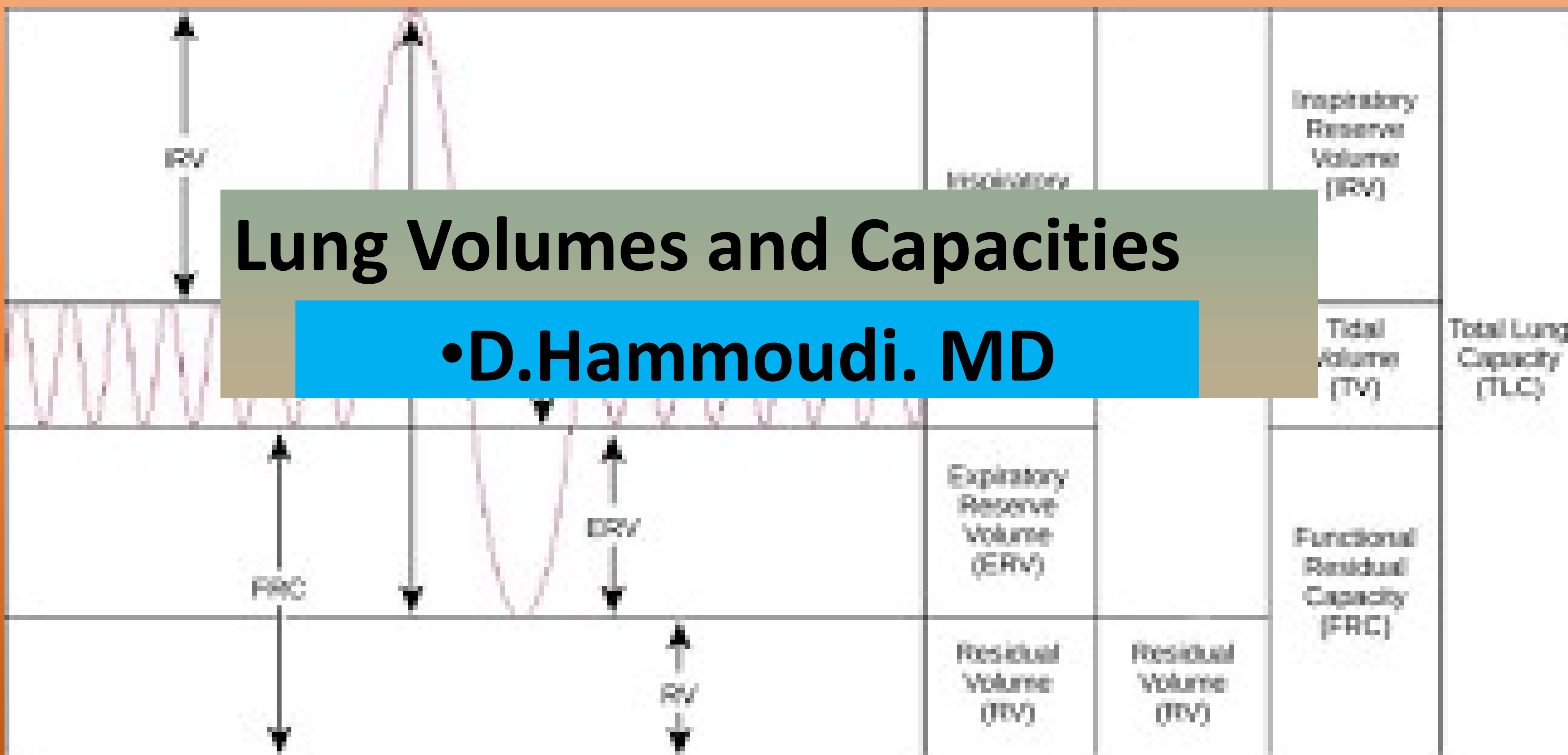
Lung Volumes and Capacities

- D.Hammoudi. MD



Respiratory System Functions

- Gas exchange: Oxygen enters blood and carbon dioxide leaves
- Regulation of blood pH: Altered by changing blood carbon dioxide levels
- Voice production: Movement of air past vocal folds makes sound and speech
- Olfaction: Smell occurs when airborne molecules drawn into nasal cavity
- Protection: Against microorganisms by preventing entry and removing them

Age-old story: Age-related respiratory changes

Structural changes

- Nose enlargement (from continued cartilage growth)
- General atrophy of the tonsils
- Tracheal deviations (from changes in the aging spine)
- Increased anteroposterior chest diameter (resulting from altered calcium metabolism)
- Calcification of costal cartilages (resulting in reduced mobility of the chest wall)
- Kyphosis (due to osteoporosis and vertebral collapse)
- Increased lung rigidity
- Decreased number and dilation of alveoli
- Reduction in respiratory fluids by 30% (heightening the risk of pulmonary infection and mucus plugs)
- Reduction in respiratory muscle strength

Pulmonary function changes

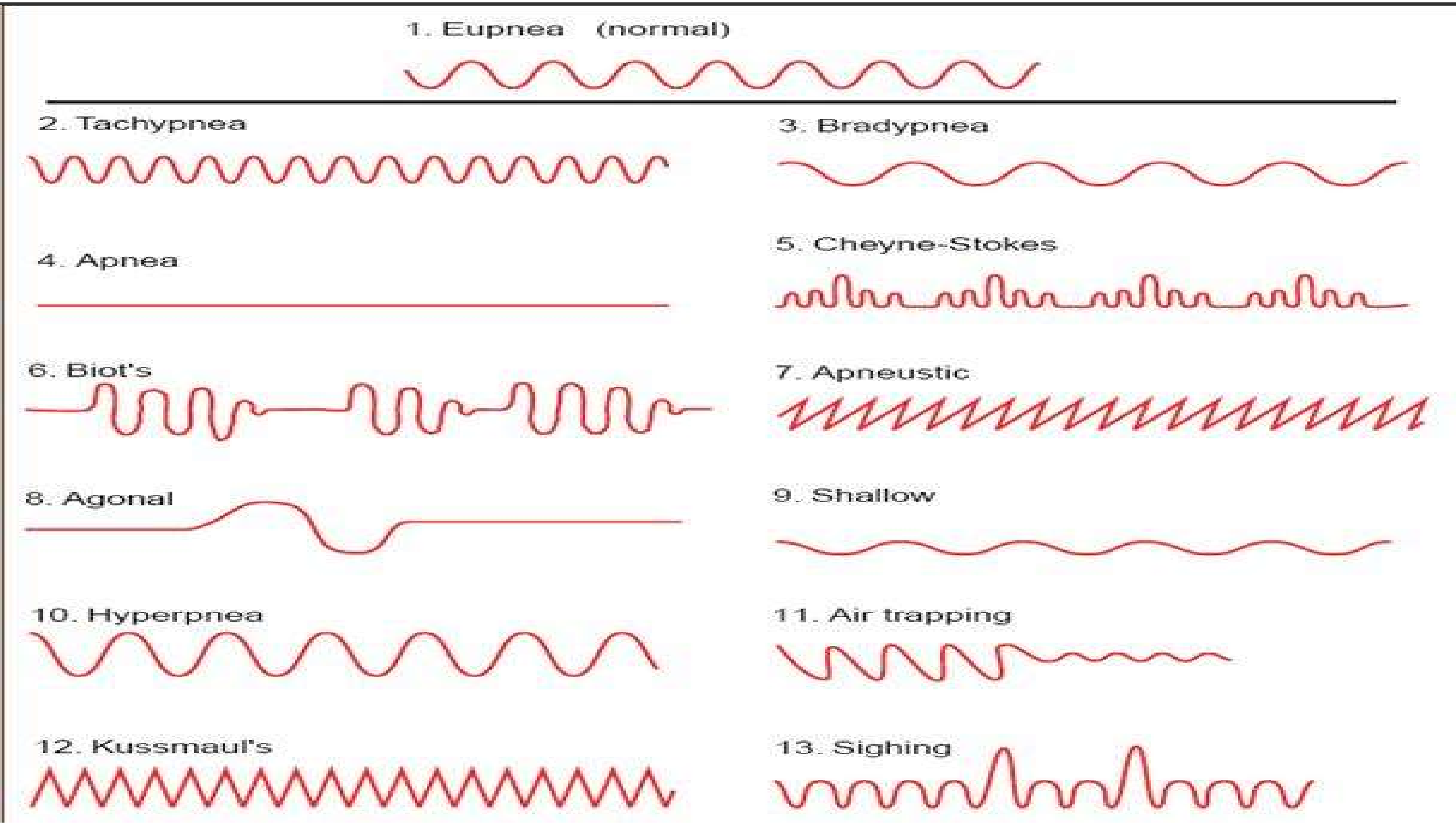
- Diminished ventilatory capacity
- Decline in diffusing capacity
- Diminished vital capacity (due to decreased inspiratory and expiratory muscle strength)
- Decreased elastic recoil capability (resulting in an elevated residual volume)
- Decreased ventilation of basal areas (due to closing of some airways)

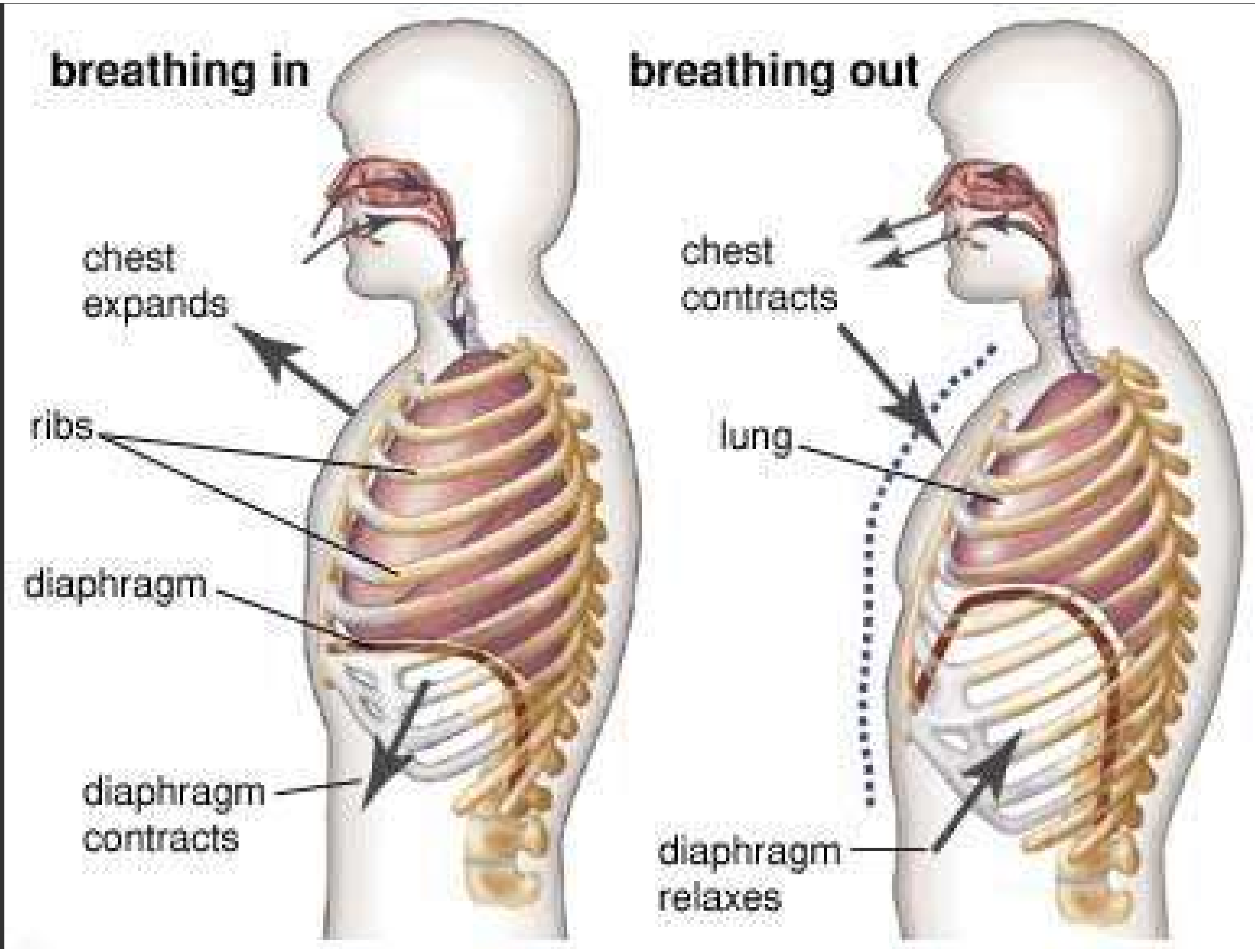
Patterns of Breathing

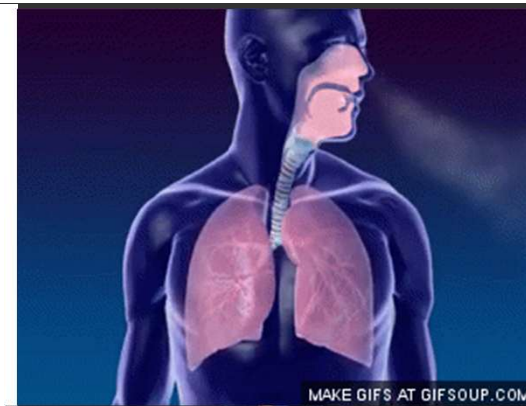
- **Eupnea**
  - **normal breathing (12-17 B/min, 500-600 ml/B)**
- **Hyperpnea**
  - **⇑ pulmonary ventilation matching ⇑ metabolic demand**
- **Hyperventilation (⇓ CO_2)**
  - **⇑ pulmonary ventilation > metabolic demand**
- **Hypoventilation (⇑ CO_2)**
  - **⇓ pulmonary ventilation < metabolic demand**

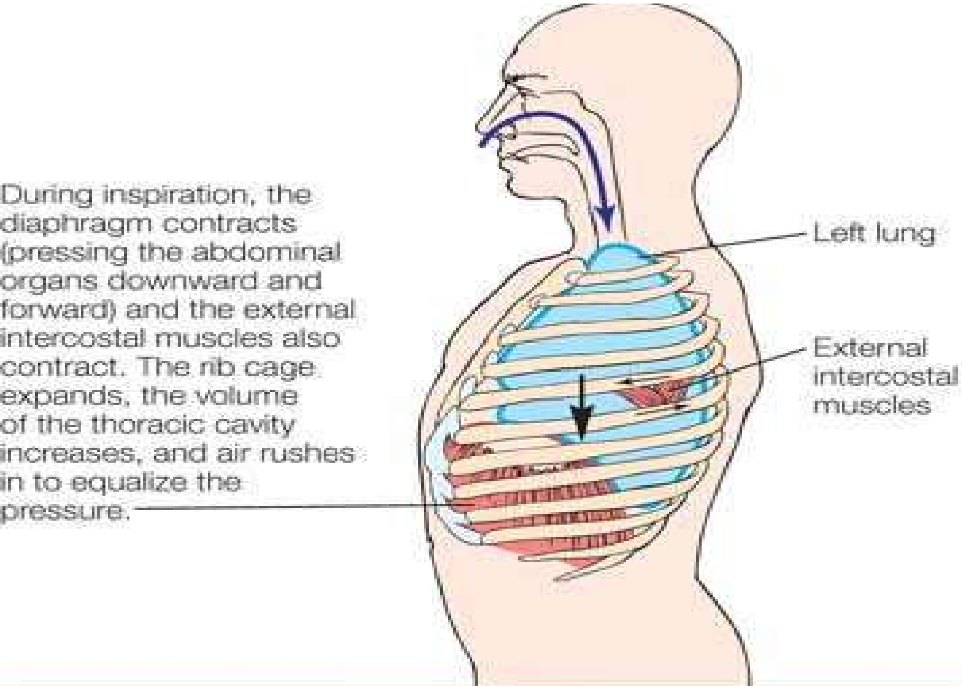
Patterns of breathing (cont.)

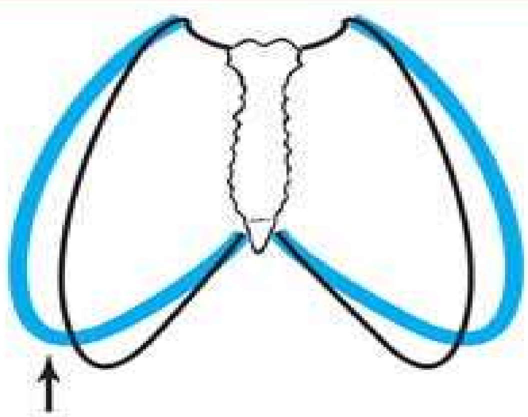
- **<u>Tachypnea</u>**
  - ⇑ frequency of respiratory rate
- <u>Apnea</u>
  - Absense of breathing. e.g. Sleep apnea
- **<u>Dyspnea</u>**
  - Difficult or labored breathing
- <u>Orthopnea</u>
  - Dyspnea when recumbent, relieved when upright. e.g. congestive heart failure, asthma, lung failure


1. Eupnea (normal)
2. Tachypnea
3. Bradypnea
4. Apnea
5. Cheyne-Stokes
6. Biot's
7. Apneustic
8. Agonal
9. Shallow
10. Hyperpnea
11. Air trapping
12. Kussmaul's
13. Sighing

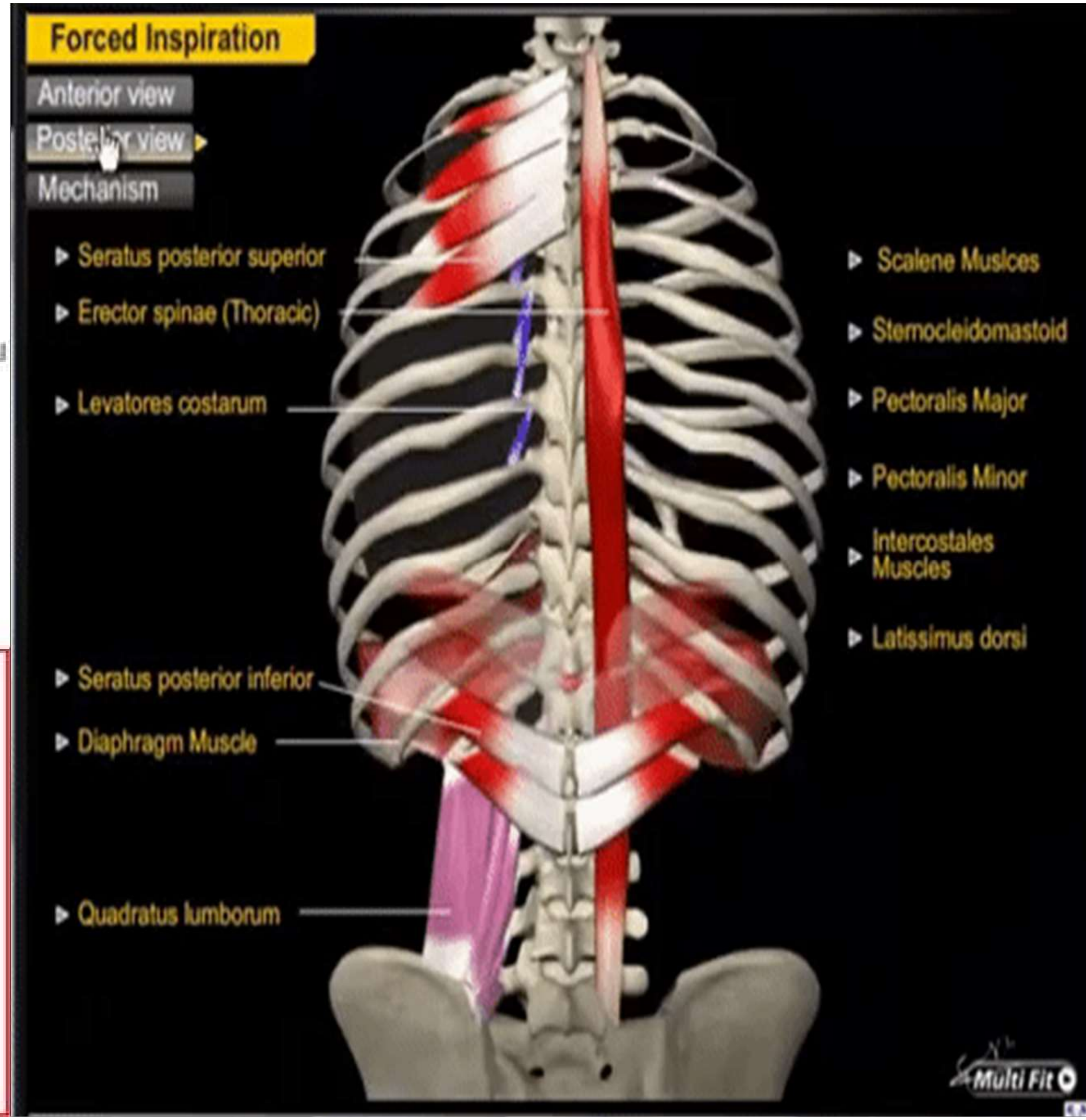

breathing in
chest
expands
ribs
diaphragm
diaphragm
contracts
breathing out
chest
contracts
lung
diaphragm
relaxes

