Dynamic mechanics of the lung

Answer to the Last class's question

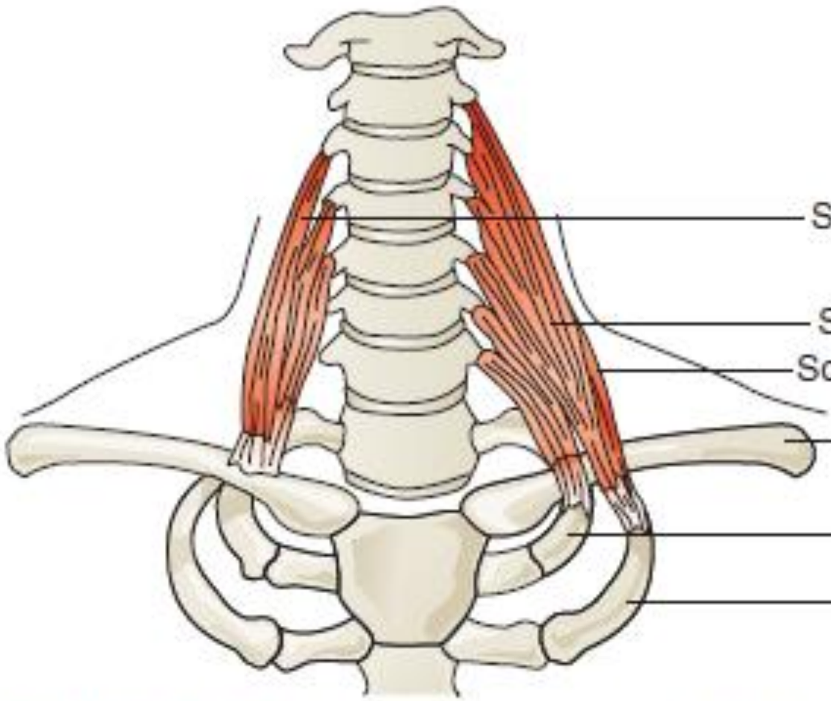


FIGURE 9-23 The scalene muscles originate from the lower cervical vertebrae and lift the clavicle and first two ribs. (From Hicks GH: Cardiopulmonary anatomy and physiology, Philadelphia, 2000, WB Saunders.)

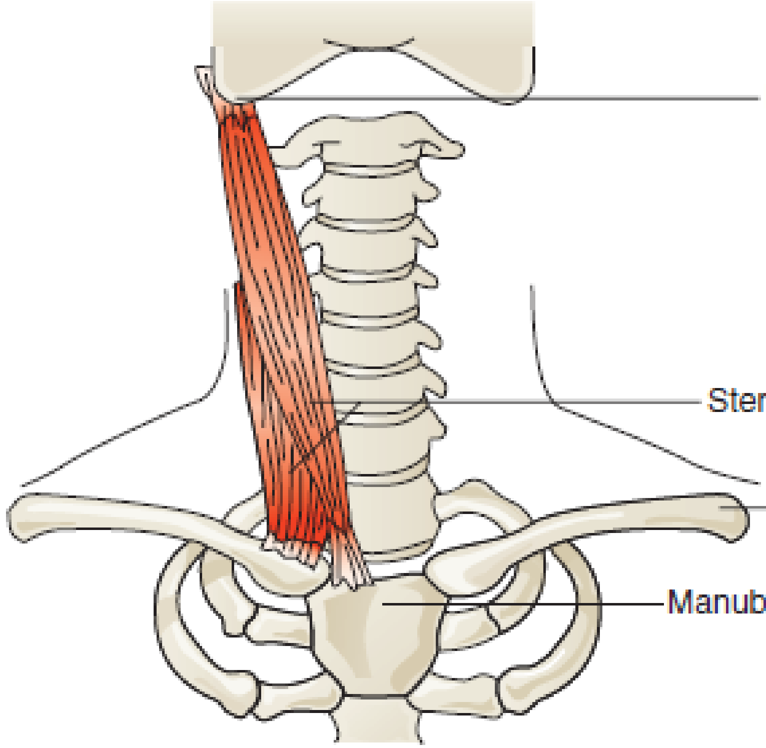


FIGURE 9-24 The sternocleidomastoid muscles originate from the manubrium and clavicle and insert on the mastoid process of the temporal bone. They lift the upper thorax when the trapezius stabilizes the head. (From Hicks GH: Cardiopulmonary anatomy and physiology, Philadelphia, 2000, WB Saunders.)

Inspiration

1. Brain initiates inspiratory effort.
2. Nerves carry the inspiratory command to the inspiratory muscles.
3. Diaphragm (and/or external intercostal muscles) contracts.
4. Thoracic volume increases as the chest wall expands.[1]
5. Intrapleural pressure becomes more negative.
6. Alveolar transmural pressure gradient increases.
7. Alveoli expand (according to their individual compliance curves) in response to the increased transmural pressure gradient. This increases alveolar elastic recoil.
8. Alveolar pressure falls below atmospheric pressure as the alveolar volume increases, thus establishing a pressure gradient for airflow.
9. Air flows into the alveoli until alveolar pressure equilibrates with atmospheric pressure.

