RESPIRATORY PHYSIOLOGY

ANATOMY OF AN INFANT'S LUNG

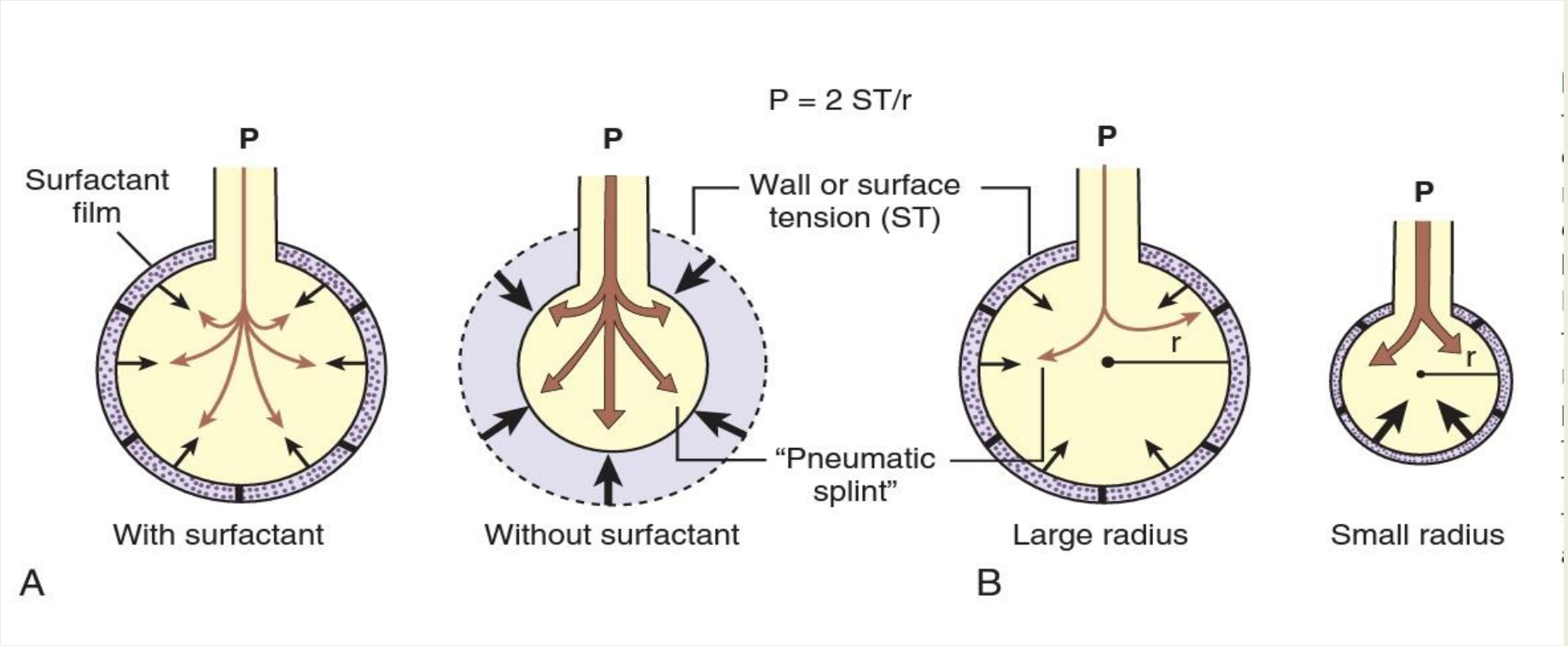
- The infant's **thorax is more cylindrical** and the **ribs are more horizontal** than oblique.
- The insertion of the infant's **diaphragm is more horizontal**, so the lower ribs tend to move inward rather than upward during inspiration, exacerbated by the compliant chest wall.
- The endurance capacity of the diaphragm is dependent on the muscle mass and the oxidative capacity of muscle fibers.
- Infants have **low muscle mass** and a **low percentage of type 1 (slow twitch) muscle fibers**. So, to sustain the WOB, the diaphragm must be provided with a continuous supply of oxygen.

- The **air–liquid interface** in the terminal air spaces and respiratory bronchioles generates **surface tension** that opposes lung expansion and promotes lung deflation.
- In premature infants, the largest contributor to elastic recoil is surface tension. **Pulmonary surfactant reduces this surface tension** and prevents collapse of lung during expiration.
- In surfactant deficiency, the terminal air spaces have a tendency to collapse, leading to **diffuse atelectasis**.
- Distending airway pressure in the form of **PEEP or CPAP** counters the development of atelectasis.

- The pressure required to counteract the tendency of the airways to collapse is described by the **Laplace relationship:**

$$P = 2ST / r^4$$

- Surfactant deficiency results in an increase in surface tension and necessitates the application of more distending pressure to counter collapse.
- The smaller the radius of curvature of the terminal bronchiole (premature infants), the more pressure is needed to hold them open or to expand them further.



- Lung compliance and airway resistance are related to **lung size**. The **smaller the lung**, the **lower the compliance** and the **greater the resistance**.
- In **term** infants, immediately after delivery, specific compliance is low but **normalizes** as fetal lung fluid is absorbed and a normal FRC is established.
- In **premature** infants, specific compliance remains **low**, due to diffuse microatelectasis and failure to achieve a normal FRC, because of the compliant chest wall.

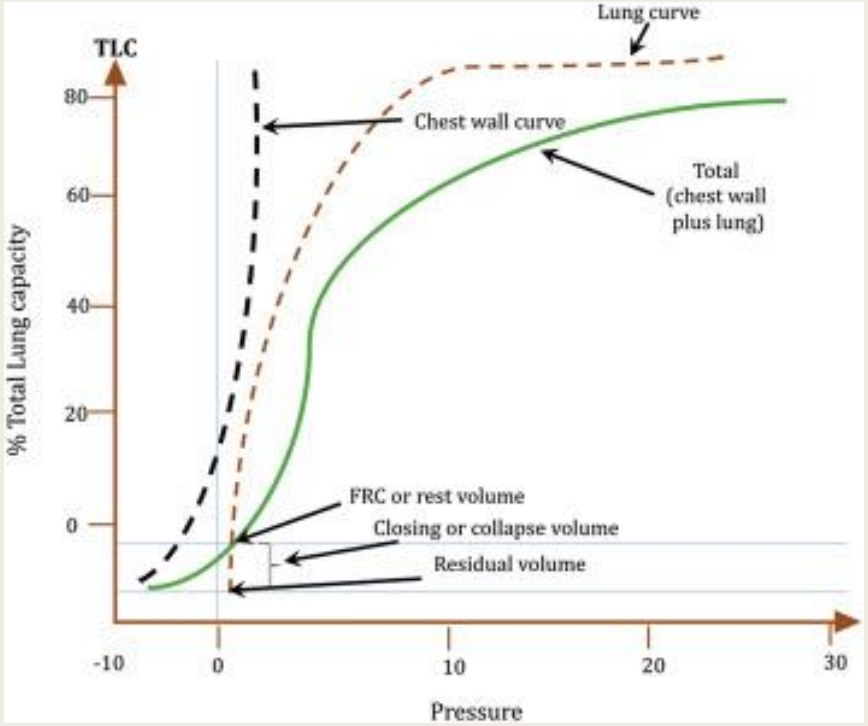
COMPLIANCE

- Compliance is a measure of the change in volume resulting from a given change in pressure:

$$C_L = \Delta V / \Delta P$$

- where C_L is lung compliance, ΔV is change in volume, and ΔP is change in pressure.
- STATIC COMPLIANCE reflects only the **elastic properties** of the lung.
- DYNAMIC COMPLIANCE reflects not only the **elastic properties** of the lungs, but also the **resistive component**.

