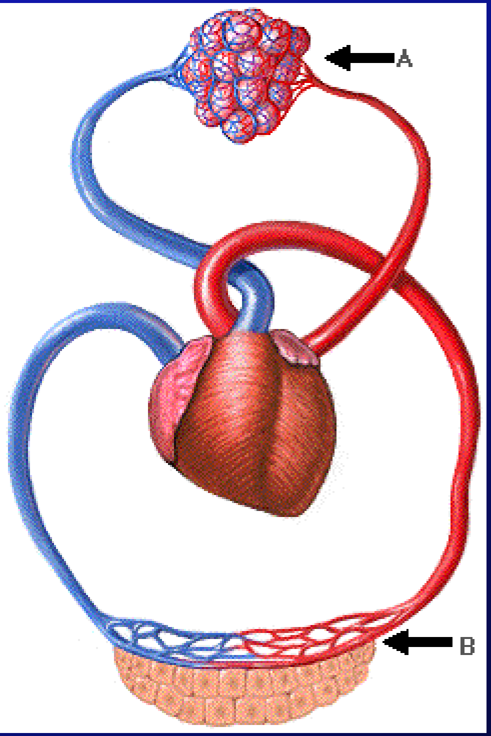
A resin cast of the arteries (red), veins (blue), and alveoli (yellow) of a human lung

Respiratory System

Prepared by:
Dorota Marczuk-Krynicka, MD, PhD

Lungs:



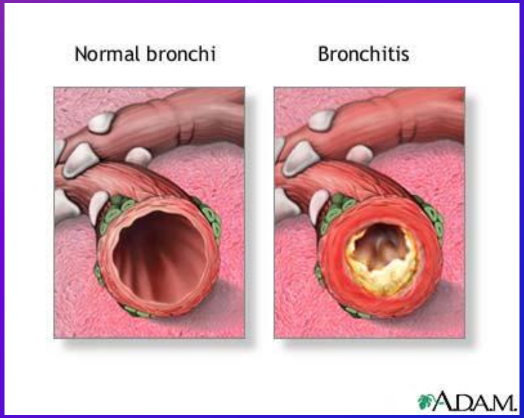
- Ventilation
- Perfusion
- Gas Exchange - Diffusion

1. Airways

   and Airway Resistance (AWR)

2. Mechanics of Breathing

   and Lung (Elastic) Recoil

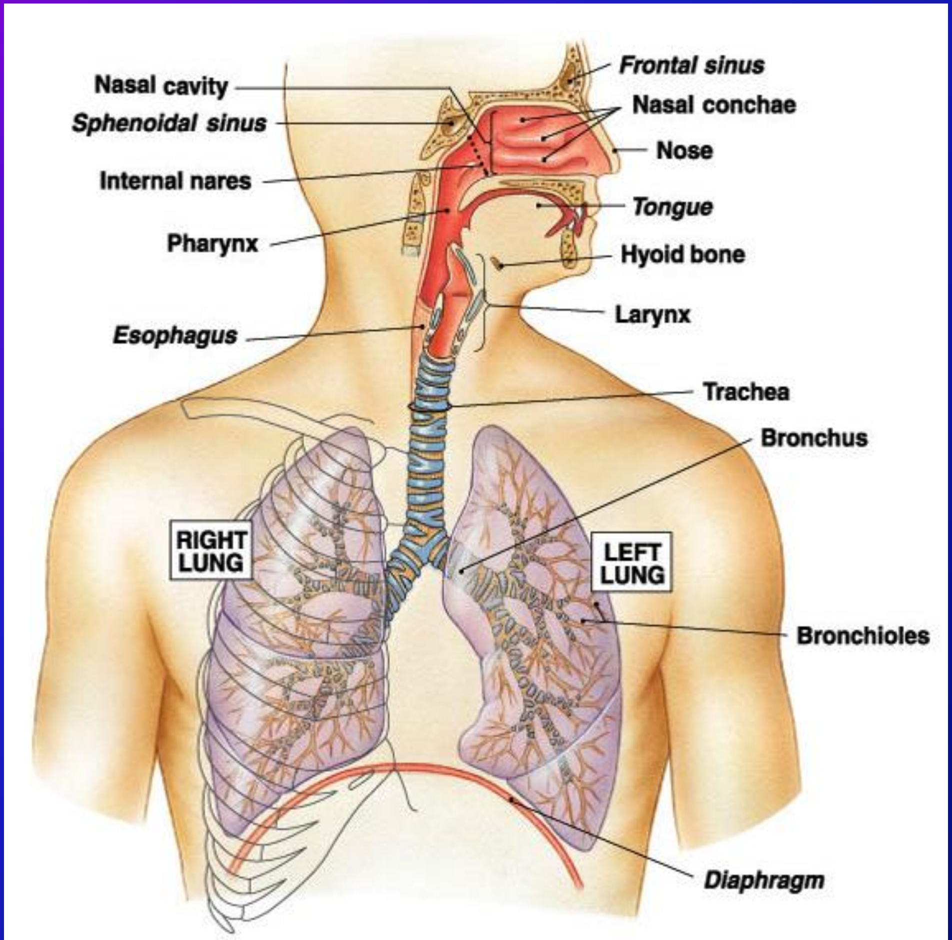


Airways

and

Airway Resistance (AWR)