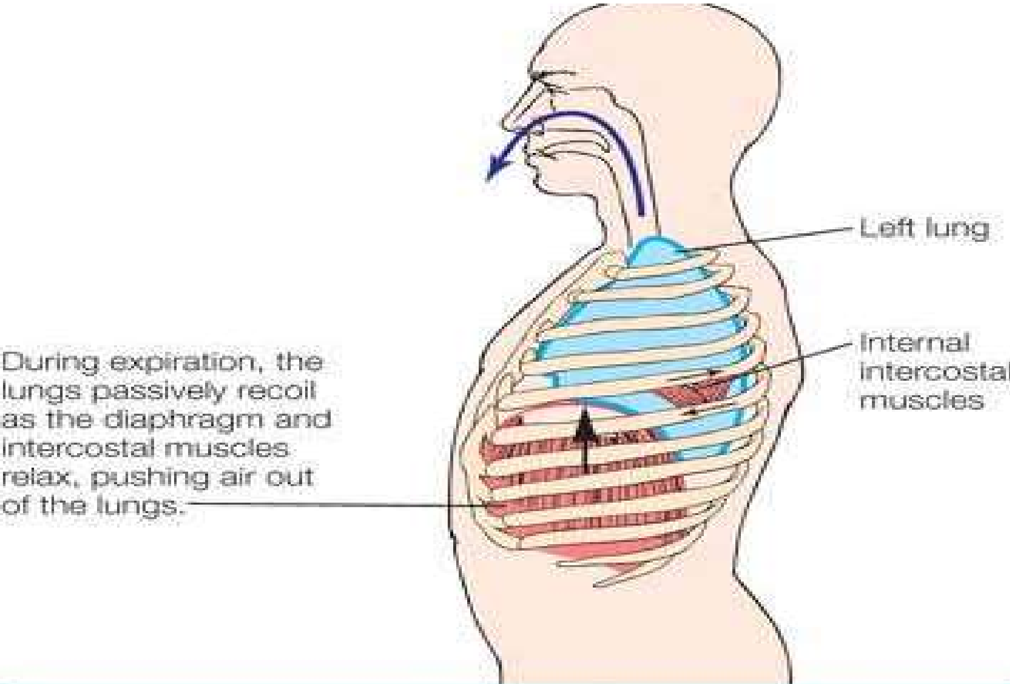

MAKE GIFS AT GIFSOUP.COM

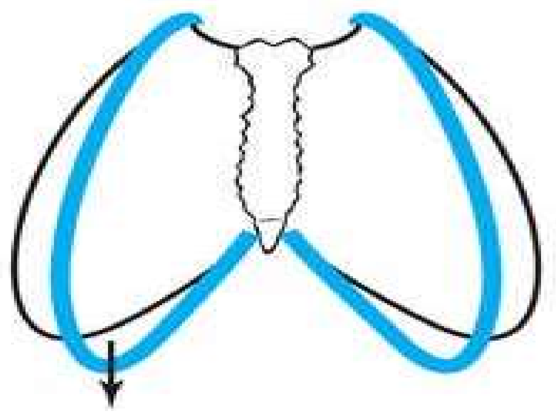




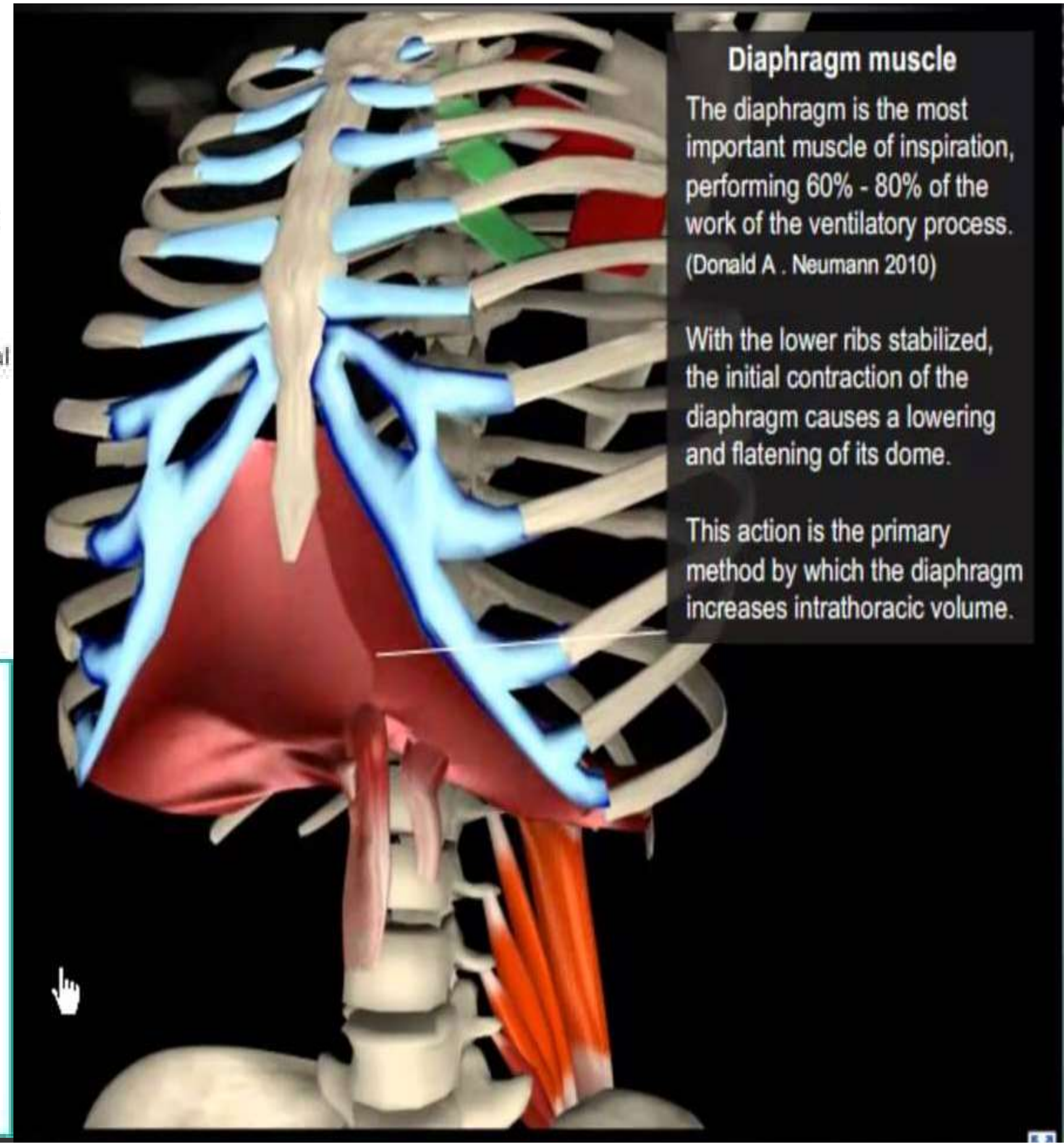
Action of the rib cage in inspiration



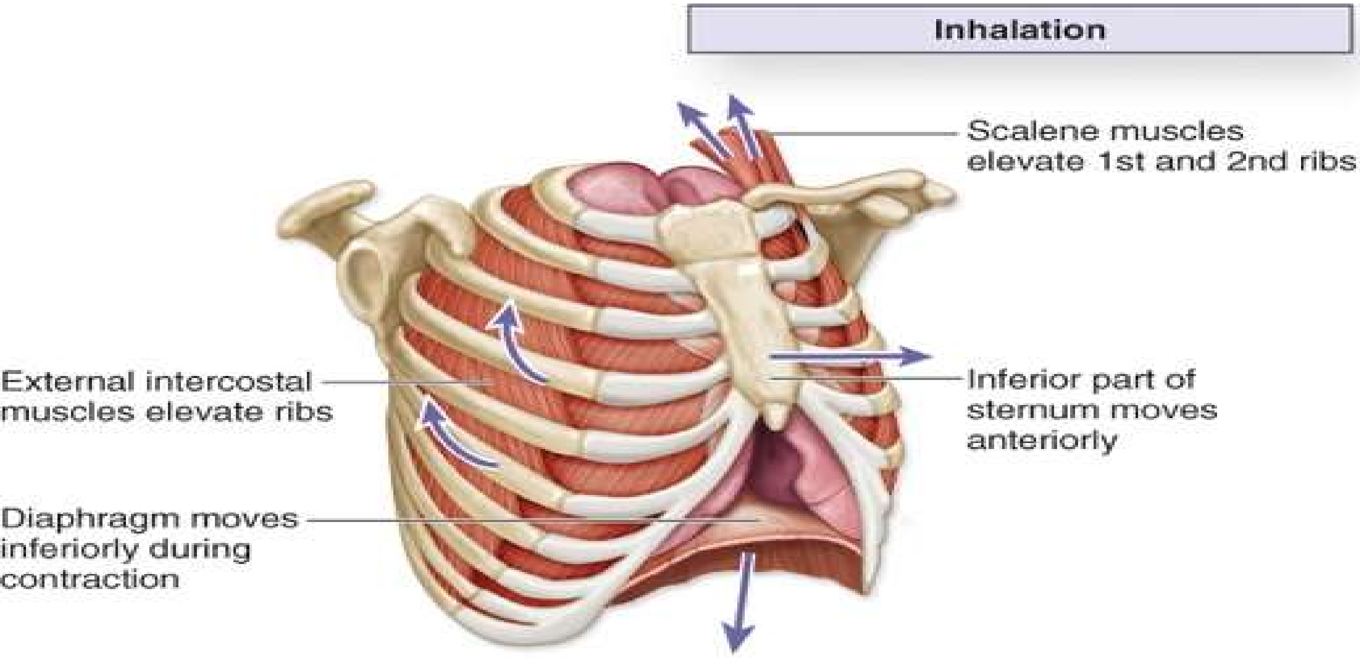


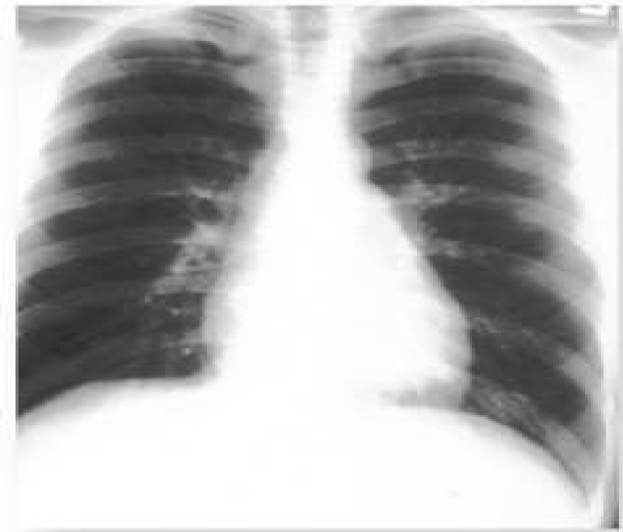


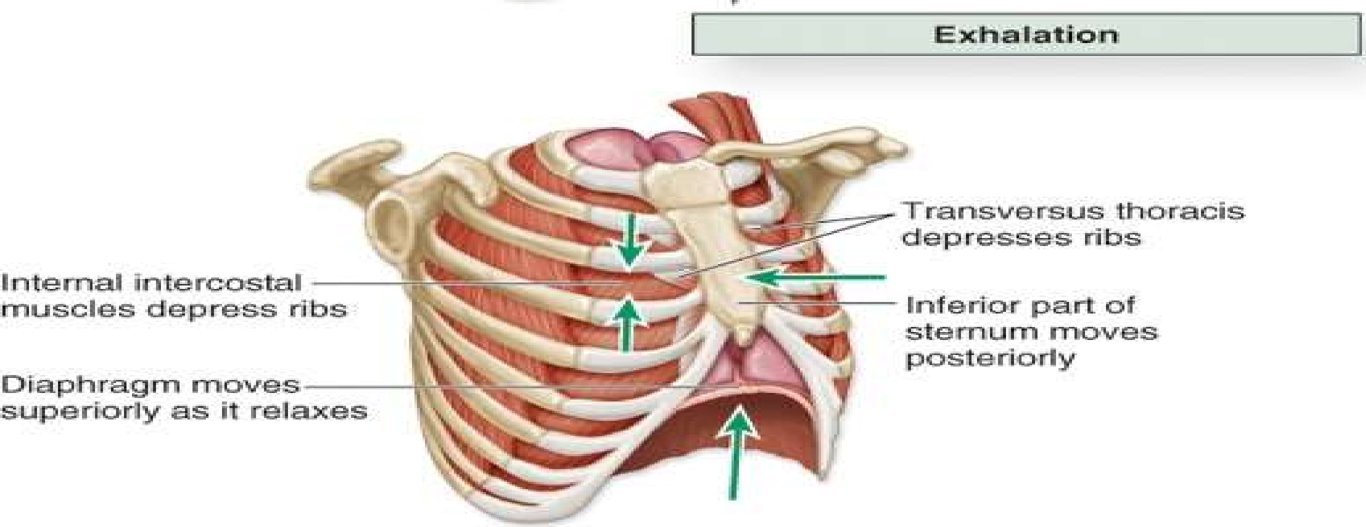
Action of the rib cage in expiration

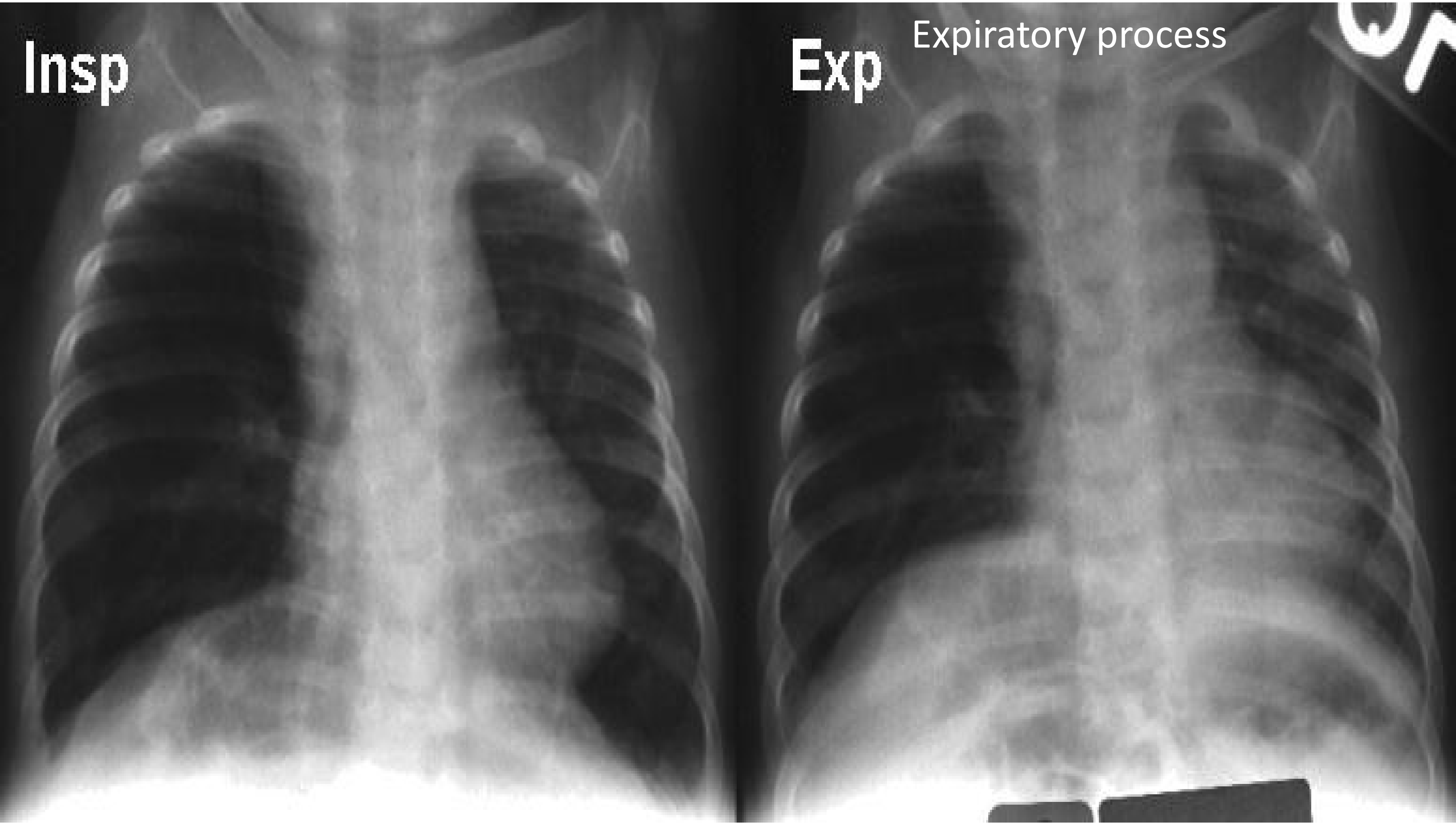


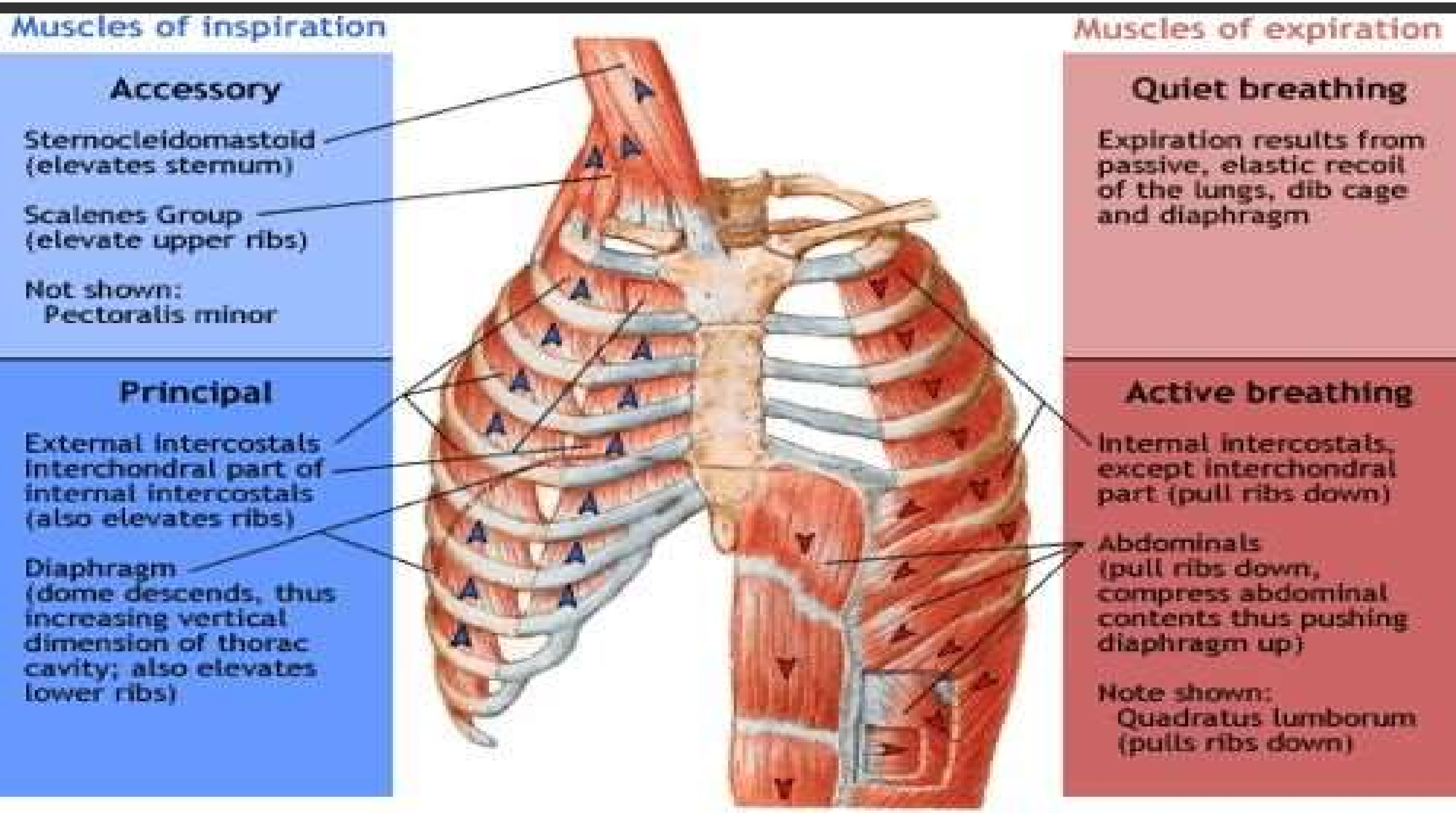
Muscles of respiration	Quiet breathing: Inspiration—diaphragm. Expiration—passive. Exercise: Inspiration—external intercostals, scalene muscles, sternomastoids. Expiration—rectus abdominis, internal and external obliques, transversus abdominis, internal intercostals.	
Important lung products	1. Surfactant—produced by type II pneumocytes, ↓ alveolar surface tension, ↑ compliance, ↓ work of inspiration 2. Prostaglandins 3. Histamine ↑ bronchoconstriction 4. Angiotensin-converting enzyme (ACE)—angiotensin I → angiotensin II; inactivates bradykinin (ACE inhibitors ↑ bradykinin and cause cough, angioedema) 5. Kallikrein—activates bradykinin	Surfactant—dipalmitoyl phosphatidylcholine (lecithin) deficient in neonatal RDS. Collapsing pressure = $\frac{2\ (\text{tension})}{\text{radius}}$

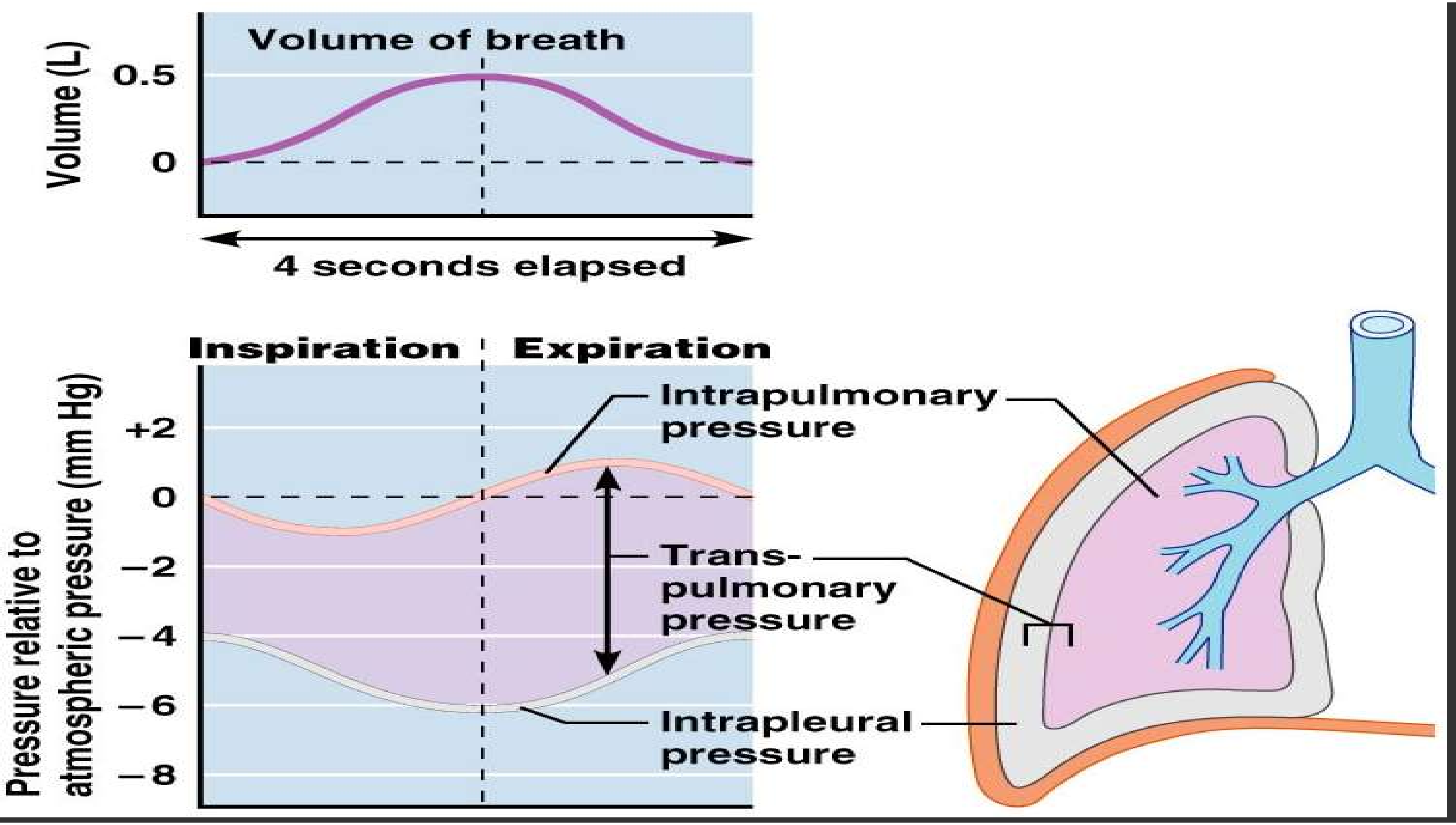

Inhalation
Scalene muscles elevate 1st and 2nd ribs
External intercostal muscles elevate ribs
Inferior part of sternum moves anteriorly
Diaphragm moves inferiorly during contraction




Exhalation
Transversus thoracis depresses ribs
Internal intercostal muscles depress ribs
Inferior part of sternum moves posteriorly
Diaphragm moves superiorly as it relaxes


Insp
Exp
Expiratory process


Muscles of inspiration
Muscles of expiration
Accessory
Sternocleidomastoid (elevates sternum)
Scalenes Group (elevate upper ribs)
Not shown: Pectoralis minor
Principal
External intercostals Interchondral part of internal intercostals (also elevates ribs)
Diaphragm (dome descends, thus increasing vertical dimension of thorac cavity; also elevates lower ribs)
Quiet breathing
Expiration results from passive, elastic recoil of the lungs, dib cage and diaphragm
Active breathing
Internal intercostals, except interchondral part (pull ribs down)
Abdominals (pull ribs down, compress abdominal contents thus pushing diaphragm up)
Note shown: Quadratus lumborum (pulls ribs down)


Volume of breath
Volume (L)
0.5
0
4 seconds elapsed
Inspiration
Expiration
Pressure relative to atmospheric pressure (mm Hg)
+2
0
−2
−4
−6
−8
Intrapulmonary pressure
Trans-pulmonary pressure
Intrapleural pressure

Intrapulmonary Pressures

- **Air entering the lungs during inspiration because the atmospheric pressure is greater than the intrapulmonary pressure**..
- **Usually during quiet inspiration, intrapulmonary pressure is at 3 mmHg below the pressure of the atmosphere. But it shows as -3mmHg.**
- **Expiration occurs when the intrapulmonary pressure is greater than the atmospheric pressure.**
- During quiet expiration it's shown as +3mmHg above atmospheric pressure.

Intrapleural Pressure

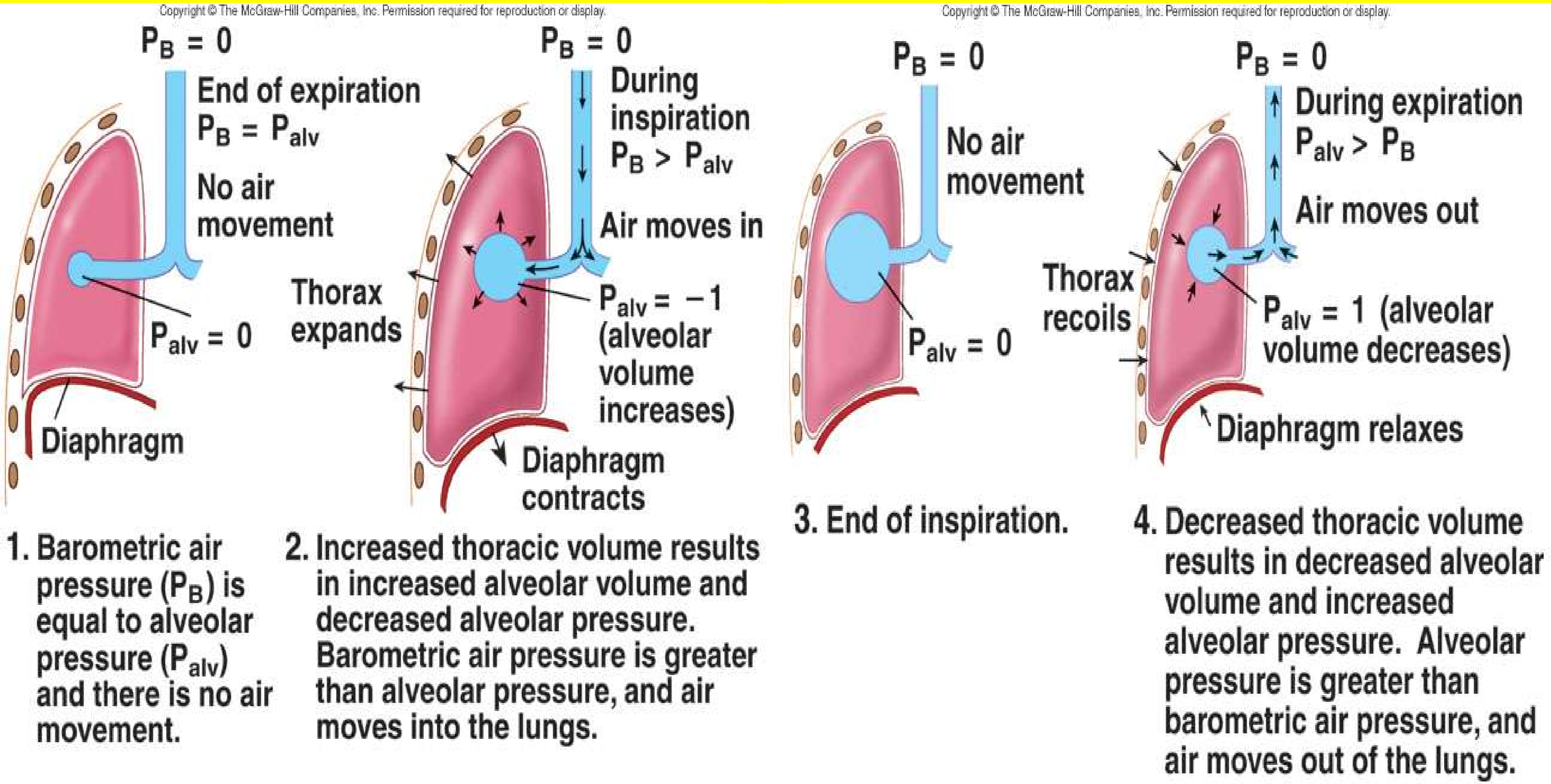
The opposing elastic recoil of the lungs and the chest wall produces a subatmospheric pressure in the intrapleural space between the two structures.

- **This intrapleural pressure is lower during inspiration because of the expansion of the thoracic cavity than it is during expiration.**
- **The intrapleural pressure is normally lower than the intraplumonary pressure during both inspiration and expiraiton.**

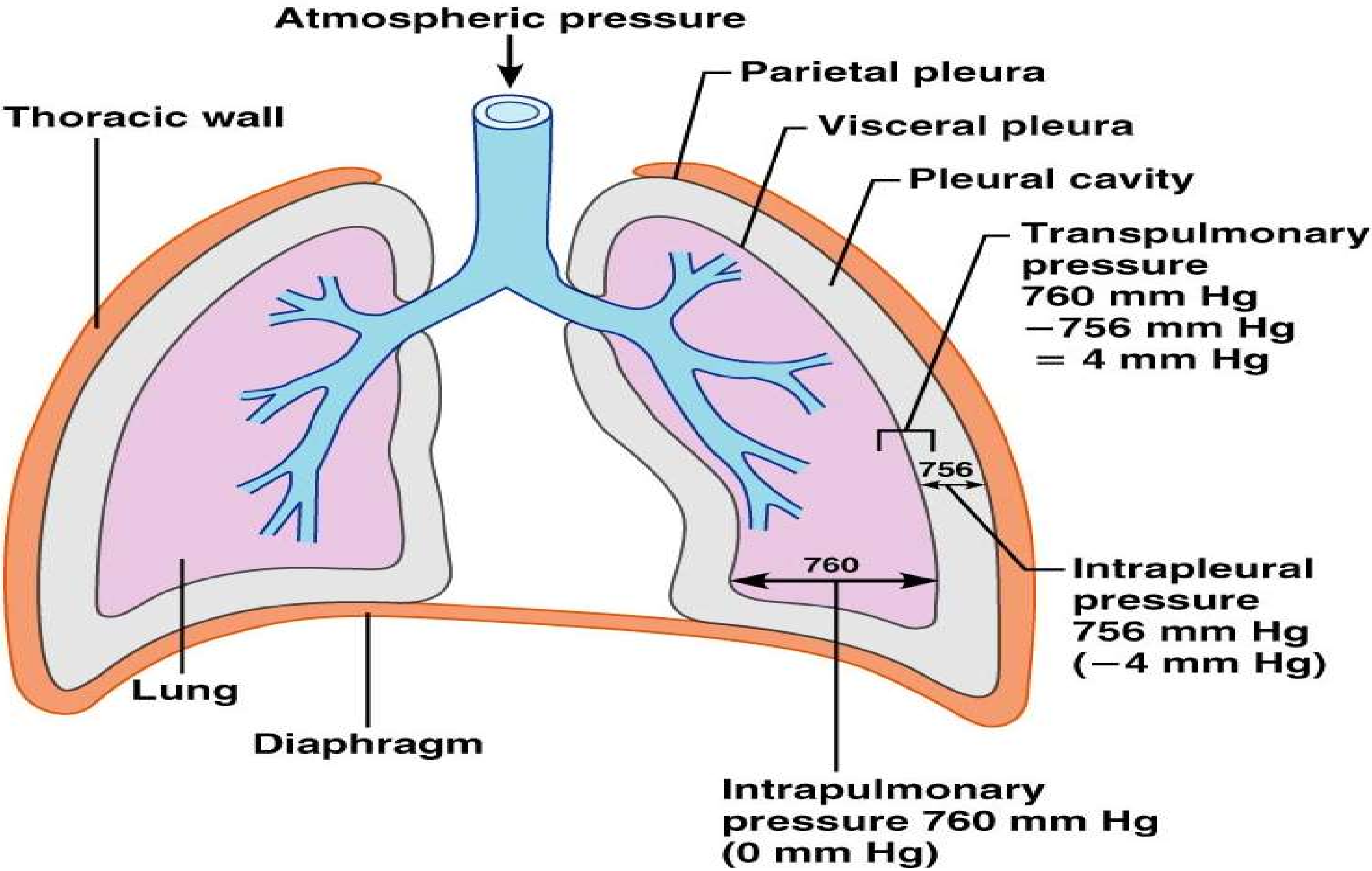
Transpulmonary Pressure

The pressure difference across the wall of the lung is transpulmonary pressure, which can also be the difference between the intrapulmonary pressure and the intrapleural pressure and keeps the lungs against the chest wall.

Alveolar Pressure Changes



Pressure Relationships



- During inspiration intrapleural pressure becomes **more negative**
- Respiration stops in late expiration because of **dynamic compression of airways**
- Total lung capacity depends on **compliance**
- Nitrogen wash out method detects **functional residual capacity**
- FRC is **not estimated by spirometry**
- **Slow and deep breathing** are the **most economical** way of breathing.

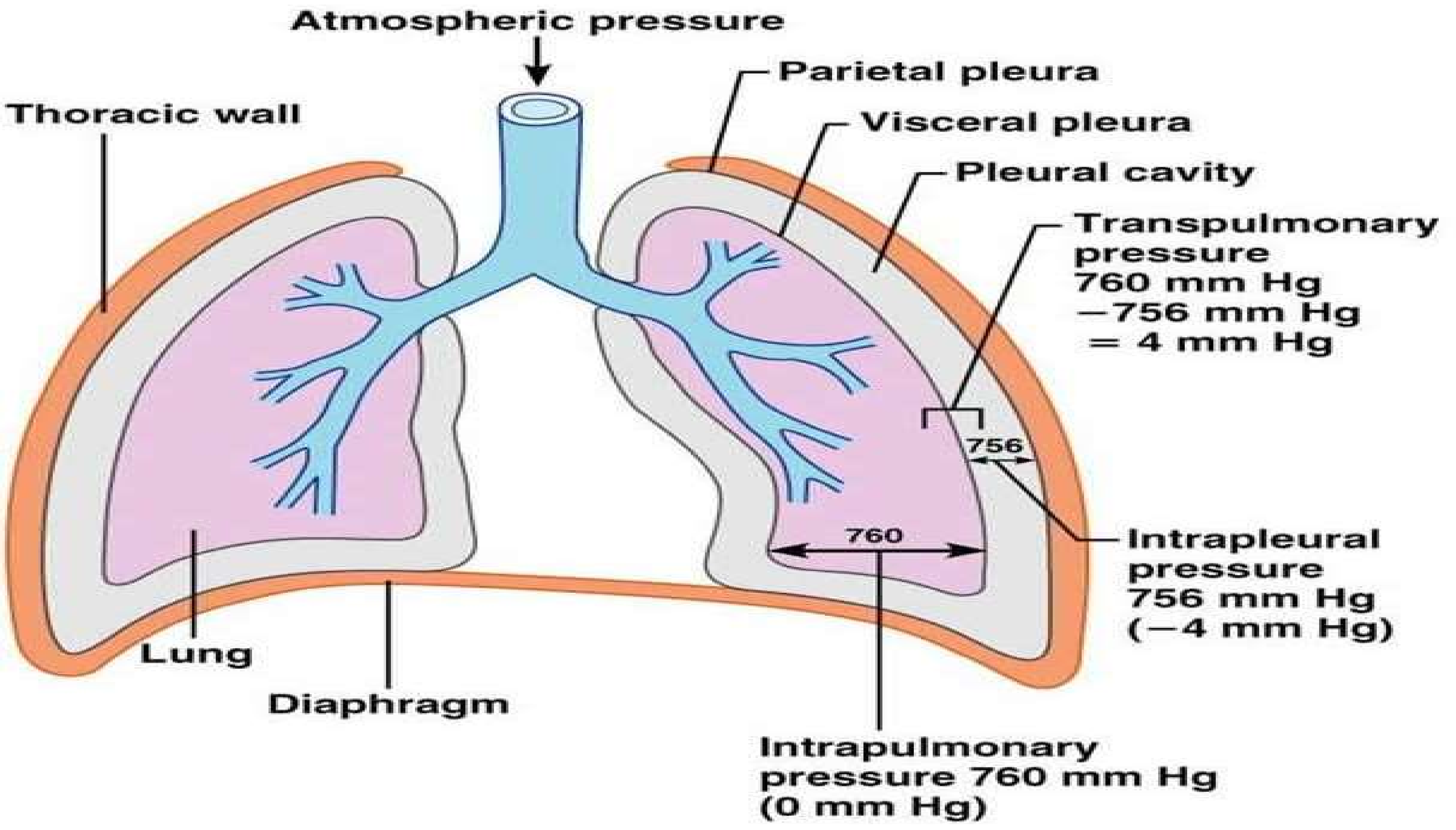
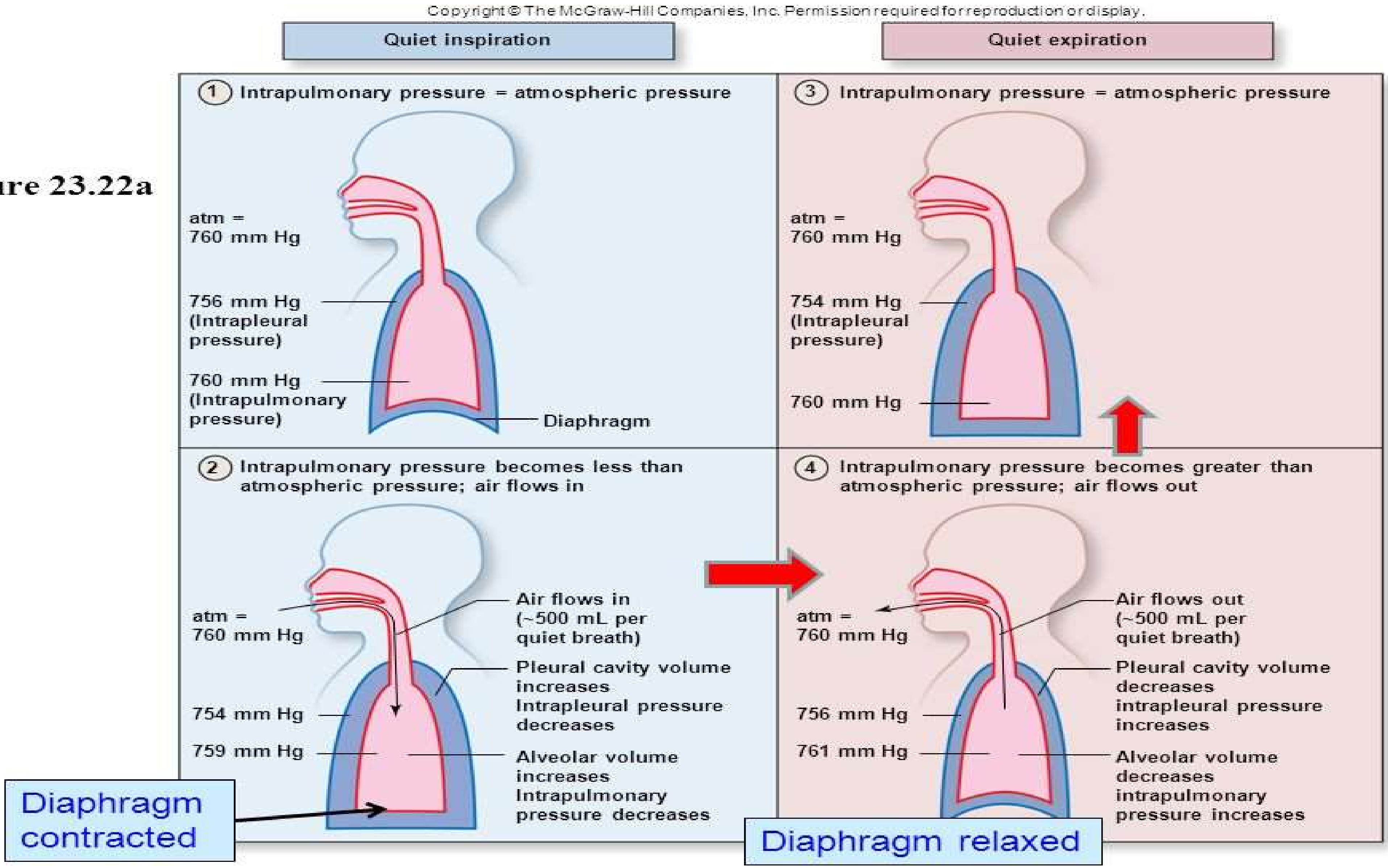

