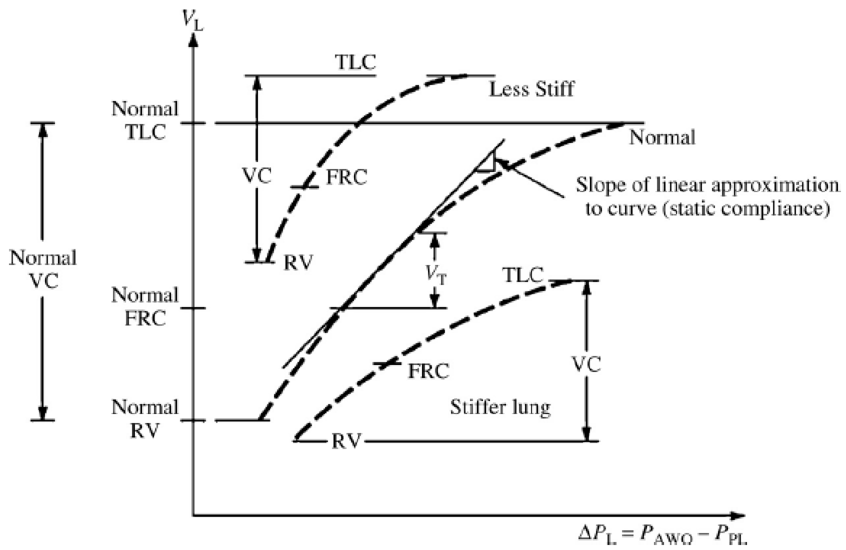
- **The slope of the linear approximation to the statically determined ΔP-V curve is the static compliance, C_{st}.**
- **we can identify a restricted, or stiff, lung by computing lung compliance at a standardized lung volume.**

○ *Static Lung Volumes*

- Although **pulmonary compliance** is a desirable parameter to obtain when the physician suspects restrictive lung disease**, it is not routinely measured because it requires the use of an esophageal balloon**, which is very unpleasant for the subject.

- **The observation** that TLC, RV, and the difference between them, VC, are reproducible and easily attained in the absence of measurements of changes in esophageal pressure.

- Figure shows that the vital capacity of the restricted subject, which can conveniently be estimated by <u>spirometry,</u> is reduced compared with that of the normal individual.



- However**, a low VC does not imply stiff lungs.** A decreased VC can result from a number of circumstances, including obstructive diseases affecting the small airways (such as asthma) and abnormalities of the chest wall and respiratory neuromuscular system (as a result of scoliosis or poliomyelitis, for example).

➢ Dynamic Mechanics During Small Volume Changes And Flows

Airway Resistance

- during resting breathing, changes in transpulmonary pressure can be expressed as a function of the changes in lung volume and gas volume flow rate that would occur if the alveoli were purely elastic structures (However, they are able to exhibit a viscoelastic type of behavior since the alveoli are not purely elastic)

$$p_{\mathrm{AWO}} - p_{\mathrm{PL}} = \frac{1}{\mathrm{Cst_L}} v_{\mathrm{L}} + R_{\mathrm{LT}} \dot{v}_{\mathrm{L}} + R_{\mathrm{AW}} q_{\mathrm{AWO}}$$

in which

- R_{LT} is the resistance of the lung tissue
- R_{AW} is the airway resistance

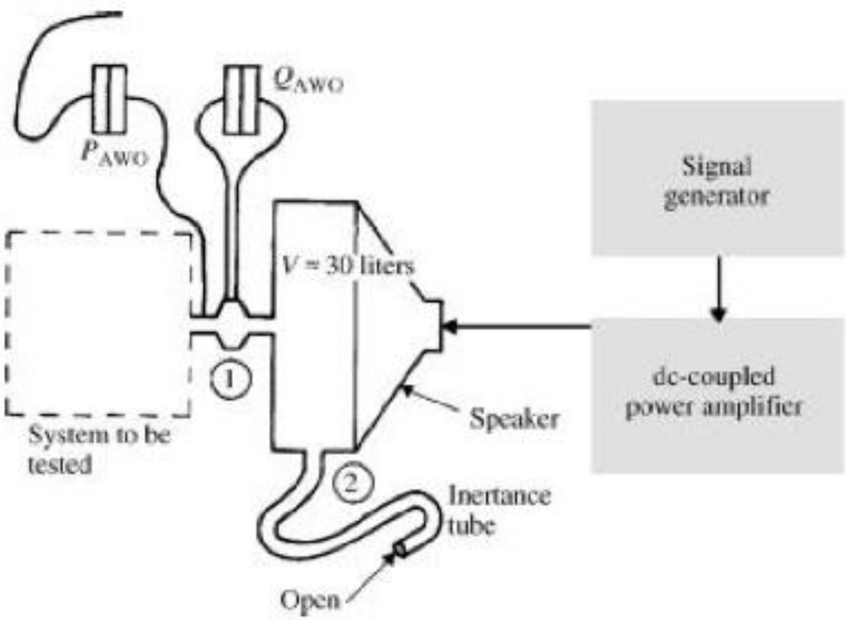
R_{AW} represents a direct measure of obstruction in the airways.

$$R_{\mathrm{AW}} = \frac{\partial (P_{\mathrm{AWO}} - P_{\mathrm{A}})}{\partial Q_{\mathrm{AWO}}}$$

- Mechanical impedance of the respiratory system have been inferred from its response to high frequency perturbations. Two procedures have been developed:

  1. forced oscillation
  2. interrupter techniques.