Expiration (Passive)

1. Brain ceases inspiratory command.
2. Inspiratory muscles relax.
3. Thoracic volume decreases, causing intrapleural pressure to become less negative and decreasing the alveolar transmural pressure gradient.[2]
4. Decreased alveolar transmural pressure gradient allows the increased alveolar elastic recoil to return the alveoli to their preinspiratory volumes.
5. Decreased alveolar volume increases alveolar pressure above atmospheric pressure, thus establishing a pressure gradient for airflow.
6. Air flows out of the alveoli until alveolar pressure equilibrates with atmospheric pressure.

Resistive (Frictional Forces) Opposing Lung Inflation

Frictional opposition occurs only when the system is in motion.

Frictional opposition to ventilation has the two components:

1. tissue viscous resistance
2. airway resistance.

Tissue Viscous Resistance: the impedance of motion (opposition to flow) caused by displacement of tissues during ventilation that includes the lungs, rib cage, diaphragm, and abdominal organs.

The frictional resistance is generated by the movement of each organ surface sliding against the other (e.g., the lung lobes sliding against each other and against the chest wall).

Tissue resistance accounts for only approximately 20% of the total resistance to lung inflation.

In conditions : obesity, pleural fibrosis, and ascites, the tissue viscous resistance increases the total impedance to ventilation.

Airway Resistance (flow resistance)

- Resistance to ventilation by the movement of gas through the airways.

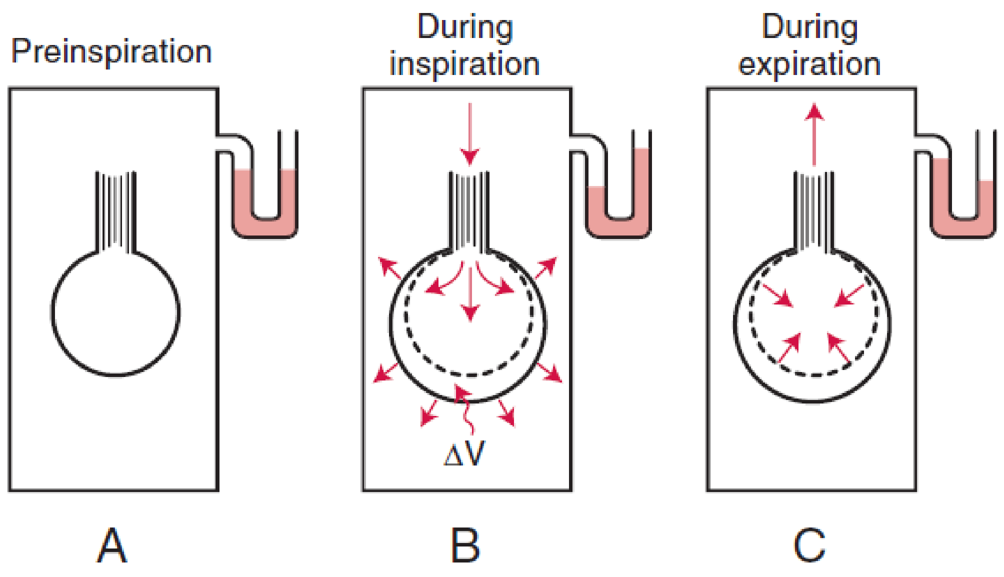
- accounts for approximately 80% of the frictional resistance to ventilation.
- -is usually expressed in units of cm $H2O$/L/sec:

$$R = \Delta P / \Delta V$$

- Airway resistance in healthy adults ranges from approximately 0.5 to 2.5 cm $H2O$/L/sec.
- To cause gas to flow into or out of the lungs at 1 L/sec, a healthy person needs to lower his alveolar pressure 0.5 to 2.5 cm $H2O$ below atmospheric pressure.