Respiratory System Divisions



- Upper tract
  - Nose, pharynx and associated structures
- Lower tract
  - Larynx, trachea, bronchi, lungs

Tracheobronchial Tree

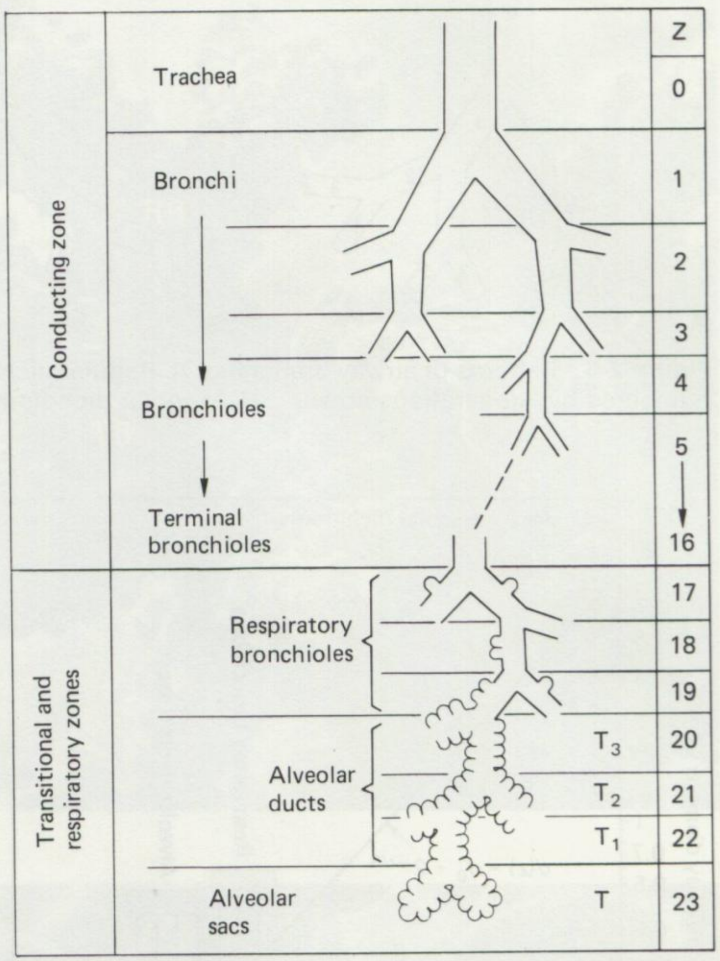
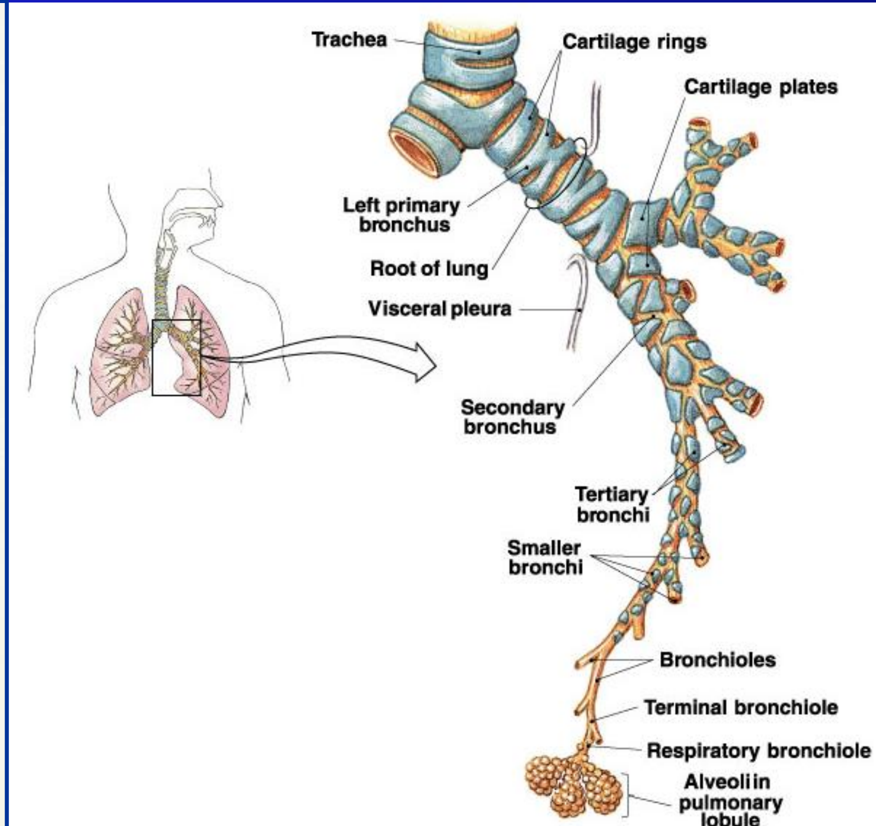


Figure 2-5 Airway branching in human lung by regularized dichotomy from trachea (generation $z = 0$) to alveolar ducts and sacs (generations 20 to 23). The first 16 generations are purely conducting; transitional airways lead into the respiratory zone made of alveoli. (*After Weibel* [21])



Volume of conducting zone
-Anatomic dead space (V_D) = (150ml)

Dead space volume does not reach alveoli.