1. Force oscillation technique to obtain the mechanical impedance of the total respiratory system.



This method consists of applying small sinusoidal pressure variations to stimulate the respiratory system at frequencies higher than the normal breathing frequency and measuring the flow response.

Figure 9.10 A speaker-driven forced oscillation system can be used to obtain the mechanical impedance of the total respiratory system during spontaneous breathing and to measure the acoustic impedance and/or frequency responses of laboratory apparatus. The high inertance of the long (8.5 m) tube at port 2 acts as a low-pass filter for flow. As the subject breathes normally, the low- frequency flow produced passes through port 1 and port 2. However, the small, high-frequency pressure variations generated by the speaker are blocked by the inertance at port 2 and are preferentially transmitted to the subject through port 1.

2. Interrupter Technique

- produce momentary complete or partial blockage of flow into and out of the airway, thereby causing pressure fluctuations at the airway opening.

- resulting patterns of flow and pressure on the subject side are continuously recorded simultaneously.

- Even though forced oscillation and interrupter techniques are similar in that they impose high frequency pressure and/or flow disturbances at the airway opening during breathing, they appear sensitive to the effects of different combinations of mechanical properties of the various respiratory structural components

Dynamic Mechanics During Large Volume Changes And Flows

Specific Airway Resistance

- The airways within the lungs are subjected to the increased and decreased tensile forces produced as the lung regions in which they are embedded inflate and deflate. Consequently, as the alveolar regions are expanded and compressed, the length and cross-sectional area of each airway generation undergo corresponding changes.

- Inverse relationship between plethysmographically determined airway resistance and the lung volume at which it is measured. The larger the volume of the lung, the more expanded the airways and the lower the resistance to flows produced during a panting maneuver, and vice versa.

$$R_{\mathrm{AW}} \cong \frac{(SR_{\mathrm{AW}})}{V_{\mathrm{TG}}}$$

where SR_{AW} is specific airway resistance and V_{TG} is volume of thoracic gas. SR_{AW} represents a property of a subject's airways normalized for his or her lung volume.

○ *Flow Limitation*

- **Another manifestation of the effects of changes in airway dimensions during ventilatory maneuvers** is the flow limitation exhibited during forced expirations.

- *isovolume pressure–flow curves can be used to determine the flow limitation exhibited during forced expiration.*

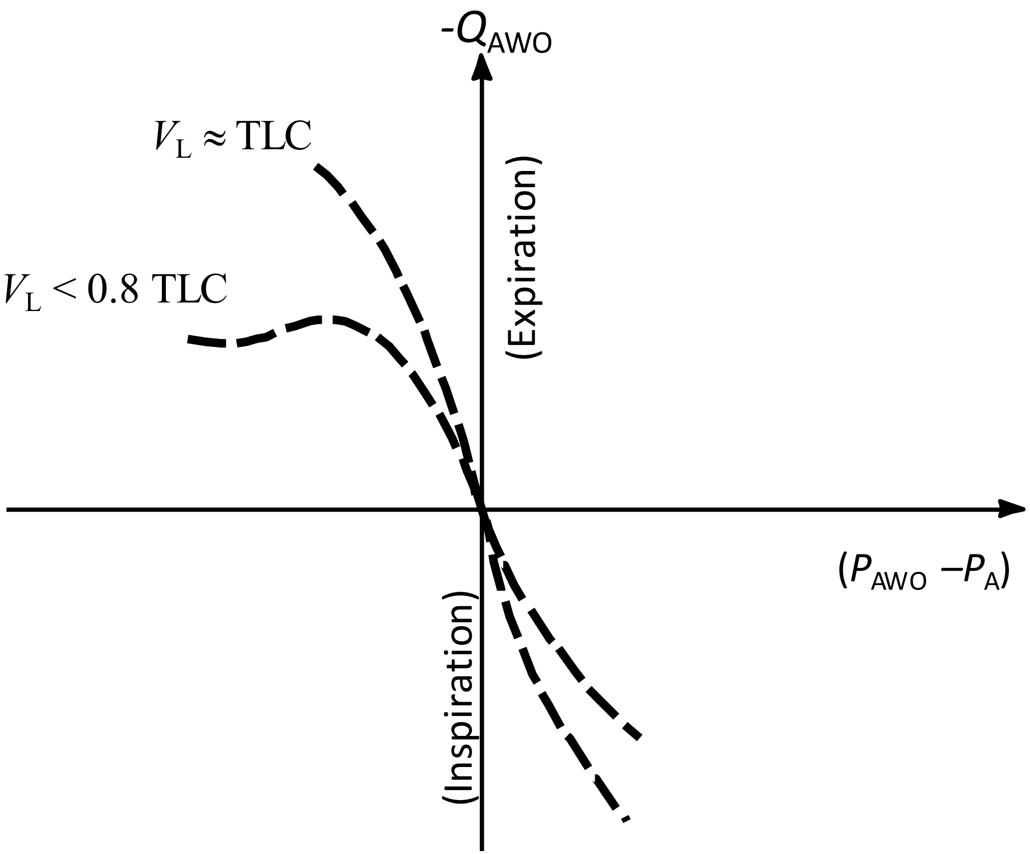


Figure 9.10 Idealized isovolume pressure-flow curves for two lung volumes for a normal respiratory system. Each curve represents a composite from numerous inspiratory-expiratory cycles, each with successively increased efforts. The pressure and flow values measured as the lungs passed through the respective volumes of interest are plotted and connected to yield the corresponding curve.