Measurement of Airway Resistance

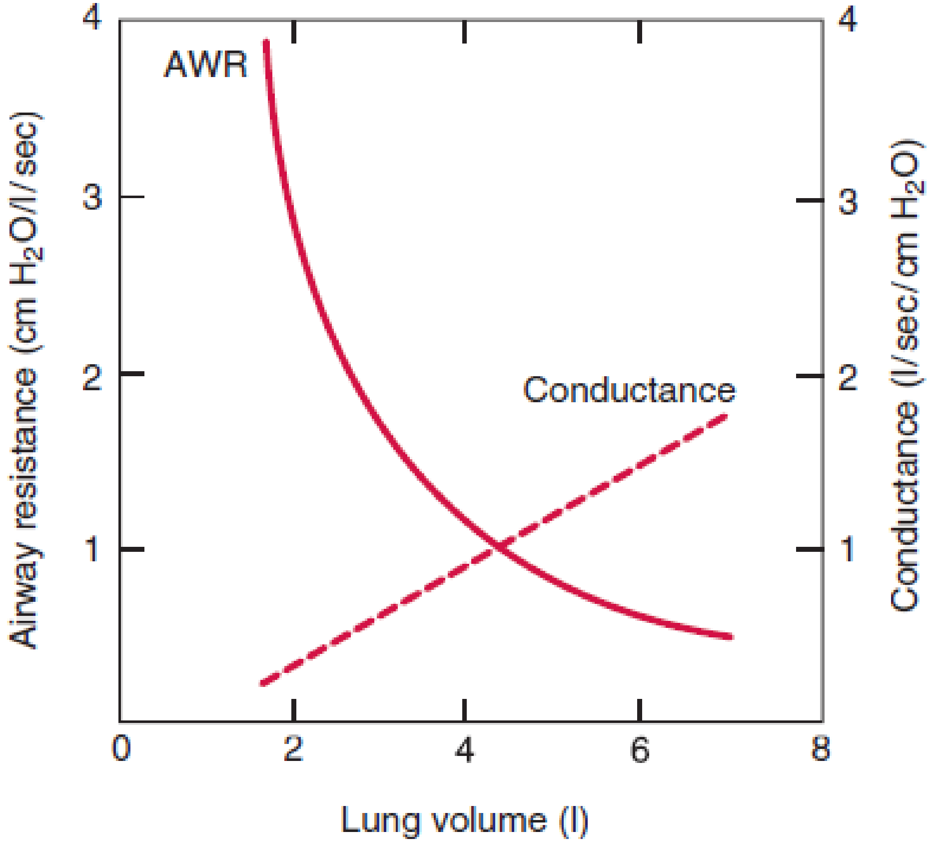
- Airway resistance is the pressure difference between the alveoli and the mouth divided by a flow rate. Mouth pressure is easily measured with a manometer. Alveolar pressure can be deduced from measurements made in a body plethysmograph.



Factors Determining Airway Resistance

Lung volume : Like the extra-alveolar blood vessels , the bronchi are supported by the radial traction of the surrounding lung tissue, and their caliber is increased as the lung expands.

As lung volume is reduced, airway resistance rises rapidly.



West, John B. Respiratory physiology : the essentials — 9th ed

Factors Affecting Resistance

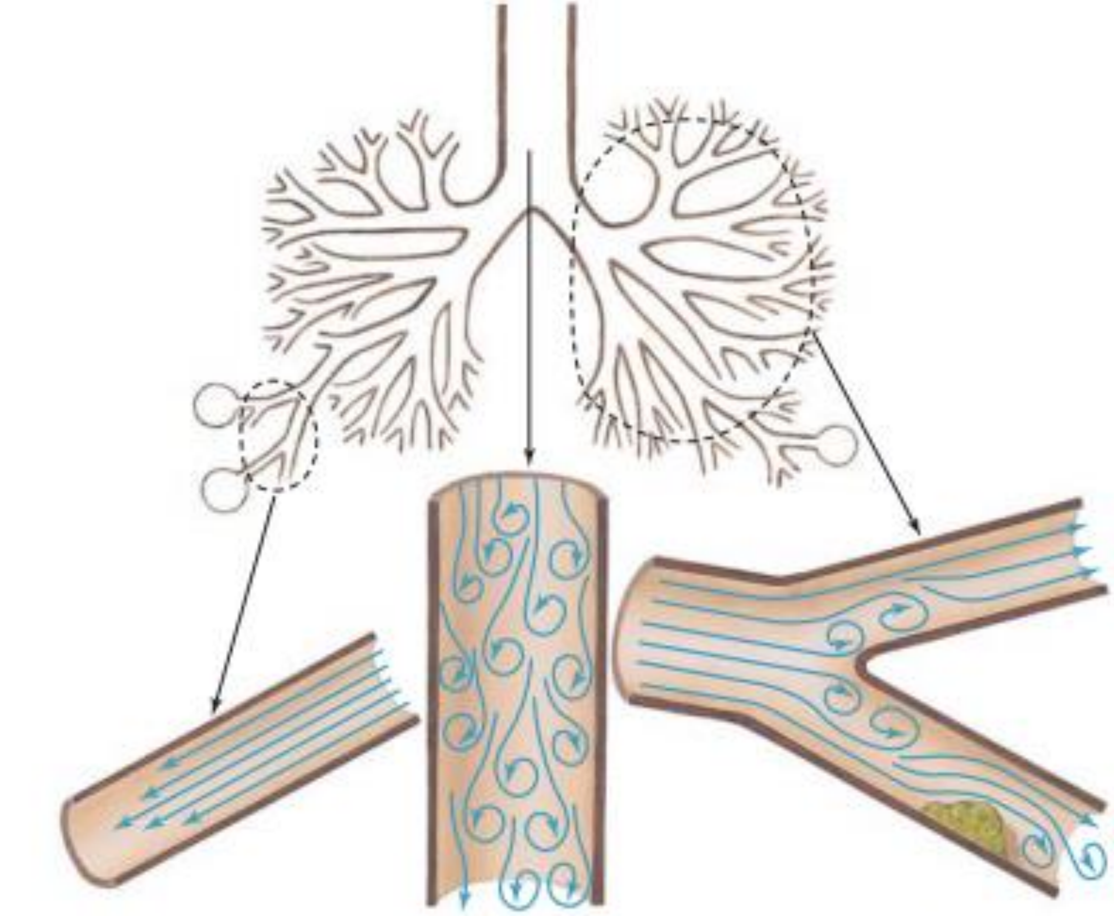
The two main patterns that characterize the flow of gas through the respiratory tract are **laminar flow and turbulent flow** . A third pattern, tracheobronchial flow, is a combination of laminar and turbulent flow.