Atmospheric pressure
Parietal pleura
Thoracic wall
Visceral pleura
Pleural cavity
Transpulmonary pressure 760 mm Hg −756 mm Hg = 4 mm Hg
756
760
Intrapleural pressure 756 mm Hg (−4 mm Hg)
Lung
Diaphragm
Intrapulmonary pressure 760 mm Hg (0 mm Hg)

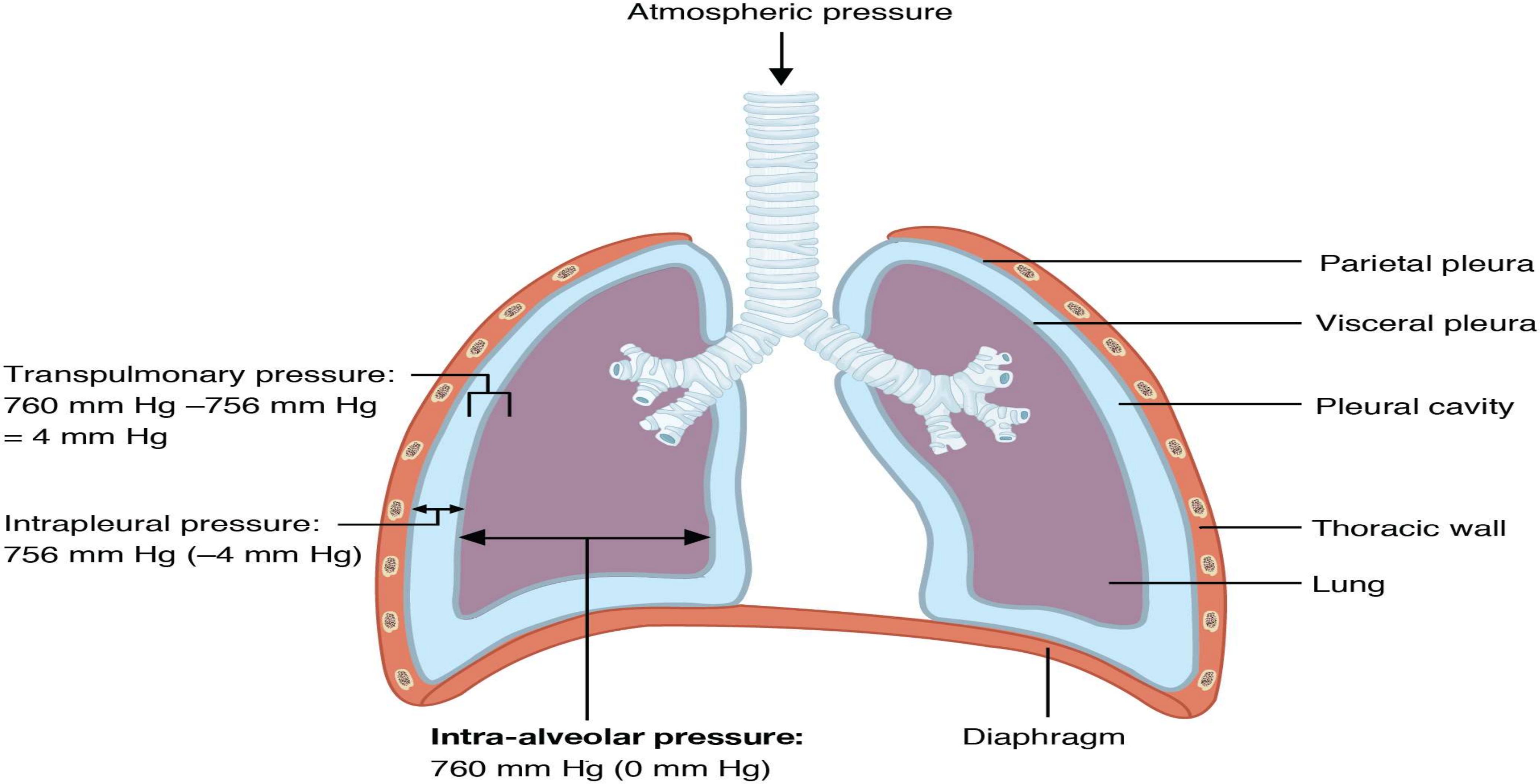
Figure 23.22a



Pressures

- **Atmospheric pressure – 760 mm Hg, 630 mm Hg here**
- **Intrapleural pressure – 756 mm Hg – pressure between pleural layers**
- **Intrapulmonary pressure – varies, pressure inside lungs**

Pressure Relationships



Laminar flow

Laminar flow, a linear pattern that occurs at low flow rates, offers minimal resistance.

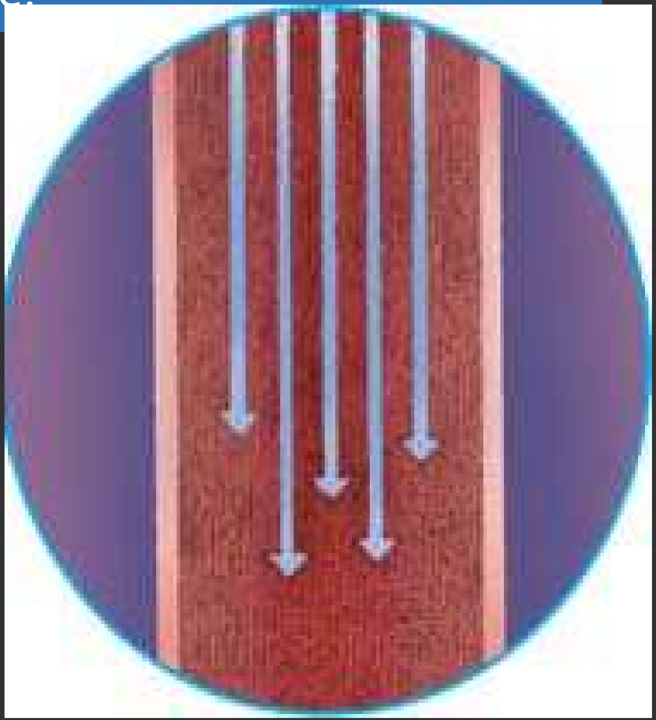
This flow type occurs mainly in the small peripheral airways of the bronchial tree.

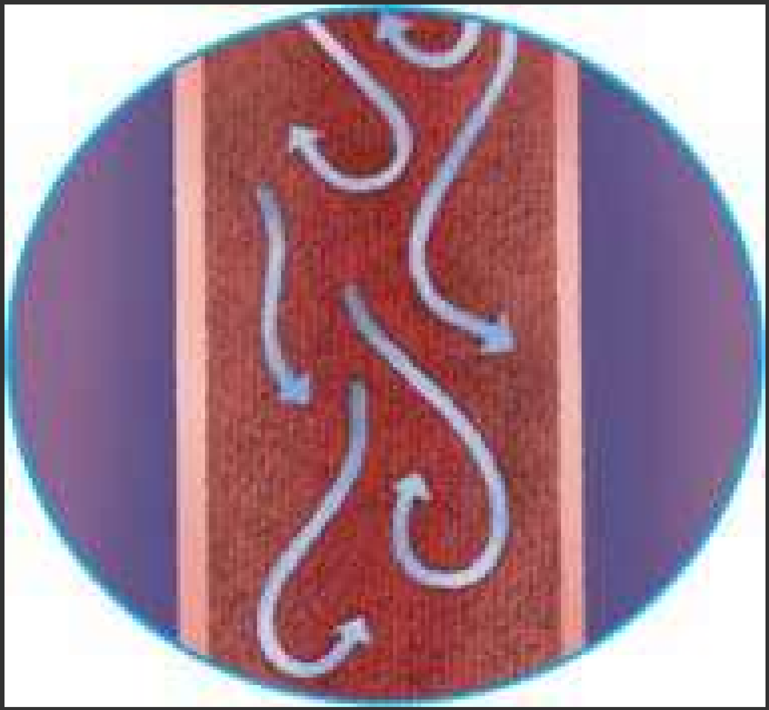
Turbulent flow

The eddying pattern of turbulent flow creates friction and increases resistance.

Turbulent flow is normal in the trachea and large central bronchi.

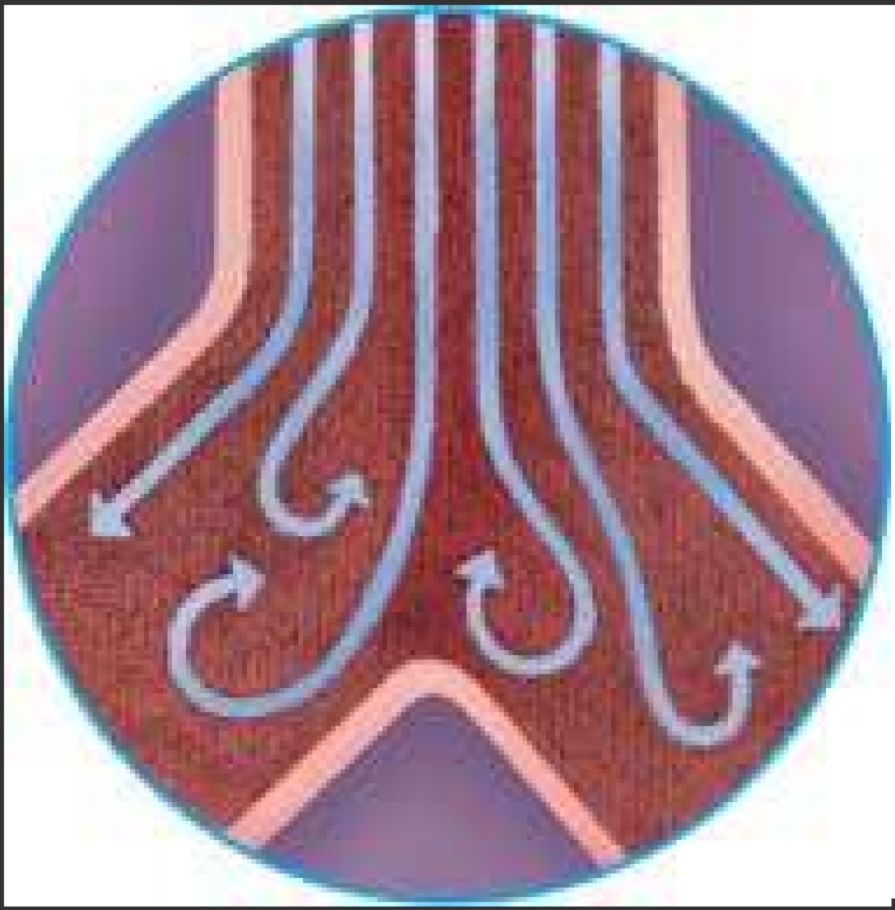
If the smaller airways become constricted or clogged with secretions, however, turbulent flow may also occur there.

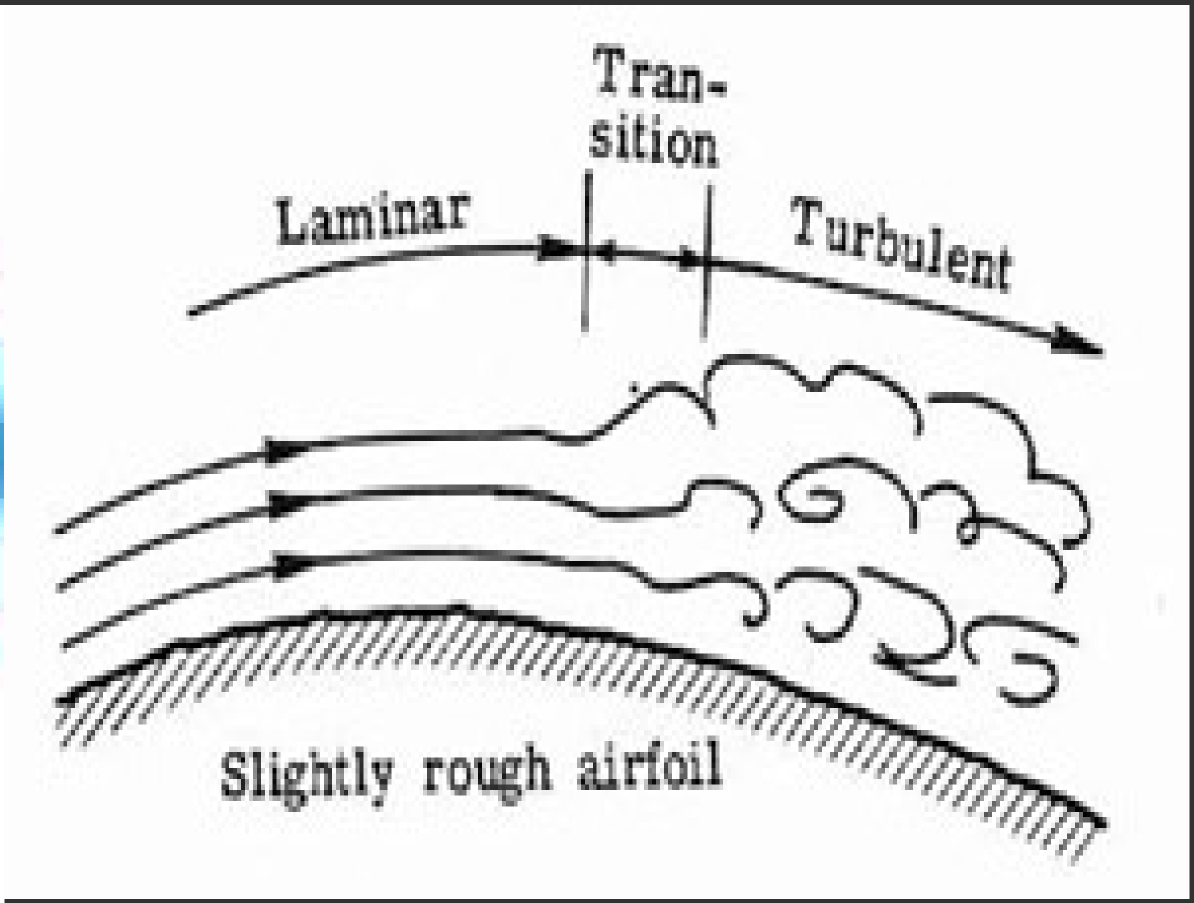




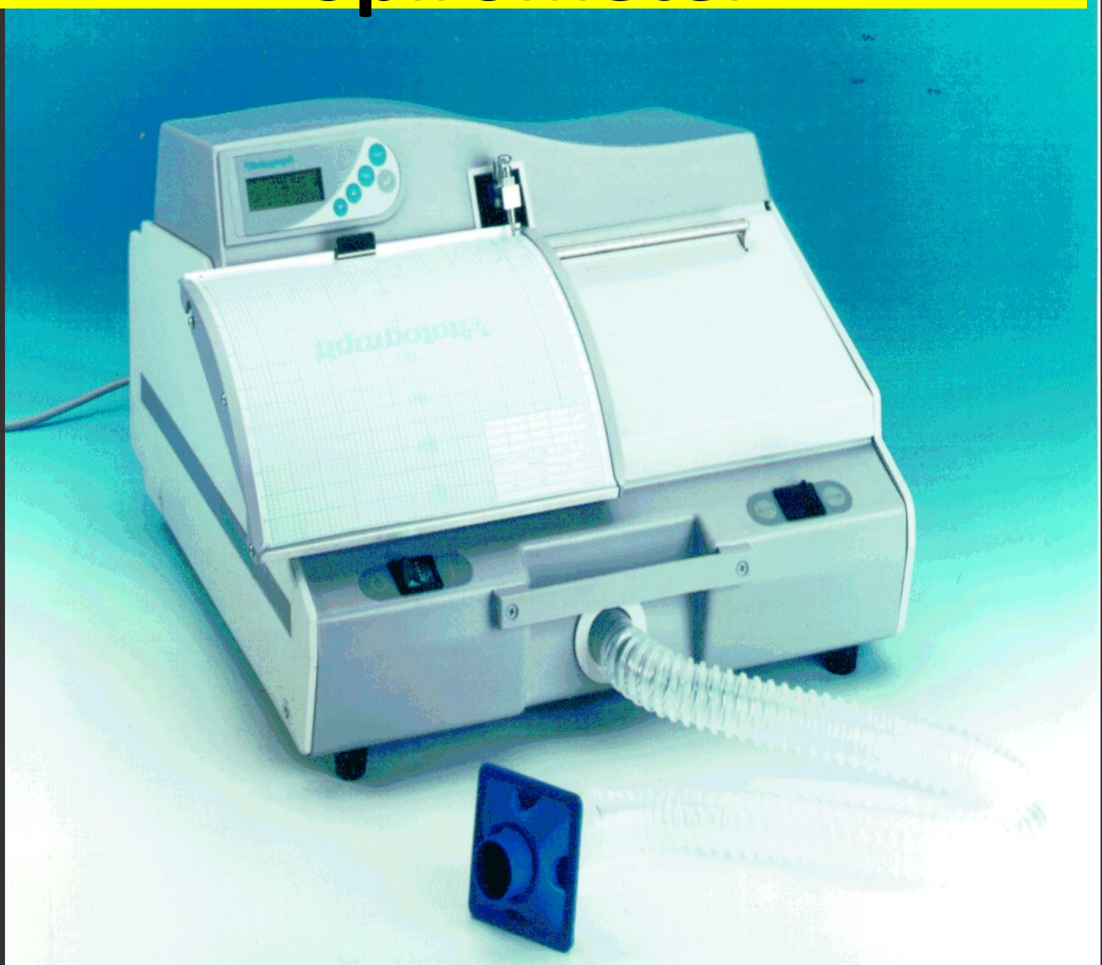
Transitional flow

A mixed pattern known as transitional flow is common at lower flow rates in the larger airways, especially where the airways narrow from obstruction, meet, or branch.

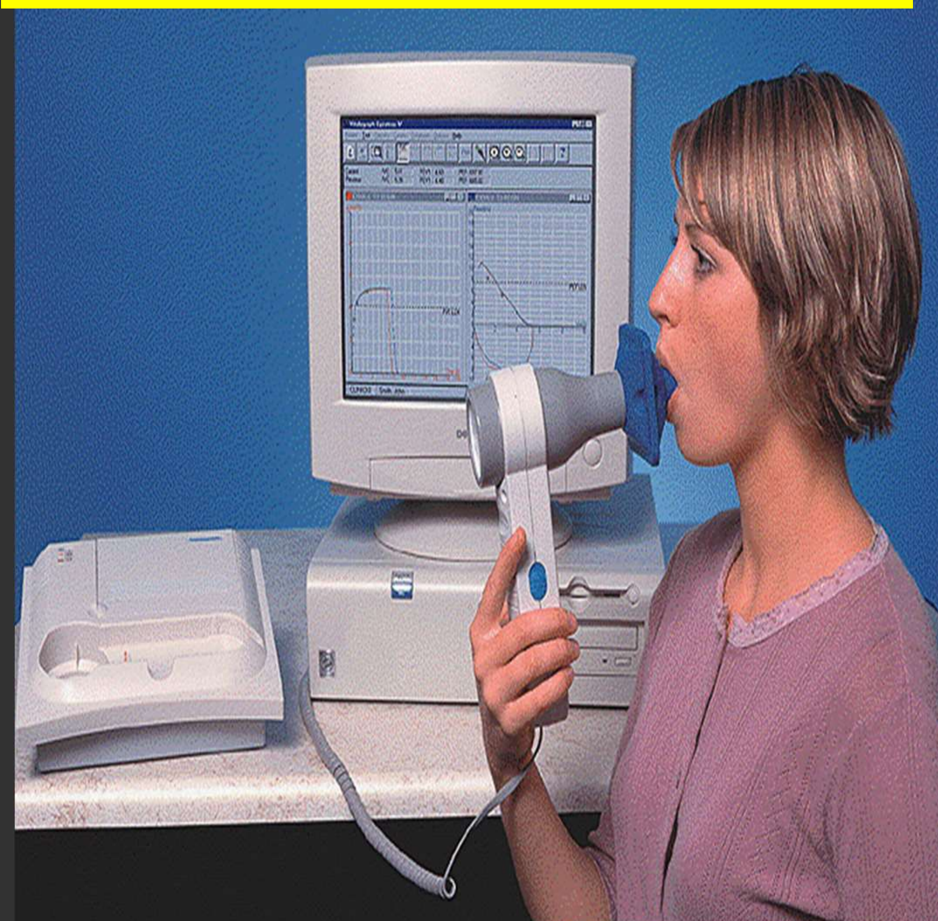




Volume Measuring Spirometer



Flow Measuring Spirometer



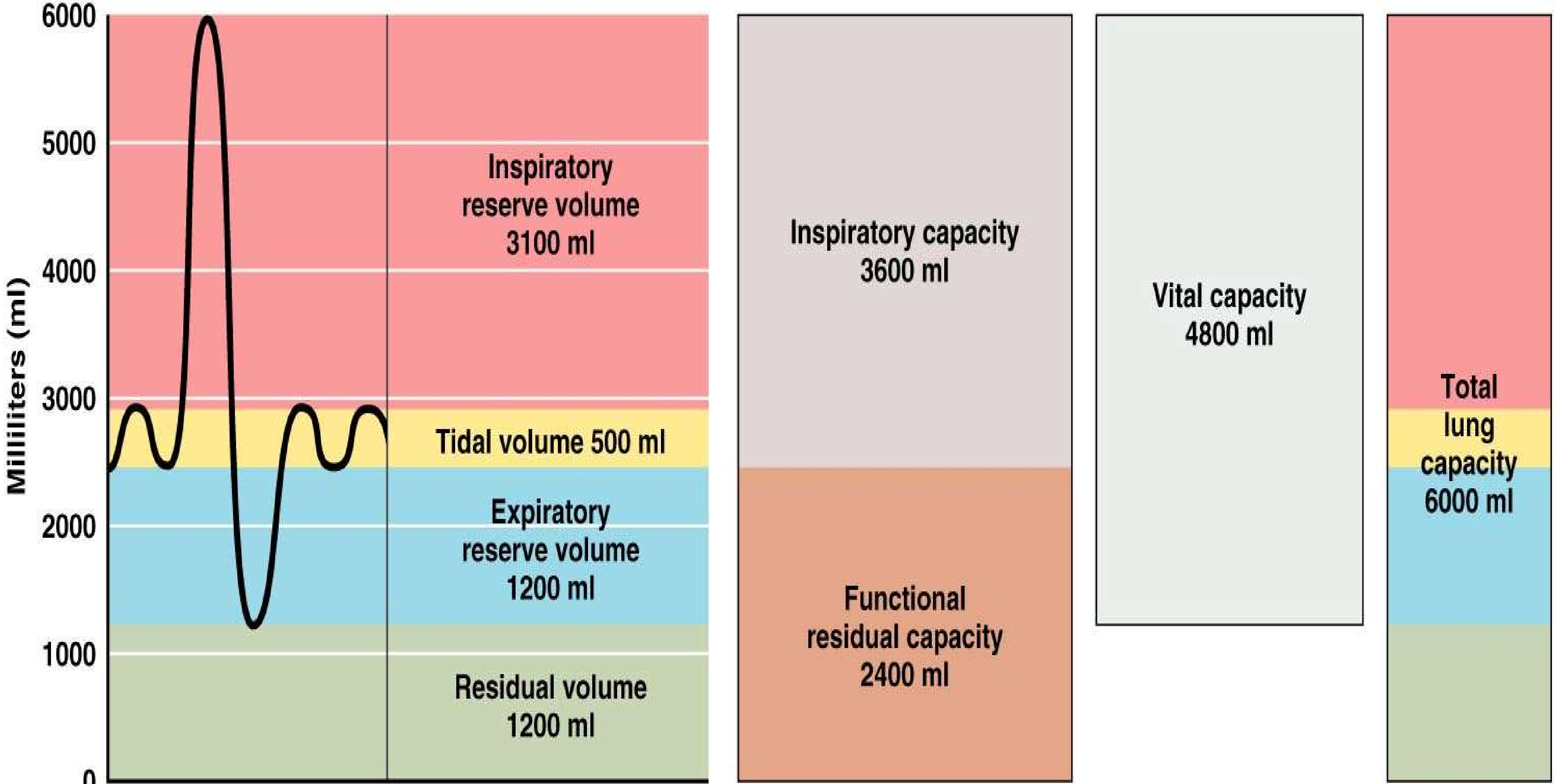
Desktop Electronic Spirometers

Small Hand-held Spirometers

Respiratory volumes

	Measurement	Adult male average value	Adult female average value	Description
Respiratory volumes	Tidal volume (TV)	500 ml	500 ml	Amount of air inhaled or exhaled with each breath under resting conditions
	Inspiratory reserve volume (IRV)	3100 ml	1900 ml	Amount of air that can be forcefully inhaled after a normal tidal volume inhalation
	Expiratory reserve volume (ERV)	1200 ml	700 ml	Amount of air that can be forcefully exhaled after a normal tidal volume exhalation
	Residual volume (RV)	1200 ml	1100 ml	Amount of air remaining in the lungs after a forced exhalation
Respiratory capacities	Total lung capacity (TLC)	6000 ml	4200 ml	Maximum amount of air contained in lungs after a maximum inspiratory effort: TLC = TV + IRV + ERV + RV
	Vital capacity (VC)	4800 ml	3100 ml	Maximum amount of air that can be expired after a maximum inspiratory effort: VC = TV + IRV + ERV (should be 80% TLC)
	Inspiratory capacity (IC)	3600 ml	2400 ml	Maximum amount of air that can be inspired after a normal expiration: IC = TV + IRV
	Functional residual capacity (FRC)	2400 ml	1800 ml	Volume of air remaining in the lungs after a normal tidal volume expiration: FRC = ERV + RV

(b) Summary of respiratory volumes and capacities for males and females



(a) Spirographic record for a male

- **The following terms describe the various lung (respiratory) volumes:**

- **The tidal volume (TV),** about 500 ml, is the ***amount of air inspired during normal, relaxed breathing***.

- **The inspiratory reserve volume (IRV),** about 3,100 ml, is the ***additional air that can be forcibly inhaled after the inspiration of a normal tidal volume***.

- **The expiratory reserve volume (ERV),** about 1,200 ml, is ***the additional air that can be forcibly exhaled after the expiration of a normal tidal volume.***

- **Residual volume (RV),** about 1,200 ml, ***is the volume of air still remaining in the lungs after the expiratory reserve volume is exhaled.***

Summing specific lung volumes produces the following lung capacities:

- **The total lung capacity (TLC),** about **6,000 ml**, **is the maximum amount of air that can fill the lungs**
  - (***TLC = TV + IRV + ERV + RV***).
- **The vital capacity (VC),** about **4,800 ml**, is **the total amount or air that can be expired after fully inhaling**
  - ***(VC = TV + IRV + ERV = approximately 80% TLC).***
- **The inspiratory capacity (IC),** about **3,600 ml**, is **the maximum amount of air that can be inspired**
  - ***(IC = TV + IRV).***
- **The functional residual capacity (FRC),** about **2,400 ml**, **is the amount of air remaining in the lungs after a normal expiration**
  - (FRC = RV + ERV).
- Some of the air in the lungs does not participate in gas exchange. Such air is located in the anatomical dead space within bronchi and bronchioles—that is, outside the alveoli.