Three features generally appear:

1. Inspiratory flow continually increases as the difference in pressure is increased at any lung volume.
2. For high lung volumes (near TLC), expiratory flow increases as the difference in pressure becomes more negative.
3. For lung volumes below about 80% of the TLC, the expiratory flow reaches a value that is never exceeded, even though the difference in pressure becomes more negative. **This condition is referred to as *flow limitation* in which the flow is effort *independent*. That is, expiratory flow cannot be increased, no matter how much expiratory efforts are increased.**

The Forced Expiratory Vital Capacity Maneuver: Maximal Expiratory Flow Volume Curve and Timed Vital Capacity Spirogram

- Flow limitation phenomena can be displayed in two clinically useful ways, both based on measures of only **volume flow of gas at the airway opening during a forced expiration from TLC to RV**. The equivalent volume of gas expired during this maneuver is the forced vital capacity (FVC).

➢ **Two alternative methods of displaying data during FVC expiration:**

1. Plot of the Volume flow of gas at the airway opening against its integral (or volume change in a spirometer) subtracted from FVC
2. Plot of the integral of expired gas volume flow (or spirometer volume change) subtracted from FVC against time

- **The first method produces the maximal expiratory flow volume (MEFV) curve,**
- **The second corresponds to the spirogram of the timed vital capacity (TVC) routinely performed as part of standard spirometry tests.**

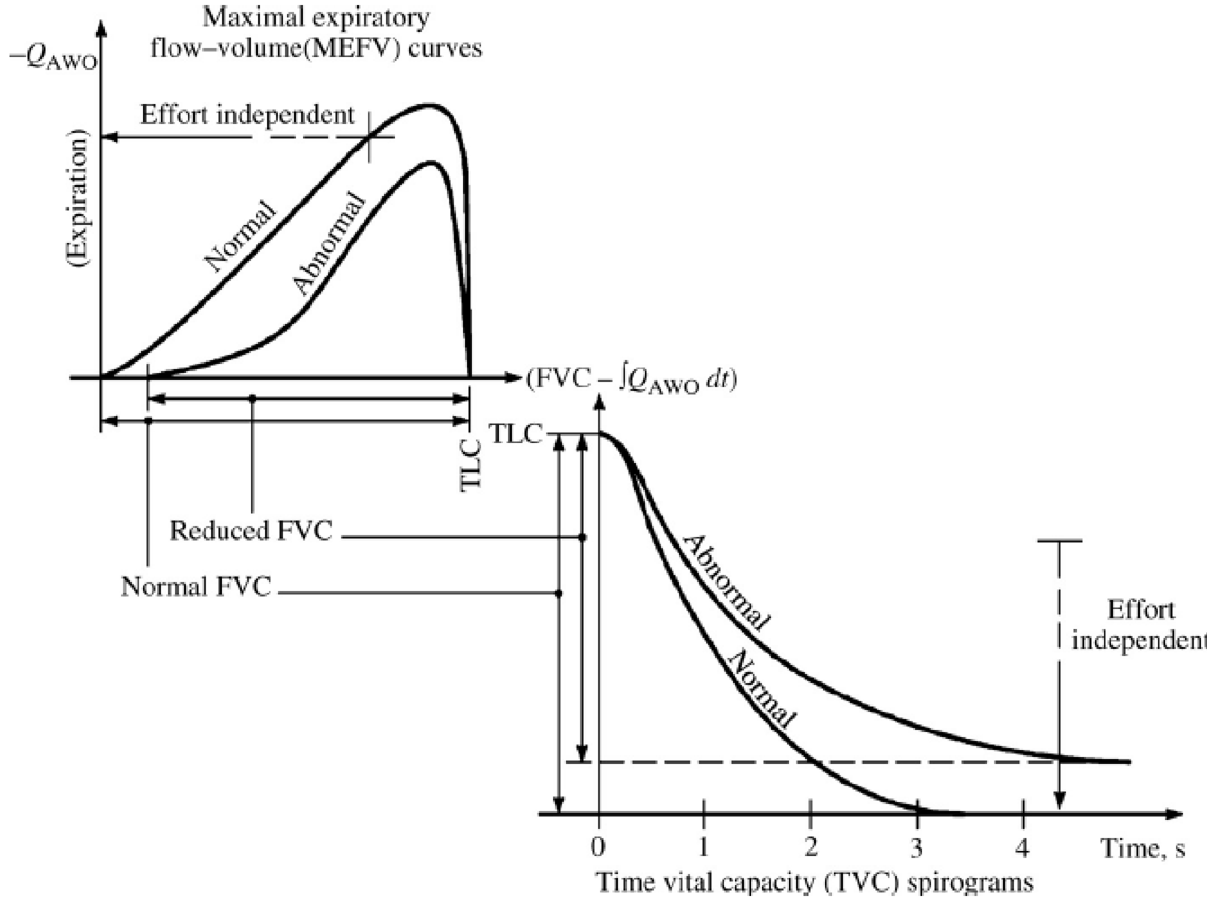


Figure 9.12 Alternative methods of displaying data produced during FVC expiration. Equivalent information can be obtained from each type of curve; however, reductions in expiratory flow are subjectively more apparent on the MEFV curve than on the timed spirogram.

- *Effort dependent curves* provide information about the larger, upper airways and the extrapulmonary parts of the ventilatory system (chest wall, respiratory muscles, and so on).