Laminar flow requires less driving pressure than turbulent flow.

Poiseuille's equation describes laminar flow through a smooth, unbranched tube of fixed dimensions (i.e., length and radius). This equation says that for gas flow to remain constant, the pressure is inversely proportional to the fourth power of the airway's radius.

That is, by reducing the radius of a tube by half requires a 16-fold pressure increase to maintain a constant flow (24 = 16)!

Clinically this means that to maintain ventilation in the presence of narrowing airways, large increases in driving pressure may be needed, resulting in marked increases in the work of breathing.



Laminar flow occurs mainly in small peripheral airways where rate of airflow through any airway is low. Driving pressure is proportional to gas viscosity.

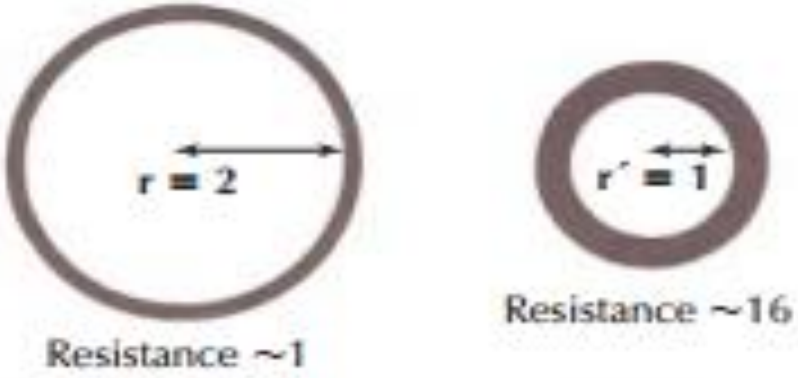
Turbulent flow occurs at high flow rates in trachea and larger airways. Driving pressure is proportional to square of flow and is dependent on gas density.

Transitional flow occurs in larger airways, particularly at branches and at sites of narrowing. Driving pressure is proportional to both gas density and gas viscosity.

Airflow through large airways tends to be turbulent, whereas flow in smaller airways tends to be laminar. Laminar flow is described by Poiseuille's law

Poiseuille’s law

Poiseuille’s law. Resistance to laminar flow is inversely proportional to tube radius to the 4th power and directly proportional to length of tube. When radius is halved, resistance is increased 16-fold. If driving pressure is constant, flow will fall to one sixteenth. Doubling length only doubles resistance. If driving pressure is constant, flow will fall to one half.



The pressure-flow characteristics for *laminar flow* were first described by the French physician Poiseuille. In straight circular tubes, the volume flow rate is given by

$$\dot{V} = \frac{P\pi r^4}{8nl}$$

where P is the driving pressure, r radius, n viscosity, and l length.

Chief Site of Airway Resistance

- Toward the periphery of the lung :The airways become more numerous but much narrower.
- Based on Poiseuille's equation with its $(radius)^4$ term, the major part of the resistance should lie in the very narrow airways.

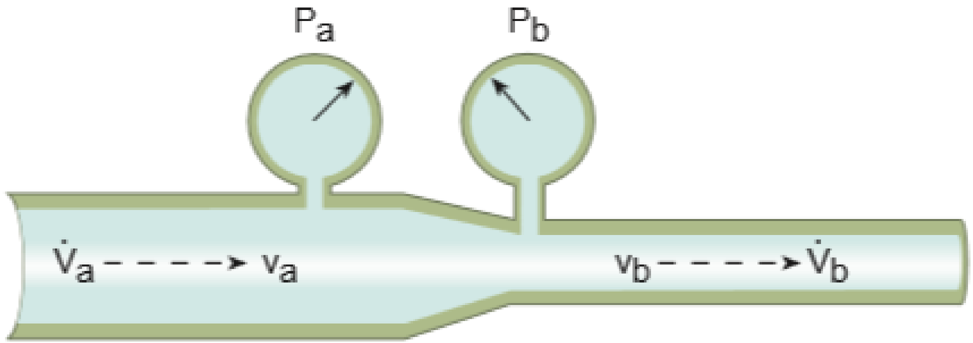
- Most of the pressure drop occurs in the airways up to the seventh generation.
- The major site of resistance is the **medium-sized bronchi** and that the very small bronchioles contribute relatively little resistance.
- Less than 20% of resistance can be attributed to airways <2 mm in diameter. The reason for this apparent paradox is the prodigious number of small airways.
- The peripheral airways constitute a "silent zone," a considerable small airway disease can precede detection of an abnormality of airway resistance .
- Patients who have increased airway resistance often breathe at high lung volumes; this helps to reduce their airway resistance.