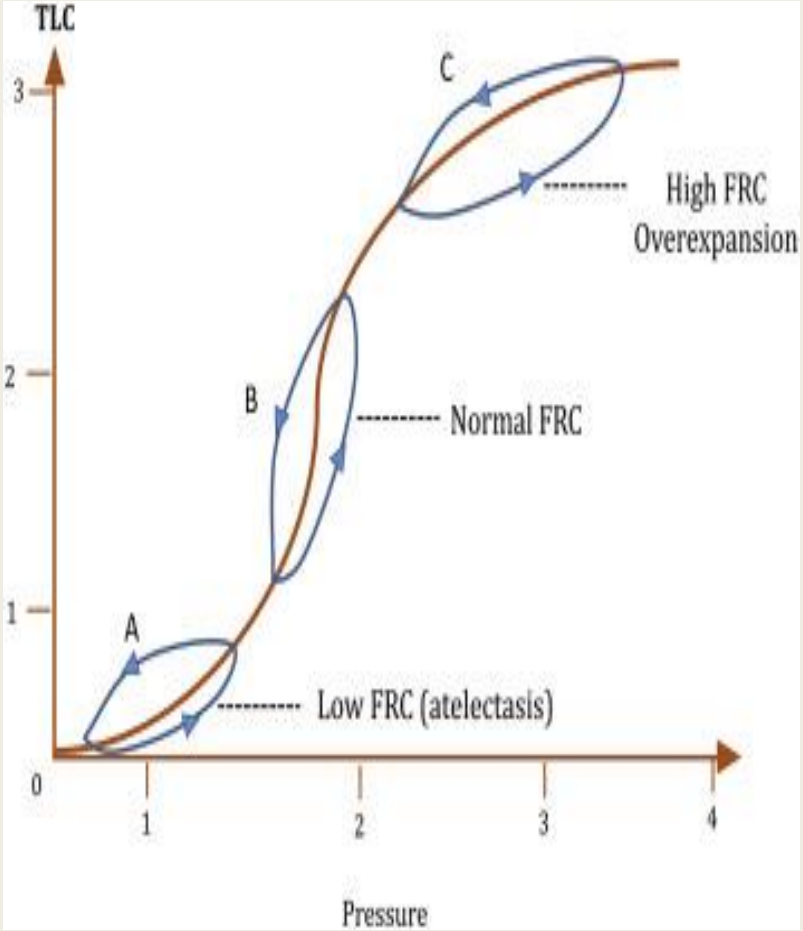
STATIC COMPLIANCE



- It is the **reciprocal of elastance**, the tendency to recoil toward its original dimensions upon removal of the distending pressure.
- It is measured by determining the transpulmonary pressure change (pressure difference between **alveolar pressure** and **pleural pressure**) after inflating the lungs with a known volume of gas.
- The difference between pleural pressures (esophageal) and atmospheric pressures (transthoracic) at different levels of lung expansion, will give a **chest wall compliance curve.**
- The lung and chest wall compliance curves together gives the total respiratory system compliance.

DYNAMIC COMPLIANCE

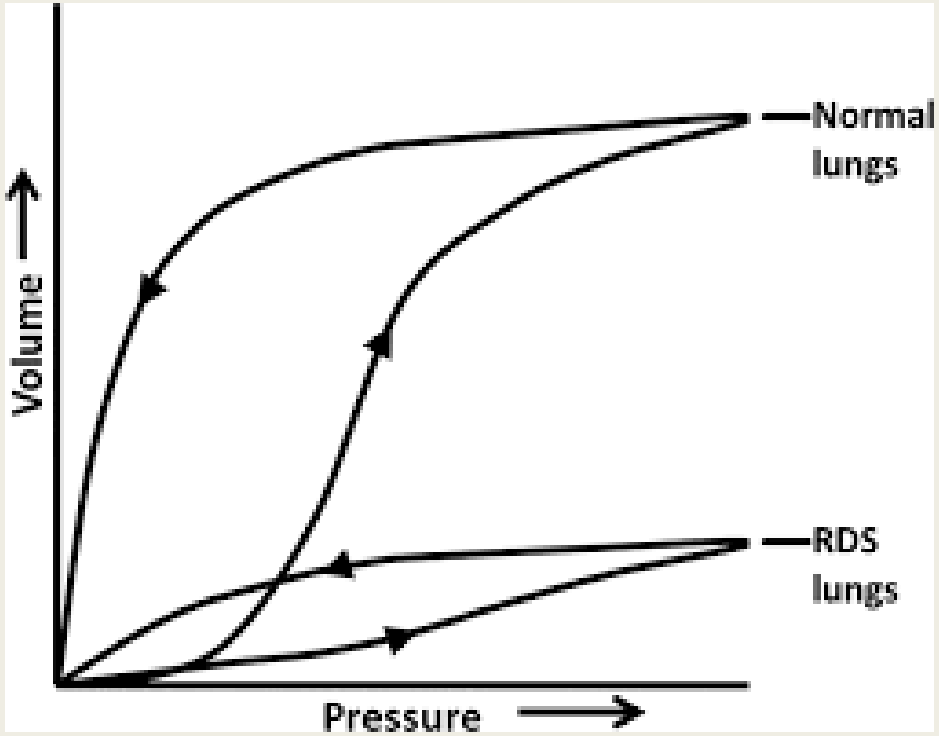
- Compliance measured during continuous breathing is called dynamic compliance.
- It measures the **change in pressure from the end of exhalation to the end of inspiration** for a given volume and is based on the assumption that **at zero flow**, the pressure difference reflects compliance.
- The **steeper the slope** of the curve connecting the points of zero flow, the **greater the compliance.**



- The overall compliance curve is **sigmoidal**.
- At low lung volume, the compliance is low; there is a small change in volume for a large change in pressure. This correlates with **underinflation.**
- Pressure is required to open up terminal airways and atelectatic terminal air spaces. The lung volume is starting below critical opening pressure.
- **Low lung volumes** are seen in **surfactant deficiency (RDS)**.

- At the center of the curve, the compliance is high; there is a large change in volume for a small change in pressure. This is where **normal tidal breathing** should occur. This is the position of maximum efficiency, the best V/Q matching and lowest pulmonary vascular resistance
- At high lung volume, the compliance is low again. This correlates with an **overinflated lung**.
- More pressure can cause airway injury and compromise venous return because of increased transmission of pressure to the pleural space.
- **High lung volumes** are seen in **obstructive lung diseases**, such as **BPD**.

IMPORTANCE OF PEEP



- **Optimum PEEP:** The level of PEEP at which static lung compliance is maximized and O_2 transport (cardiac output and O_2 content) is greatest.
- In RDS, if there is **no PEEP**, there will be repeated collapse and re-opening of the terminal airways from below critical opening pressure.
- This leads to cellular injury, interstitial edema and increase in inflammatory mediators. (**atelectotrauma**).
- Mechanical ventilation **without PEEP** leads to **surfactant inactivation** resulting in worsening of lung compliance.