- The effort-independent region reflects mechanics of the smaller airways and parenchyma of the lungs.

❑ Measurement of Gas Concentration

Analysis of the composition of gas mixtures is one of the primary methods of obtaining information about lung function.

➢ Mass Spectroscopy

A mass spectrometer is an apparatus that produces a stream of charged particles (ions) from a substance being analyzed, separates the ions into a spectrum according to their mass-to-charge ratios, and determines the relative abundance of each type of ion presents.

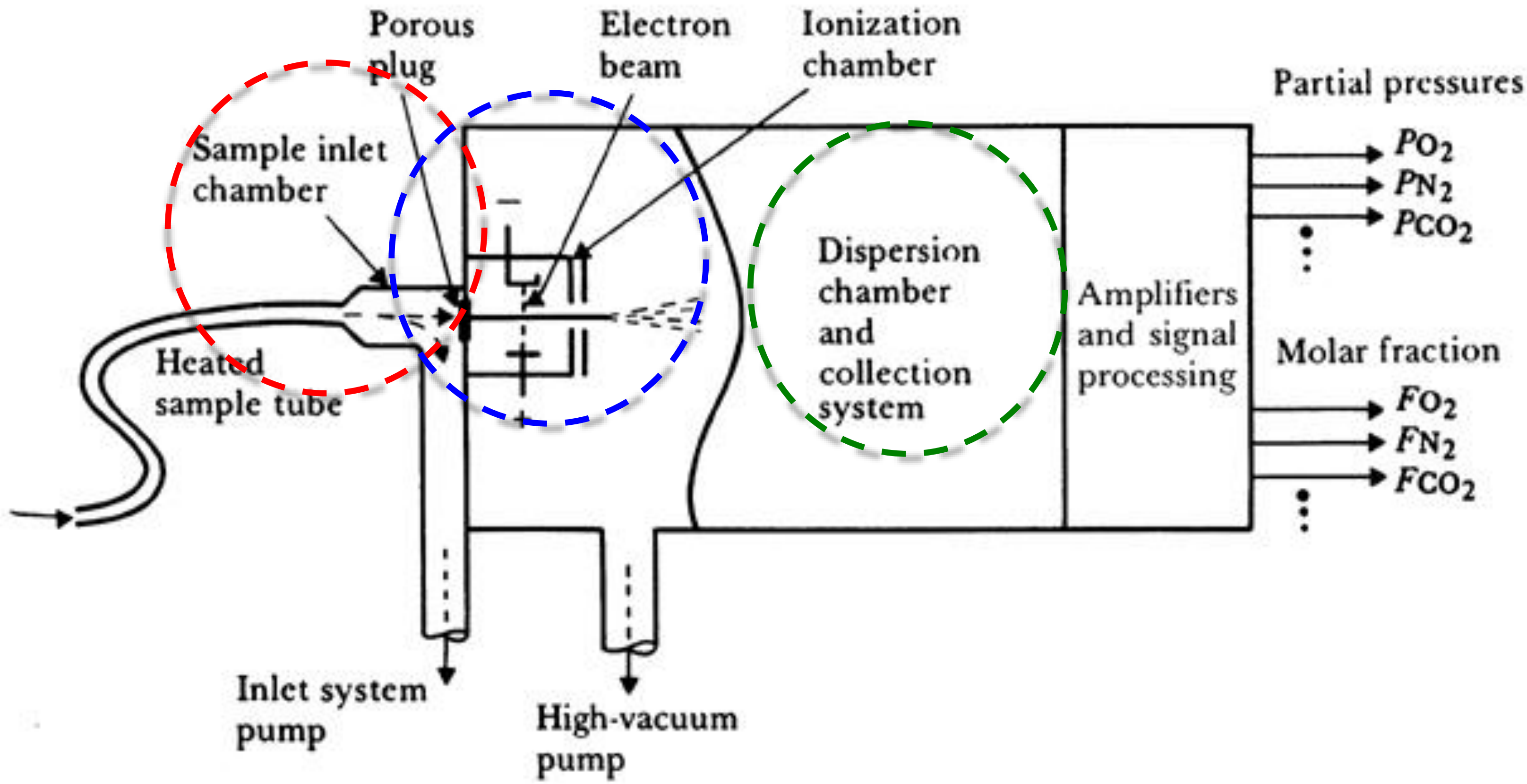


Figure 9.12 Essential elements of a medical mass spectrometer.

➢ Infrared Spectroscopy

- This is because most gases absorb infrared "light" and do so only at distinct, highly characteristic wavelengths, thus yielding what has been called a molecular fingerprint.

Minimum five essential components for transmission and photoacoustic systems

① Source of radiation of the required wavelengths
② Chopper
③ Sample cell
④ Detector
⑤ Signal processing and display equipment