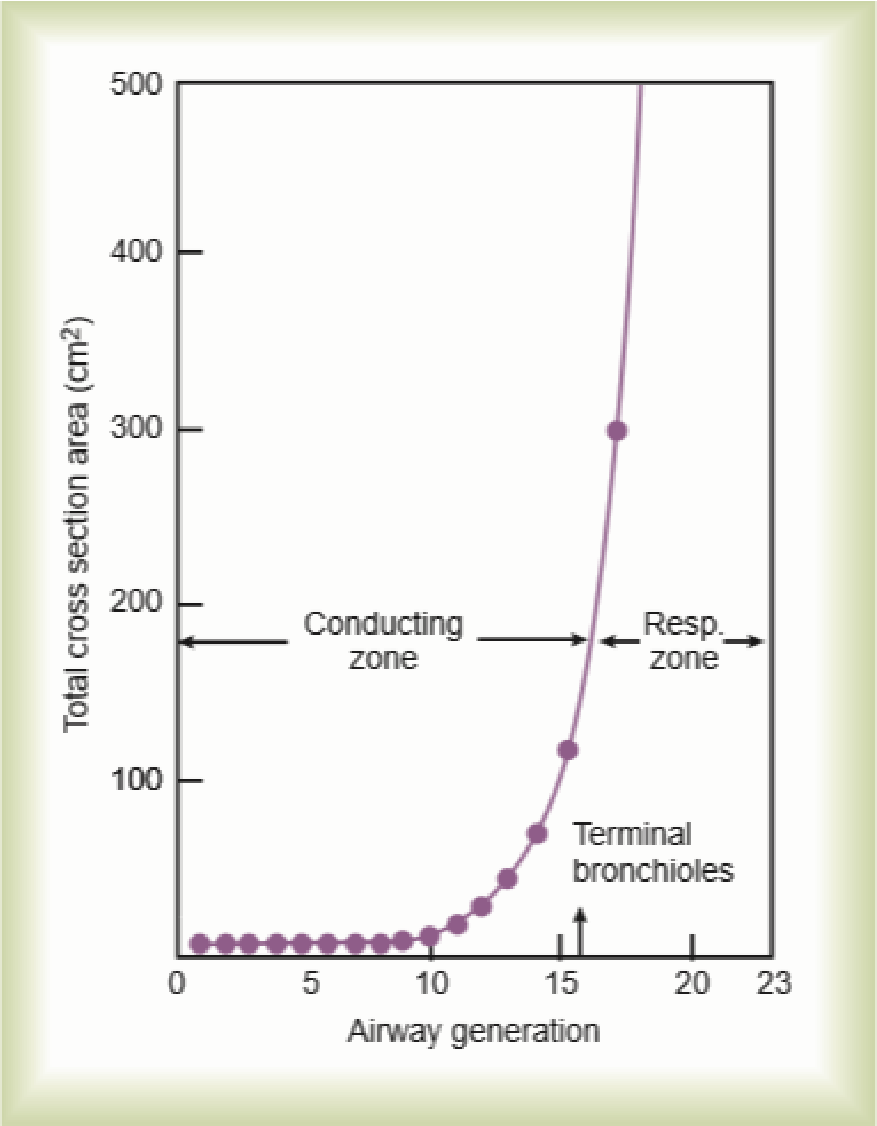
Distribution of Resistance

- 80% of the resistance to gas flow occurs in the nose, mouth, and large airways, where flow is mainly turbulent.
- 20% of the total resistance to flow is attributable to airways smaller than 2 mm in diameter, where flow is mainly laminar.
- Branching of the tracheobronchial tree increases the cross-sectional area with each airway generation. As gas moves from the mouth to the alveoli, the combined cross-sectional area of the airways increases exponentially (> 30-fold).
- The velocity of gas flow and resistance in a branching system arranged in parallel is inversely related to the cross-sectional area of the airways (**bernoulli principle**)
- The resistance to flow in small airways is very low. The driving pressure across these airways is less than 1% of the total driving pressure for the system.