Conducting Zone - roles:

- Air distribution to the gas exchange surface
- Warming and humidifying the air
- Serving as a part of body defence system
- Preventing the alveolar oxygen and carbon dioxide partial pressures from extreme changing

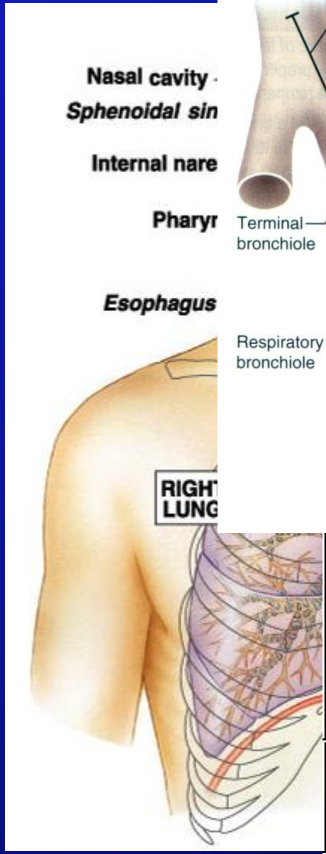
❑ Atmospheric air (dry) – *fresh air*

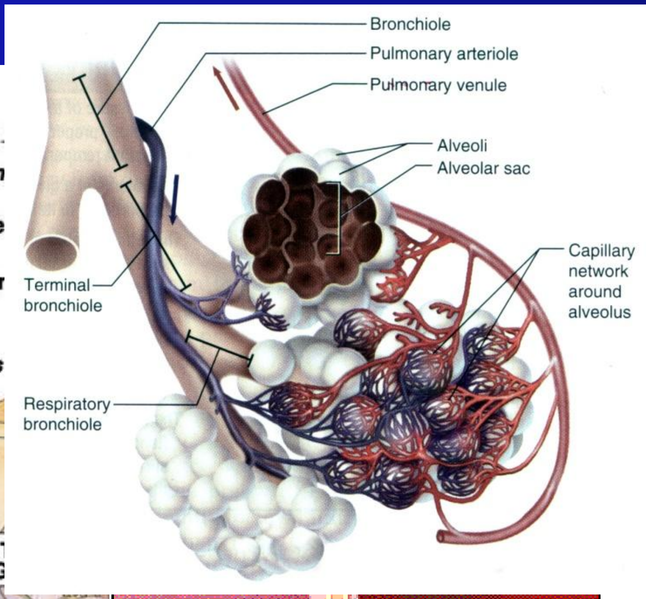
- P_{O2} = 160 mm Hg
- P_{CO2} = 0.3 mm Hg

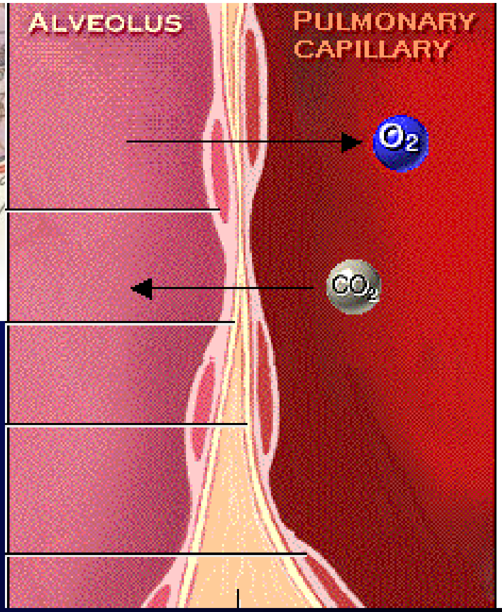
500 ml

Details → Lecture

3 000 ml (1 200 ml)







❑ Alveolar air - *old air*

- $P_{A_{O2}}$ = 100 mm Hg (105 mm Hg)
- $P_{A_{CO2}}$ = 40 mm Hg

Partial pressue = Total pressure x Fractional gas concentration

- At sea level - Total Barometric Pressure (TBP) = **760 mm Hg**

- Concentration of O_2 - 21%
-
- **Atmospheric air – *fresh air* (dry, atmospheric air):**

$$\mathbf{P_{O_2} = 760 \text{ mm Hg} \times 0{,}21 = 159{,}6 \text{ mmHg}}$$

- Concentration of CO_2 - 0,04%, P_{CO_2} = 760 mm Hg x 0,0004 = 0,3 mmHg

Tidal volume		Breathing frequency		Minute volume
500 ml	x	12 times/min	=	6000 ml

Minute volume (ventilation)