Alveolar Ventilation

- **<u>Alveolar ventilation rate (AVR)</u>** –
- measures the flow of fresh gases into and out of the alveoli during a particular time

AVR	**=**	**frequency**	**X**	**(TV – dead space)**
(ml/min)		**(breaths/min)**		**(ml/breath)**

- Slow, deep breathing increases AVR and rapid, shallow breathing decreases AVR

Dead Space

- **Anatomical dead space** – volume of the conducting respiratory passages (150 ml)
- **Alveolar dead space** – alveoli that cease to act in gas exchange due to collapse or obstruction
- **Total dead space** – sum of alveolar and anatomical dead spaces

Respiration division

Respiration is divided into 4 processes:

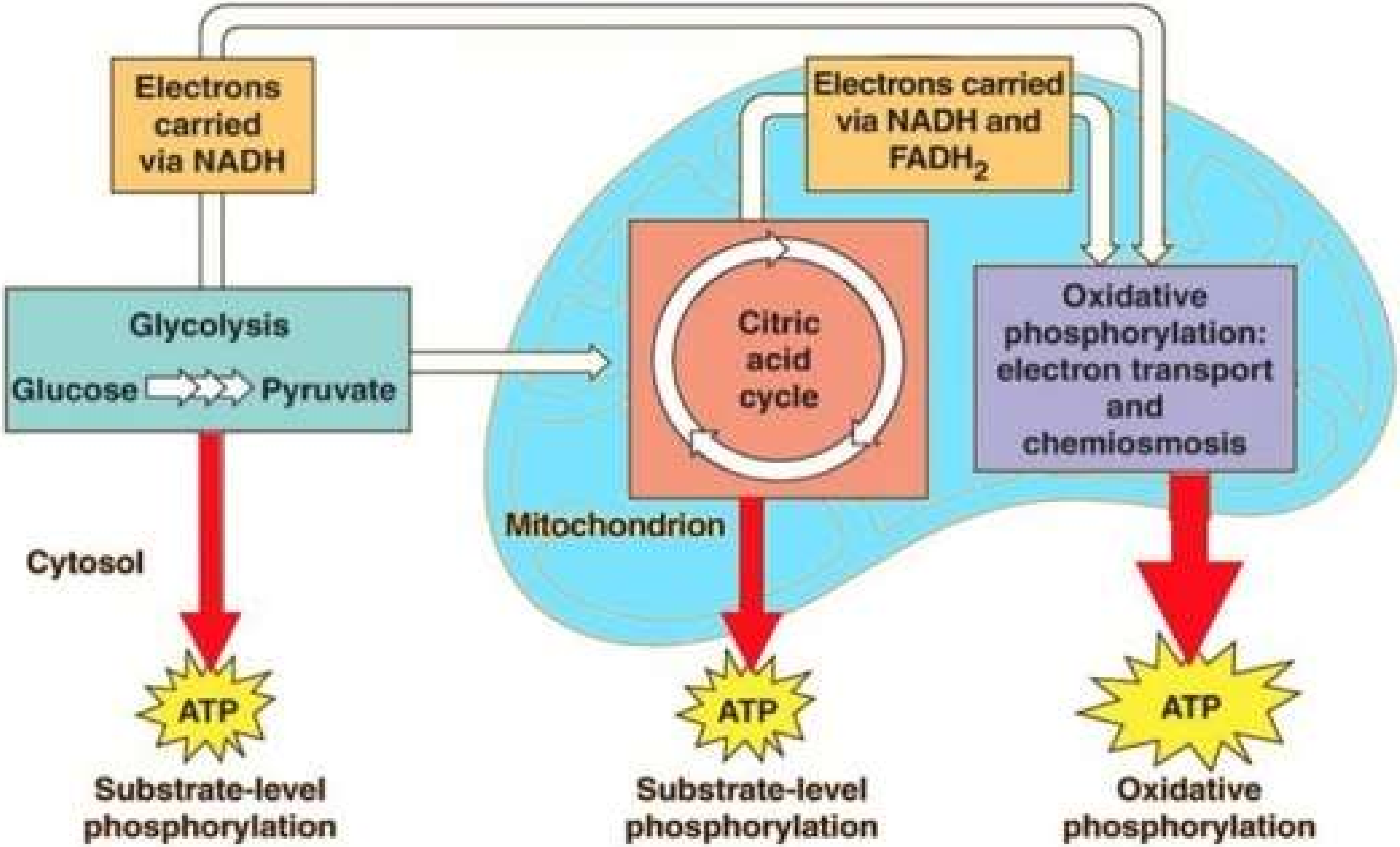
1. **Pulmonary ventilation** is the movement of air into/out of the lungs

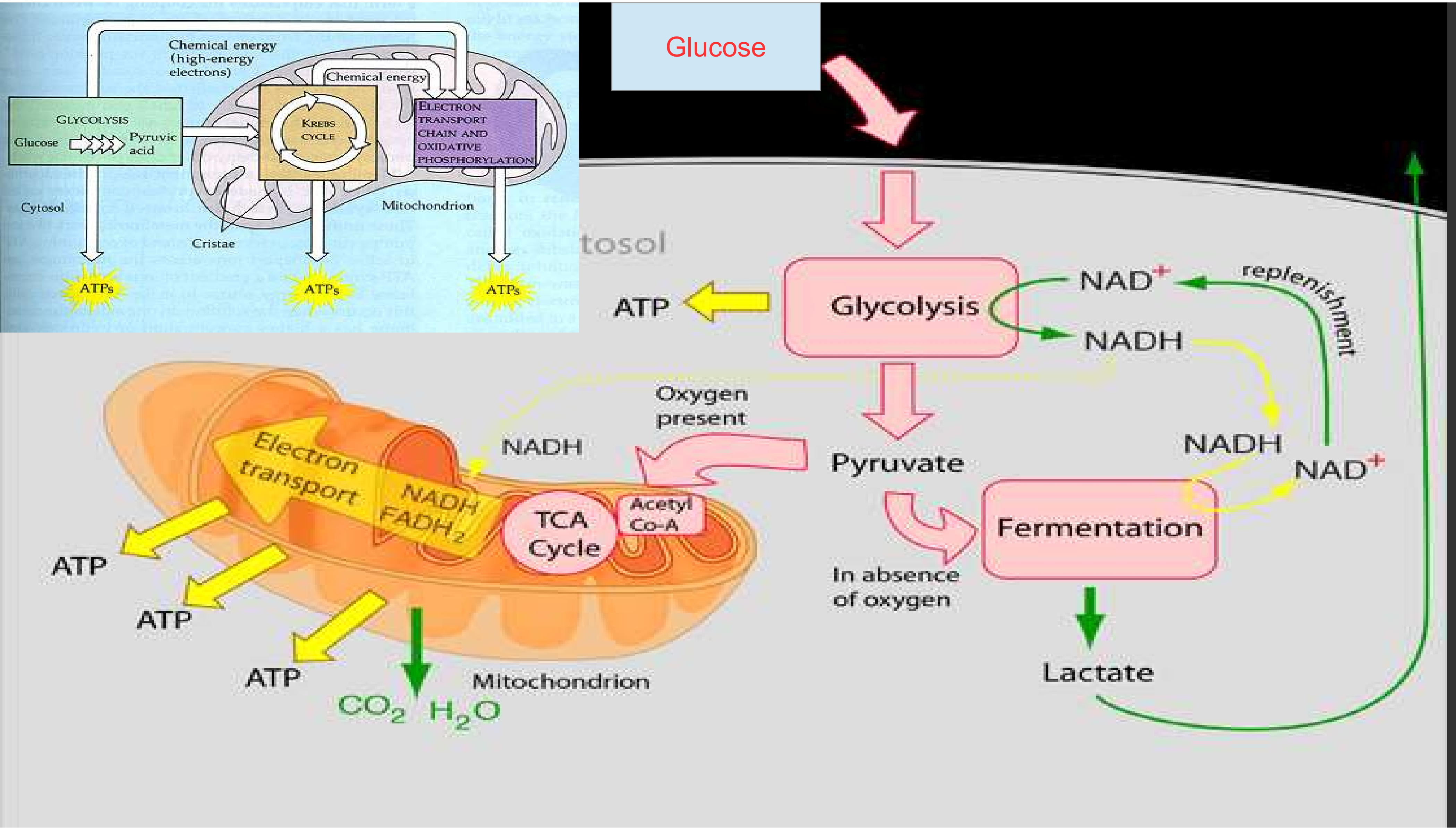
2. **External respiration** is the movement of O_2 from the lungs to the blood and CO_2 from the blood to the lungs.

3. **Internal respiration** is the movement of O_2 from the blood to the cell interior and CO_2 from the cell interior to the blood.

4. **Cellular respiration** is the breakdown of glucose, fatty acids and amino acids that occurs in mitochondria and results in production of ATP.

It requires O_2 and produces CO_2. (Note that this type of cellular respiration, which requires O_2, is known as "aerobic metabolism," whereas breakdown of glucose that produces ATP but does not require O_2 is "anaerobic metabolism.")


Electrons carried via NADH
Electrons carried via NADH and $FADH_2$
Glycolysis
Glucose
Pyruvate
Citric acid cycle
Oxidative phosphorylation: electron transport and chemiosmosis
Mitochondrion
Cytosol
ATP
ATP
ATP
Substrate-level phosphorylation
Substrate-level phosphorylation
Oxidative phosphorylation


Chemical energy (high-energy electrons)
Chemical energy
GLYCOLYSIS
Glucose
Pyruvic acid
KREBS CYCLE
ELECTRON TRANSPORT CHAIN AND OXIDATIVE PHOSPHORYLATION
Cytosol
Mitochondrion
Cristae
ATPs
ATPs
ATPs
Glucose
tosol
ATP
Glycolysis
NAD+
NADH
replenishment
Oxygen present
NADH
Pyruvate
NADH
NAD+
Electron transport
NADH
FADH2
TCA Cycle
Acetyl Co-A
Fermentation
In absence of oxygen
ATP
ATP
ATP
Lactate
Mitochondrion
CO2 H2O

Compliance

- Describes distensibility of respiratory system
- Describes change in lung volume for a given change in pressure (C = V/P)
- ↑ compliance in emphysema
- ↓ compliance in pulmonary fibrosis, pulmonary edema, ARDS, chest wall disease

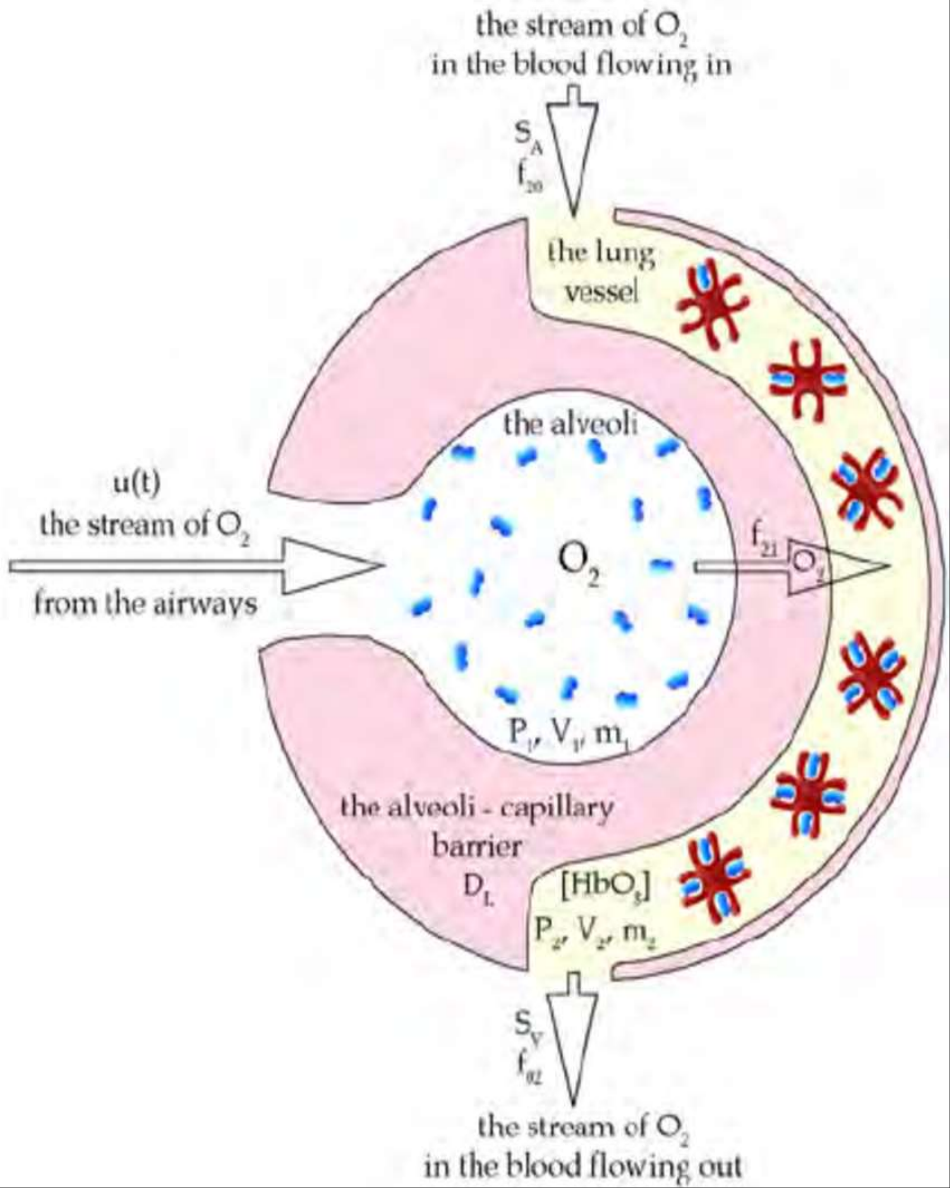
- Measure of the ease with which lungs and thorax expand
  - The greater the compliance, the easier it is for a change in pressure to cause expansion
  - A lower-than-normal compliance means the lungs and thorax are harder to expand
    - Conditions that decrease compliance
      - Pulmonary fibrosis
      - Pulmonary edema
      - Respiratory distress syndrome

Elastance

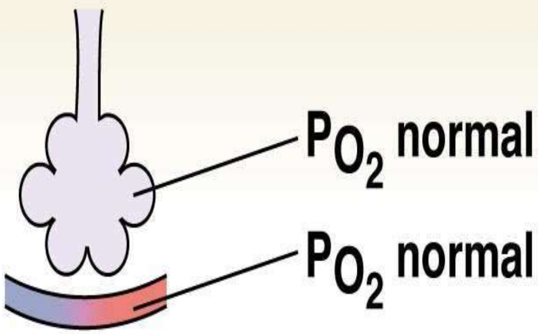
- Describes elastic properties (inverse of compliance, elastance = P/V)
- Lungs tend to collapse inward
- Chest wall tends to expand outward

4 rules for diffusion of gas

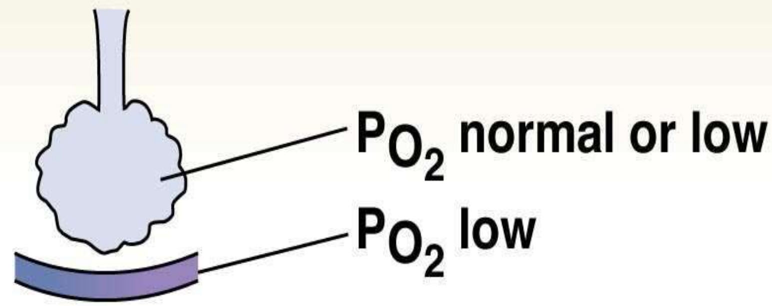
- Surface area
- Thickness
- Concentration
- Distance



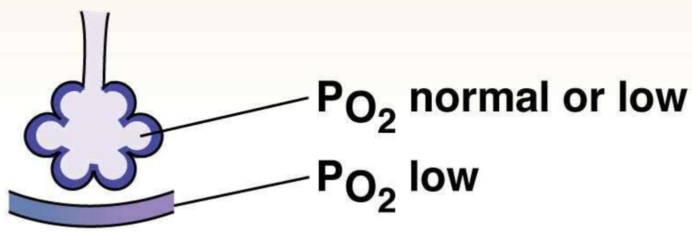
(a) Normal lung



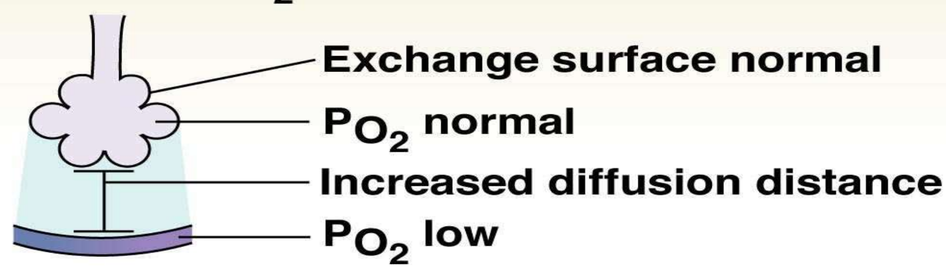
(b) Emphysema: destruction of alveoli reduces surface area for gas exchange.



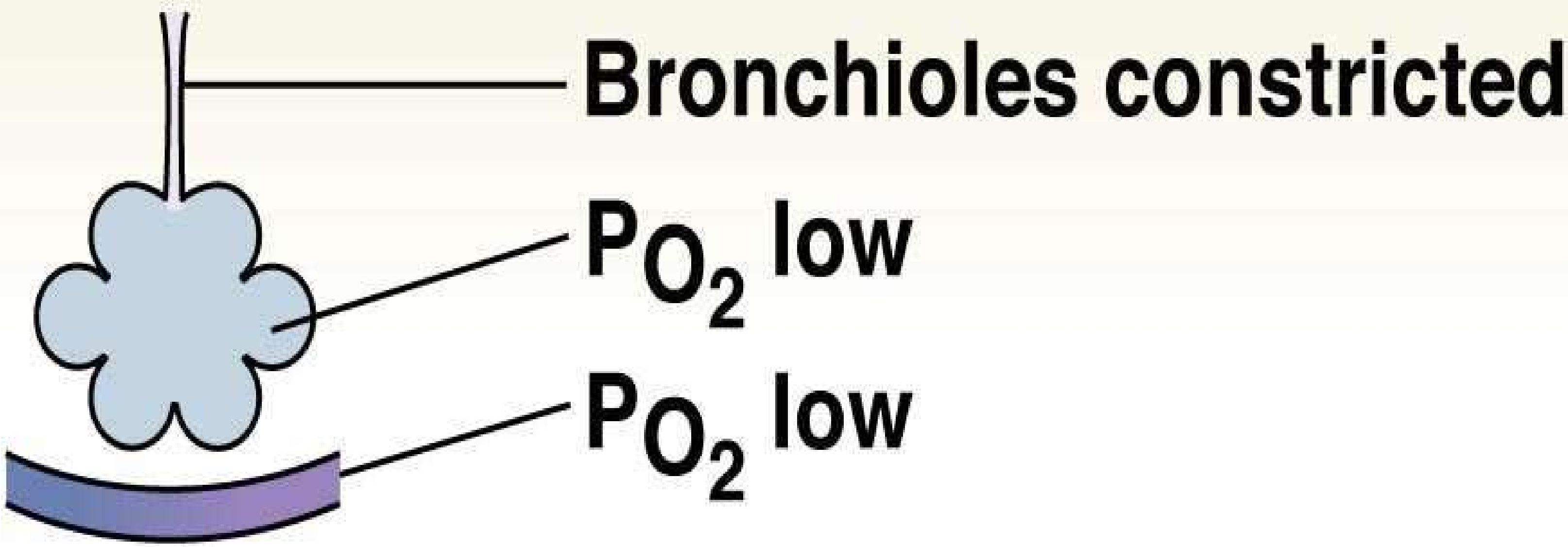
(c) Fibrotic lung disease: thickened alveolar membrane slows gas exchange. Loss of lung compliance may decrease alveolar ventilation.



(d) Pulmonary edema: fluid in interstitial space increases diffusion distance. Arterial P_{CO_2} may be normal due to higher CO_2 solubility in water.



(e) Asthma: increased airway resistance decreases airway ventilation.



Diaphragm structures

Structures perforating diaphragm:

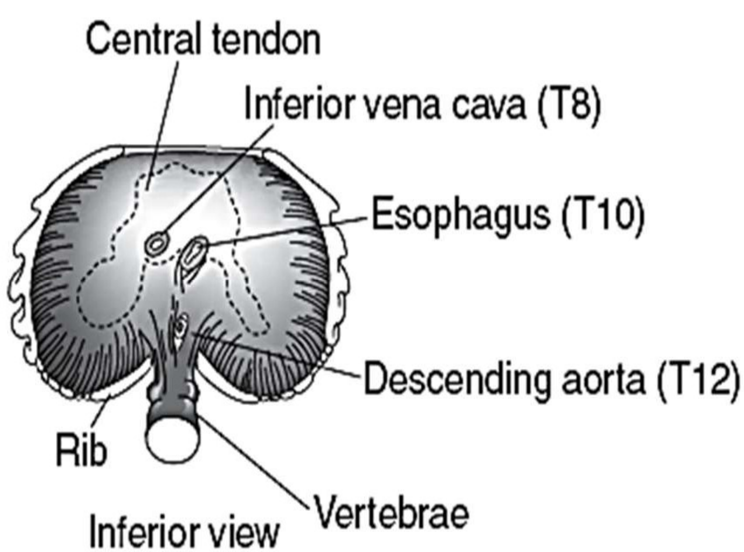
- At T8: IVC.
- At T10: esophagus, vagus (2 trunks).
- At T12: aorta (red), thoracic duct (white), azygous vein (blue).

Number of letters = T level:

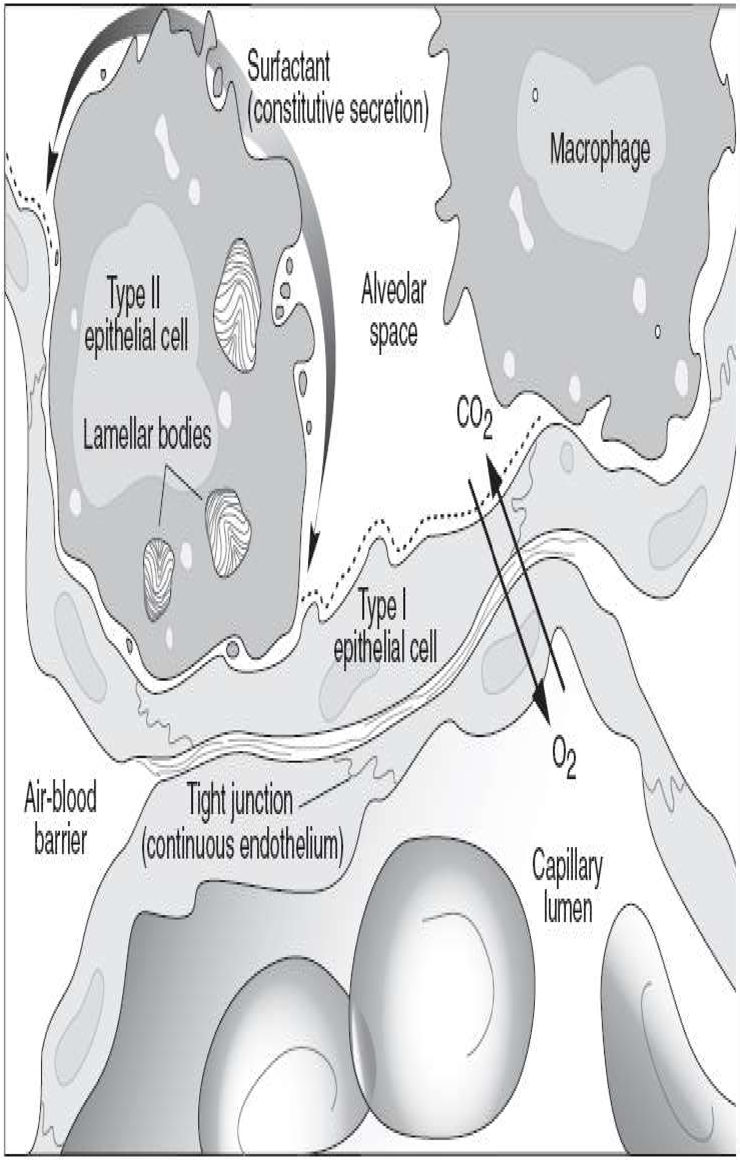
- T8: vena cava
- T10: (o)esophagus
- T12: aortic hiatus

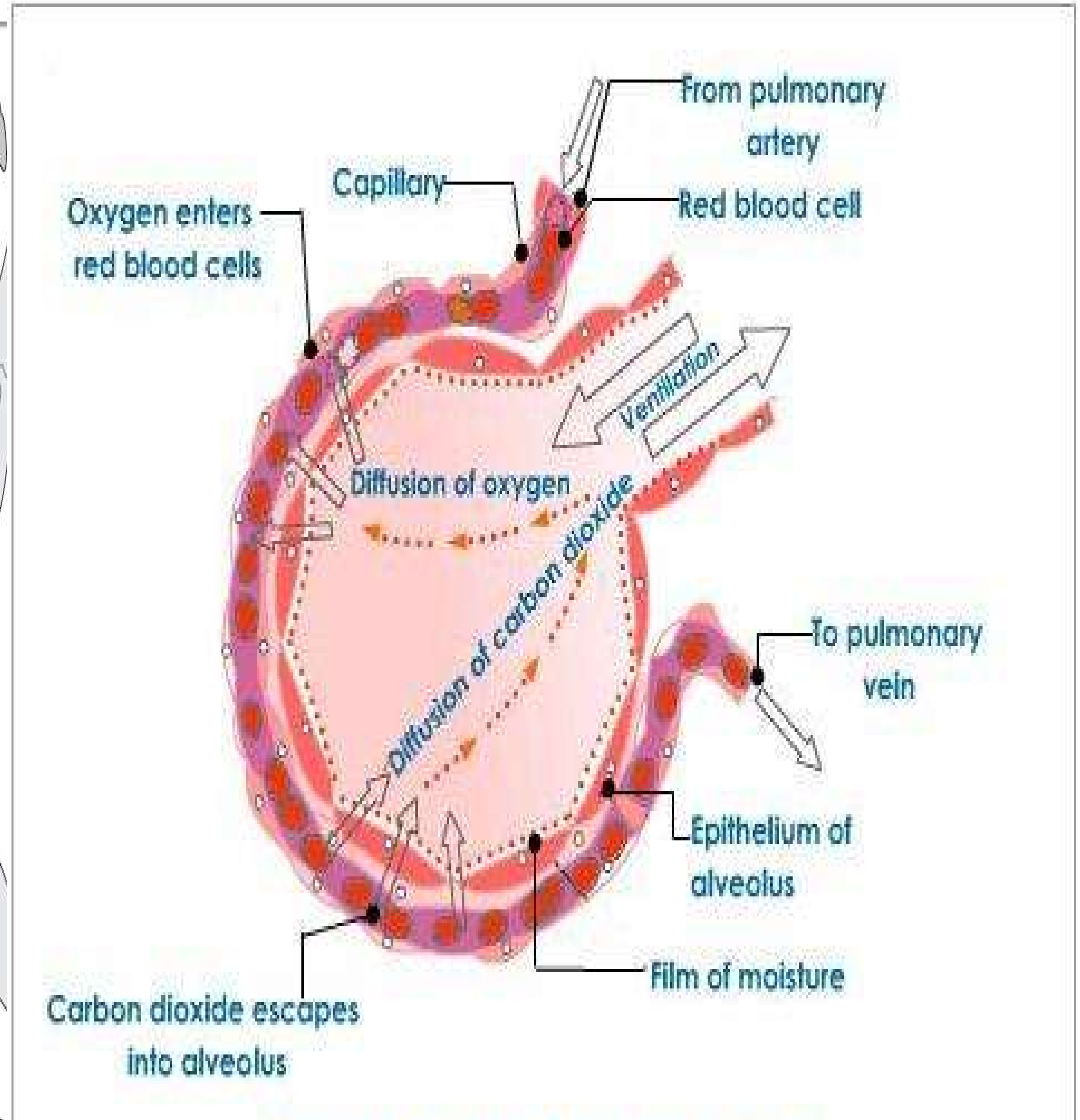
Diaphragm is innervated by C3, 4, and 5 (phrenic nerve). Pain from the diaphragm can be referred to the shoulder.

"C3, 4, 5 keeps the diaphragm alive."



Gas exchange barrier

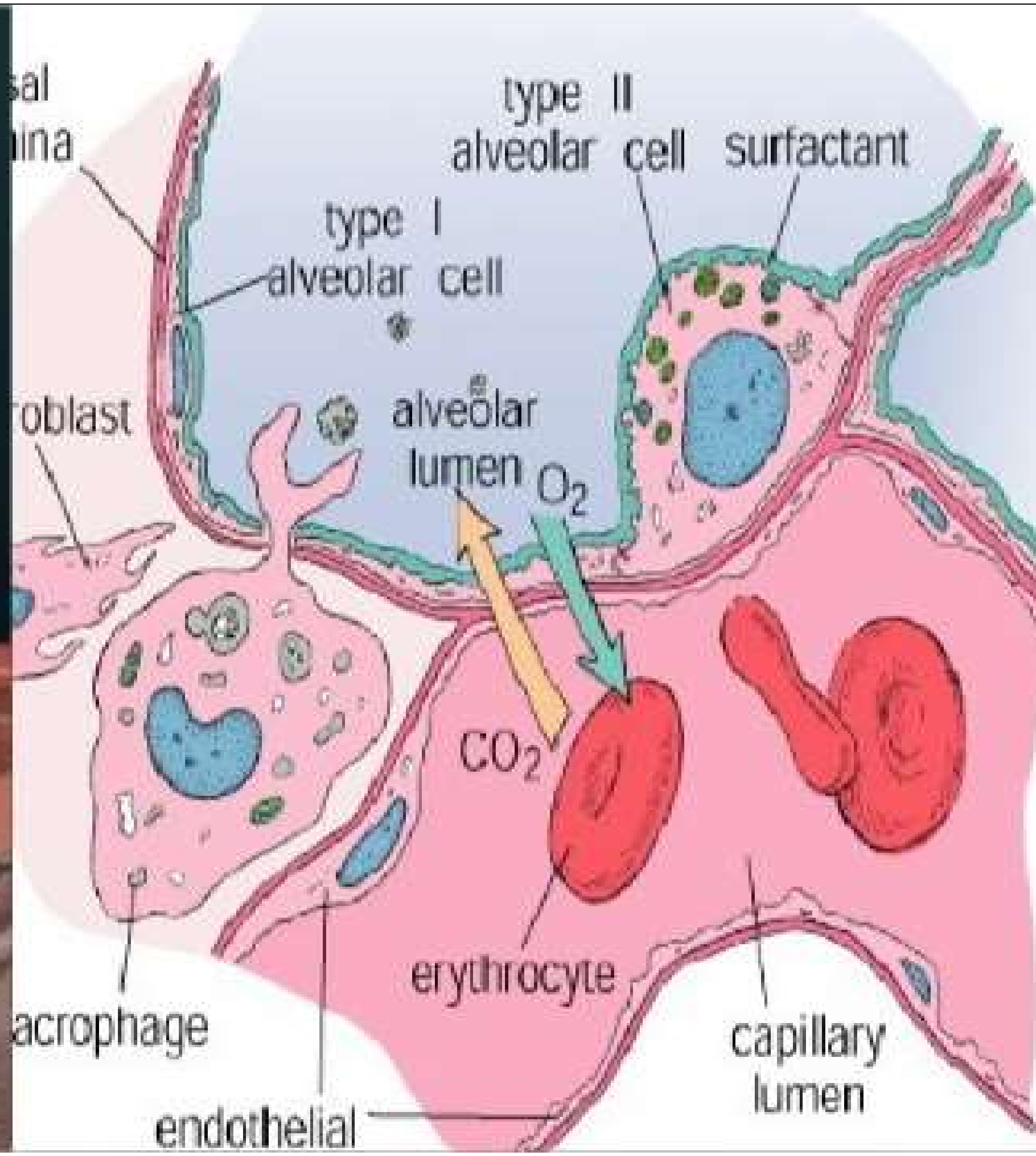




Gaseous Exchange in the Alveolus of Man

Blood air barrier:

Wall through which gas exchange occur. It is present in() blood in the capillaries & air within lung alveoli.



Pneumocytes	Pseudocolumnar ciliated cells extend to the respiratory bronchioles; goblet cells extend only to the terminal bronchioles. Type I cells (97% of alveolar surfaces) line the alveoli. Squamous; thin for optimal gas diffusion. Type II cells (3%) secrete pulmonary surfactant (dipalmitoyl phosphatidylcholine), which ↓ the alveolar surface tension. Cuboidal and clustered. Also serve as precursors to type I cells and other type II cells. Type II cells proliferate during lung damage. Clara cells—nonciliated; columnar with secretory granules. Secrete component of surfactant; degrade toxins; act as reserve cells.	Mucus secretions are swept out of the lungs toward the mouth by ciliated cells. A lecithin-to-sphingomyelin ratio of > 2.0 in amniotic fluid is indicative of fetal lung maturity.