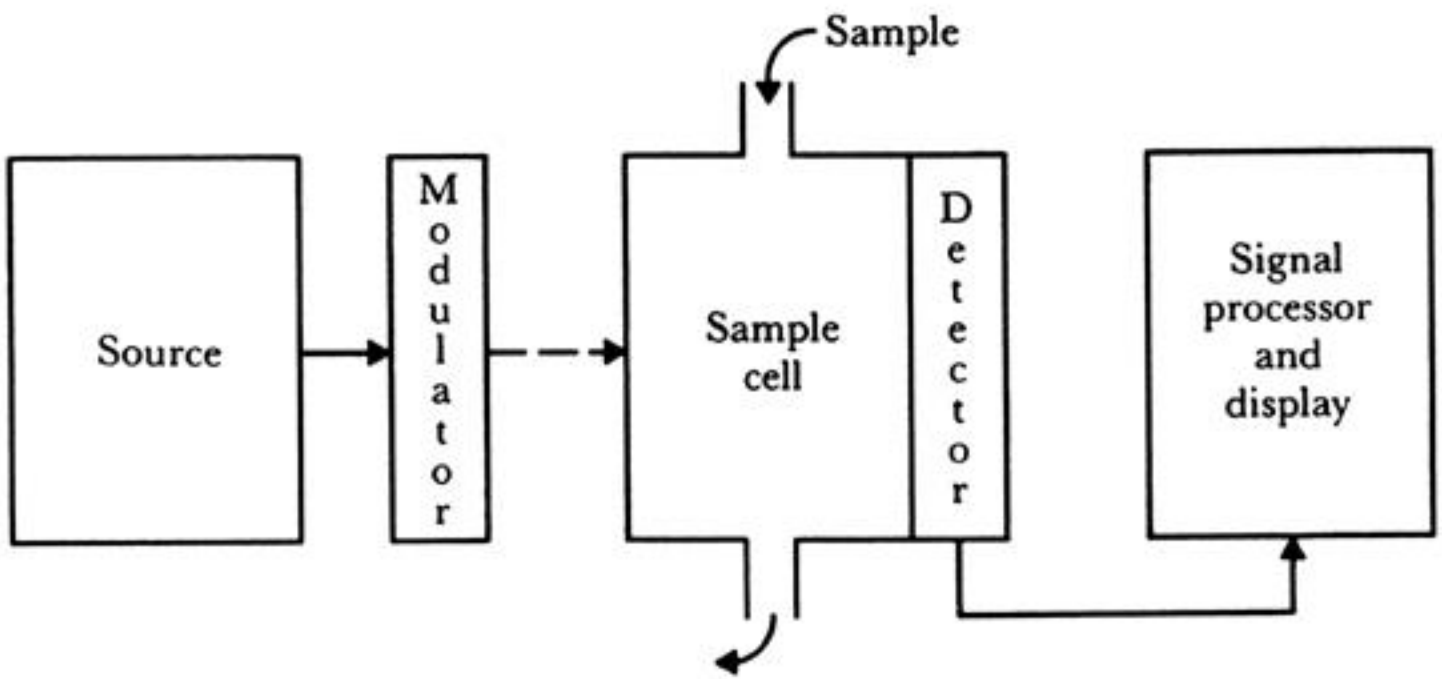
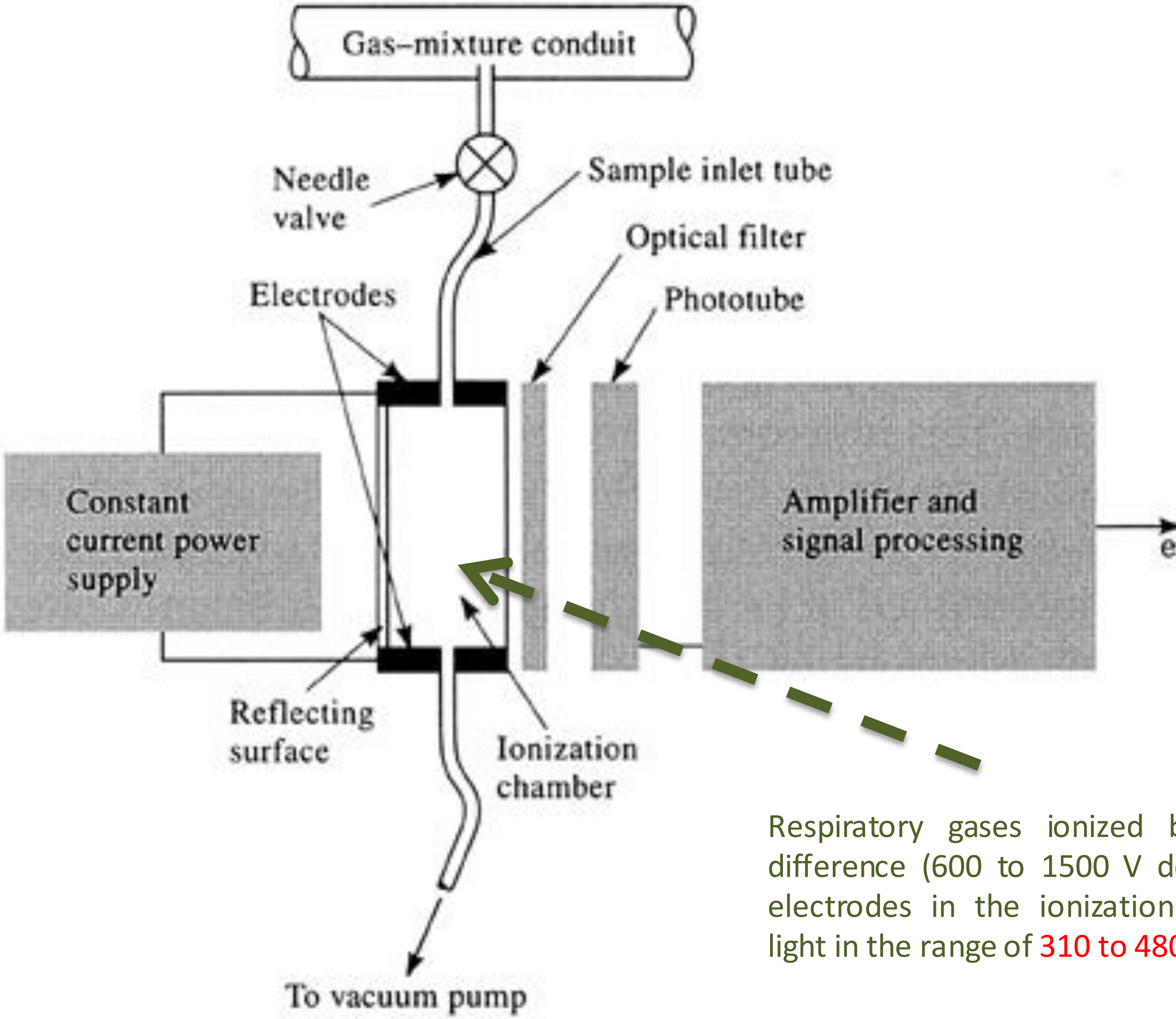