total volume of air that enters the respiratory system each minute

Tidal volume **Breathing frequency** **Minute volume**

500 ml x 12 times/min = 6000 ml

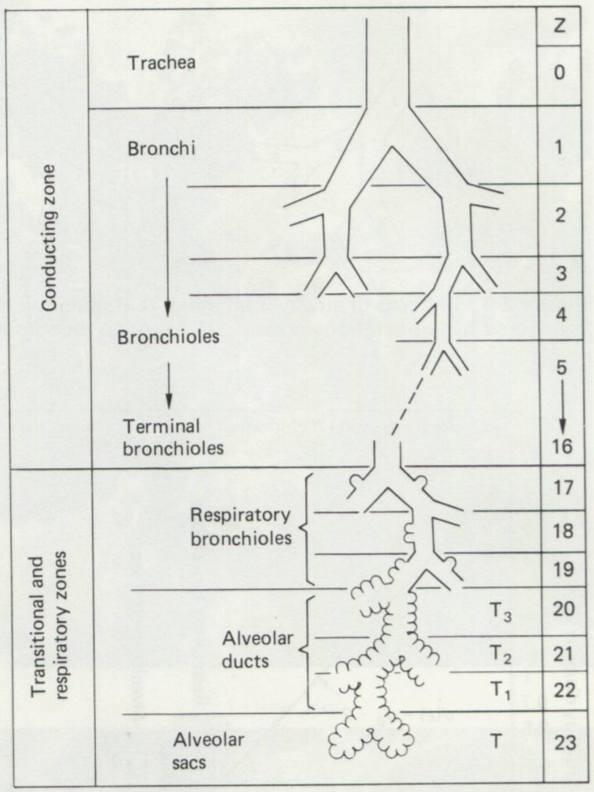


Figure 2-5 Airway branching in human lung by regularized dichotomy from trachea (generation $z = 0$) to alveolar ducts and sacs (generations 20 to 23). The first 16 generations are purely conducting; transitional airways lead into the respiratory zone made of alveoli. (*After Weibel* [*21*])

Anatomic dead space (V_D)
= volume of conducting zone (150 ml)

Alveolar ventilation

- volume of fresh air that reaches the alveoli each minute

- minute ventilation corrected for dead space ventilation

(Tidal volume - dead space) x Breathing frequency = Alveolar ventilation

(500 ml - 150 ml) x 12 times/min = 4200 ml

fresh air

Effect of Breathing Patterns on Alveolar Ventilation

Subject	Tidal Volume (ml)	x	Frequency (breaths/min)	=	Minute Volume (ml/min)	-	Dead space Ventilation (ml/min)	=	Alveolar Ventilation (ml/min)
A	1000	x	6	=	6000	-	900 (150x6)	=	5100
B	500	x	12	=	6000	-	1800 (150x12)	=	4200
C	250	x	24	=	6000	-	3600 (150x24)	=	2400

The more rapid and shallow breathing the worse the alveolar ventilation

❑ Airway resistance (AWR,R):

$$R = \frac{8\eta l}{\pi r^{4\ (5)}}$$

❑ Airflow:

$$\dot{V} = \frac{\Delta P}{R}$$

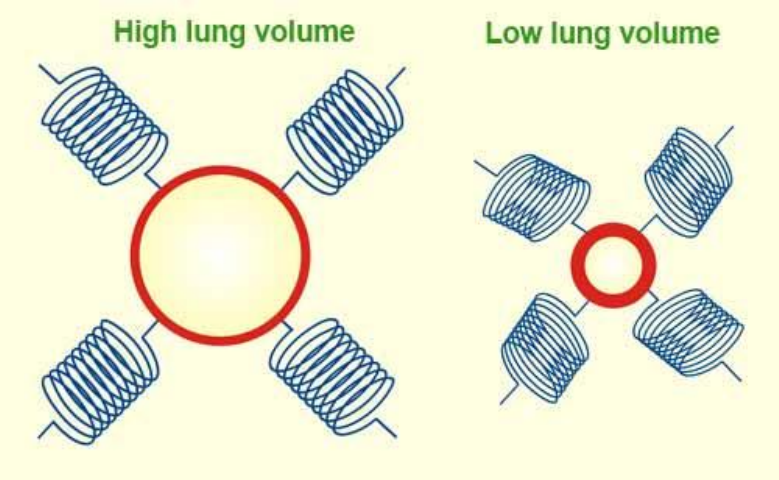
- If r decreases by the factor of ***4****, the airway resistance will increase by a factor* ***256****, and air flow will decrease by a factor of* ***256***

r → R (AWR) → Airflow (V)

Factors Affecting AWR

❑Lung volume

1. Radial traction exerted on the airways by the surrounding lung tissue



Inspiration

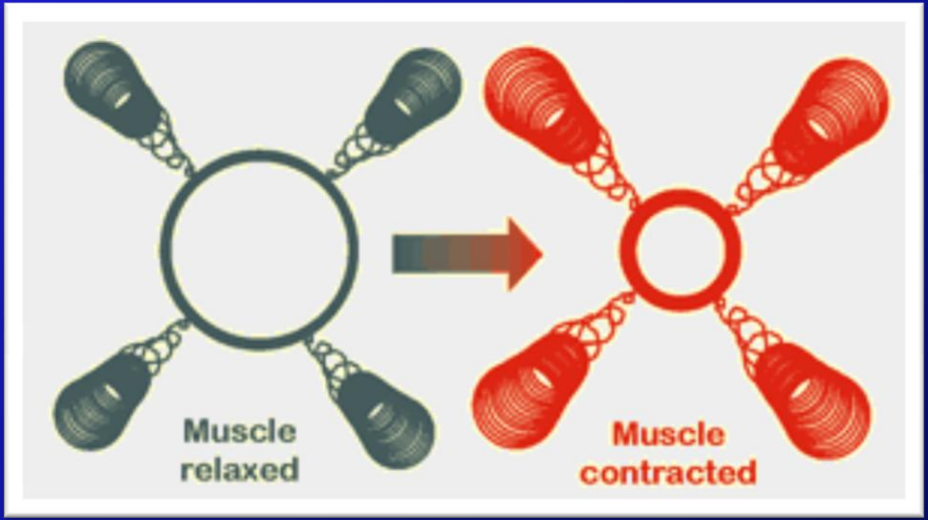
AWR decreases

2. ↓ in pressure inside the chest
3. Less impulses from Vagus

Expiration - AWR increases !