- Once atelectasis occurs, surfactant turnover is increased, and V/Q mismatch with increased intrapulmonary right-to-left shunting develops.
- A higher distending pressure (**volutrauma**) and higher FiO_2 (**oxidative injury**) will be required to maintain lung volume causing further injury.
- Therefore, **early establishment of an appropriate FRC**, administration of surfactant, and use of CPAP or PEEP are required in RDS.
- If the PEEP is raised **above the optimal level**, the dynamic compliance decreases, venous return and cardiac output are compromised.
- **CDH-** overdistention of the hypoplastic lung occurs into the “empty” hemithorax after surgical repair of the defect. Since they have a reduced number of alveoli, they develop areas of pulmonary emphysema that persist into early childhood.
- Therefore, **rapid expansion of the lungs is avoided** in the treatment of CDH.

RESISTANCE

- Resistance is the result of friction.
- **Viscous resistance** is the resistance generated by *tissue elements moving past one another.* (40%)
- **Airway resistance** is the resistance that occurs *between moving molecules in the gas stream and between these moving molecules and the wall of the respiratory system.*
- High viscous resistance is caused by **high tissue density** (i.e, a low ratio of lung volume to lung weight) and the **higher amount of pulmonary interstitial fluid**, seen after cesarean section causing TTNB. A reduction in tissue and airway resistance has been shown after administration of **furosemide**.

- When flow is **laminar**, resistance to flow of gas through a tube is described by **Poiseuille's law**:

$$R \propto L \times \eta / r^4$$

- where R = resistance, L = length of the tube, h = viscosity of the gas, and r = radius.

FLOW RATE

- Average values for airway resistance in normal, spontaneously breathing newborn infants are between 20-30 cm H_2O/L/s.
- Nasal airway resistance causes 2/3 of total upper airway resistance; the glottis and larynx contribute <10%; and the trachea and first four or five generations of bronchi account for the remainder.
- Average peak inspiratory and expiratory flow rates in spontaneously breathing term infants are approximately 2.9 and 2.2 L/min, respectively.
- Flow rates that exceed the critical levels produce disproportionately large increases in airway resistance.

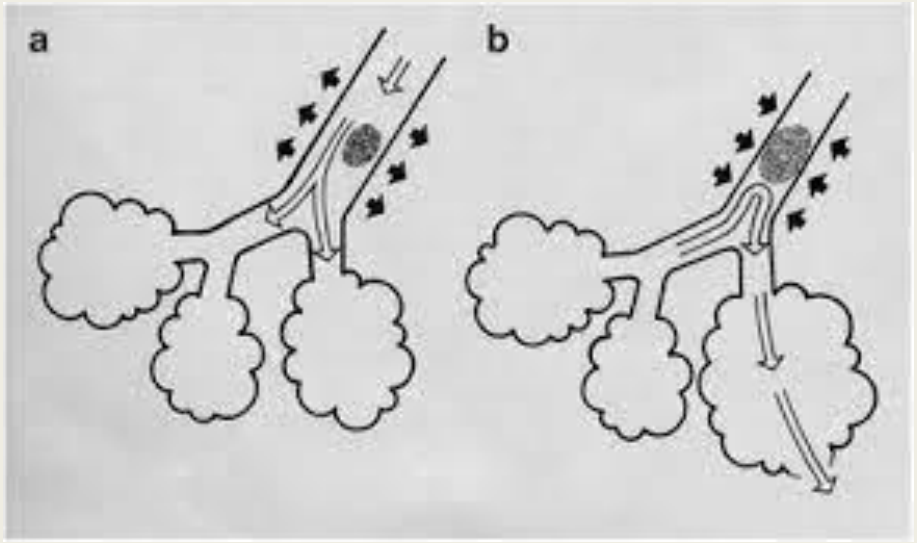
AIRWAY OR TUBE LENGTH

- Resistance is linearly proportional to tube length. The shorter the tube, the lower the resistance; hence, it is good practice to cut ETTs to shorter lengths.

AIRWAY OR TUBE DIAMETER

- A reduction in the radius by half results in a 16-fold increase in resistance. This is why ELBW infants are difficult to wean from mechanical ventilation.
- **Resistance during inspiration** is **less than resistance during expiration** because the airways dilate upon inspiration.

- There is an *inverse, nonlinear relationship* between **airway resistance** and **lung volume**, because airway size increases as FRC increases.
- Lung volume recruitment in atelectasis reduces resistance to airflow.

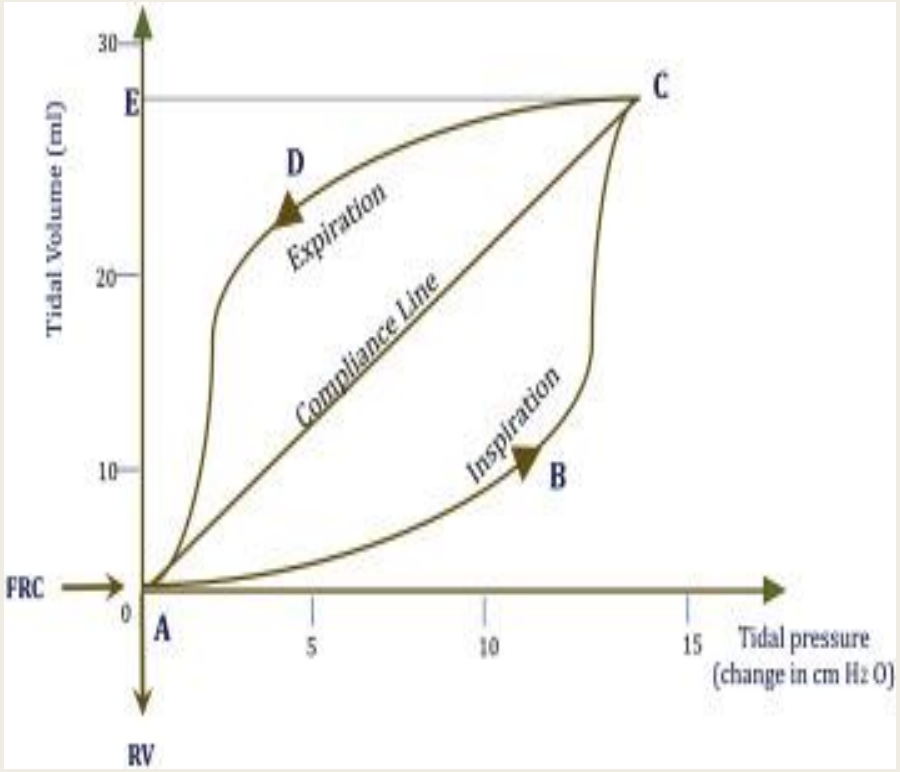


Air trapping behind meconium in an airway, causing alveolar overexpansion and rupture. **Ball–valve mechanism**, in which (A) tidal gas passes meconium on inspiration, when the airways dilate but (B) does not exit on expiration, when the airways constrict.

VISCOSITY AND DENSITY

- The relationship between **airway resistance** and the **density of the gas** in turbulent flow is *directly proportional and linear*.
- Decreasing the density of the gas in heliox (a mixture of 80% helium and 20% O_2) reduces upper airway resistance and WOB in patients with obstructive disorders such as laryngeal edema, tracheal stenosis, and BPD.