Figure 9.13 General arrangements of the components of an infrared spectroscopy system.

➢ Emission spectroscopy

- detect the concentration of a single gas species in a mixture by measuring the intensity of the light in a given wave- length range produced when the gas mixture is ionized at very low pressures.



Respiratory gases ionized by the voltage difference (600 to 1500 V dc) between the electrodes in the ionization chamber emit light in the range of 310 to 480 nm

Figure 9.14 N_2 analyzer employing emission spectroscopy.

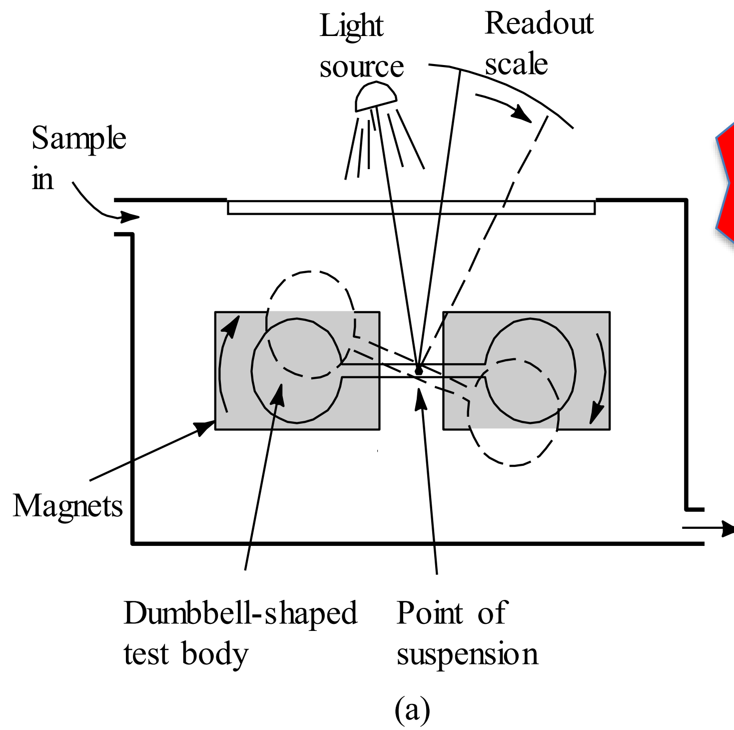
❑Measurement Of Oxygen Concentration

Emission and IR absorption instruments cannot measure the concentration of oxygen in gas mixtures. However, oxygen can be measured by mass spectrometers, polarographic sensors, galvanic sensors, fuel-cell sensors, and paramagnetic sensors.

Oxygen Analyzers

Oxygen is unusual among gases in that it is attracted by a magnetic field

- **The concentration of oxygen can be determined either by measuring the deflection of the test body about its suspension axis (via the reflection of a light beam by a mirror placed on the test body at its center of rotation [Figure 9.16(a)] or by measuring the torque required to maintain the dumbbell in its oxygen-free equilibrium position.**



Watch movie # R4

Figure 9.16 Oxygen analyzers (a) Diagram of the top view of a balance-type paramagnetic oxygen analyzer. The test body either is allowed to rotate (as shown) or is held in place by counter torque, which is measured to determine the oxygen concentration in the gas mixture. (b) Diagram of a differential pressure and a magneto-acoustic oxygen analyzer.

❑ Gas-phase Transport

Tests of gas-phase transport are concerned with questions arising from two of the objectives :

(1) How is the inspired gas (ventilation) distributed in the lungs?
(2) What is the equivalent volume of inspired gas that is not taking part in the exchange of gas with the blood? In other words, what is the effective dead space of the lung?