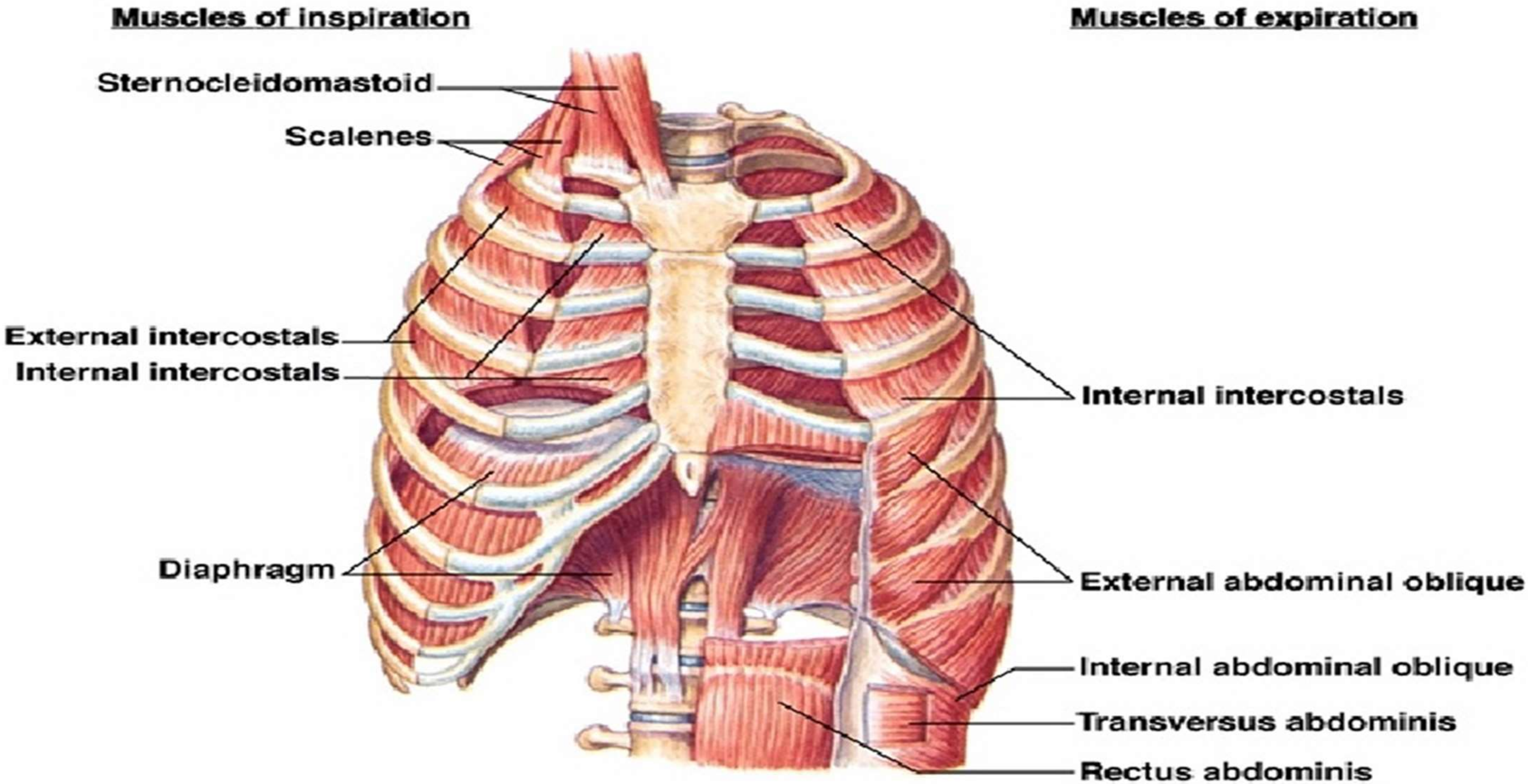
Club cells →

Club cells, also known as bronchiolar exocrine cells, and originally known as **Clara cells**, are dome-shaped cells with short microvilli, found in the small airways (bronchioles) of the lungs. Club cells are found in the ciliated simple epithelium

Muscles of respiration

Quiet breathing:
- Inspiration—–diaphragm.
- Expiration—–passive.

Exercise:
- Inspiration—–external intercostals, scalene muscles, sternomastoids.
- Expiration—–rectus abdominis, internal and external obliques, transversus abdominis, internal intercostals.



Muscles of inspiration
Muscles of expiration
Sternocleidomastoid
Scalenes
External intercostals
Internal intercostals
Diaphragm
Internal intercostals
External abdominal oblique
Internal abdominal oblique
Transversus abdominis
Rectus abdominis

Deep Forceful Breathing

- **Deep Inhalation**

  During deep forceful inhalation accessory muscles of inhalation participate to increase size of thoracic cavity

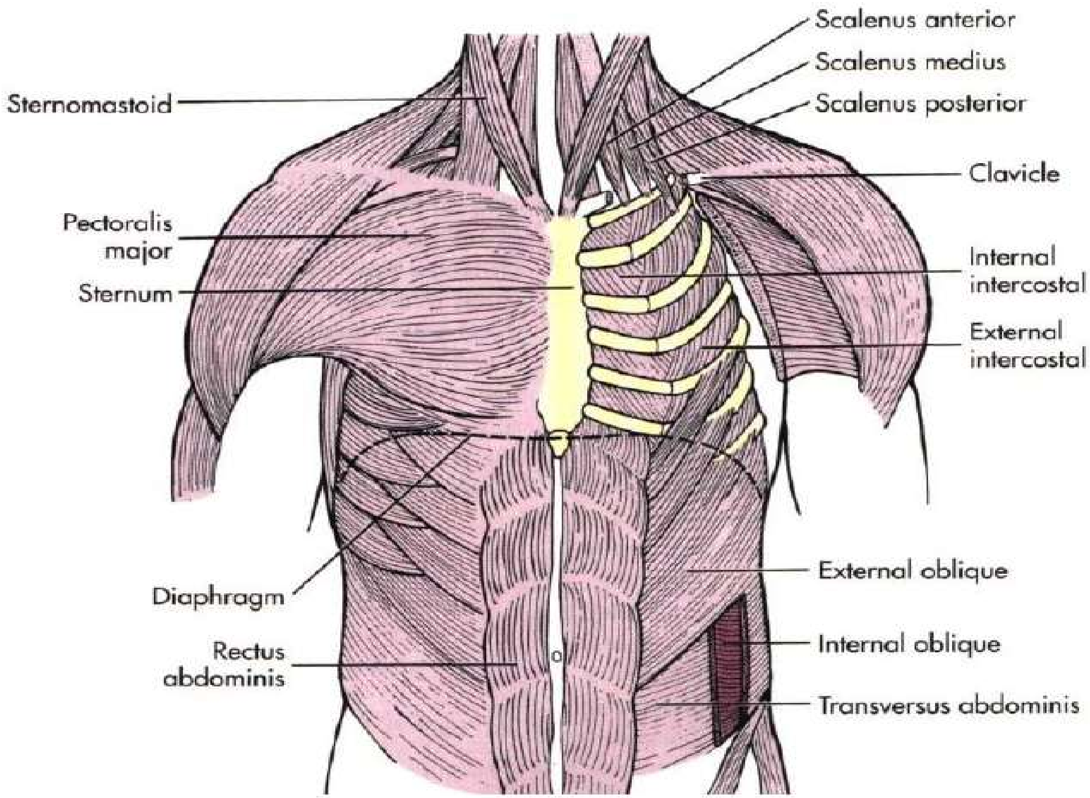
  - **Sternocleidomastoid – elevate sternum**
  - **Scalenes – elevate first two ribs**
  - **Pectoralis minor – elevate 3rd–5th ribs**

- **Deep Exhalation**

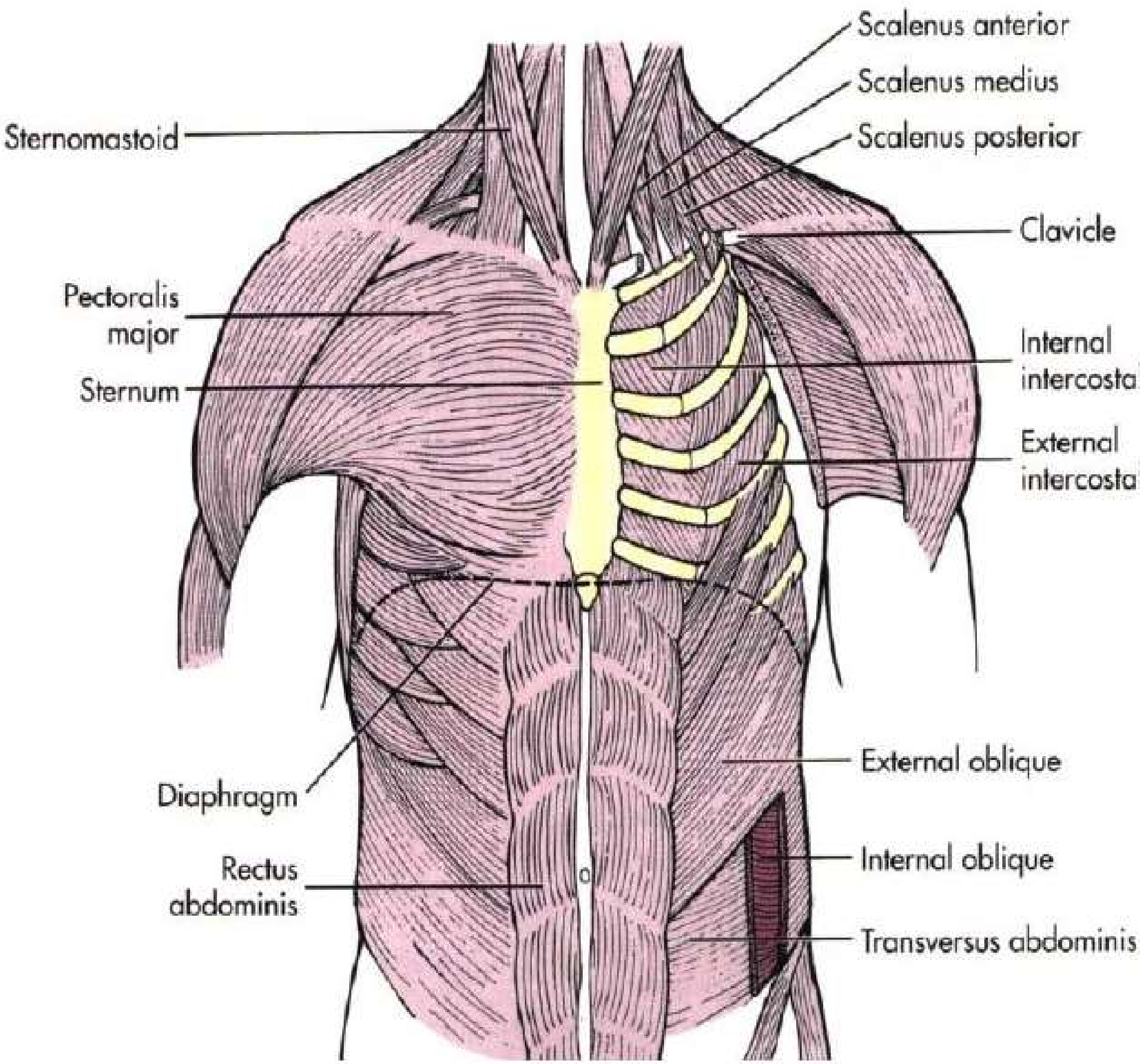
  Exhalation during forceful breathing is active process

  - **Muscles of exhalation increase pressure in abdomen and thorax**
    - Abdominals
    - Internal intercostals

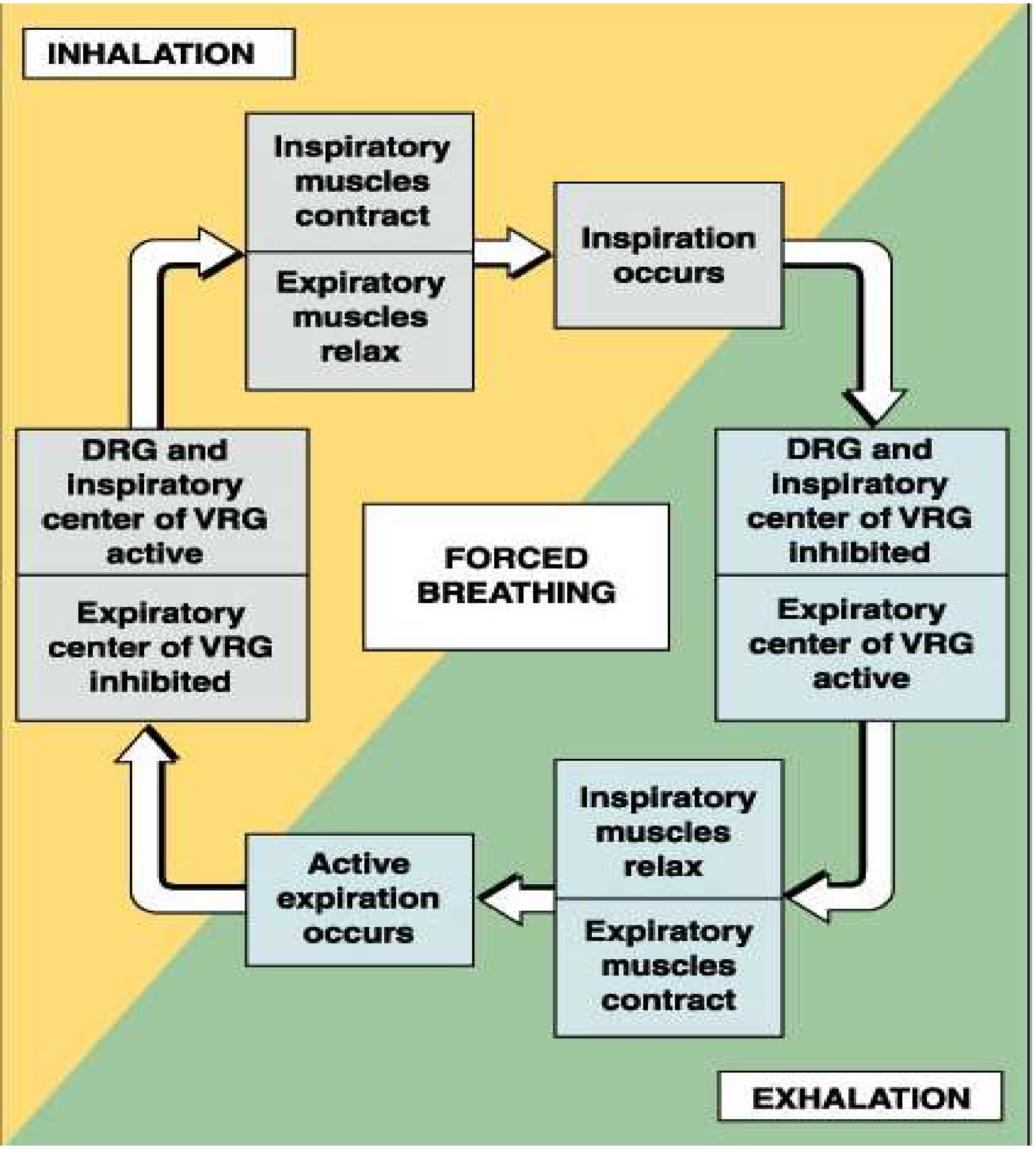
Respiratory Muscles

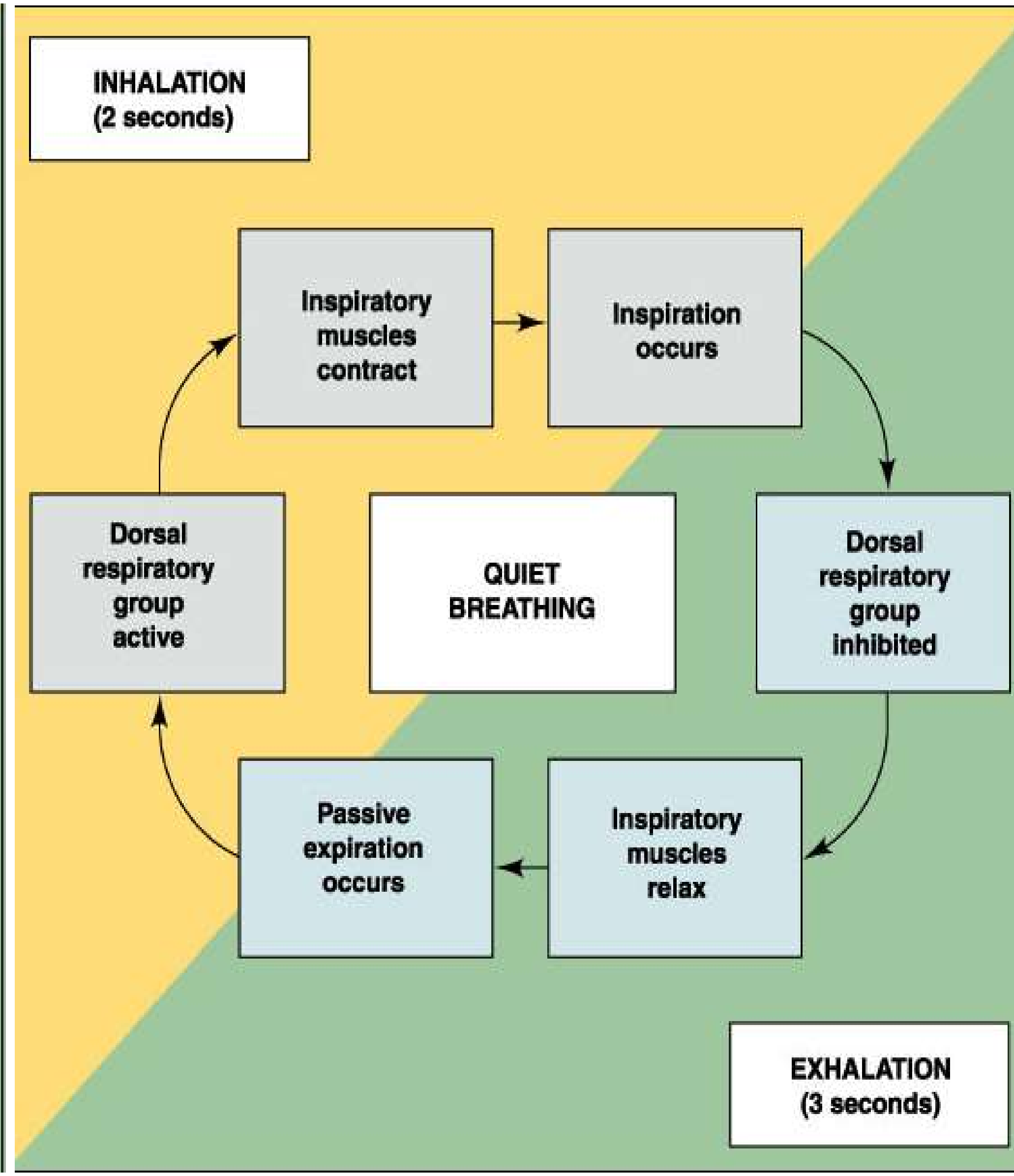


- Scalene Muscles
  - Neck muscles
  - Attach to 1st /2nd rib
  - Assist ventilatory demands
  - Alveolar pressure > -10cmH20
- Sternomastoid
  - Manubrium / clavicle
- Pectoralis Major
  - Clavicle / sternum



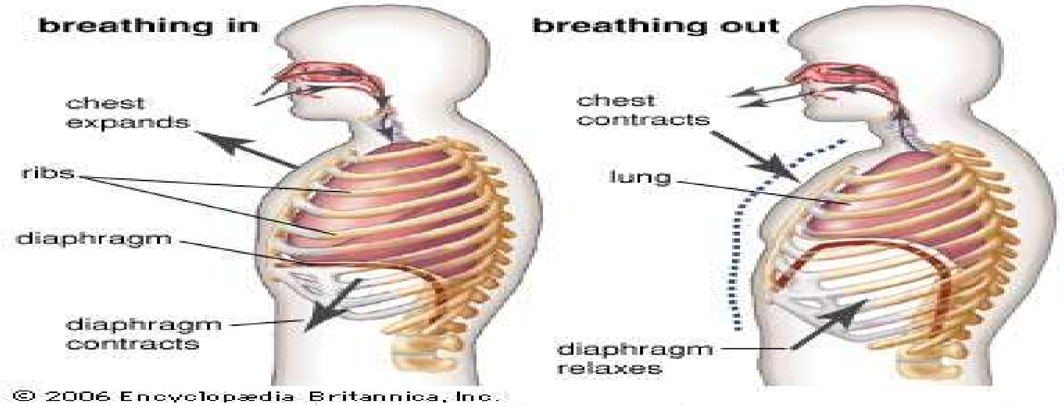
- Abdominal Muscles
  - External oblique
  - Internal oblique
  - Transverse abdominus
  - Rectus abdominus
- Inactive during quiet breathing
- Active > 40L/min

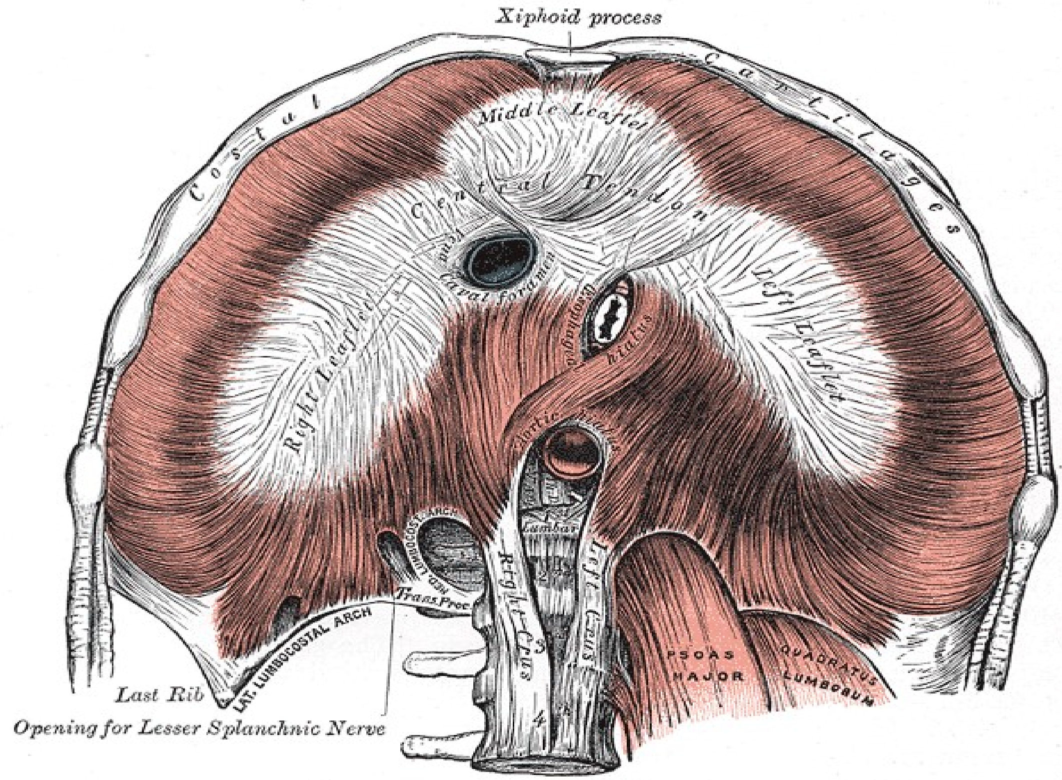

INHALATION
Inspiratory muscles contract
Expiratory muscles relax
Inspiration occurs
DRG and inspiratory center of VRG active
Expiratory center of VRG inhibited
FORCED BREATHING
DRG and inspiratory center of VRG inhibited
Expiratory center of VRG active
Inspiratory muscles relax
Expiratory muscles contract
Active expiration occurs
EXHALATION


INHALATION (2 seconds)
Inspiratory muscles contract
Inspiration occurs
Dorsal respiratory group active
QUIET BREATHING
Dorsal respiratory group inhibited
Passive expiration occurs
Inspiratory muscles relax
EXHALATION (3 seconds)

- Primary Ventilatory Muscles
  - Diaphragm

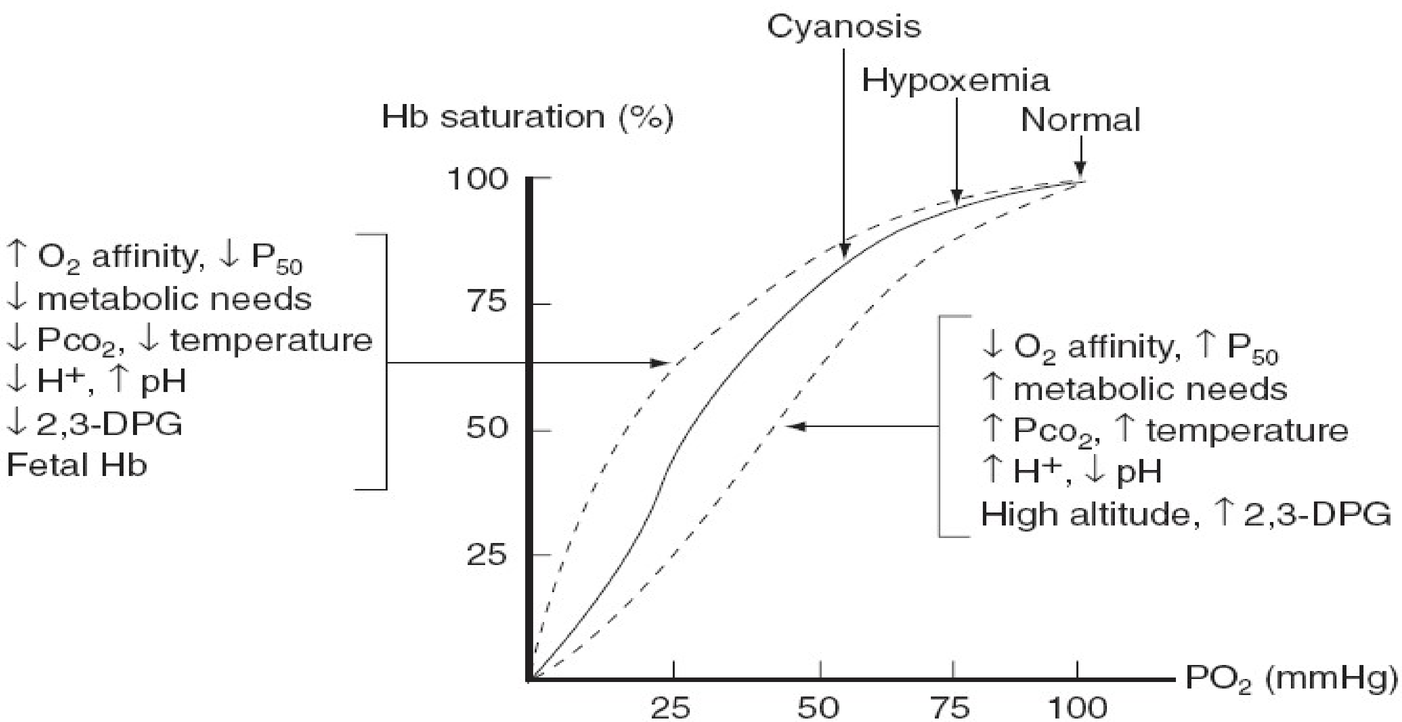
    - Divides Chest/Abdomen
    - 75% of gas movement
    - 1.5cm movement during quiet breathing
  - Inspiration – contraction
  - Expiration – relaxation
    - Elastic Recoil





Important lung products	1. Surfactant—produced by type II pneumocytes, ↓ alveolar surface tension, ↑ compliance, ↓ work of inspiration 2. Prostaglandins 3. Histamine ↑ bronchoconstriction 4. Angiotensin-converting enzyme (ACE)—angiotensin I → angiotensin II; inactivates bradykinin (ACE inhibitors ↑ bradykinin and cause cough, angioedema) 5. Kallikrein—activates bradykinin	**Surfactant**—dipalmitoyl phosphatidylcholine (lecithin) deficient in neonatal RDS. Collapsing pressure = $\frac{2\ (\text{tension})}{\text{radius}}$

Oxygen-hemoglobin dissociation curve



Sigmoidal shape due to positive cooperativity, i.e., hemoglobin can bind 4 oxygen molecules and has higher affinity for each subsequent oxygen molecule bound.

When curve shifts to the right, ↓ affinity of hemoglobin for O_2 (facilitates unloading of O_2 to tissue).

An ↑ in all factors (except pH) causes a shift of the curve to the right.

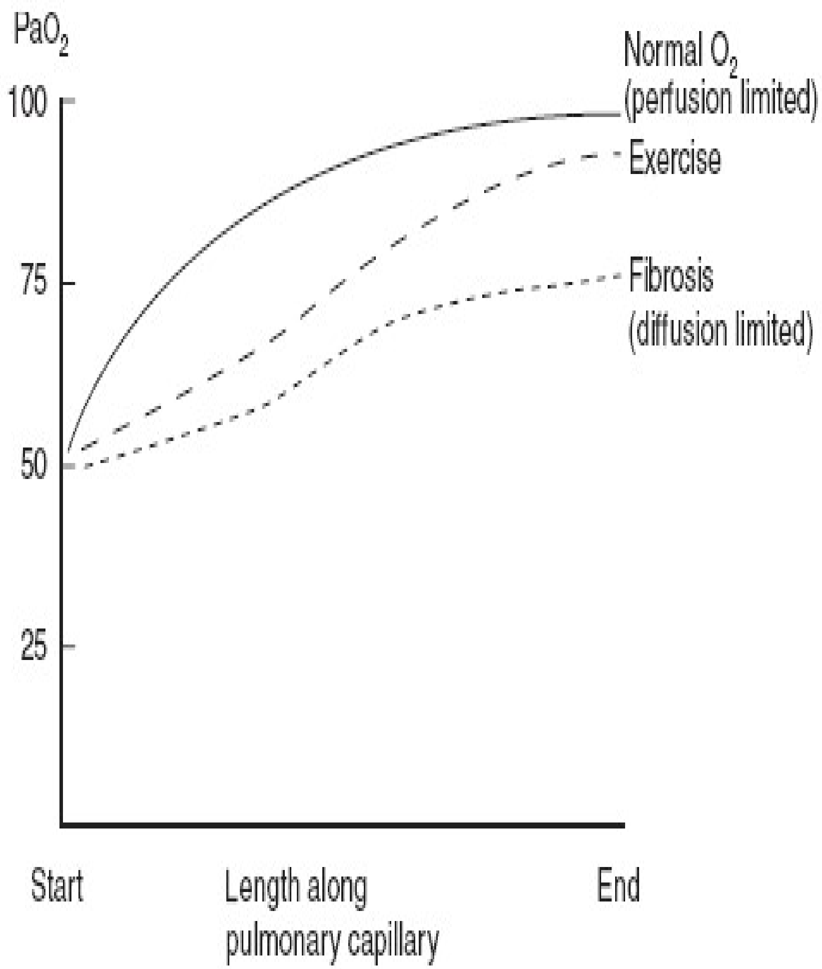
A ↓ in all factors (except pH) causes a shift of the curve to the left.

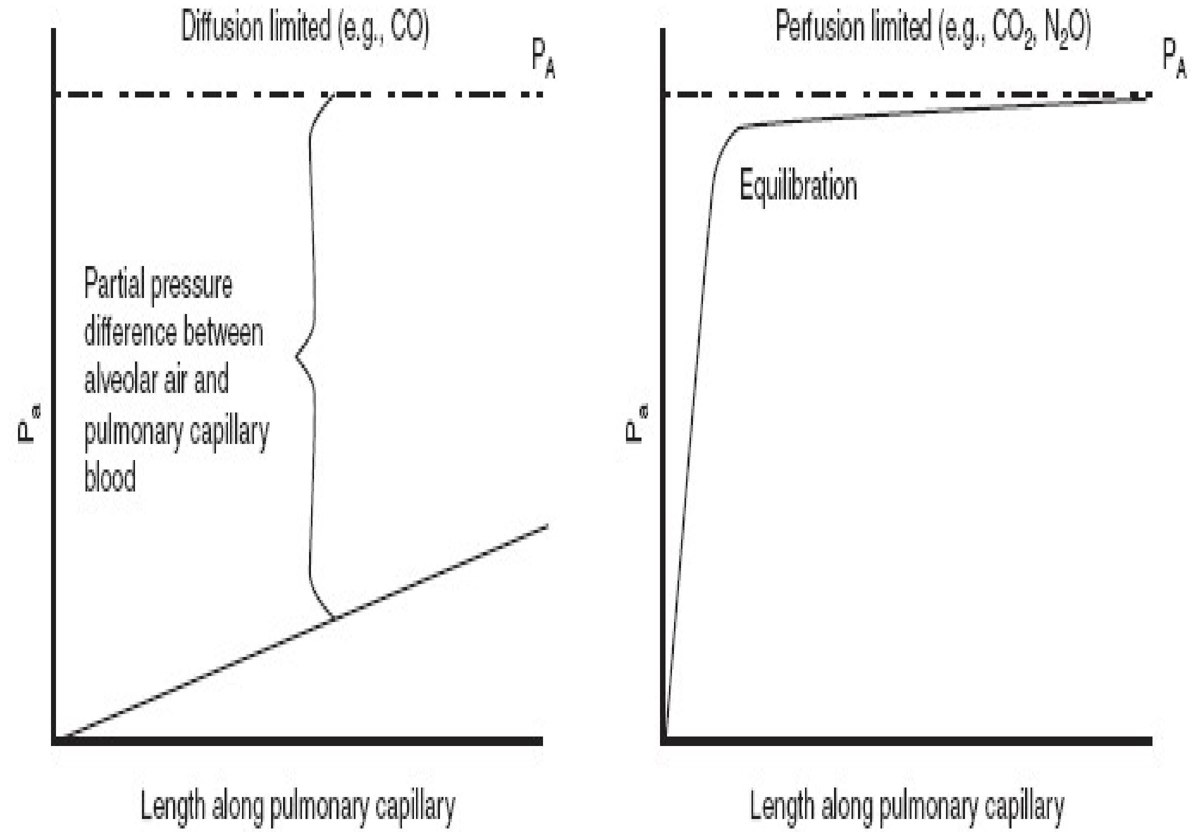
Fetal Hb has a higher affinity for oxygen than adult Hb, so its dissociation curve is shifted left.