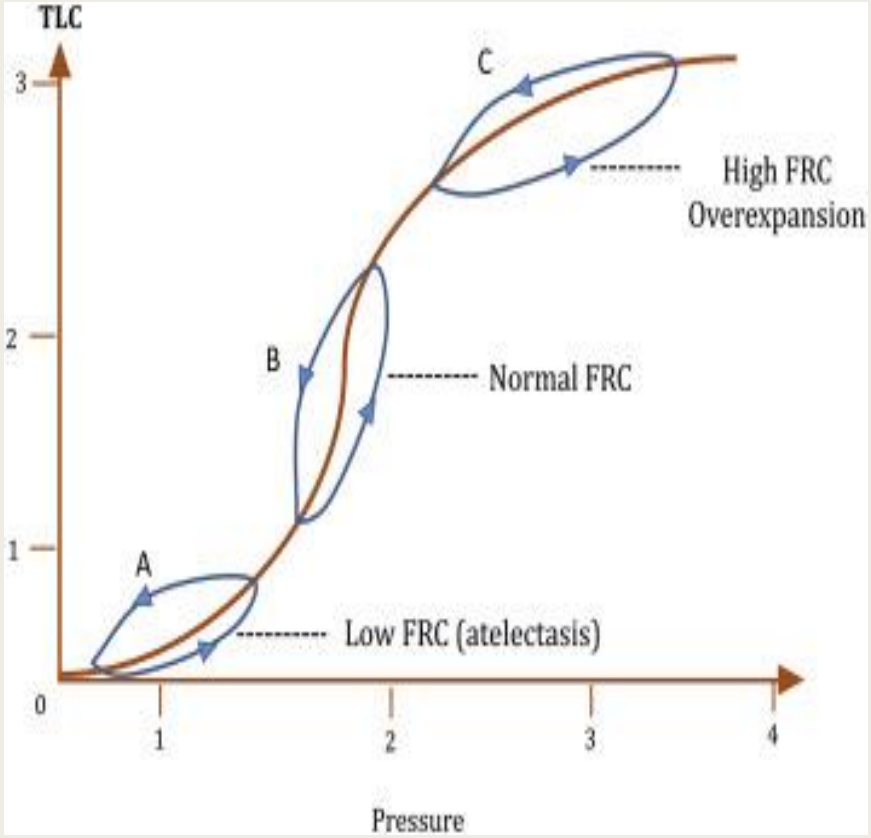
WORK OF BREATHING



- For gas to move into the lungs, force must be exerted to overcome the **elastic and frictional resistive forces**.
- Work of breathing = Pressure (force) x Volume (displacement)
- WOB is simply the area under the pressure-volume curve
- ABCA - work done in overcoming **frictional resistance during inspiration**
- ACEA - work done in overcoming **elastic resistance** which incorporates the **frictional resistance during expiration** (ACDA)
- ABCEA - total work done during the respiratory cycle

- Workload depends on the elastic properties of the lung and chest wall, airway resistance, tidal volume (V_T), and respiratory rate.
- A portion of the energy generated by the inspiratory muscles is stored (as **potential energy**) in the *lungs' elastic components*; this energy is returned during exhalation, hence it is also referred to as **non-dissipative work**, in contrast to the *frictional forces* that are lost or **dissipated** as heat.
- In infants, **energy expenditure** correlates with **oxygen consumption**. (increased in RDS and BPD). Mechanical ventilation reduces oxygen consumption by decreasing the infant's WOB.

WOB in different states



- In cases of **atelectasis,** PEEP or CPAP reduces WOB by *increasing FRC and compliance*.
- If the lung is already overinflated, increasing CDP will not result in a decrease in WOB.
- **Alveolar over-distention** causes an **increase in $PaCO_2$** and a **decrease in PaO_2,** despite an increase in FRC.
- Except in **BPD,** where lung overinflation is the result of airway collapse. Here, higher CDP will maintain airway patency and relieve air trapping, reducing lung volume to a more normal level.

TIME CONSTANT

- The time constant is a measure of how quickly the lungs can inflate or deflate, i.e., how long it takes for alveolar and proximal airway pressures to equilibrate.
- Passive exhalation depends on the **elastic recoil** of the lungs and chest wall, and the major force opposing exhalation is **airway resistance.**
- The expiratory time constant (K_t) is directly related to both lung compliance (C_L), which is the inverse of elastic recoil, and airway resistance (R_{aw}):

$$K_t = C_L \times R_{aw}$$

- One time constant is defined as the time it takes the alveoli (capacitor) to discharge 63% of its V_T (electrical charge) through the airways (resistor) to the mouth or ventilator (electrical) circuit.
- By the end of three time constants, 95% of the V_T is discharged.
- When this model is applied to a normal newborn with a compliance of 0.005 L/cm H_2O and a resistance of 30 cm H_2O/L/s,
- **One time constant = 0.15 seconds**
- **Three time constants = 0.45 seconds**.
- So, 95% of the last V_T should be emptied from the lung within 0.45 seconds of when exhalation begins in a spontaneously breathing infant.
- Inspiratory time constants are roughly **half** as long as expiratory, largely because airway diameter increases during inspiration.
- This gives the normal **1:2 inspiratory/expiratory (I:E) ratio** with spontaneous breathing.

DYNAMIC PEEP/ INADVERTENT PEEP/ **AUTO-PEEP**

- Occurs in cases of incomplete emptying of a previously inspired breath due to an increase in airway resistance with no or only a modest reduction in lung compliance;
- When the pattern of assisted ventilation does not allow sufficient time for exhalation, and the lungs have an abnormally long time constant;
- If there is a mismatch between the time constant of the respiratory system (time constant of the patient + that of the ETT + that of the ventilator circuit) and the expiratory time setting on the ventilator.
- In these situations, the end result is **gas trapping**.
- This gas trapping is accompanied by an **increase in lung volume** and a **buildup of pressure in the alveoli and distal airways.**

- Important clinical and radiographic signs of gas trapping and auto-PEEP include:

1. Radiographic evidence of overexpansion (e.g., increased AP diameter of the thorax, flattened diaphragm below the ninth posterior ribs, intercostal pleural bulging),
2. Decreased chest wall movement during assisted ventilation,
3. Hypercarbia that does not respond to an increase in ventilator rate (or even worsens),
4. Signs of cardiovascular compromise, such as mottled skin, a decrease in arterial BP, an increase in CVP, or metabolic acidosis.

- Any decrease in compliance makes the time constant shorter, and therefore **tachypnea** is the usual clinical sign of any condition leading to decreased compliance.

- **ELBW infants with RDS** have *decreased compliance* but initially relatively *normal airway resistance*.
- This means that the **time constants are extremely short**. Equilibration of the airway and alveolar pressures occurs very quickly (i.e., early in the inspiratory cycle).
- Reynolds estimated that the time constant in RDS may be as short as 0.05 seconds. This means that 95% of the pressure applied to the airway is delivered to the alveoli within 0.15 seconds.
- Short time constants make rapid-rate conventional ventilation feasible in these infants and makes them ideal candidates for **high-frequency ventilation (HFV).**

- **Term** infants with **meconium aspiration** or older growing **preterm** infants with **BPD** have *elevated airway resistance* and **longer time constants**; therefore, they are most at risk of inadvertent PEEP.
- They should be ventilated with **slower respiratory rates** and **longer inspiratory and, especially, expiratory times**. Evidence of air trapping should be actively sought by examining ventilator waveforms before clinical signs of CO_2 retention and hemodynamic impairment develop.