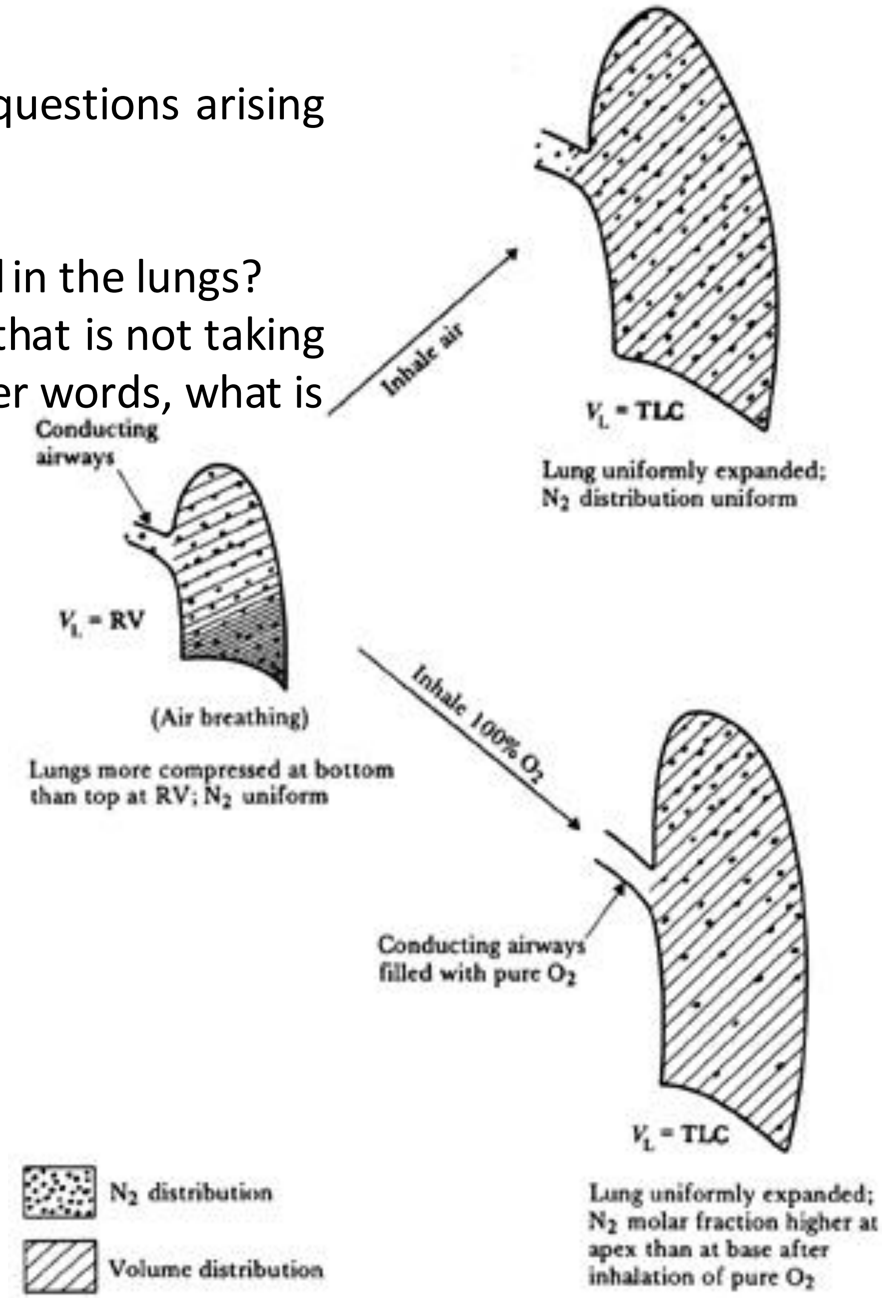
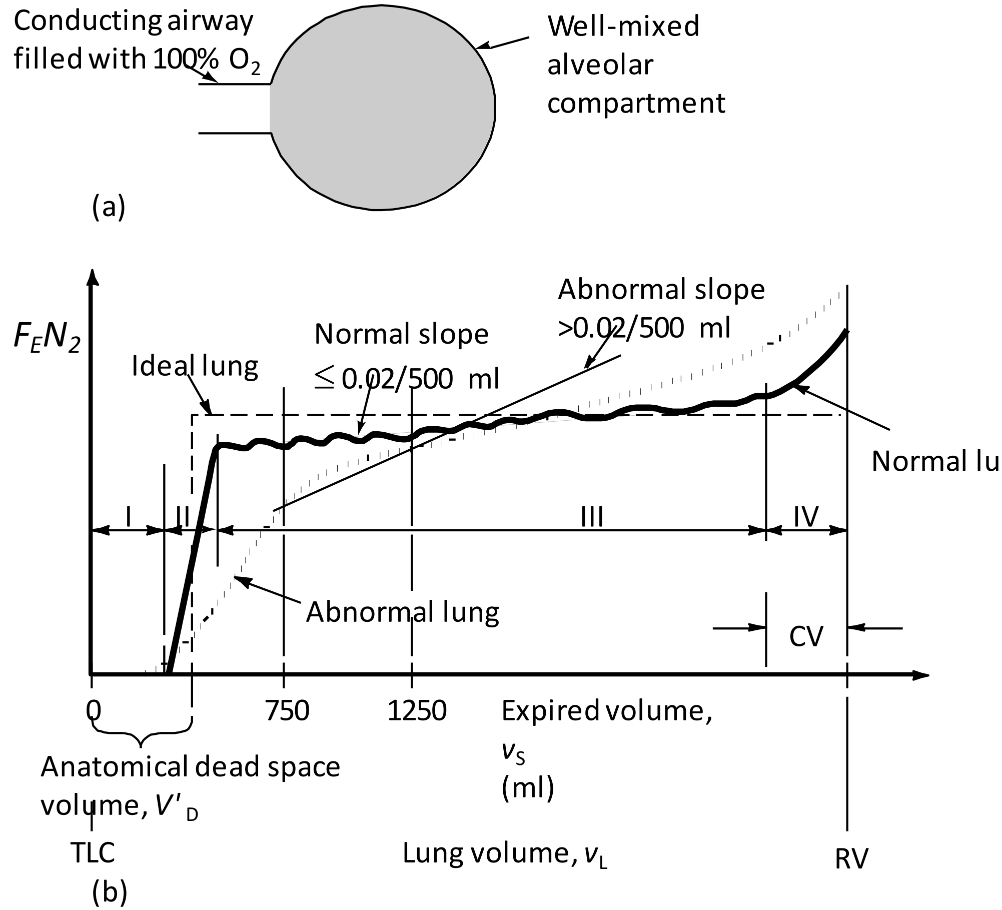


Figure 9.16 Distributions of volume and gas species at RV and TLC for a vital-capacity inspiration of air or pure oxygen.