Bernoulli Principle

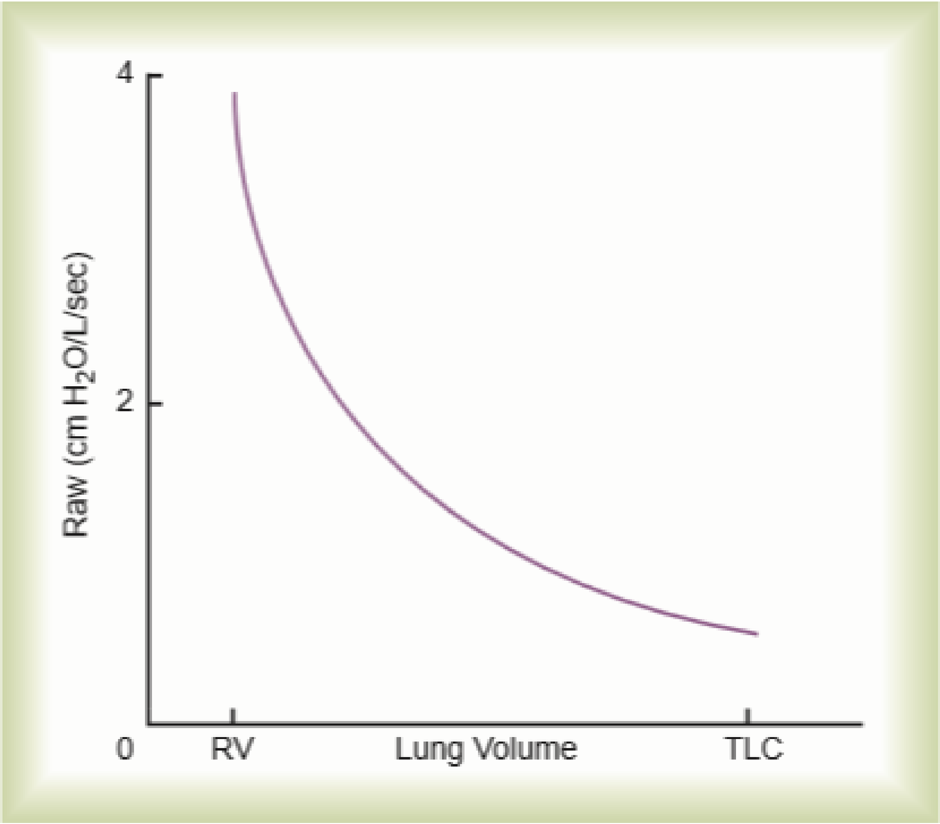
- In a steady flow, the sum of all forms of energy in a fluid is the same at all points along the path of flow. The sum of kinetic energy, potential energy, and internal energy remains constant.
- The Bernoulli principle states that an increase in the velocity of the fluid results in a decrease in the sum of its static pressure, potential energy, and internal energy.
- Fluid is flowing through a tube at a point with a certain velocity (va) and a lateral pressure (Pa). According to the law of continuity, as the fluid moves into the narrow or constricted portion of the tube, its velocity must increase (vb > va). According to the Bernoulli theorem, the higher velocity at point b should result in a lower lateral pressure at that point (Pb < Pa).
- As a fluid flows through the constriction, its velocity increases and its lateral pressure decreases.





Cross-sectional area of the airways plotted against airway generation.
The first 15 or airway generations represent a conducting zone : **The anatomic dead space.**
The gas-exchange surface increases markedly at the level of the terminal bronchiole

- During inspiration, the stretch of surrounding lung tissue and widening transpulmonary pressure gradient increase the diameter of the airways. The increase in airway diameter with increasing lung volume decreases airway resistance.
- As lung volume decreases toward RV, airway diameters decrease and airway resistance dramatically increases; wheezing is most often heard during exhalation.



Change in airway resistance (Raw) related to lung volume.
Resistance to airflow is highly dependent on lung volume.

Mechanics of exhalation

- Airway caliber is determined by anatomic (i.e., physical) support provided to the airways and pressure differences across their walls.
- The larger airways depend mainly on cartilaginous support.
- The smaller airways depend on support provided by surrounding lung parenchyma.
- The transpulmonary pressure gradient help stabilize the smaller airways mainly.
- Airway pressure varies minimally and is usually close to zero (atmospheric pressure).
- During a forced exhalation, contraction of expiratory muscles can increase pleural pressure above atmospheric pressure.

- During **forced exhalation**

$$P_A = \text{pleural pressure} + \text{elastic recoil pressure of the lung.}$$

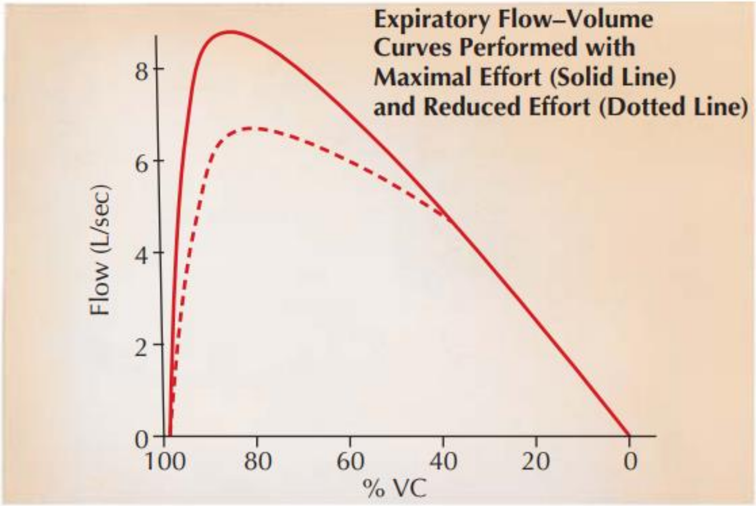
- During exhalation, the pressure along the airway decreases as gas flows from the alveoli toward the mouth.
- At some point along the airway, the pressure inside the airway equals the pressure outside in the pleural space. This point is referred to as the **equal pressure point (EPP).**
- Downstream from this point, pleural pressure exceeds the airway pressure. The resulting increase in transmural pressure gradient causes airway compression and can lead to **collapse**.
- Then the airflow becomes effort independent with airway caliber and elastic recoil pressure determining flow.
- In airways of **healthy persons**, airway collapse occurs only with forced exhalation and at low lung volumes.