MECHANISM OF GAS TRANSPORT

- Gas flows down a **pressure gradient** and diffuses down a **concentration gradient**.
- The predominant mechanism of gas transport by **convection** is **bulk flow**, whereas the predominant mechanism of gas transport by **diffusion** is **Brownian motion**.
- Interpleural pressure is more negative than alveolar pressure, which is more negative than mouth and atmospheric pressures**.** **(*PIP* < P_{alv} < P_{atm})**. The pressure gradient created results in gas flowing into the lungs.
- During PPV, the upper airway of the infant is connected to a device that generates a positive-pressure gradient down which gas can flow during inspiration.
- The pressure in the ventilator circuit and in the upper airway is greater than the alveolar pressure, which is greater than the interpleural pressure, which is greater than the atmospheric pressure. (**Paw > P_{alv} > PIP > P_{atm})**
- The negative intrathoracic pressure during spontaneous or negative pressure respiration facilitates venous return to the heart.
- PPV alters this physiology and leads to some degree of impedance of venous return, adversely affecting cardiac output.

- The amount of gas inspired in a single spontaneous breath or delivered through an ETT during a single cycle of the ventilator is called the **tidal volume (V_T)**.
- V_T in mL multiplied by the number of inflations per minute or respirator frequency (f), is called **minute ventilation (V_E):**

$$V_E = V_T \times f$$

- The portion of the incoming V_T that fails to arrive at the level of the respiratory bronchioles and alveoli but instead remains in the **conducting airways** occupies the space known as the **anatomic dead space**.
- Another portion of V_T may be delivered to **unperfused or under-perfused alveoli**. Because gas exchange does not take place in these units, the volume that they constitute is called **alveolar dead space.**
- Together, anatomic dead space and alveolar dead space make up **total or physiologic dead space (V_{DS}).**
- The ratio of **dead space to V_T (V_{DS}/V_T)** defines **wasted ventilation**, which reflects the proportion of tidal gas delivered that is not involved in gas exchange. In general, rapid shallow breathing is inefficient because of a high V_{DS} to V_T ratio.

- CO_2 diffuses more easily than oxygen across the alveolar/capillary wall, despite the relatively low concentration gradient between the alveoli and the capillary blood.
- The effectiveness of CO_2 removal is dependent on the effectiveness of alveolar ventilation.
- The movement of any gas across a semipermeable membrane is governed by **Fick's equation for diffusion**:

$$\boldsymbol{dQ / dt = k \text{ x } A \text{ x } dC / dl}$$

where, dQ/dt is the rate of diffusion (mL/min) k is the diffusion coefficient of the gas

A is the area available for diffusion

dC is the concentration difference across the membrane

dl is the length of the diffusion pathway

- Egs. are **atelectasis,** which will reduce the area available for gas exchange, **interstitial pulmonary edema** and Very immature infants whose lungs have **not yet undergone thinning of the interstitium** which will increase the diffusion pathway, will reduce the effectiveness of CO_2 removal.

OXYGENATION

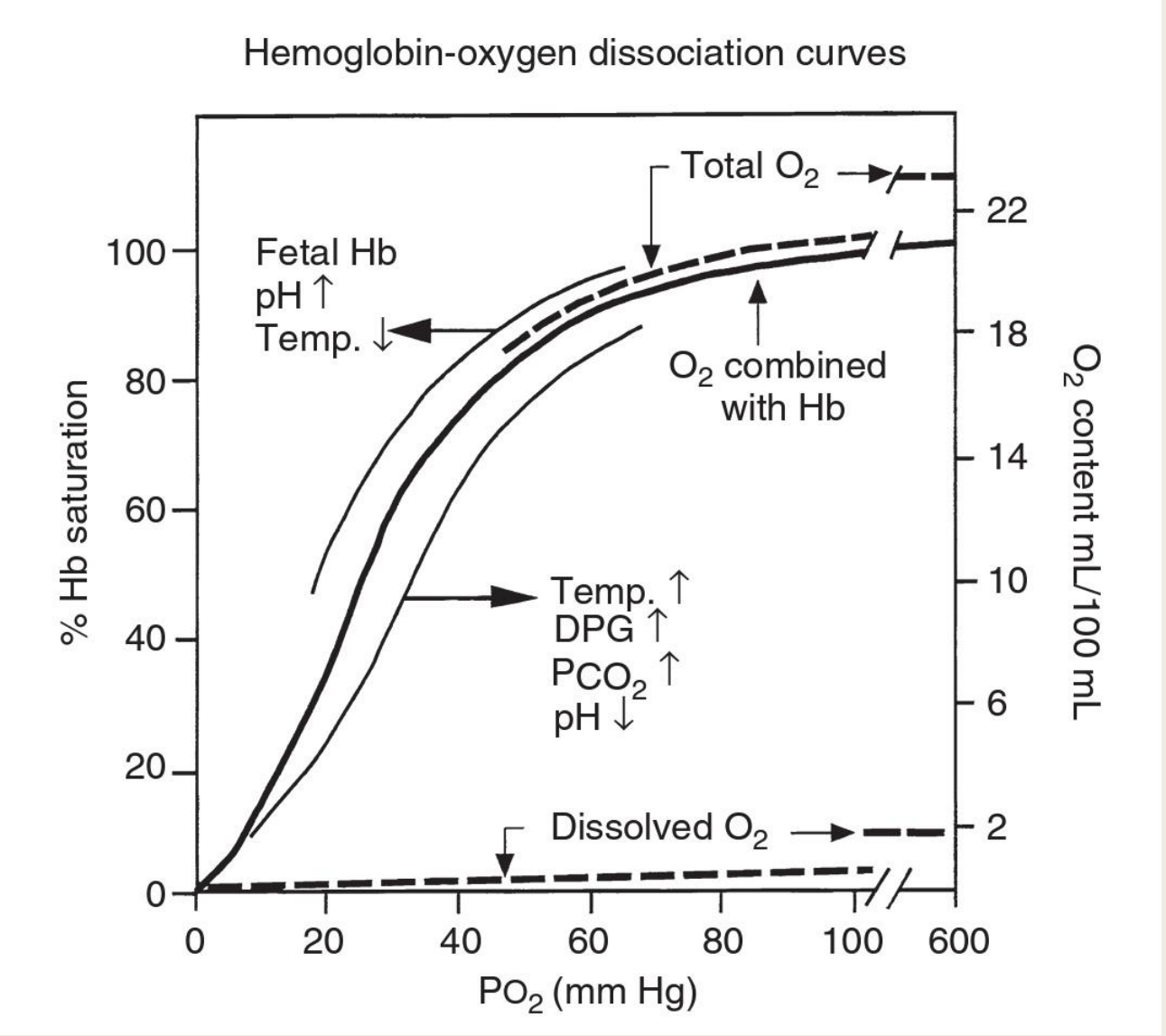
- Oxygen transport to the tissues depends on the **oxygen-carrying capacity of the blood** and the **rate of blood flow**.
- Oxygen is contained in the blood in two forms: (1) bound to **hemoglobin and** (2) dissolved in the **plasma**
- The amount of oxygen in arterial blood is called *oxygen content* (CaO_2).

$$CaO_2 = (1.34 \times Hb \times SaO_2) + (0.003 \times PaO_2)$$

- where one gm of Hb will bind 1.34 mL of O_2 when fully saturated with oxygen; and SaO_2 is the arterial oxygen saturation.
- The dissolved portion of O_2 in blood is linearly related to PO_2. Hence, oxygen content increases 0.003 mL per 100 mL of blood with every 1mm Hg increase in PO_2.