Right shift—**CADET** face **right:**

- **C**O_2
- **A**cid/**A**ltitude
- **D**PG (2,3-DPG)
- **E**xercise
- **T**emperature

Pulmonary circulation	Normally a low-resistance, high-compliance system. PO_2 and PCO_2 exert opposite effects on pulmonary and systemic circulation. A ↓ in PaO_2 causes a hypoxic vasoconstriction that shifts blood away from poorly ventilated regions of lung to well-ventilated regions of lung. 1. Perfusion limited—O_2 (normal health), CO_2, N_2O. Gas equilibrates early along the length of the capillary. Diffusion can be ↑ only if blood flow ↑. 2. Diffusion limited—O_2 (emphysema, fibrosis), CO. Gas does not equilibrate by the time blood reaches the end of the capillary.	A consequence of pulmonary hypertension is cor pulmonale and subsequent right ventricular failure (jugular venous distention, edema, hepatomegaly).





P_a = partial pressure of gas in pulmonary capillary blood
P_A = partial pressure of gas in alveolar air

Pulmonary vascular resistance (PVR)	$PVR = \frac{P_{pulm\ artery} - P_{L\ atrium}}{Cardiac\ output}$ Remember: $\Delta P = Q \times R$, so $R = \Delta P / Q$. $R = 8\eta l / \pi r^4$	$P_{pulm\ artery}$ = pressure in pulmonary artery. $P_{L\ atrium}$ = pulmonary wedge pressure. η = the viscosity of inspired air; l = airway length; r = airway radius.

Oxygen content of blood	O_2 content = (O_2 binding capacity × % saturation) + dissolved O_2. Normally 1 g Hb can bind 1.34 mL O_2; normal Hb amount in blood is 15 g/dL. Cyanosis results when Hb is < 5 g/dL. O_2 binding capacity ≈ 20.1 mL O_2 / dL. O_2 content of arterial blood ↓ as Hb falls, but O_2 saturation and arterial Po_2 do not. Arterial Po_2 ↓ with chronic lung disease because physiologic shunt ↓ O_2 extraction ratio. Oxygen delivery to tissues = cardiac output × oxygen content of blood.

Alveolar gas equation

$$PA_{O_2} = PI_{O_2} - \frac{PA_{CO_2}}{R}$$

Can normally be approximated:

$PA_{O_2} = 150 - Pa_{CO_2} / 0.8$

PA_{O_2} = alveolar P_{O_2} (mmHg).

PI_{O_2} = P_{O_2} in inspired air (mmHg).

PA_{CO_2} = alveolar P_{CO_2} (mmHg).

R = respiratory quotient.

A-a gradient = $PA_{O_2} - Pa_{O_2}$ = 10–15 mmHg.

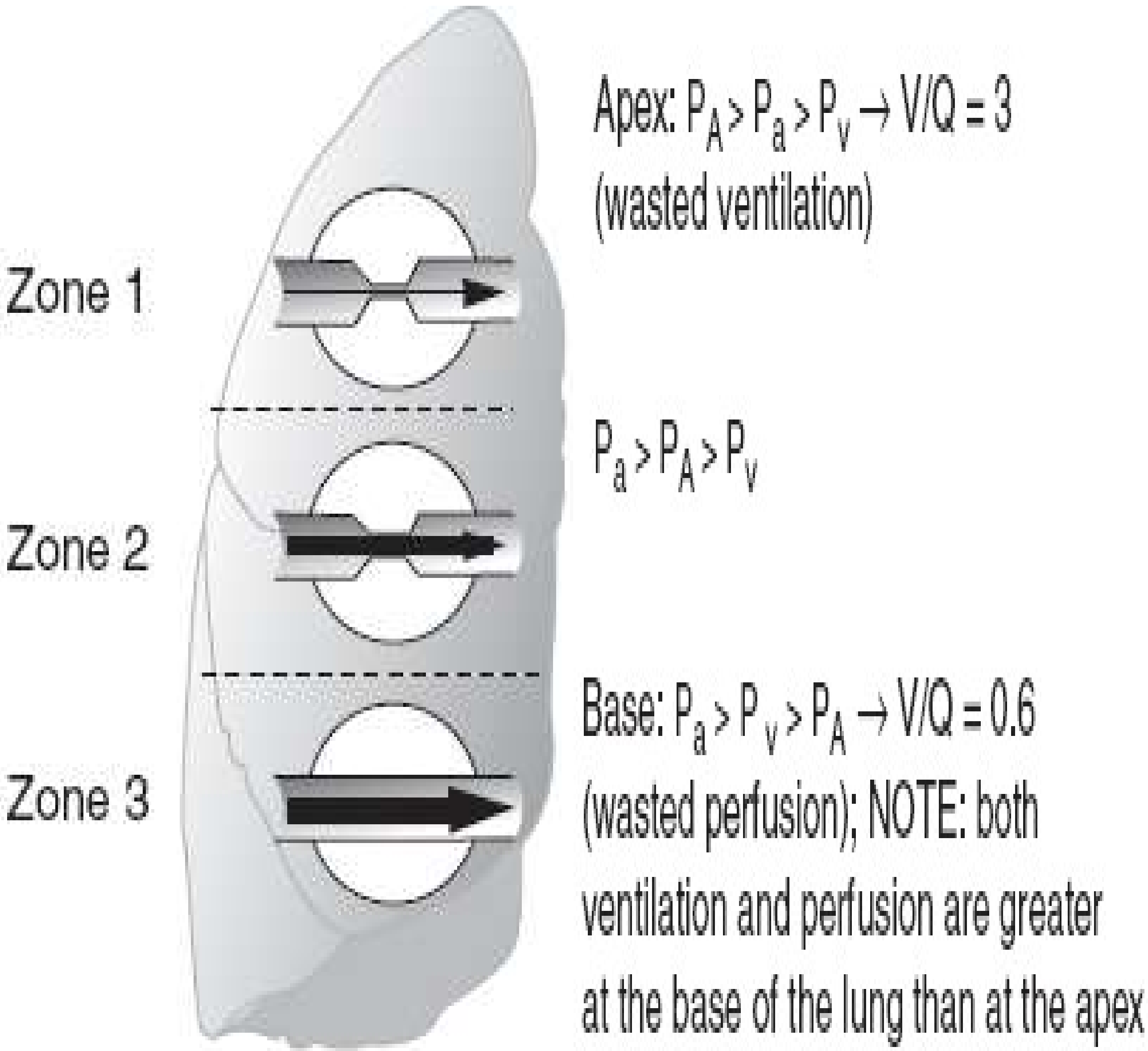
↑ A-a gradient may occur in hypoxemia; causes include shunting, V/Q mismatch, fibrosis (diffusion block).

Ideally, ventilation is matched to perfusion (i.e., V/Q = 1) in order for adequate gas exchange to occur.

Lung zones:

1. Apex of the lung—V/Q = 3 (wasted ventilation)
2. Base of the lung—V/Q = 0.6 (wasted perfusion)

Both ventilation and perfusion are greater at the base of the lung than at the apex of the lung.



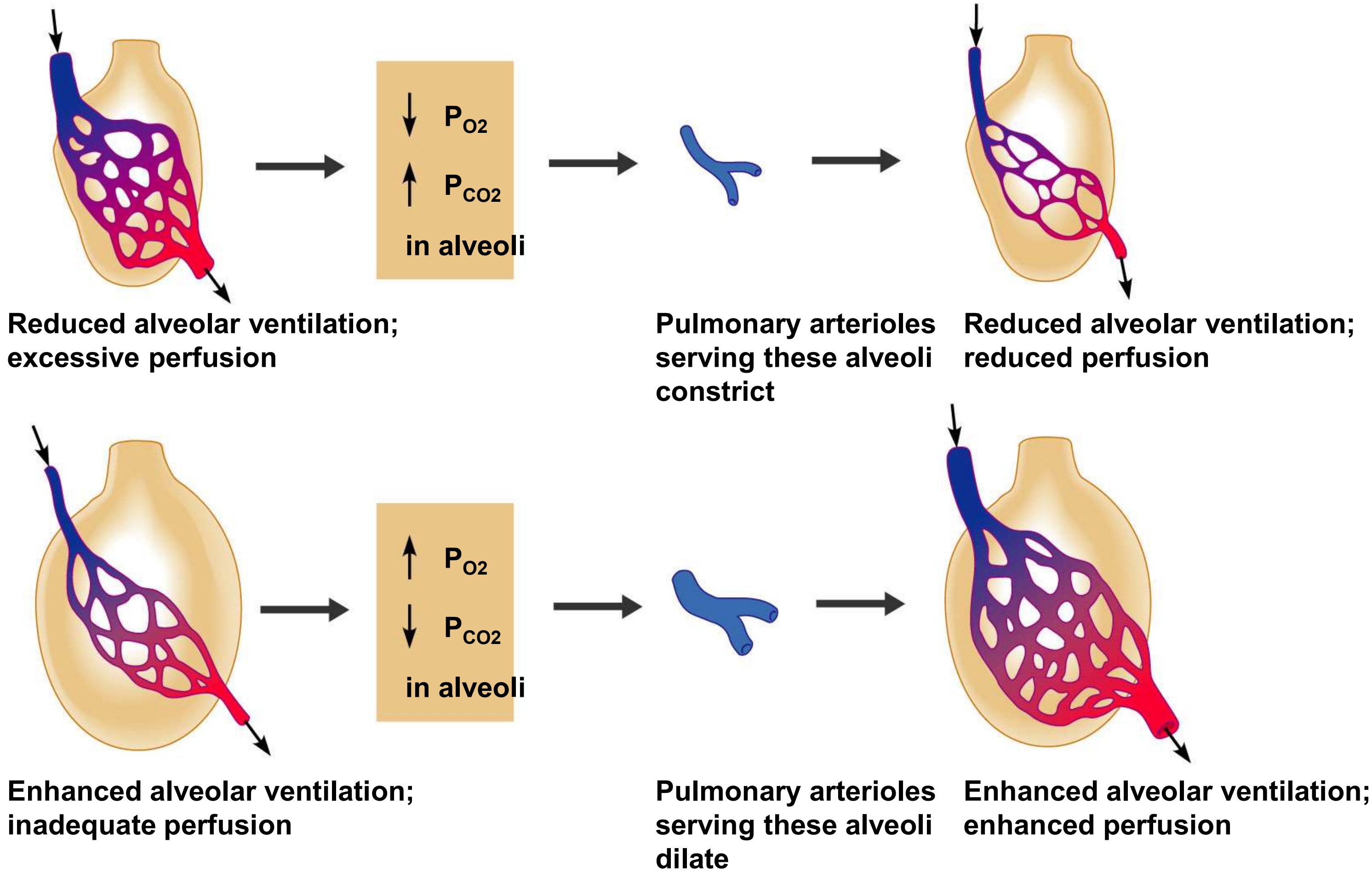
With exercise (↑ cardiac output), there is vasodilation of apical capillaries, resulting in a V/Q ratio that approaches 1.

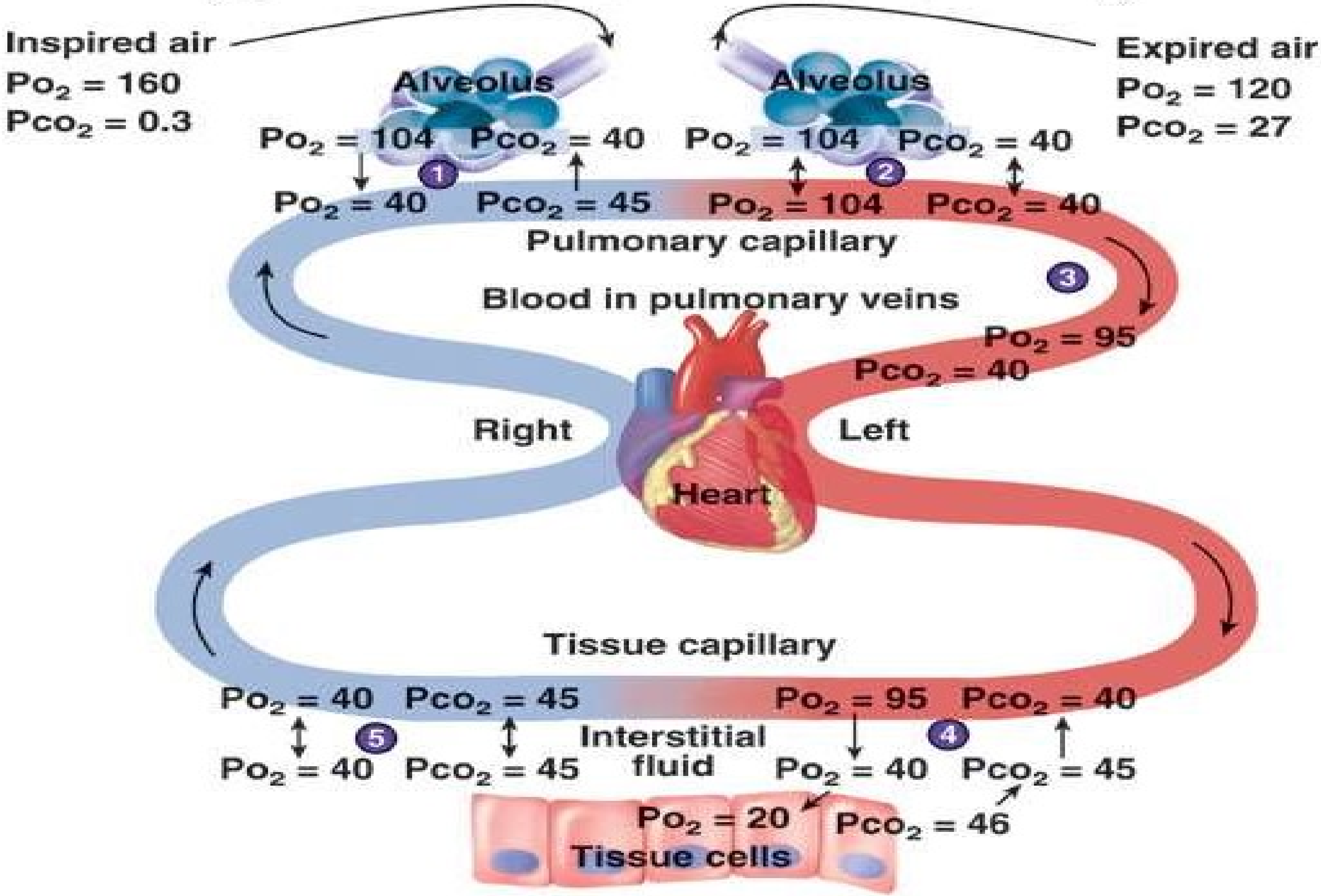
Certain organisms that thrive in high O_2 (e.g., TB) flourish in the apex.

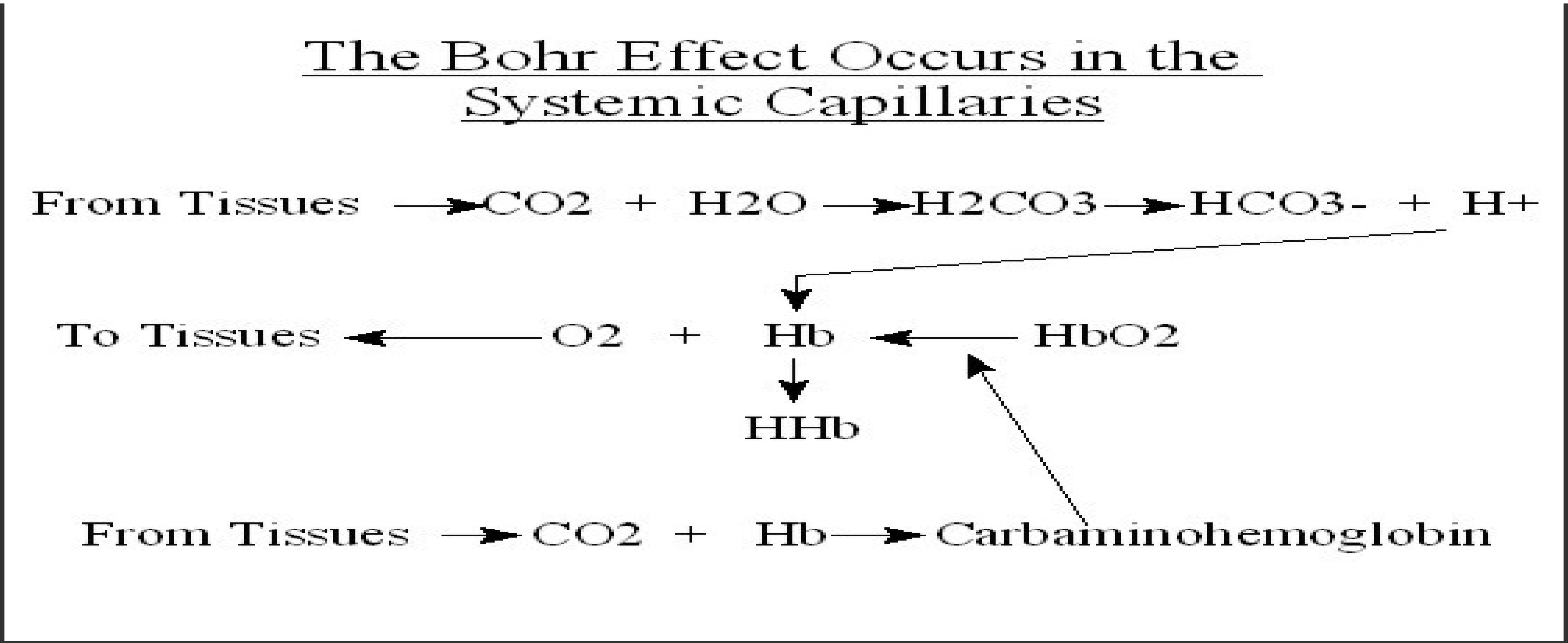
$V/Q \rightarrow 0$ = airway obstruction (shunt). In shunt, 100% O_2 does not improve Po_2.

$V/Q \rightarrow \infty$ = blood flow obstruction (physiologic dead space). Assuming < 100% dead space, 100% O_2 improves Po_2.

Ventilation-Perfusion Coupling




Inspired air
Po2 = 160
Pco2 = 0.3
Alveolus
Po2 = 104
Pco2 = 40
1
Po2 = 40
Pco2 = 45
Alveolus
Po2 = 104
Pco2 = 40
2
Po2 = 104
Pco2 = 40
Expired air
Po2 = 120
Pco2 = 27
Pulmonary capillary
3
Blood in pulmonary veins
Po2 = 95
Pco2 = 40
Right
Left
Heart
Tissue capillary
Po2 = 40
Pco2 = 45
5
Po2 = 40
Pco2 = 45
Interstitial fluid
Po2 = 95
Pco2 = 40
4
Po2 = 40
Pco2 = 45
Po2 = 20
Pco2 = 46
Tissue cells



The Bohr Effect describes the result of **increasing CO_2 in causing more oxygen unloading from hemoglobin.**

It results from two circumstances:

1)the effect of lowering pH

2) the effect of carbaminohemoglobin in stimulating oxygen unloading

Main Gases of the Atmosphere

Gas	Symbol	Approximate %
Nitrogen	N_2	78.6
Oxygen	O_2	20.9
Carbon Dioxide	CO_2	0.04
Water Vapor	H_2O	0.46

Gas Exchange

Partial Pressure

Each gas in atmosphere contributes to the entire atmospheric pressure, denoted as P

Gases in liquid

Gas enters liquid and dissolves in proportion to its partial pressure

O2 and CO2 Exchange by DIFFUSION

- PO2 is 105 mmHg in alveoli and 40 in alveolar capillaries
- PCO2 is 45 in alveolar capillaries and 40 in alveoli

Partial Pressures

Oxygen is 21% of atmosphere

760 mmHg x .21 = 160 mmHg PO2

This mixes with “old” air already in alveolus to arrive at PO2 of 105 mmHg

Partial Pressures

Carbon dioxide is .04% of atmosphere

760 mmHg x .0004 = .3 mm Hg PCO_2

This mixes with high CO_2 levels from residual volume in the alveoli to arrive at PCO_2 of 40 mmHg

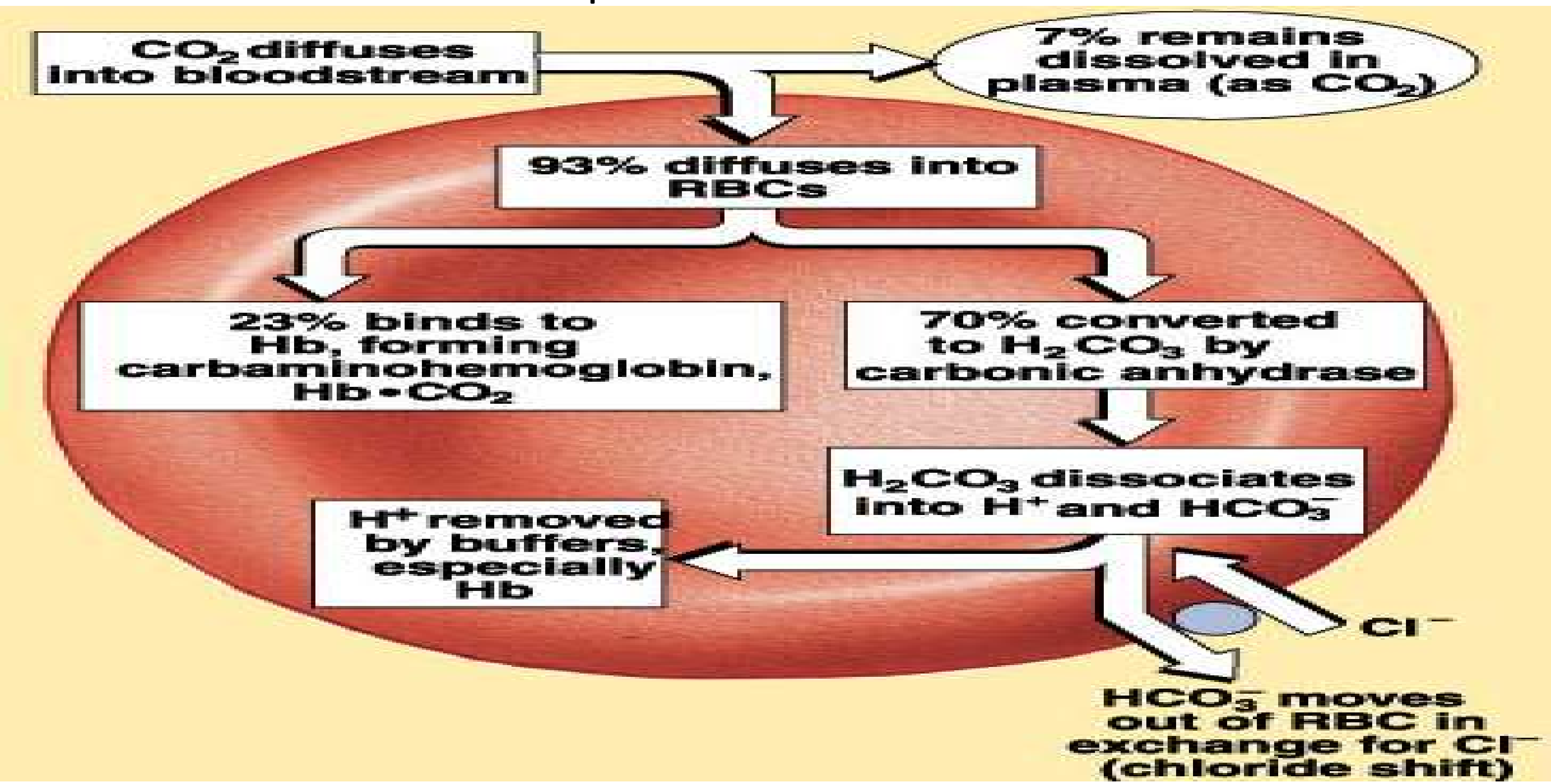
Carbon Dioxide Transport

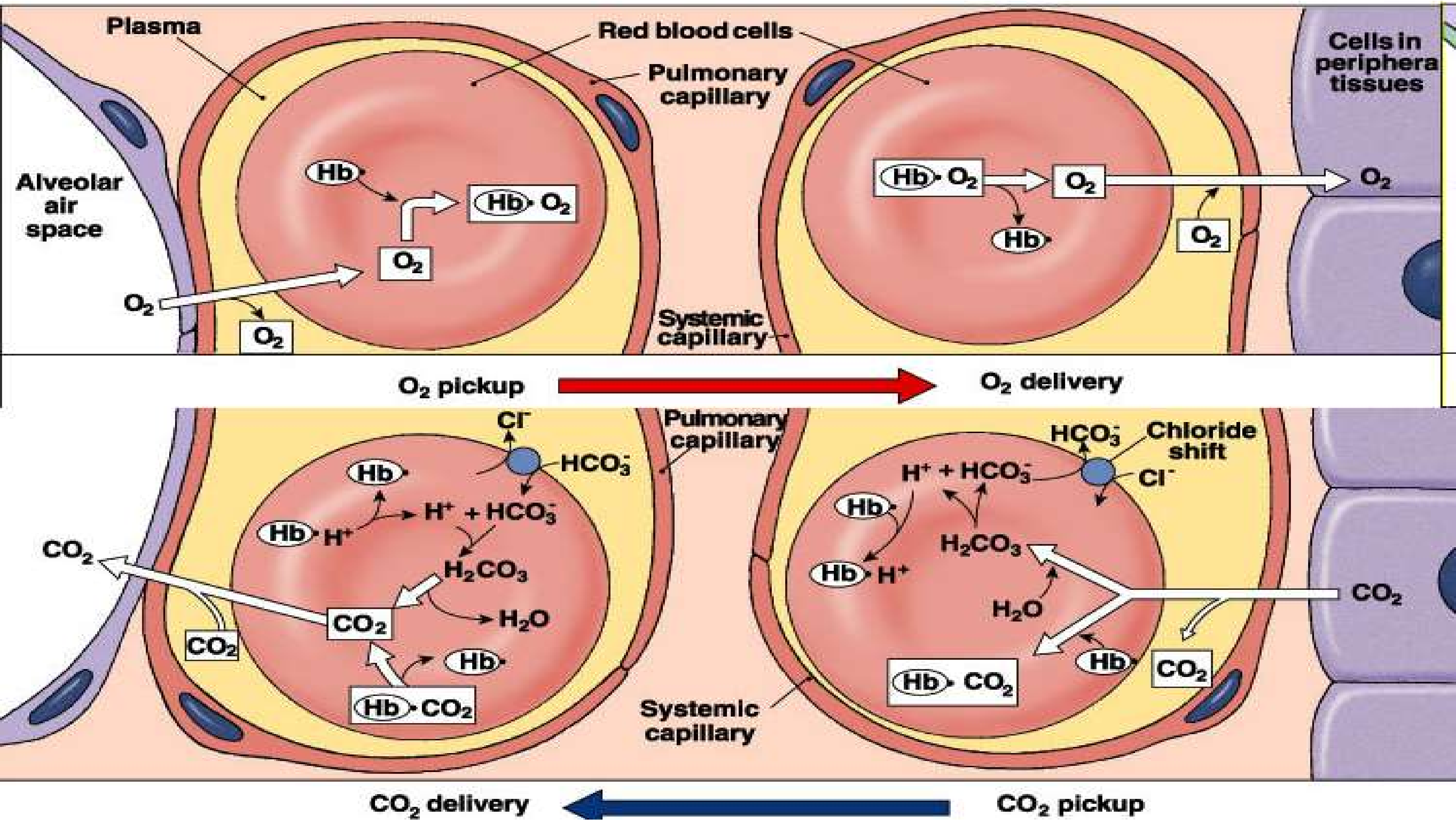
Method	Percentage
Dissolved in Plasma	7 - 10 %
Chemically Bound to Hemoglobin in RBC's	20 - 30 %
As Bicarbonate Ion in Plasma	60 -70 %

Oxygen Transport

Method	Percentage
Dissolved in Plasma	1.5 %
Combined with Hemoglobin	98.5 %

CO2 Transport and Cl- Movement

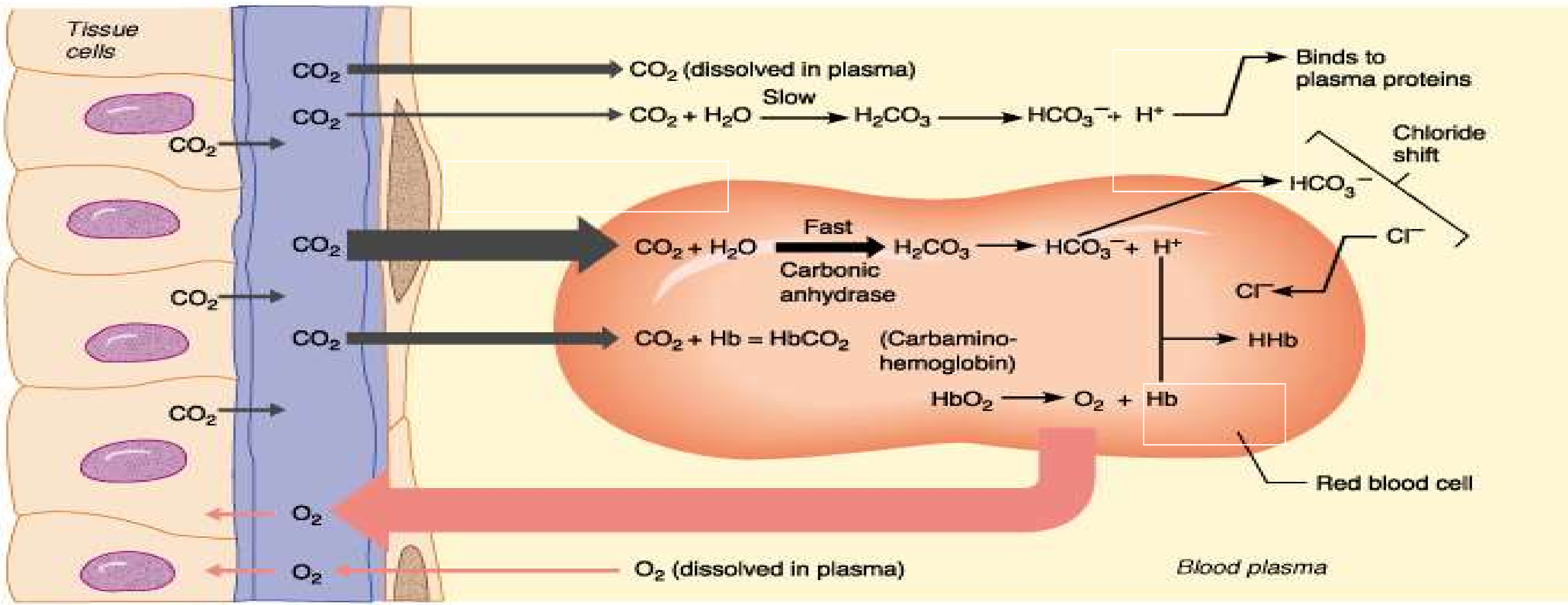




Plasma
Red blood cells
Pulmonary capillary
Cells in periphera tissues
Alveolar air space
Hb
Hb · O2
O2
O2
O2
Systemic capillary
Hb · O2
O2
Hb
O2
O2
O2 pickup
O2 delivery
Cl⁻
HCO3⁻
Pulmonary capillary
Hb
Hb · H⁺
H⁺ + HCO3⁻
H2CO3
CO2
CO2
H2O
CO2
Hb
Hb · CO2
HCO3⁻
Chloride shift
H⁺ + HCO3⁻
Cl⁻
Hb
H2CO3
Hb · H⁺
CO2
H2O
Hb
CO2
Hb · CO2
Systemic capillary
CO2 delivery
CO2 pickup