Dynamic compression of airways during expiration

- Airway resistance is also affected by dynamic compression, which is the compression of airways during forced expiration.
- An expiratory flow–volume curve: the subject performs a forced vital capacity maneuver, inspiring to total lung capacity and then exhaling as forcibly as possible to residual volume.

■ The **peak** of this curve represents **the peak expiratory flow rate (PEFR).**

■ The **downward slope** (expiratory phase) of the flow volume curve is **effort-independent**; during this phase of the curve, **flow is limited by dynamic compression** of the airways.



Netters

- Tissue support opposes the collapsing force created by negative transmural pressure gradients. In pulmonary emphysema, the elastic tissue supporting the small airways is damaged.
- Destruction of elastic tissue, such as occurs in emphysema, has multiple outcomes. It increases the compliance of the lung (i.e., elastic recoil decreases).
- The combination of decreased elastic recoil and loss of support for the small airways allows the airways to collapse during exhalation. Airway collapse causes air trapping and increase in the resting volume of the lung.
- Expiratory flow is reduced by airway collapse during exhalation (called flow limitation) and can occur during tidal breathing when emphysematous changes in the lung are severe.
- By exhaling through "pursed lips," a patient with emphysema changes the pressure at the airway opening.
- The gentle back pressure created counters the tendency for small airways to collapse by moving the EPP toward larger airways

Effects of Autonomic Nerves on Airway Resistance

■ Activation of **parasympathetic nerves** innervating smooth muscle of conducting airways causes bronchoconstriction and promotes glandular secretions in the lungs.

■ Activation of **sympathetic nerves** innervating smooth muscle of conducting airways results in **bronchodilation and reduced airway resistance** (through activation of β2-adrenergic receptor-linked pathways) in mammalian species, although human lungs have little sympathetic innervation.

Release of epinephrine by the adrenal medulla during sympathetic activation will also reduce airway resistance through activation of the pulmonary β2-receptor mechanism.

WORK OF BREATHING

The respiratory muscles do the work for normal breathing.

This work requires energy to overcome the elastic and frictional forces opposing inflation.

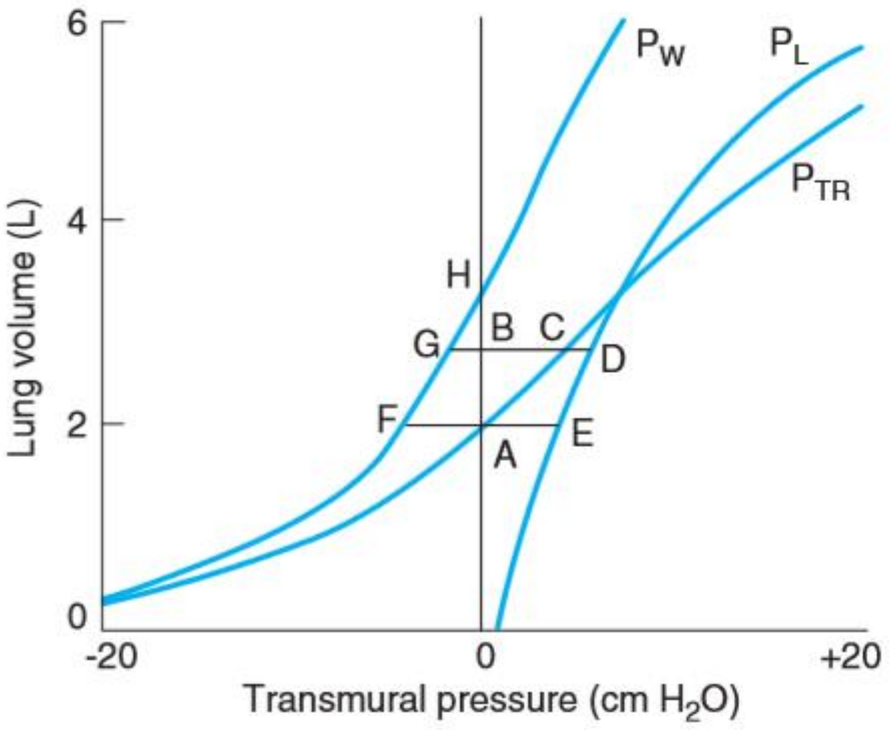
Assessment of mechanical work involves measurement of the physical parameters of force and distance as they relate to moving air into and out of the lung.

Assessment of metabolic work involves measurement of the $O2$ cost of breathing.

The work of exhaling is recovered from potential energy “stored” in the expanded lung and thorax during inhalation. However, forced exhalation requires additional work by the expiratory muscles.

The actual work of forced expiration depends on the mechanical properties of the lungs and thorax.