- Each Hb molecule can bind reversibly up to four molecules of O_2.
- The Hb-bound portion of the O_2 content is nonlinear with respect to PO_2. This relationship is illustrated by the **oxyhemoglobin dissociation curve**, which is **sigmoid** in shape.
- The amount of O_2 that binds to hemoglobin increases quickly at low PO_2 values but begins to level off at PO_2 values >40 mm Hg.
- After PO_2 exceeds 90 to 100 mm Hg, the curve flattens. Once the hemoglobin is saturated, further increases in PO_2 do not increase the content of bound oxygen.
- The total amount of O_2 carried by Hb depends on the Hb concentration and the blood's oxygen saturation.

- Several factors affect hemoglobin's affinity for oxygen. (1) percentages of fetal and adult Hb present, (2) effect of 2,3- diphosphoglycerate, (3) pH, and (4) temperature.
- A greater % of fetal Hb (in premature infants), a decrease in 2,3-DPG (in premature infants with RDS), alkalization of the pH (metabolic alkalosis), a reduction in PCO_2 (secondary to hyperventilation), and a decrease in body temperature (as occurs during open heart surgery or therapeutic hypothermia) all **increase the O_2 affinity of Hb** (**shift the oxyhemoglobin dissociation curve to the left**). This means that the same level of hemoglobin saturation can be achieved at lower PO_2 values.
- In contrast, a reduction in fetal Hb% (e.g., after transfusion of adult donor blood to a newborn infant), increased production of 2,3-DPG (in healthy newborns shortly after birth or with adaptation to high altitudes), a more acidic pH, CO_2 retention, and febrile illness each result in a **reduction in O_2 affinity** (**shift of the oxyhemoglobin dissociation curve to the right)**


Hemoglobin-oxygen dissociation curves
Total O_2
Fetal Hb
pH ↑
Temp. ↓
O_2 combined with Hb
Temp. ↑
DPG ↑
PCO_2 ↑
pH ↓
Dissolved O_2
% Hb saturation
O_2 content mL/100 mL
100
80
60
40
20
0
22
18
14
10
6
2
0
20
40
60
80
100
600
PO_2 (mm Hg)

- These shifts in the oxyhemoglobin dissociation curve promote O_2 uptake in the lungs, O_2 release at the tissue level, or both.
- When pulmonary arterial blood (which is rich in CO_2 and poor in O_2) passes through the lung's capillaries, it releases its CO_2; this raises the local pH, which increases O_2 affinity. This allows more of the incoming O_2 to be bound to Hb, thus maximizing the concentration gradient down which O_2 diffuses from the alveoli into the pulmonary capillary plasma.
- Similarly, when systemic arterial blood (which is rich in O_2 and low in CO_2) enters the tissue capillaries, it picks up CO_2 (which is in high concentration in the tissues). As a result, pH and O_2 affinity are lowered; this allows Hb to release its O_2 without significantly decreasing PO_2 and thus helps to maintain the concentration gradient down which O_2 diffuses into the tissues. This is known as the **Bohr effect.**
- The **Haldane effect** refers to phenomenon whereby increased oxygen tension in the pulmonary capillary blood enhances the release of CO_2 from Hb and enhances its diffusion into the alveoli.

- The **greater affinity of fetal Hb for oxygen**, together with the **relative polycythemia** normally seen in newborns, allows the fetus to maintain adequate tissue oxygen delivery in the relatively hypoxemic environment **in utero**.
- The PaO_2 and SaO_2 in the healthy fetus are only about 25 mm Hg and 60% respectively. This is why normal newborn infants emerge from the womb quite cyanotic. SpO_2 in the healthy newborn infant increases gradually after birth and does not normally reach 90% until 5 to 10 minutes of life.
- Rapid increases in PaO_2, such as occur when delivery room resuscitation is carried out with 100% oxygen, appear to result in delayed onset of spontaneous breathing and increased mortality.
- SaO_2 levels of 85% to 92% appear to be adequate for newborns, and higher values may predispose the antioxidant-deficient preterm infant to the dangers of hyperoxia and damage from reactive oxygen species.
- It has been shown that the O_2 demands of most **extremely premature infants** can be met by maintaining PaO_2 levels just above 50 mm Hg or SaO_2 levels just above 88%.

- **PaO_2** (mm of Hg): The partial pressure of O_2 in **arterial blood** is the tension or partial pressure of O_2 dissolved in the arterial blood plasma. This oxygen is in equilibrium with the oxygen that is bound to hemoglobin. PaO_2 is measured by the blood gas analysis. It is a useful indicator of the **degree of O_2 uptake through the lungs**.
- **FiO_2** (%) : The fraction of inspired O_2 is the proportion of O_2 in the inspired gas. FiO_2 is measured directly with an O_2 analyzer. The FiO_2 in room air is approximately 0.21.
- **PAO_2** : The partial pressure of O_2 in **alveolar gas** is the tension of O_2 present in the alveoli. PAO_2 represents the amount of O_2 available for diffusion into the pulmonary capillary blood.
- **$PACO_2$** : The partial pressure of CO_2 in the alveoli, is nearly identical to partial pressure of CO_2 in the arterial blood, or **$PaCO_2$.**

- The partial pressure of water vapor at 100% relative humidity at body temperature and normal atmospheric pressure is 47 mm Hg.
- One additional correction factor must be used. This is called the *respiratory quotient* (RQ), which is the ratio of CO_2 excretion to O_2 uptake. The respiratory quotient ranges from approximately 0.8 to slightly greater than 1.0, depending on diet.
- To calculate PAO_2, we use the alveolar gas equation:

PAO_2 = [(barometric pressure – partial pressure of water vapor) x FiO_2] – ($PaCO_2$ / RQ)

- At sea level, with normal $PaCO_2$ of 40 mm Hg and respiratory quotient of 0.8, the alveolar gas equation for breathing room air is as follows:
- PAO_2 =[(760 - 47) x 0.21] - 40 / 0.8
- Therefore, PAO_2 is approximately 150 – 50 = 100
- The alveolar gas equation is useful in calculating a variety of indexes of oxygenation and the FiO_2 need of an infant with compromised gas exchange, in situations like travelling at higher altitude or in a commercial aircraft cabin pressurized to 7000 or 8000 ft above sea level.