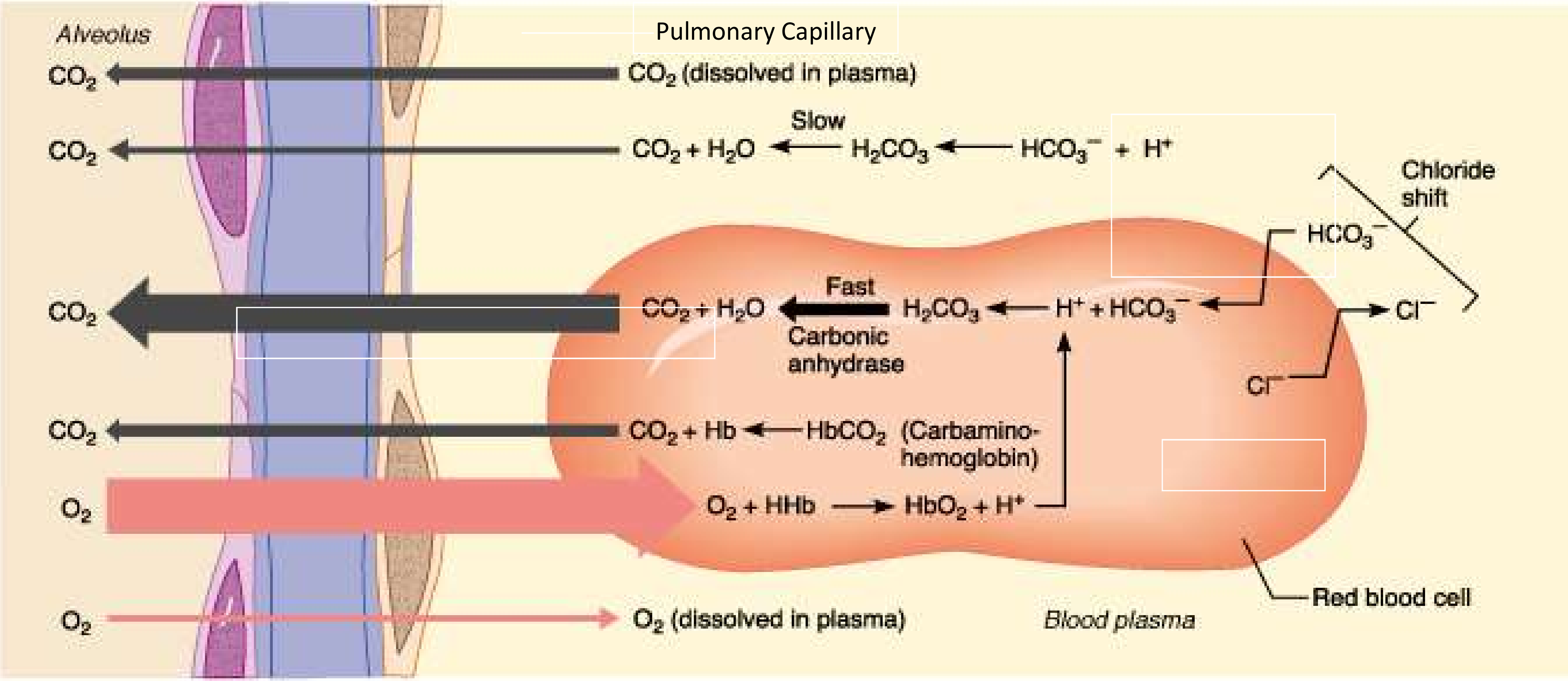
Chloride Shift in Tissue Capillaries

Tissue Capillary



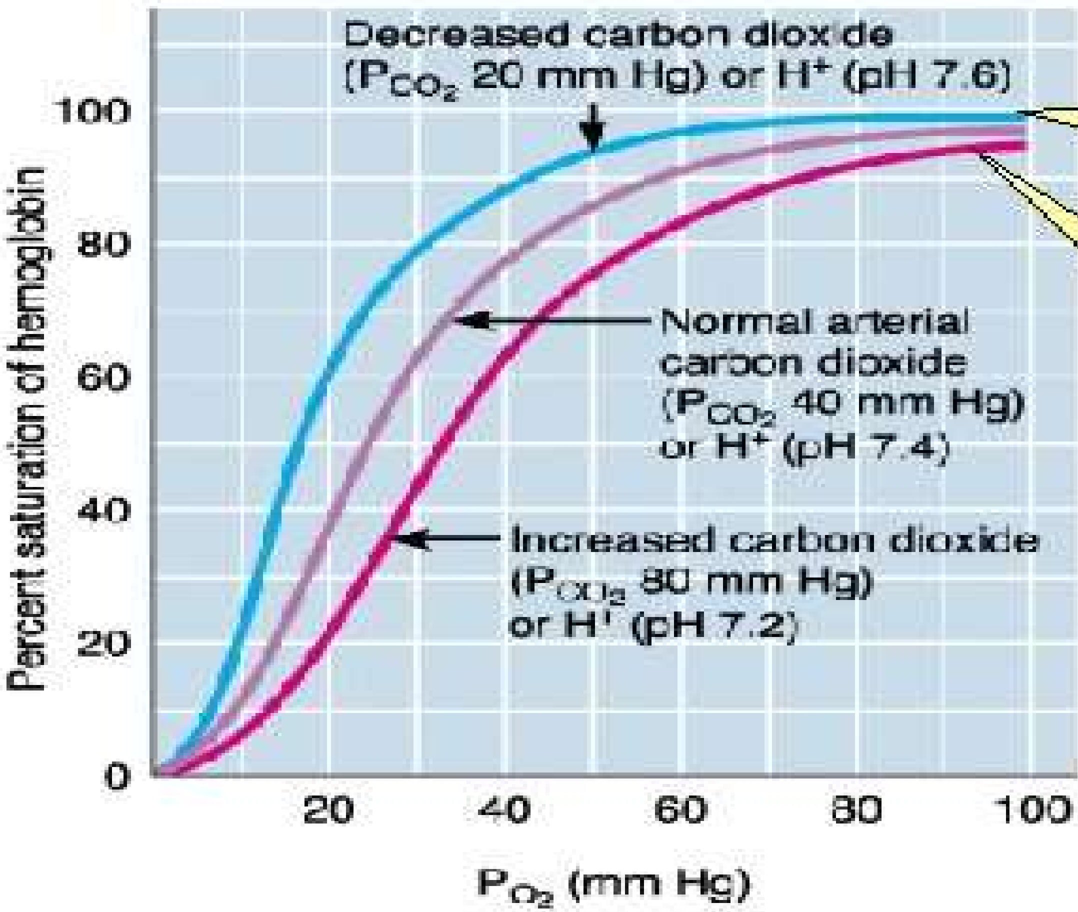
(a) Oxygen release and carbon dioxide pickup at the tissues

Chloride Shift in Pulmonary Capillaries



(b) Oxygen pickup and carbon dioxide release in the lungs

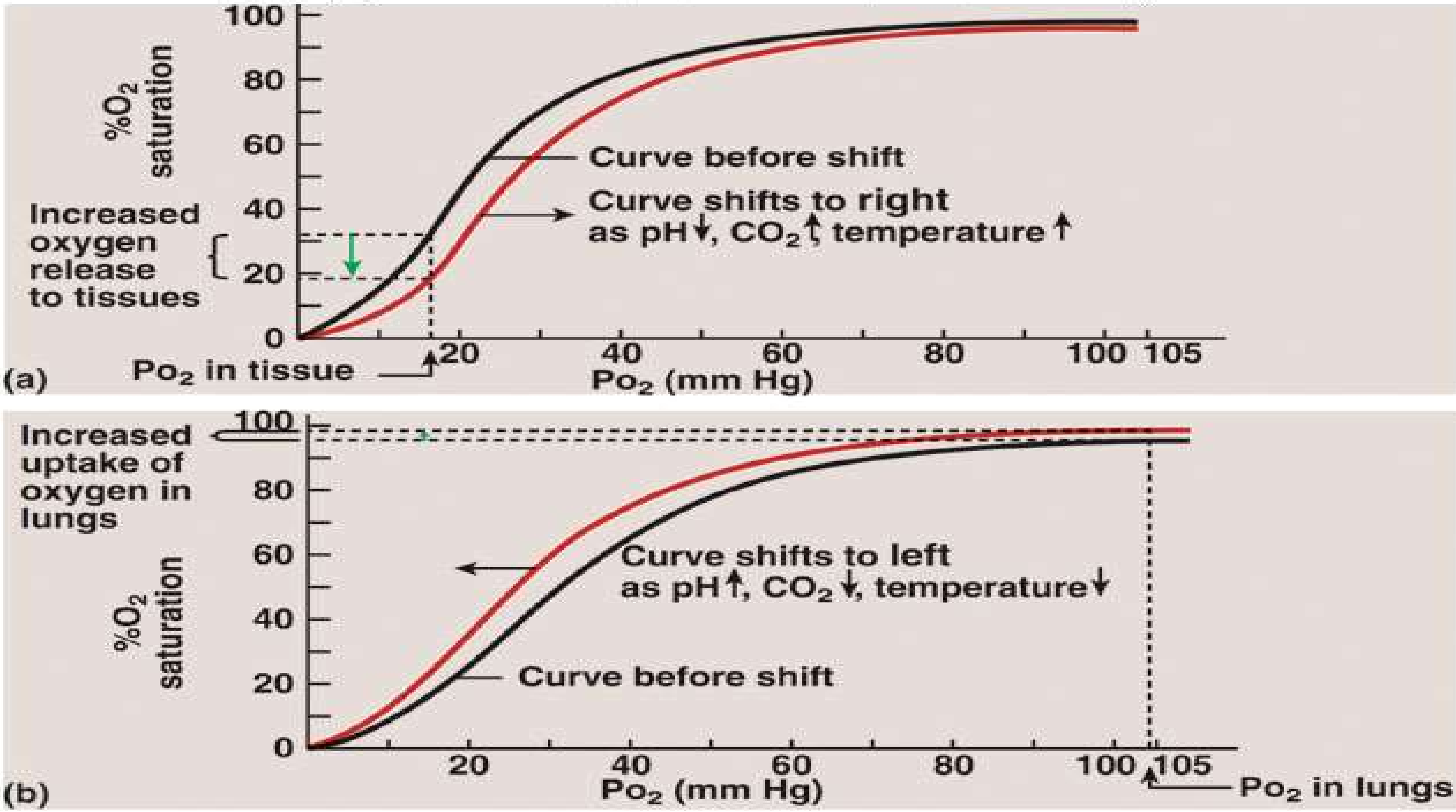
Effect of pH on Respiration



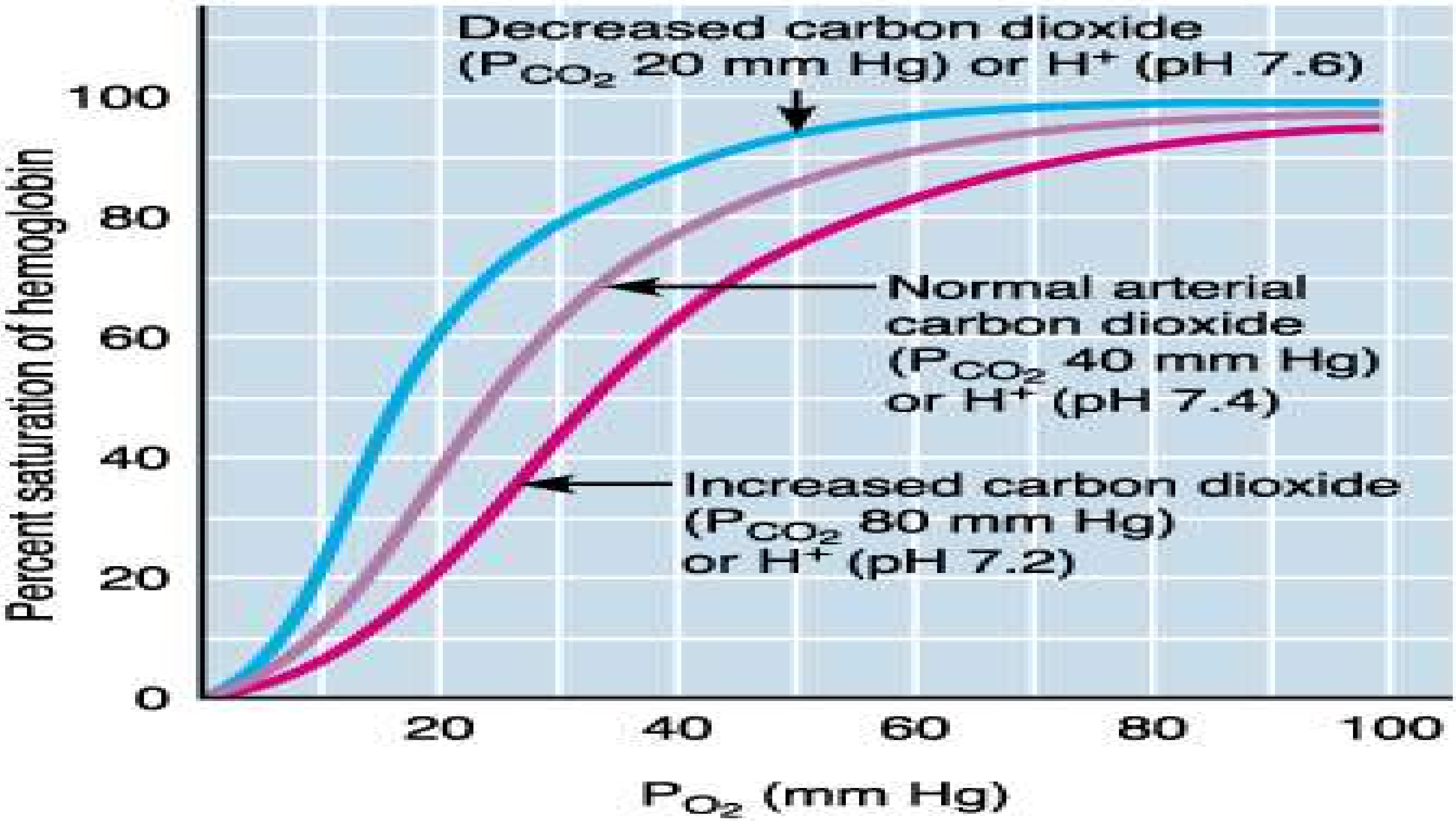
(b)

↑ pH resulting from ↓CO2 or H+ increases the association of oxygen with hemoglobin.

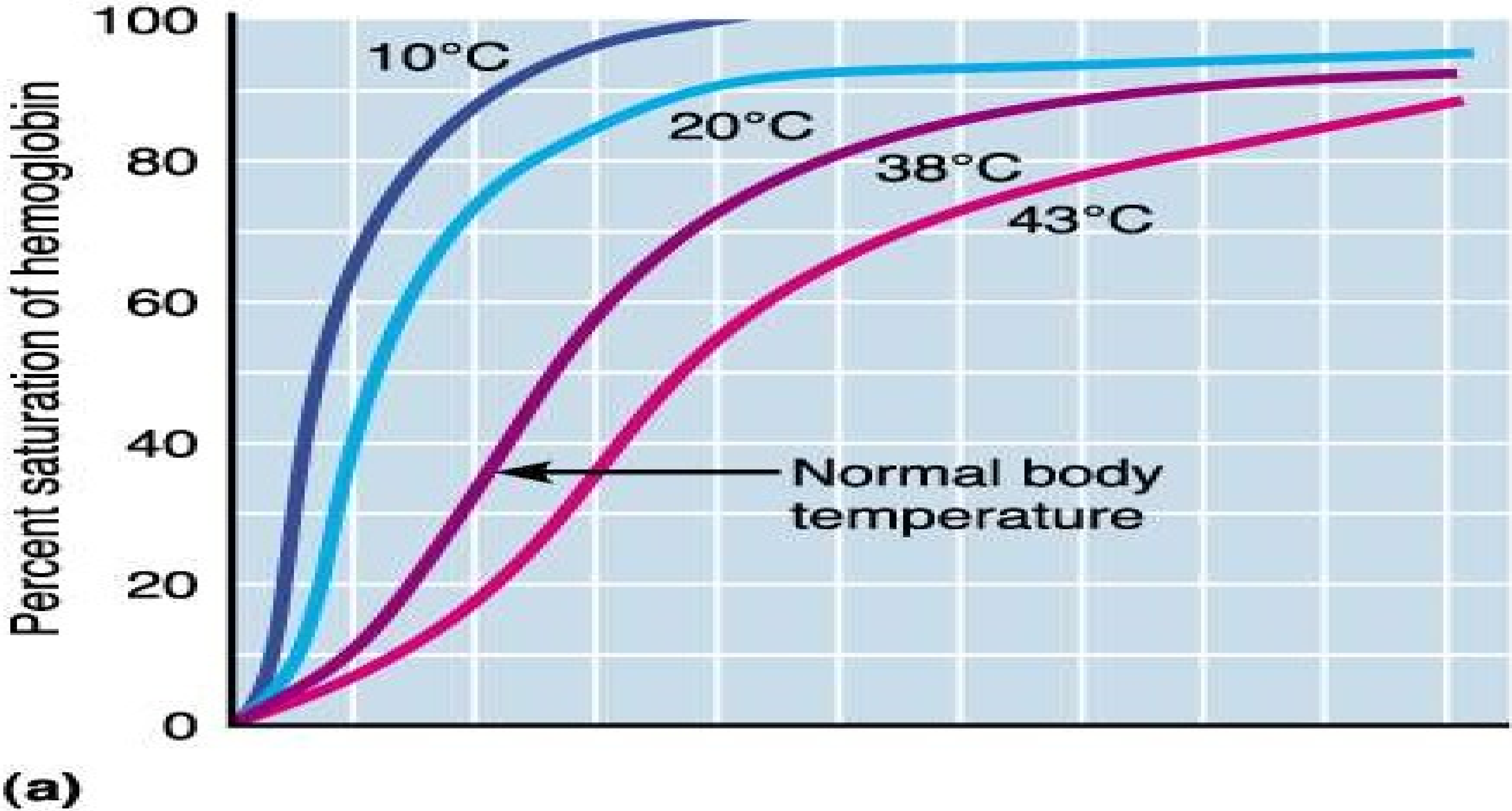
↓ pH resulting from ↑CO2 or H+ decreases the association of oxygen with hemoglobin.

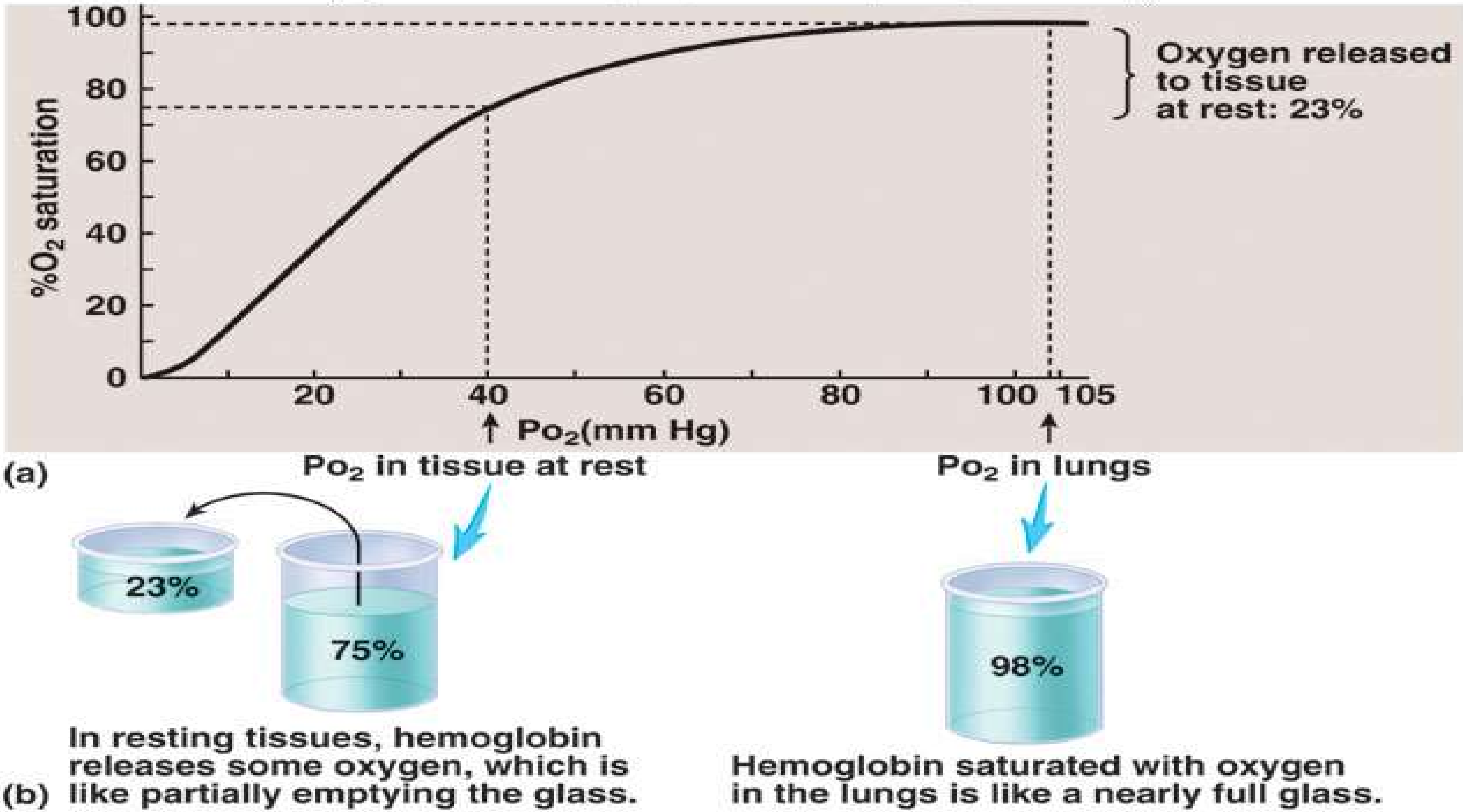


100
80
60
40
20
0
%O_2 saturation
Increased oxygen release to tissues
Curve before shift
Curve shifts to right as pH↓, CO_2↑, temperature↑
20
40
60
80
100
105
(a)
Po_2 in tissue
Po_2 (mm Hg)
Increased uptake of oxygen in lungs
Curve shifts to left as pH↑, CO_2↓, temperature↓
Curve before shift
(b)
Po_2 in lungs

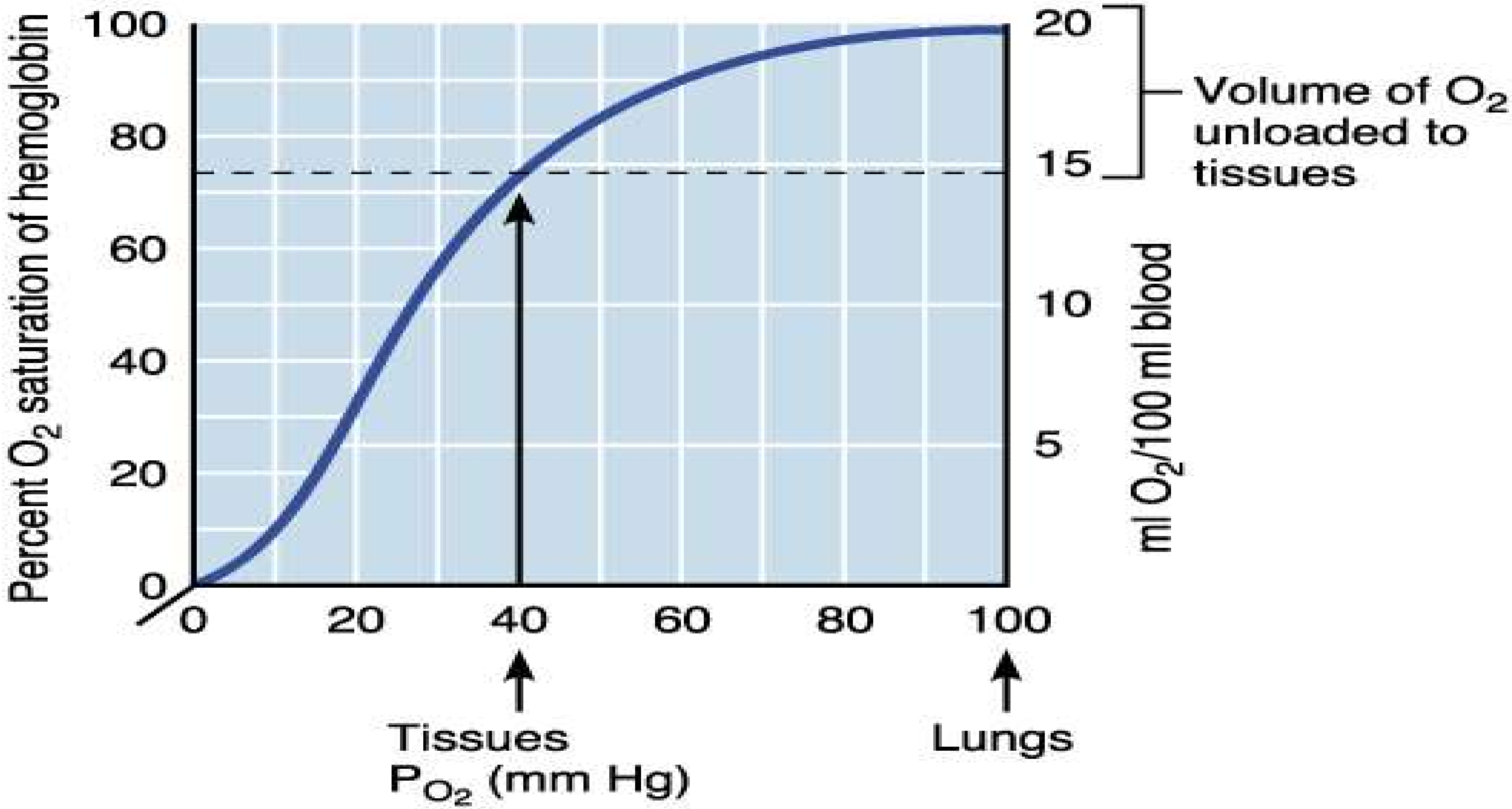

Decreased carbon dioxide
(P_{CO_2} 20 mm Hg) or H^+ (pH 7.6)
Normal arterial
carbon dioxide
(P_{CO_2} 40 mm Hg)
or H^+ (pH 7.4)
Increased carbon dioxide
(P_{CO_2} 80 mm Hg)
or H^+ (pH 7.2)
Percent saturation of hemoglobin
100
80
60
40
20
0
20
40
60
80
100
P_{O_2} (mm Hg)

(b)

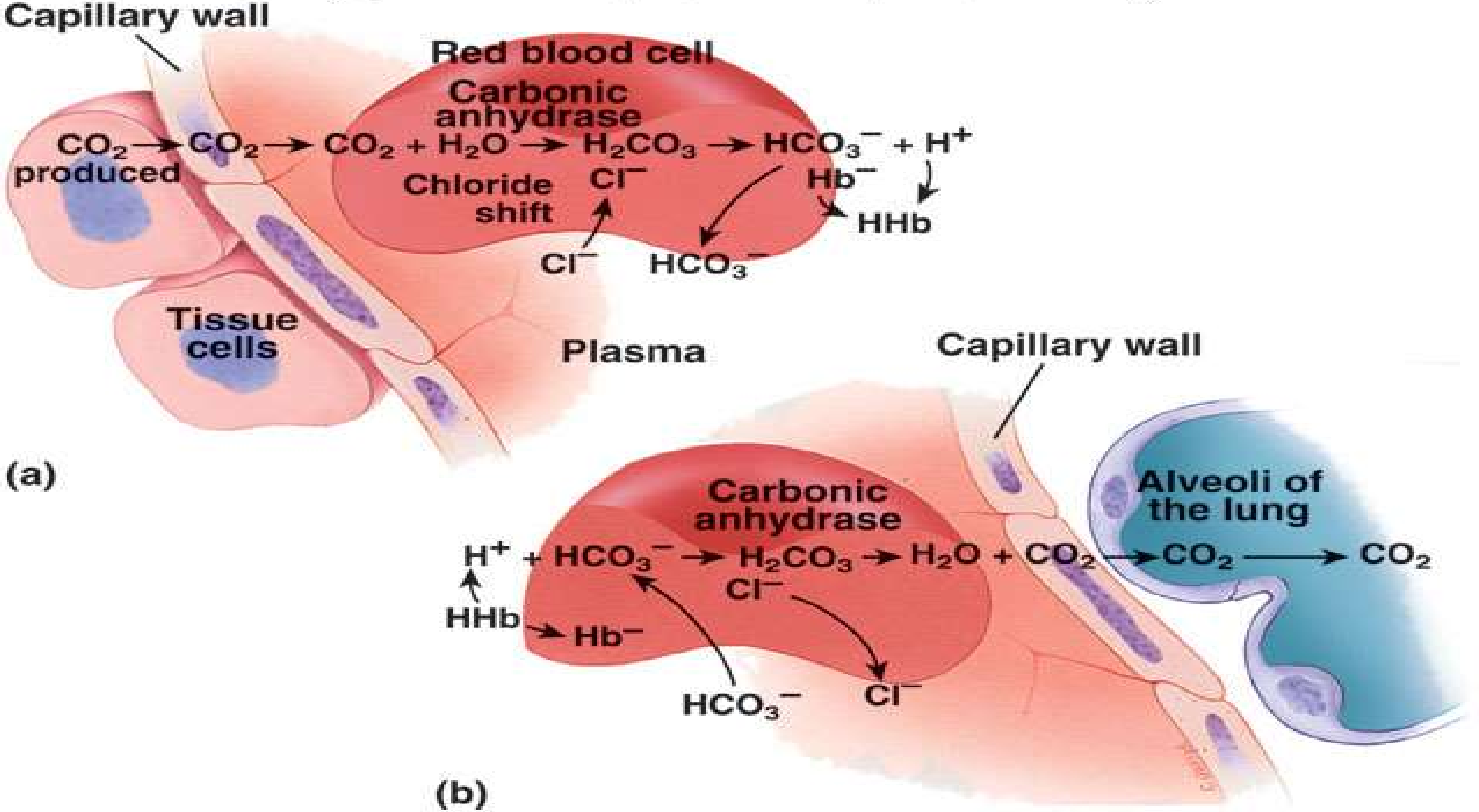

100
80
60
40
20
0
Percent saturation of hemoglobin
10°C
20°C
38°C
43°C
Normal body
temperature
(a)



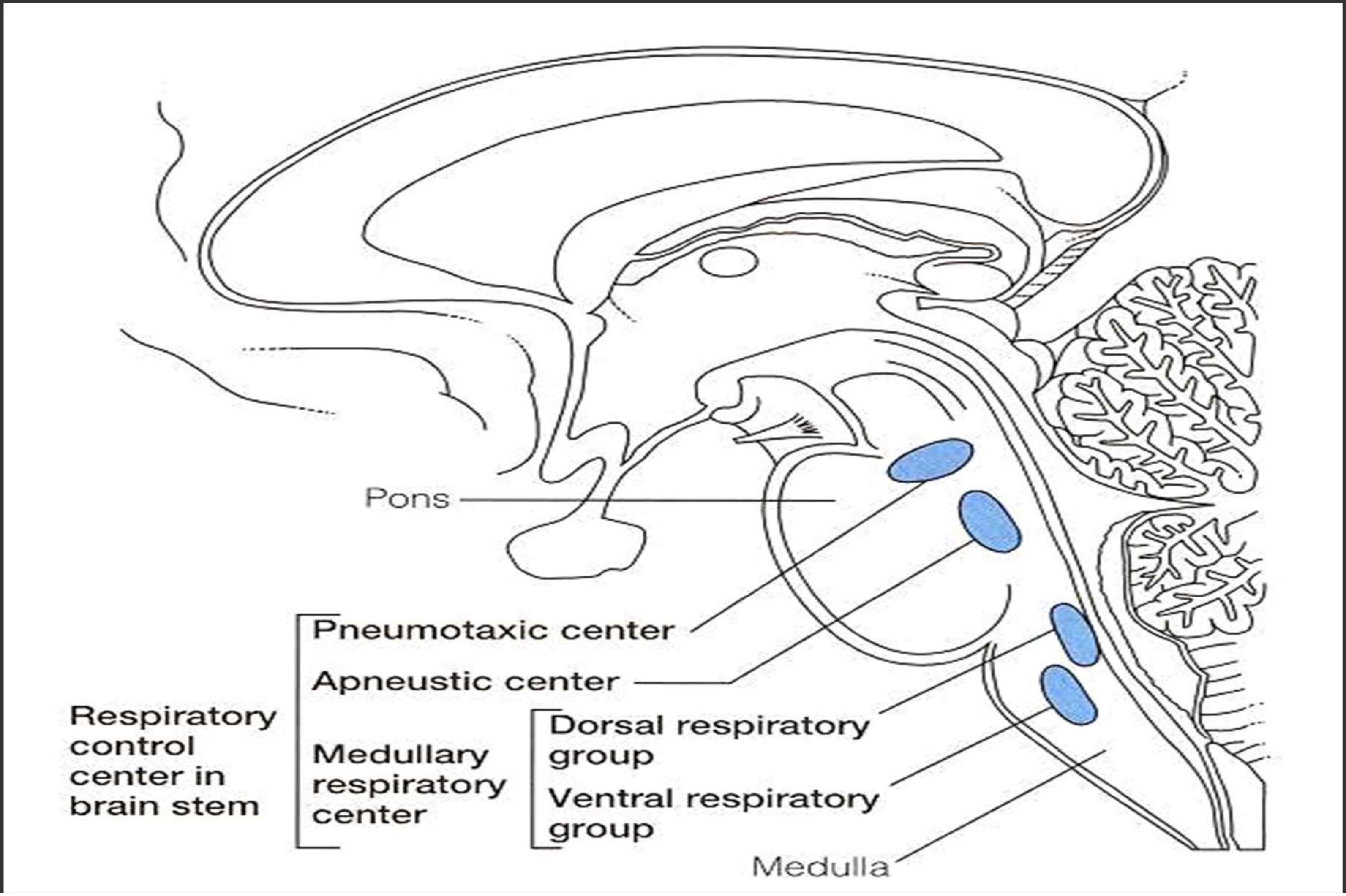
100
80
60
40
20
0
%O_2 saturation
20
40
60
80
100 105
Po_2(mm Hg)
Oxygen released to tissue at rest: 23%
(a)
Po_2 in tissue at rest
Po_2 in lungs
23%
75%
98%
(b) In resting tissues, hemoglobin releases some oxygen, which is like partially emptying the glass.
Hemoglobin saturated with oxygen in the lungs is like a nearly full glass.