<u>The single-breath N_2 washout</u> can yield three useful pieces of information:

1. an estimate of the anatomical dead space (approximately the volume of the conducting airways);
2. a measure of the distribution of ventilation—that is, the relative local rates of filling and emptying of the regions of the lungs;
3. an index of small-airway mechanical function, the closing volume CV.



- Normal lungs exhibit four identifiable regions or phases on the F_EN_2-versus-volume plot.
- **During phase I**, lung volume changes but F_EN_2 is zero as pure O_2 is emptied from the conducting airways past the N_2 sensor.
- **Phase II i**s the transition between the emptying of the anatomical dead space and the arrival of mixed alveolar gas at the N_2 sensor.
- **Phase III** is a (sloping) plateau corresponding to the emptying of the mixed alveolar gas from all parts of the lungs. Oscillations of F_EN_2 during phase III have been attributed to local emptying of areas of different FN_2 caused by the changes in volume associated with the heartbeat**.**
- **Phase IV** signifies a drastic change in the rates of emptying of the dependent parts of the lungs. It is dramatically evident if the lung is normal or has only minimal small-airways disease.

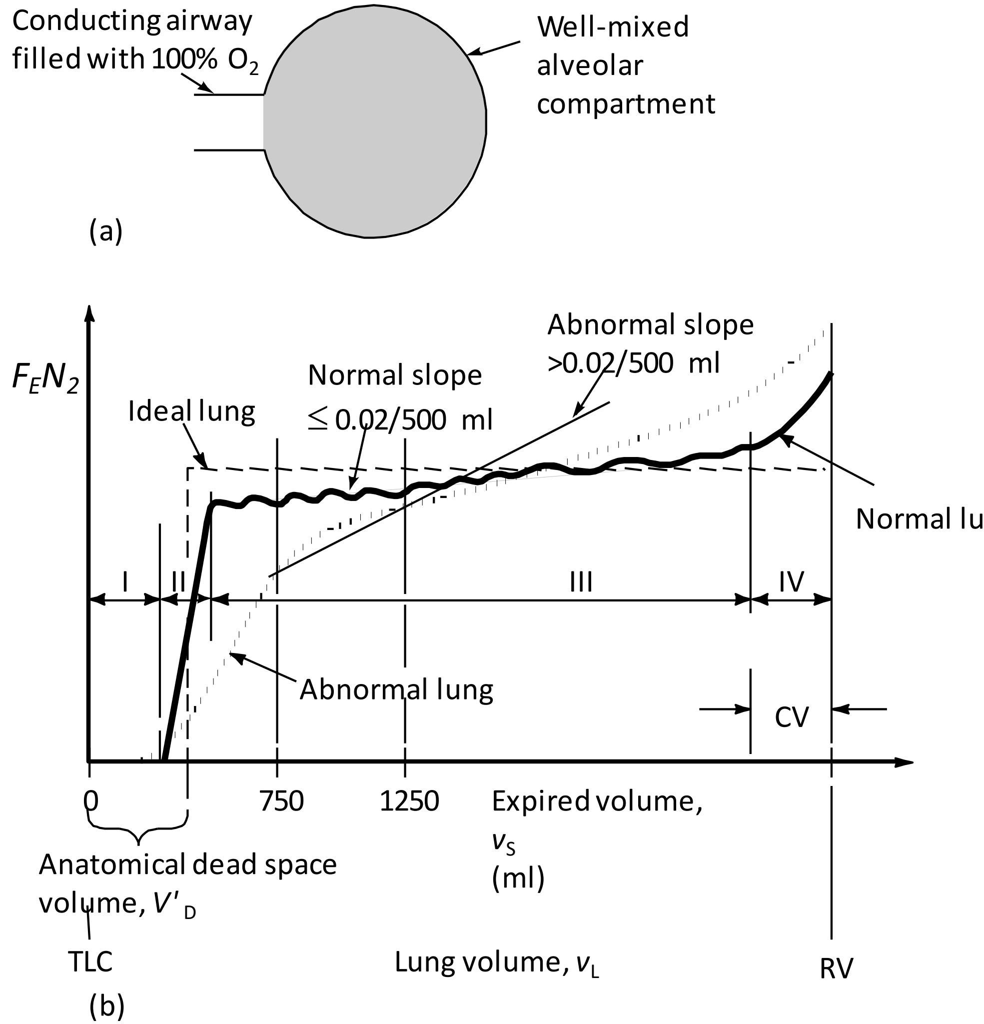


Figure 9.17 single-breath nitrogen-washout maneuver (a) An idealized model of a lung at the end of a vital-capacity inspiration of pure O_2, preceded by breathing of normal air. (b) Single-breath N_2-washout curves for idealized lung, normal lung, and abnormal lung. Parameters of these curves include anatomical dead space, slope of phase III, and closing volume.