- Some values derived from blood gases serve as useful clinical indicators of disease severity and used as criteria for initiation of invasive or costly therapies.
- Arterial–alveolar O_2 tension ratio : (**PaO_2:PAO_2**, or the a:A ratio). The a:A ratio should be **close to 1** in a healthy infant. A ratio of **less than 0.3** indicates severe compromise of oxygen transfer.
- Alveolar–arterial O_2 gradient or difference : ($AaDO_2$ = **PAO_2 - PaO_2**). In healthy infants, $AaDO_2$ is **less than 20** in room air. Calculating $AaDO_2$ allows the clinician to estimate disease severity and appropriate FiO_2 change when PaO_2 is high.
- **Oxygenation index : (*P*aw x FiO_2 x 100)/PaO_2**
- An oxygenation index **greater than 15** signifies **severe respiratory compromise**.
- An oxygenation index of **40 or more** indicates a **mortality risk** of 80% and continues to be used as an **indication for extracorporeal membrane oxygenation (ECMO).**

EFFECTS OF ALTERING VENTILATOR SETTINGS ON OXYGENATION

- Oxygen uptake through the lungs can be increased by

  (1) increasing PAO_2 by increasing the FiO_2

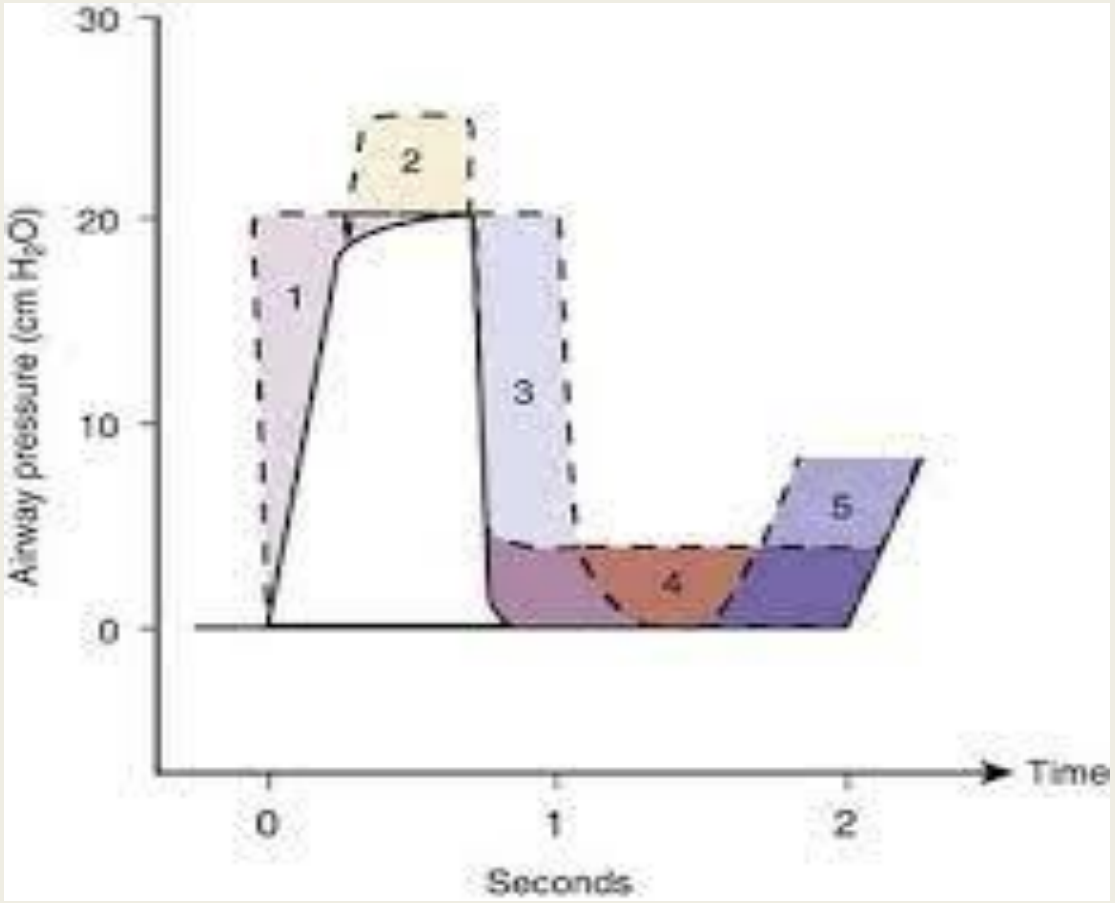
  (2) optimizing lung volume (optimizing V/Q matching and increasing the surface area for gas exchange), and

  (3) maximizing pulmonary blood flow (avoiding lung over-expansion that increases PVR and preventing blood from flowing right to left through extrapulmonary shunts)

- There are functionally two ventilator changes available to the clinician:

  1. Alter $\underline{Fi}O_2$

  2. Alter *P*aw



- Five different ways to increase mean airway pressure:

(1) increase inspiratory flow rate or rise time, producing a square-wave inspiratory pattern;
(2) increase peak inspiratory pressure;
(3) reverse the inspiratory-to-expiratory ratio or prolong the inspiratory time (I-time) without changing the rate;
(4) increase positive end-expiratory pressure; and
(5) increase ventilatory rate by reducing expiratory time without changing the I-time.

- The rate of upstroke (also known as rise time) has a relatively minor impact.
- Higher frequency and higher PIP both may result in inadvertent hyperventilation.
- Prolongation of the inspiratory time to the point of inverse I:E ratio is potentially the most dangerous measure and is no longer done.
- In practice, increasing PEEP appears to be the safest and most effective way to achieve optimal *P*aw, in part because normally, the greatest proportion of the respiratory cycle is the expiratory phase.

THANK YOU

- Other mechanisms of gas transport, particularly relating to HFV, are described below.
- They include **axial convection, radial diffusive mixing, coaxial flow, viscous shear, asymmetrical velocity profiles,** and **the pendelluft effect**.

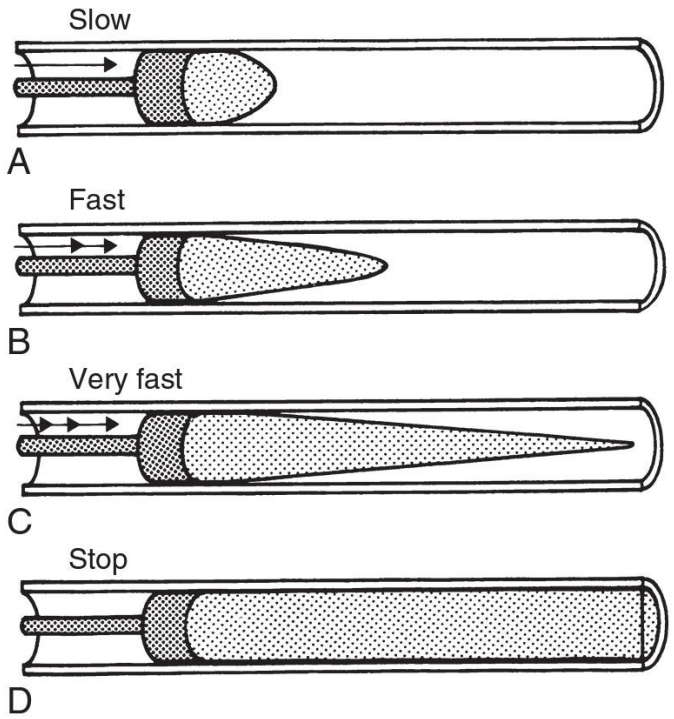
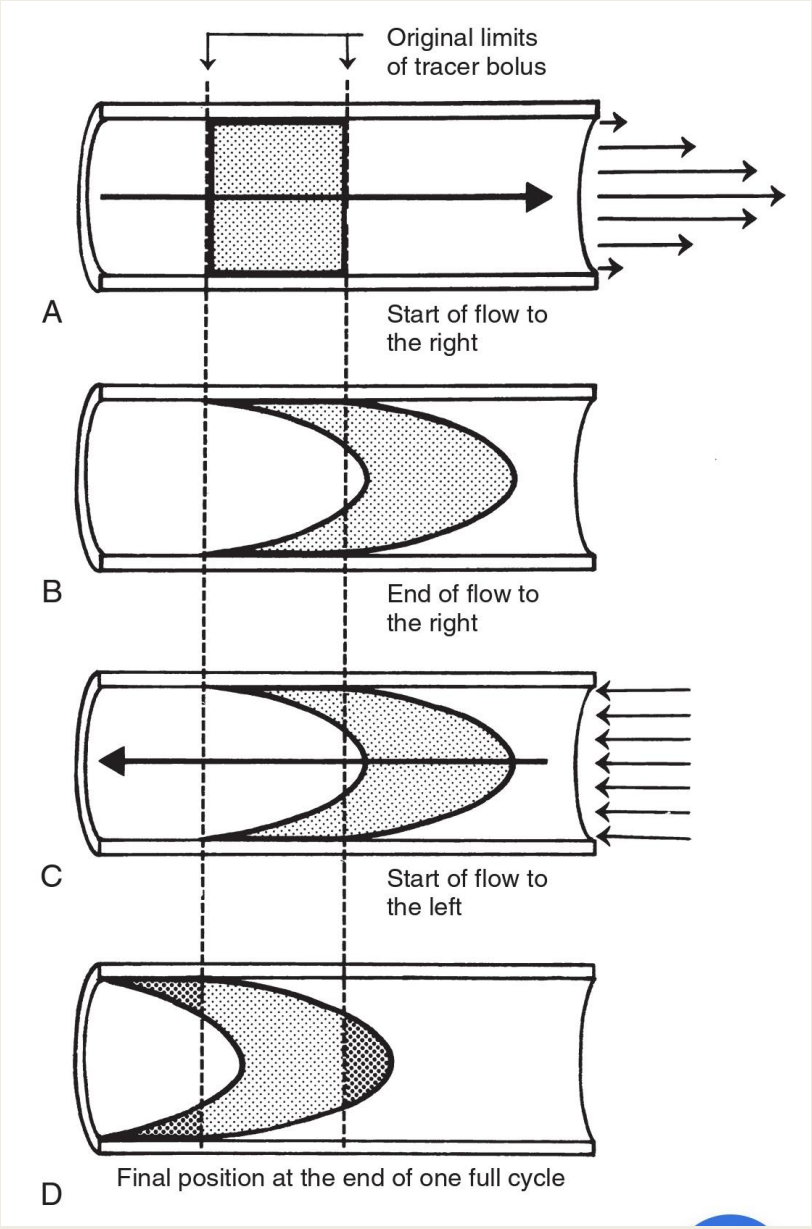