Factors Affecting AWR

- Contraction or relaxation of bronchial smooth muscles



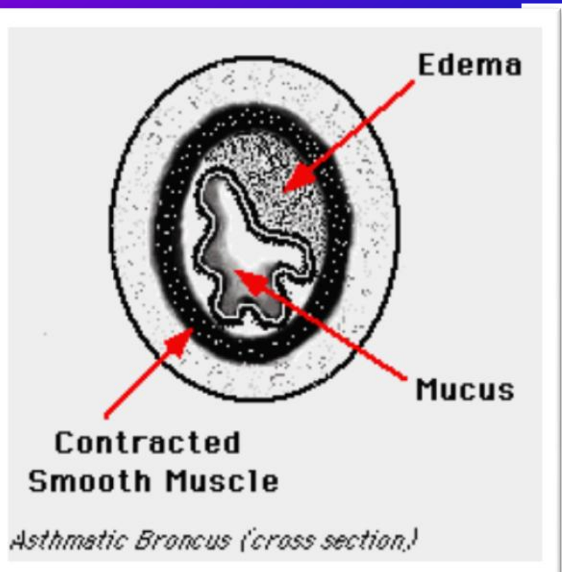
RELAXATION (dilation, ↓AWR) **CONTRACTION (narrowing, ↑AWR)**

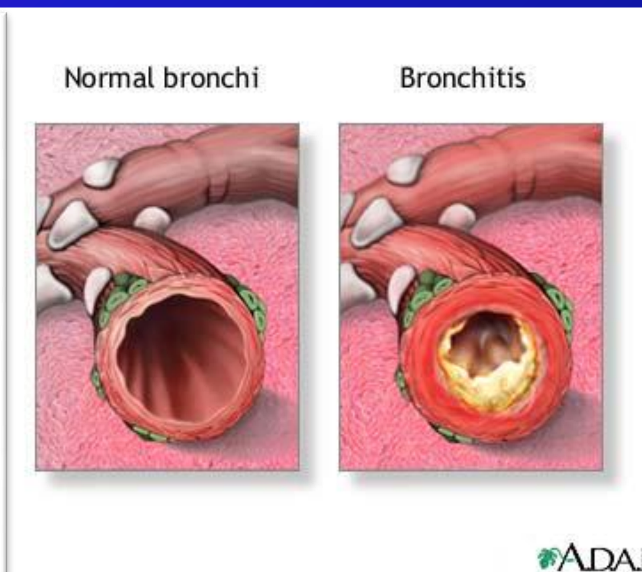
Stimulation:

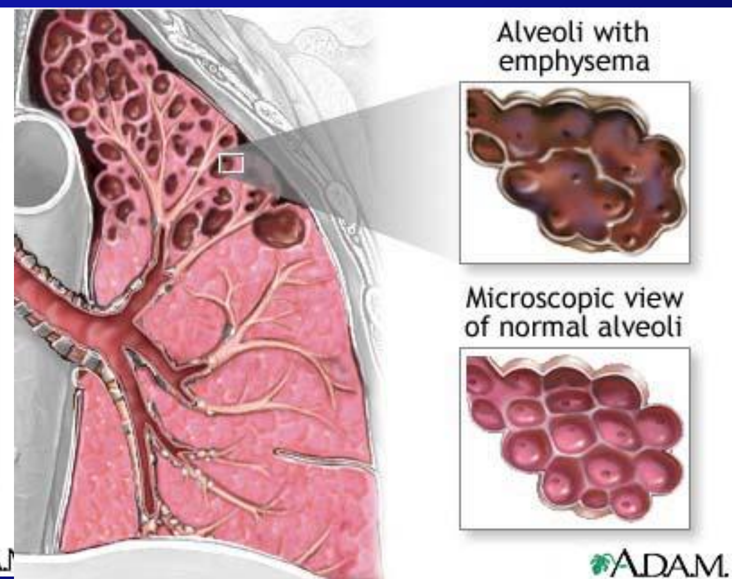
RELAXATION	CONTRACTION
-Sympathetic (adrenergic)	***- Parasympathetic (cholinergic)***
- β_2 adrenergic receptors	***- Muscarinic receptors***
Epinephrine	***Irritants***
β_2 -agonists	