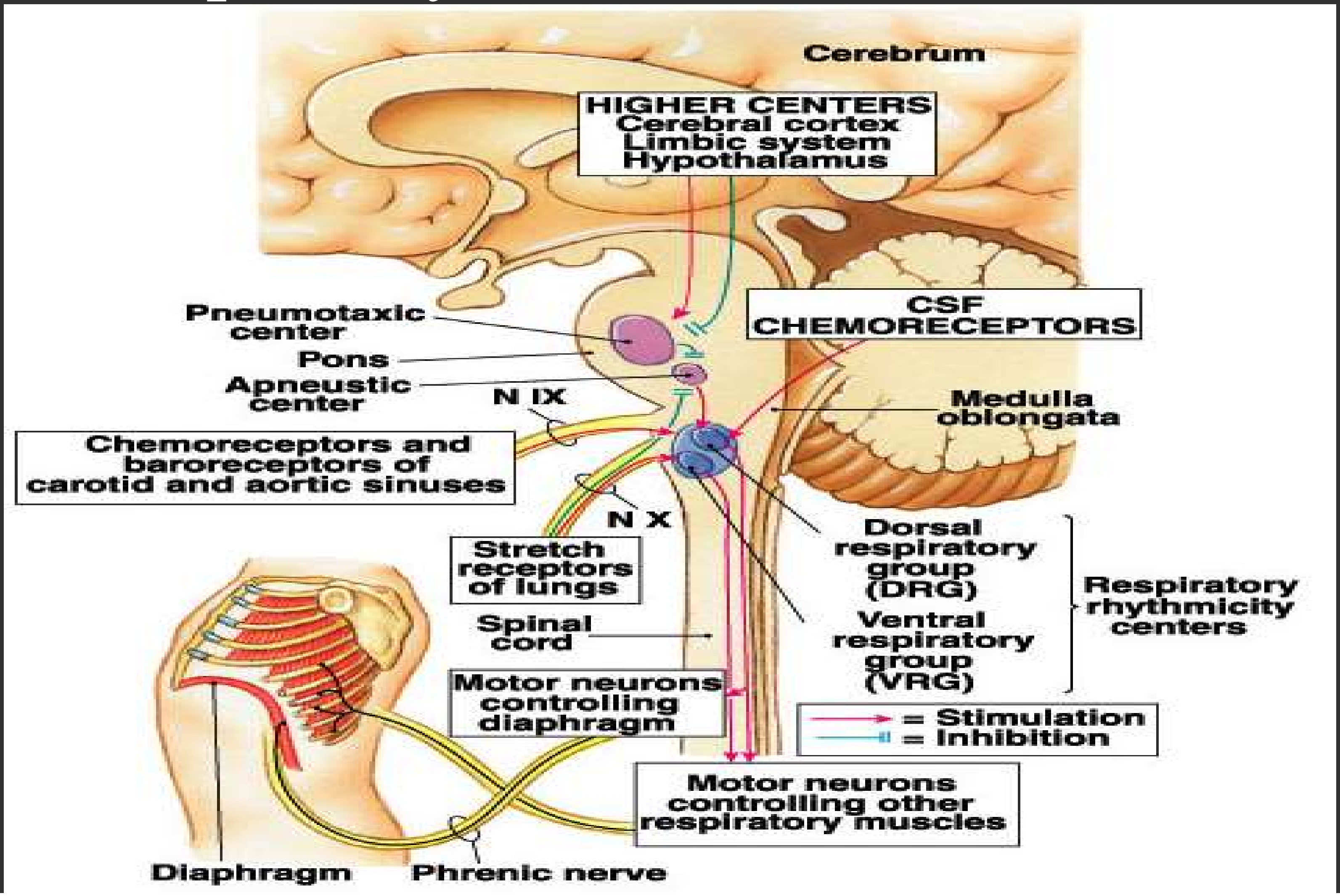
Percent O_2 saturation of hemoglobin
100
80
60
40
20
0
20
15
10
5
Volume of O_2 unloaded to tissues
ml O_2/100 ml blood
0
20
40
60
80
100
Tissues
Lungs
P_{O_2} (mm Hg)


Capillary wall
Red blood cell
Carbonic anhydrase
CO2 produced → CO2 → CO2 + H2O → H2CO3 → HCO3− + H+
Chloride shift
Cl−
Hb−
HHb
Cl−
HCO3−
Tissue cells
Plasma
(a)
Capillary wall
Carbonic anhydrase
Alveoli of the lung
H+ + HCO3− → H2CO3 → H2O + CO2 → CO2 → CO2
Cl−
HHb → Hb−
HCO3−
Cl−
(b)

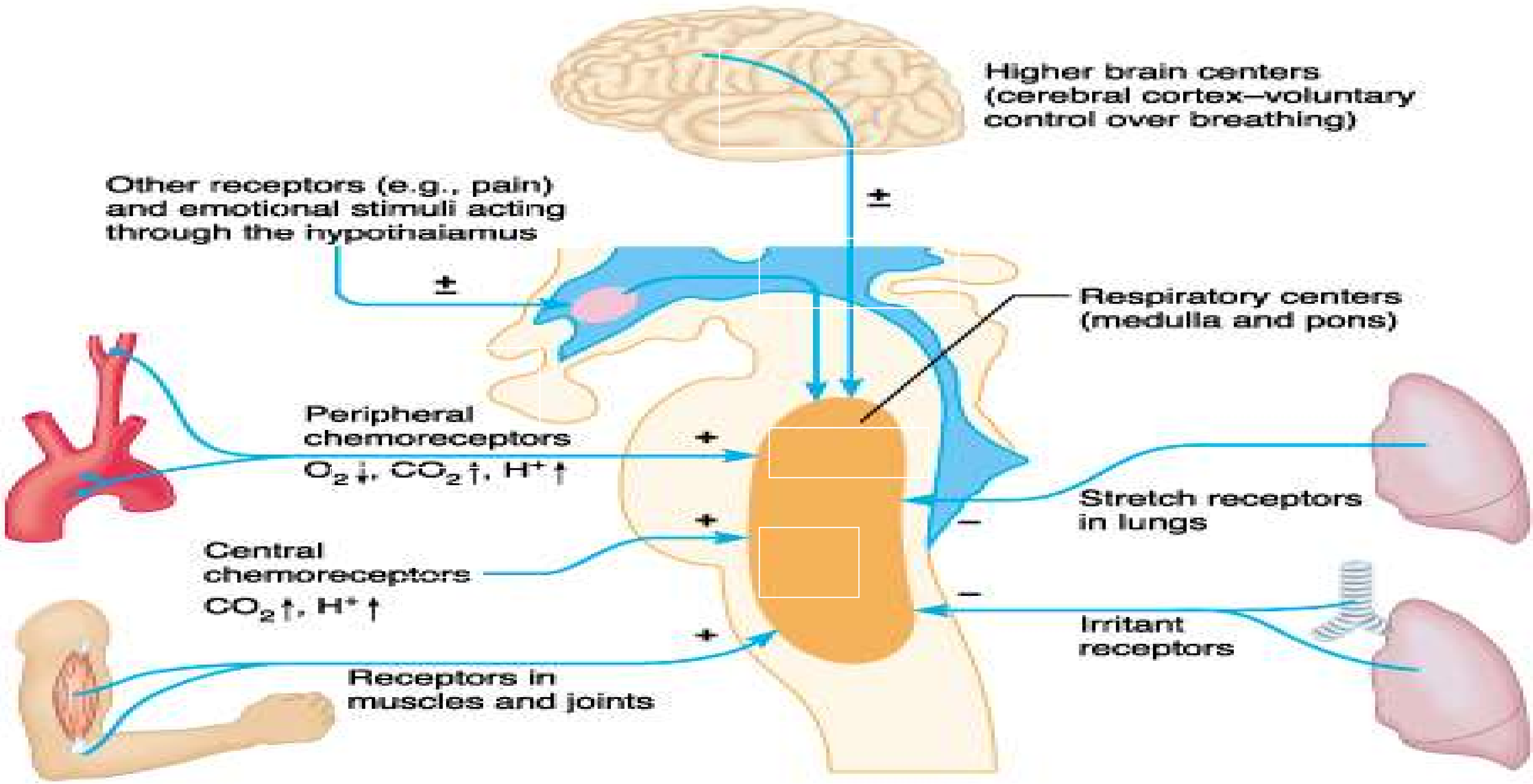
Respiratory Centers

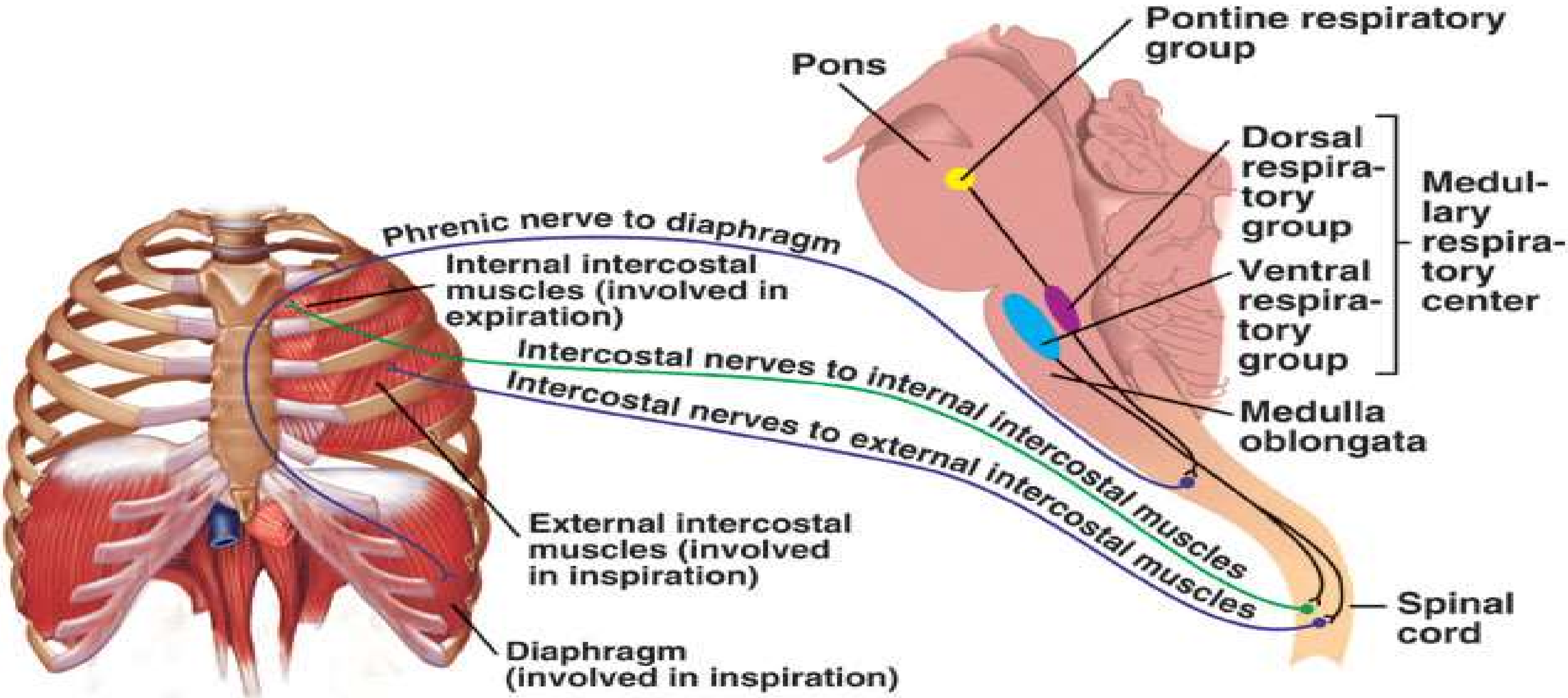


Respiratory Structures in Brainstem

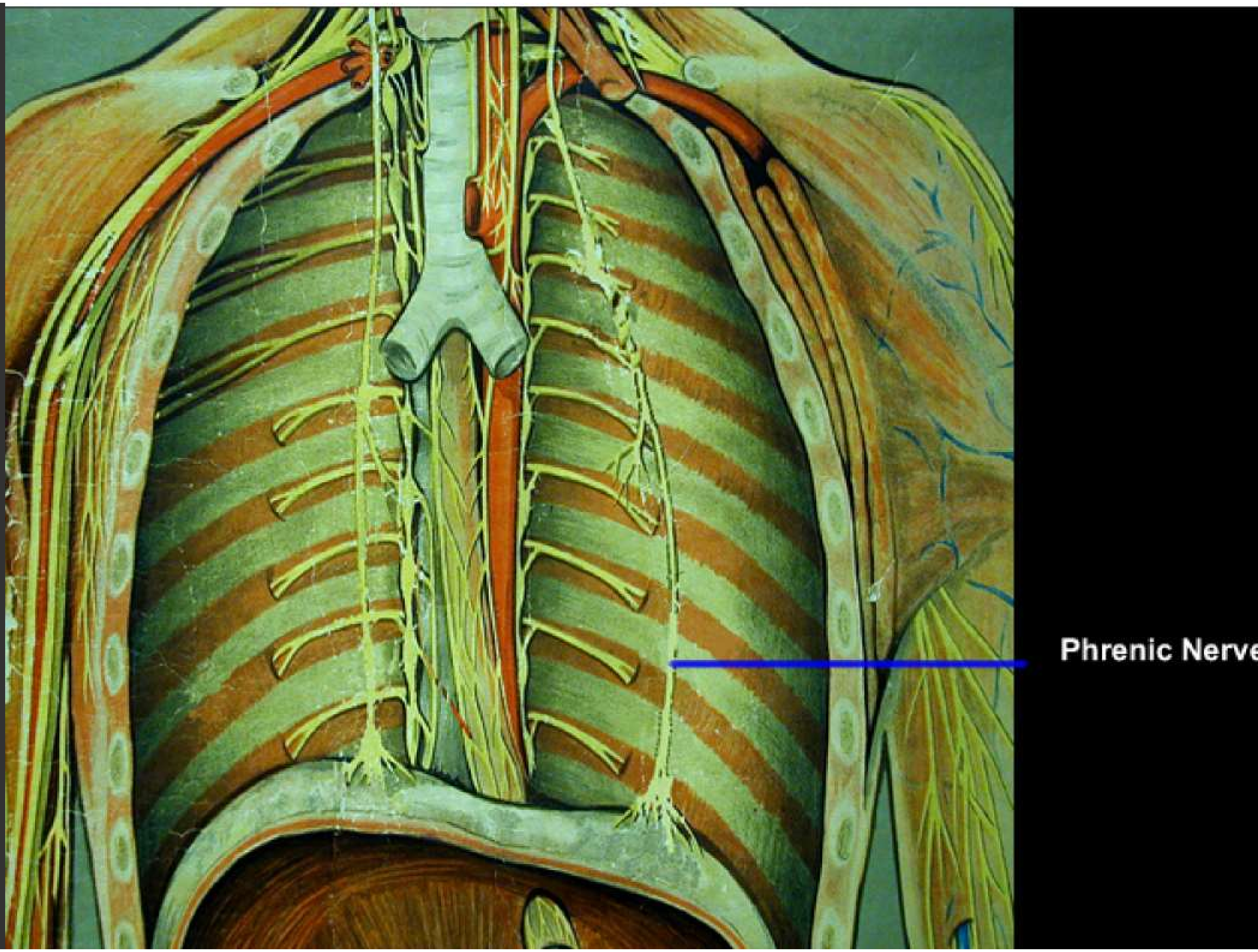


Factors Influencing Respiration




Pontine respiratory group
Pons
Dorsal respiratory group
Medullary respiratory center
Ventral respiratory group
Phrenic nerve to diaphragm
Internal intercostal muscles (involved in expiration)
Intercostal nerves to internal intercostal muscles
Intercostal nerves to external intercostal muscles
Medulla oblongata
External intercostal muscles (involved in inspiration)
Spinal cord
Diaphragm (involved in inspiration)

REMEMBER
THE CAT


Phrenic Nerve

Two Sets of Chemoreceptors Exist

Central Chemoreceptors

- Responsive to increased arterial PCO2
- Act by way of CSF [H+] .

Peripheral Chemoreceptors

- Responsive to decreased arterial PO2
- Responsive to increased arterial PCO2
- Responsive to increased H+ ion concentration.

Peripheral Chemoreceptors

Carotid bodies

Sensitive to: PaO_2, $PaCO_2$, and pH

Afferents in glossopharyngeal nerve.

Aortic bodies

Sensitive to: PaO_2, $PaCO_2$, but not pH

Afferents in vagus

Significance of Hering-Breuer

Limits the degree of inspiration and prevents overinflation of the lungs

Normal adults. Receptors **are not activated at end normal tidal volumes.**

- Become Important during exercise when tidal volume is increased.
- Become Important in Chronic obstructive lung diseases when lungs are more distended.

Infants. Probably help terminate normal inspiration.

Hering-Breuer Reflex or Pulmonary Stretch Reflex

Including pulmonary inflation reflex and pulmonary deflation reflex

Receptor: Slowly adapting stretch receptors (SARs) in bronchial airways.

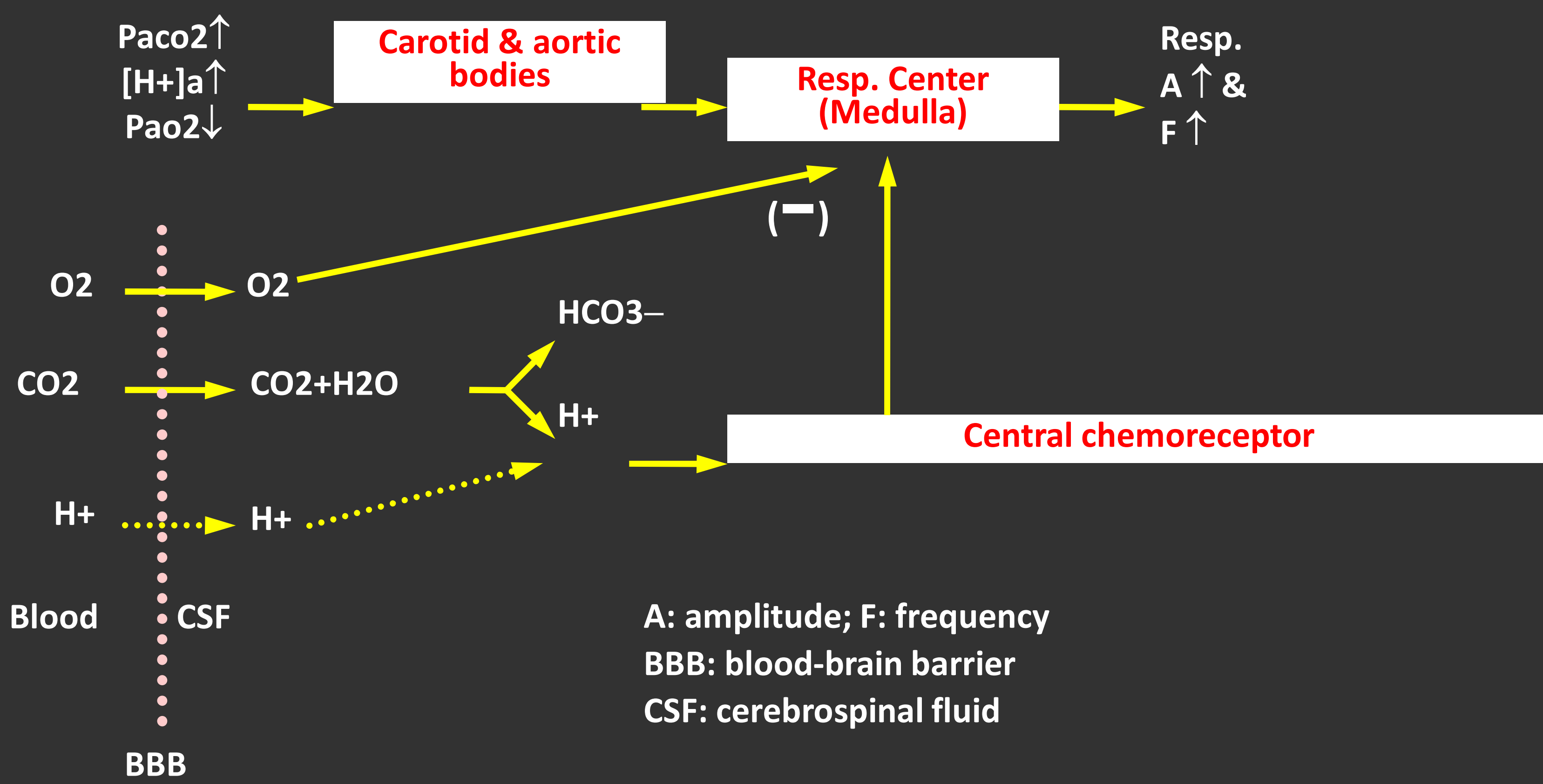
Afferent: **vagus nerve**

Pulmonary inflation reflex:

Terminate inspiration.

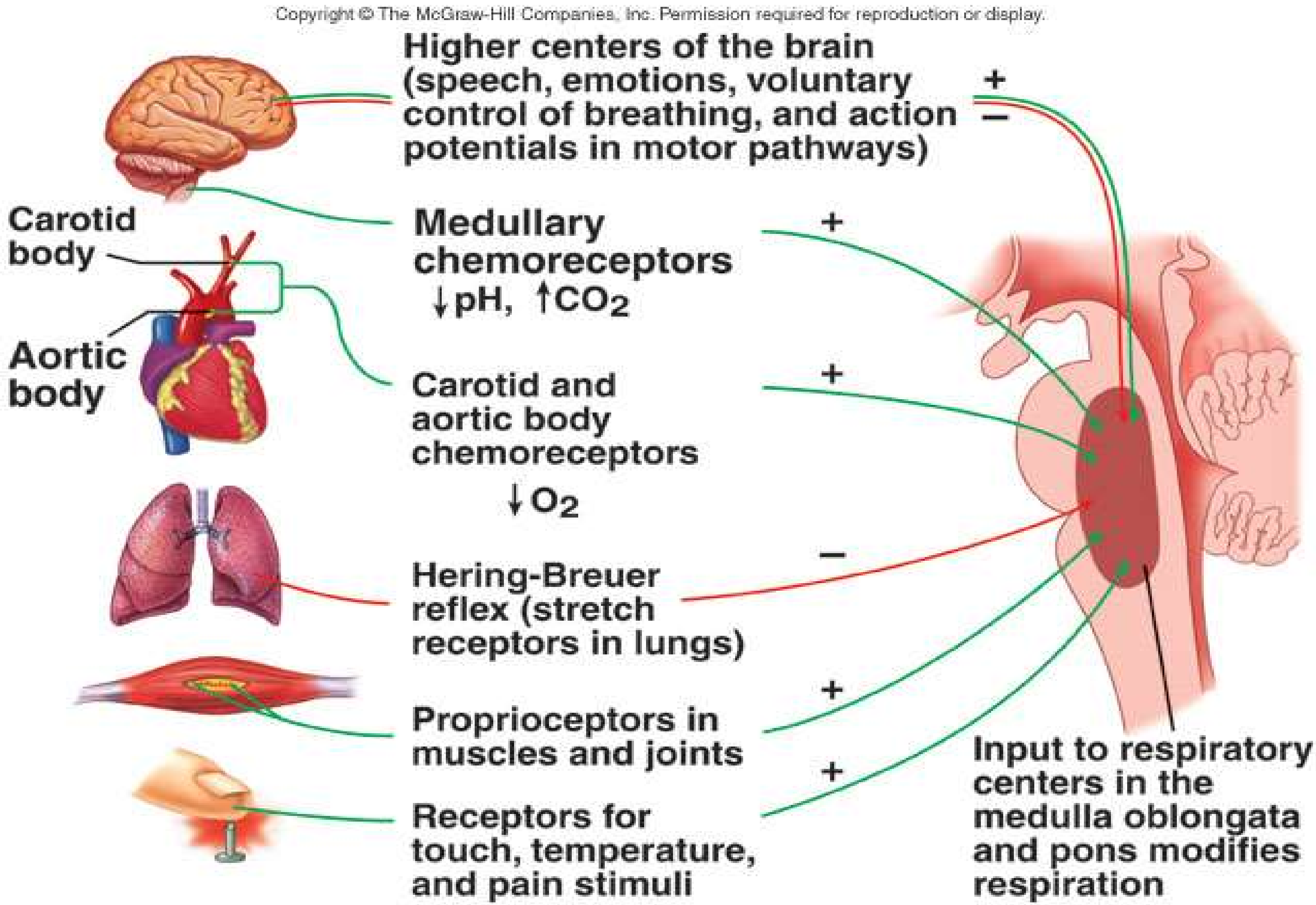
By speeding inspiratory termination they increase respiratory frequency.

Sustained stimulation of SARs: causes activation of expiratory neurons



Paco2↑
[H+]a↑
Pao2↓
Carotid & aortic bodies
Resp. Center (Medulla)
Resp.
A ↑ &
F ↑
(−)
O2
O2
CO2
CO2+H2O
HCO3−
H+
H+
H+
Central chemoreceptor
Blood
CSF
BBB
A: amplitude; F: frequency
BBB: blood-brain barrier
CSF: cerebrospinal fluid

Modifying Respiration



Response to High Altitude

- • increased Ventilation (EARLIEST CHANGE)
- • increased Sensitivity of central receptors
- • increased Response of carotid bodies
- • increased Erythropoietin
- • increased 2 3 DPG
- • increased Mitochondria
- • increased Renal excretion of Bicarbonate

• Respiratory alkalosis

• Pulmonary edema when occurs is due to **increased pulmonary capillary pressure**

•High altitude → ↓ atmospheric pressure (Patm) and ↓ alveolar PO_2

•Ventilation

- •↓ alveolar PO_2 → ↑ respiratory rate (hyperventilation)
  - •↓ alveolar PO_2 stimulates peripheral chemoreceptors in aortic bodies and carotid bodies to instruct medullary inspiration center to increase respiratory rate

•Arterial blood

- •↑ ventilation rate → ↑ PaO_2 and ↓ $PaCO_2$ → respiratory alkalosis

• <u>A number of physiologic changes occur in a person living at high altitude.</u>

- The diminished barometric pressure at high altitude
- causes alveolar hypoxia and arterial hypoxia.
- Pulmonary vasoconstriction occurs in response to alveolar hypoxia; therefore, the diameter of the pulmonary vessels would be greater in the brother living at sea level.
- Increased erythropoietin production , caused by arterial hypoxia, leads to increases in hematocrit in people living at high altitude

• Mitochondrial density increases in people chronically exposed to the hypoxemia caused by living at high altitude

• At high altitudes, the ventilation rate increases, causing a respiratory alkalosis.
The kidney then compensates by increasing the excretion of HCO3

• Increasing the rate of respiration is a very useful adaptation to the hypoxic conditions of high altitude.
The primary stimulus is the hypoxic stimulation of peripheral chemoreceptors.