Fig. 2.11 Spike theory of panting or high-frequency ventilation. **(A–C)** The quicker or more "energy dense" the puff (or inspiratory pulse), the sharper the spike and the farther it extends into the airway. **(D)** If the pulse is suddenly stopped at end inspiration, mixing occurs instantaneously. (Modified from Henderson Y, Chillingworth FP, Whitney JL: The respiratory dead space. Am J Physiol 38:1, 1915.)

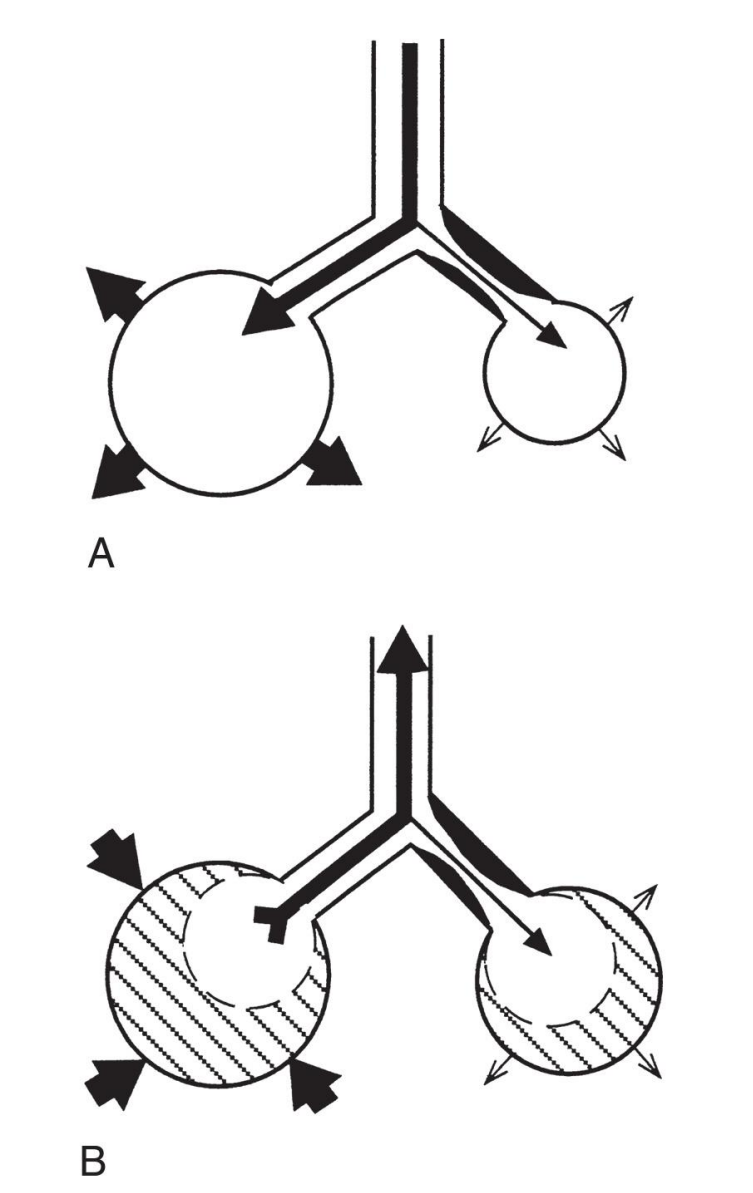
- In 1915, Henderson et al hypothesized that low-volume inspiratory pulses of gas moved down the center of the airway as **axial spikes** and that these spikes dissipated at the end of each "breath".
- The faster the inspiratory pulse, the farther it penetrated down the conducting airway and the larger the boundary of mixing between the molecules of the incoming gas (with high O_2 and low CO_2) and the outgoing gas (with high CO_2 and low O_2).
- During this kind of breathing, both convection and molecular diffusion are enhanced or facilitated.



- During exhalation, the flow velocity is lower (1:2 I:E ratio) and the velocity profiles are more uniform across the entire lumen rather than being cone shaped.

- The pulse of gas originally occupying the lumen of the airway is displaced to the right (i.e., toward the patient's alveoli), and an equal volume of gas is displaced to the left.

- This occurs even though the **net displacement** of the piston at the end of a cycle of HFOV is **zero**.



- The back-and-forth currents of gas through lung units with unequal time constants are called ***pendelluft***. This gas flow is produced because of local differences in airway resistance and lung compliance that are accentuated under conditions of high velocity flow.
- This leads to regional differences in rates of inflation and deflation. “Fast units” with short time constants inflate and deflate more rapidly, emptying out into the conducting airways to be “inhaled” by “slow units” still in the process of filling.
- Pendelluft thus improves gas mixing and exchange.

- The provision of a greater interface or boundary area between inspiratory and expiratory gases with their different O_2 and CO_2 partial pressures is known as **radial diffusive mixing.**
- During HFV, with each inspiration, gas molecules near the center of the airway flow farther than those adjacent to the walls of the airway, because the gas traveling down the center of the airway encounters less resistance.
- At the end of the inspiratory phase, the contour of the leading edge of the inspired gas is **cone shaped**, having a larger diffusion interface with the preexisting gas than with the disk shaped one.