Obstructive pattern

- ↑ airway resistance
- ↓ rate at which air can move through the lungs

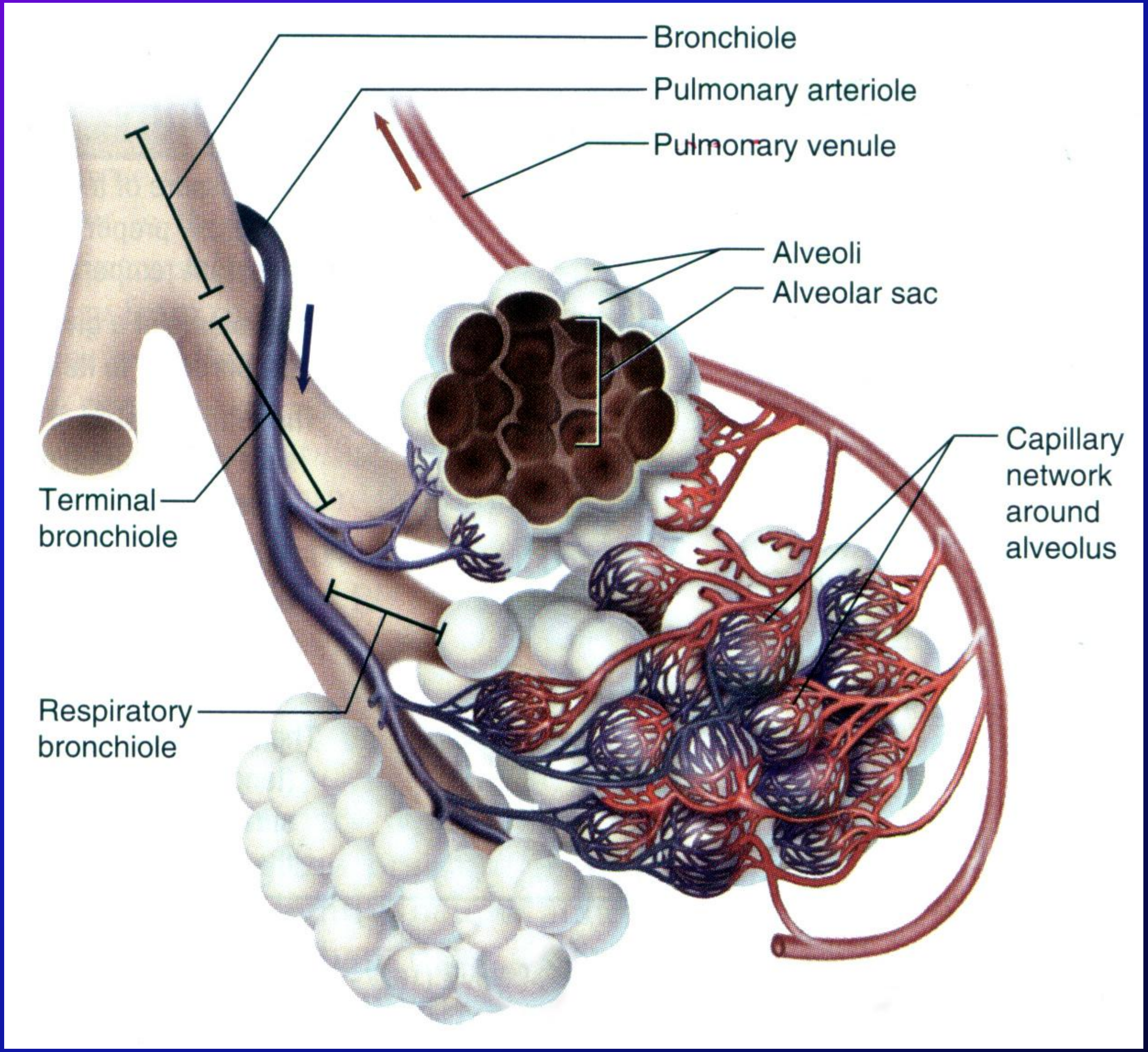






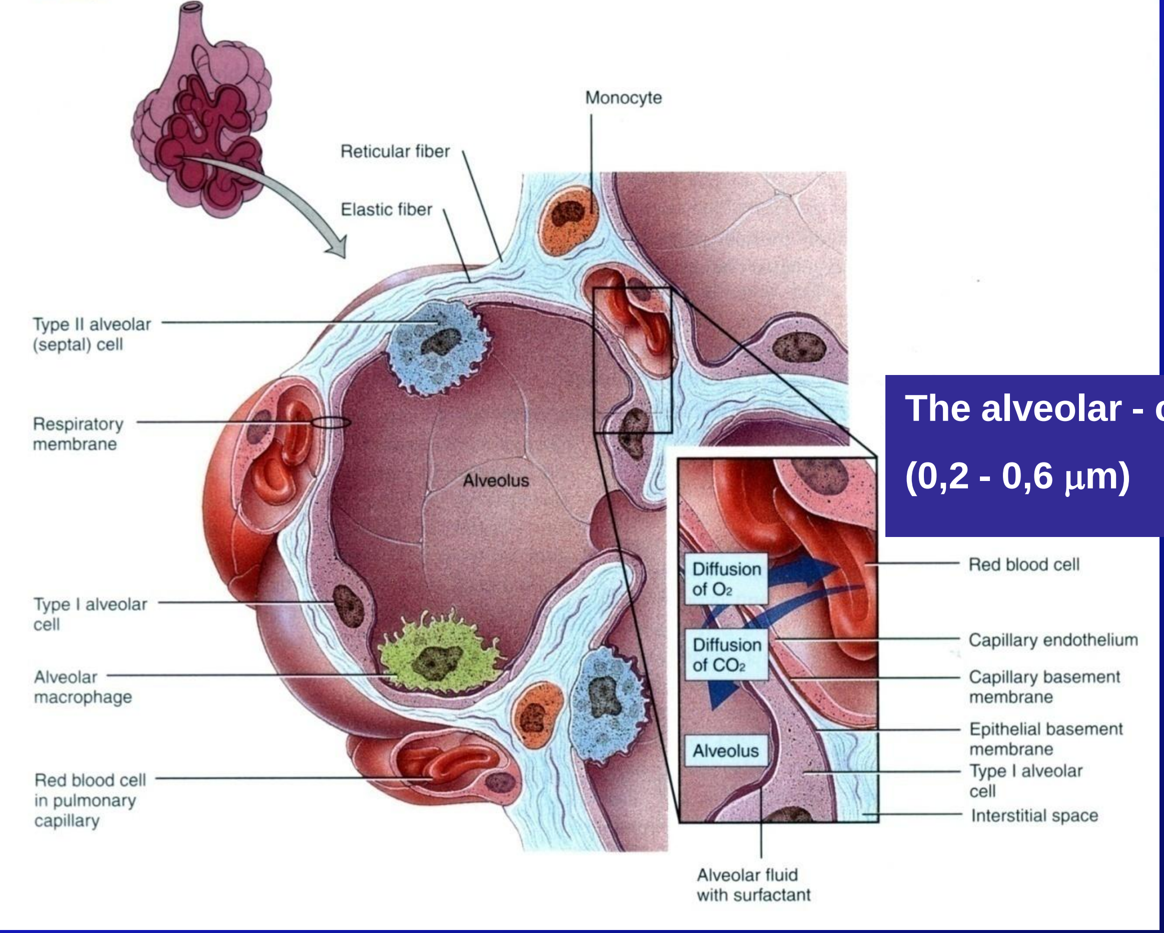
Asthma **Chronic bronchitis** **Emphysema**