- The work of breathing can be calculated from the pressure–volume curve because pressure times volume ($g/cm^2 \times cm^3 = g \times cm$) has the same dimensions as work (force × distance).
- The total elastic work required for inspiration is represented by the area ABCA. The actual elastic work required to increase the volume of the lungs alone is area ABDEA.
- The amount of elastic work required to inflate the whole respiratory system is less than the amount required to inflate the lungs alone because part of the work comes from elastic energy stored in the thorax. The elastic energy lost from the thorax (area AFGBA) is equal to that gained by the lungs (area AEDCA).



Work of breathing

- Elastic work; approximately 65% of the total work, moving inelastic tissues (viscous resistance; 7% of total), and moving air through the respiratory passages (airway resistance; 28% of total).

Elastic Work

- The elastic work of breathing is the work done to overcome the elastic recoil of the chest wall and the pulmonary parenchyma and the work done to overcome the surface tension of the alveoli.
- **Restrictive diseases are those diseases in which the elastic work of breathing is increased.**

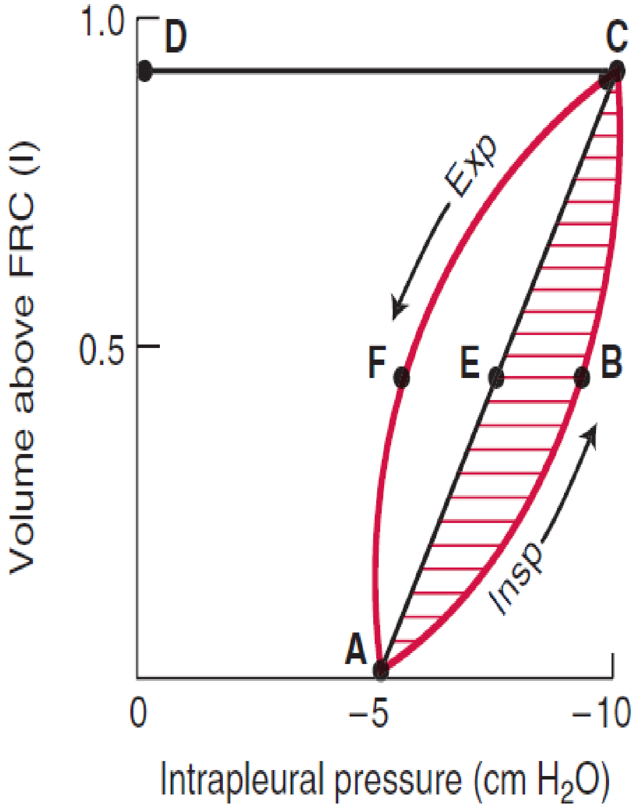
Resistive Work

- The resistive work of breathing is the work done to overcome the tissue resistance and the airways resistance.
- The tissue resistance may be elevated in conditions such as sarcoidosis.
- Elevated airways resistance is much more common and is seen in obstructive diseases such as asthma, bronchitis, and emphysema; upper airway obstruction; and accidental aspirations of foreign objects.
- The resistive work of breathing can be extremely great during a *forced expiration,* when dynamic compression occurs. This is especially true in patients who already have elevated airways resistance during normal, quiet breathing.

Work Done on the Lung

During inspiration, the intrapleural pressure follows the curve ABC, and the work done on the lung is given by the area 0ABCD0. Of this, the trapezoid 0AECD0 represents the work required to overcome the elastic forces, and the hatched area ABCEA represents the work overcoming viscous (airway and tissue) resistance.

The higher the airway resistance or the inspiratory flow rate, the more negative (rightward) would be the intrapleural pressure excursion between *A* and *C* and the larger the area.



Energy Required for Respiration

- . During normal quiet respiration, only 3 to 5 percent of the total energy expended by the body is required for pulmonary ventilation.
- During heavy exercise, the amount of energy required can increase as much as 30-50 fold, especially if the person has any degree of increased airway resistance or decreased pulmonary compliance.

Work of breathing: influence of breathing pattern

- Work of breathing increases when deep breaths are taken (increased TV means more work to overcome elastic forces).
- Work of breathing increases when respiratory rate increases (increased minute ventilation requires more flow resistance to overcome).
- Patients with pulmonary fibrosis (more elastic work) breathe more shallow and more rapidly.
- Patients with obstructive lung disease (non elastic work, high resistive work) breathe more slowly and deeply.

Dynamic Compliance

- The change in the volume of the lungs divided by the change in the alveolar-distending pressure *during the course of a breath.*
- At low breathing frequencies, < 15 breaths per minute and lower, dynamic compliance (DC) = static compliance(SC)

(during TV, small change in alveolar surface area is not able to bring additional surfactant to surface)

- At higher breathing frequencies, DC>SC (more surfactant and more compliance)

- In patients with elevated resistance to airflow in some of their small airways, the DC/SC ratio falls as breathing frequency is increased. This indicates that changes in dynamic compliance reflect changes in airways resistance as well as changes in the compliance of alveoli.

- **Sighing and yawning increase dynamic compliance by increasing tidal volume via restoring the normal surfactant layer.**