COPD



The Alveoli:

- 300 million in both lungs
- an average diameter: 0,1 - 0,3 millimeter



The alveolar - capillary membrane

(0,2 - 0,6 μm)

Transfer of gasses

Directly related to:

- Driving pressure across the alveolar - capillary membrane
- Area of membrane (70 m^2)
- Solubility of gas

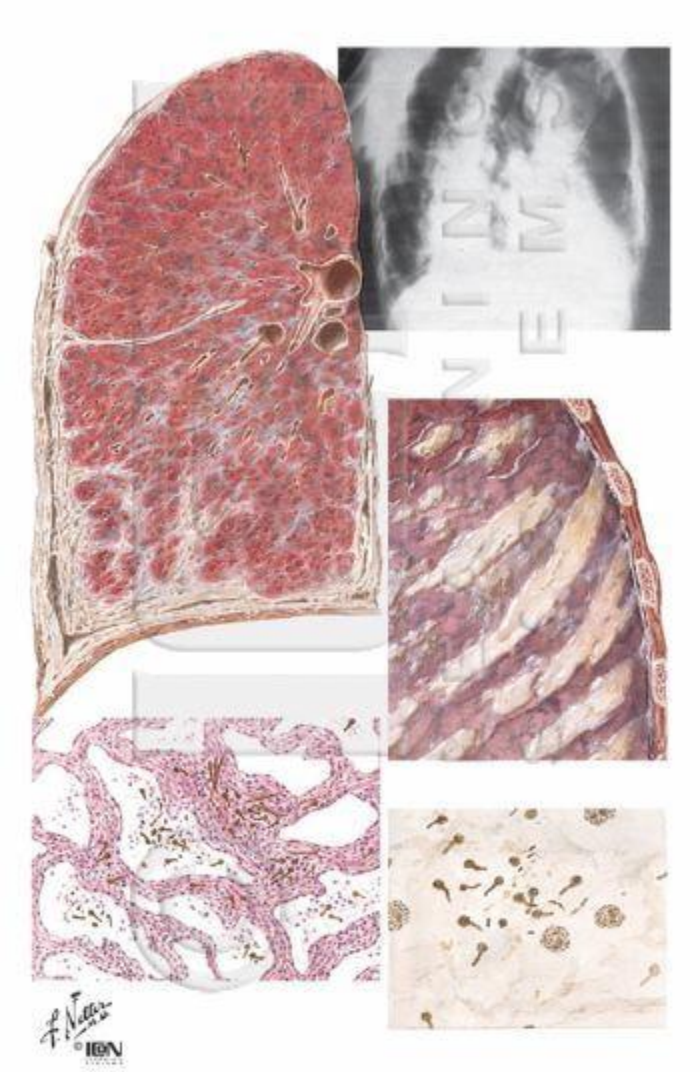
Inversely related to:

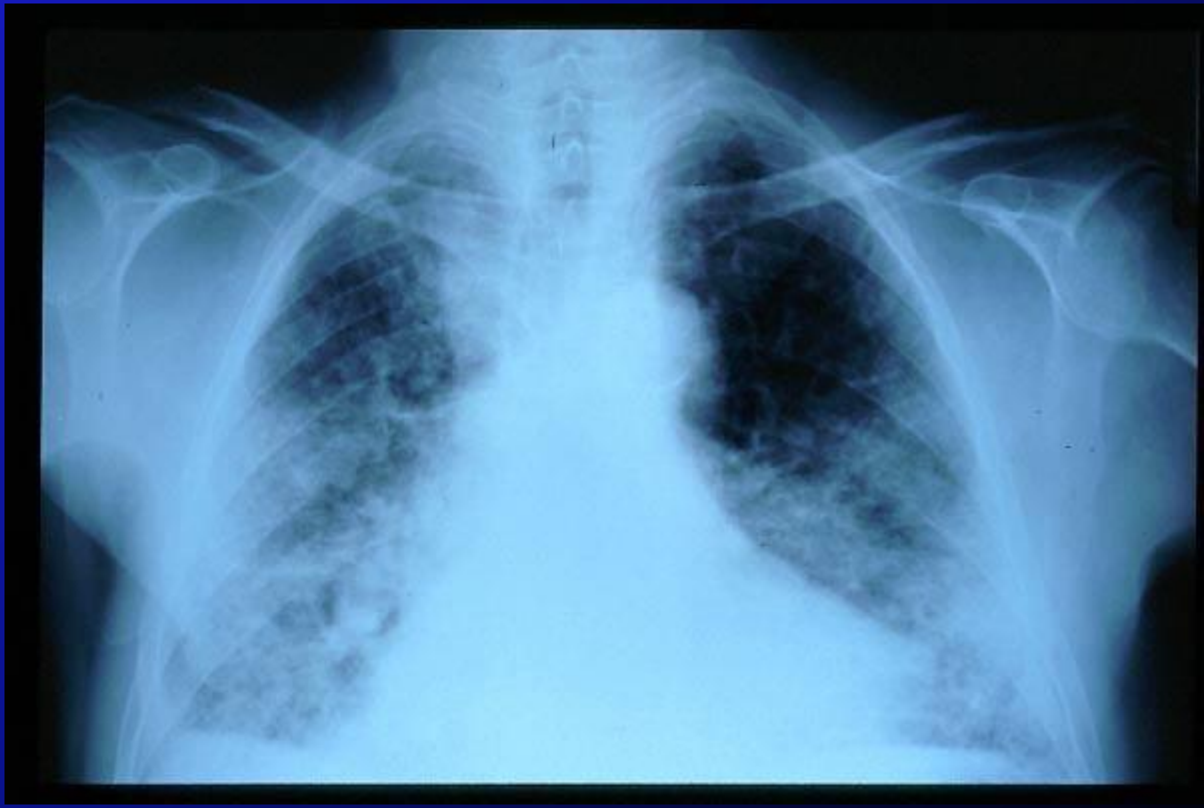
Length of diffusion pathway

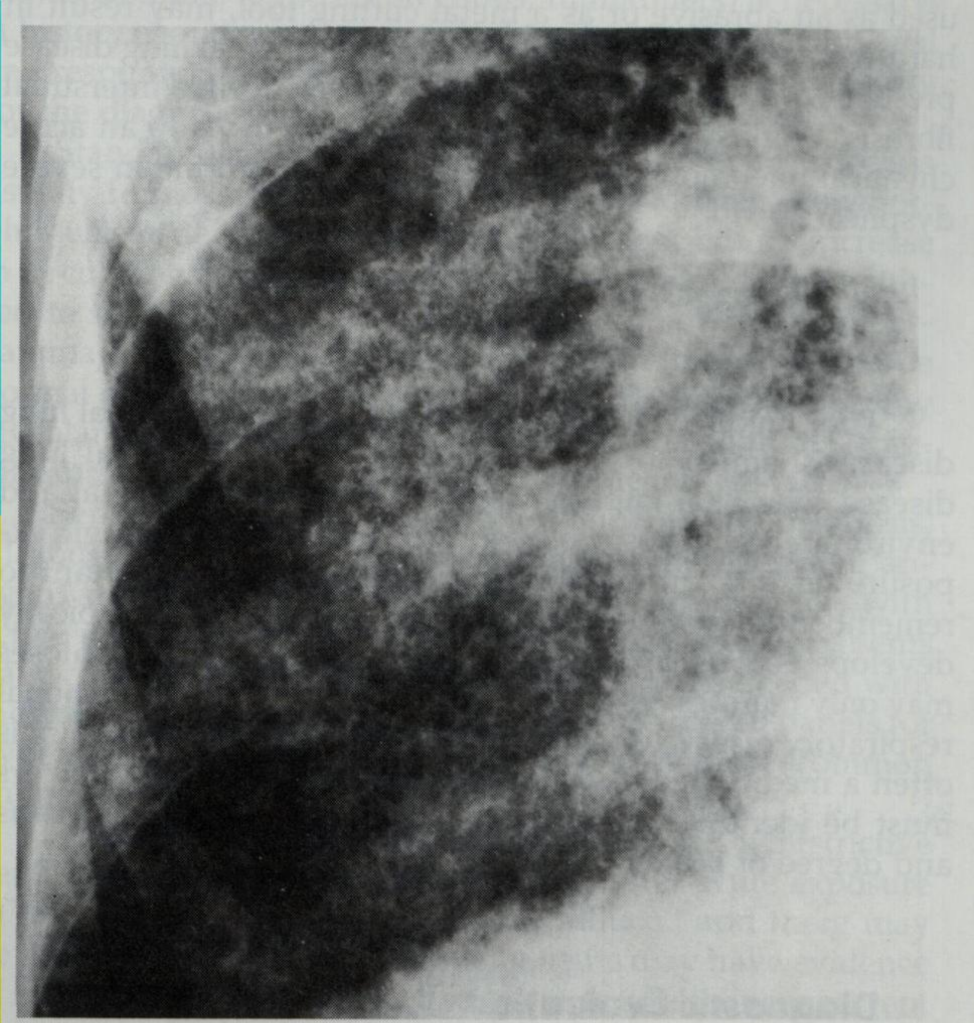
Square root of molecular weight of gas

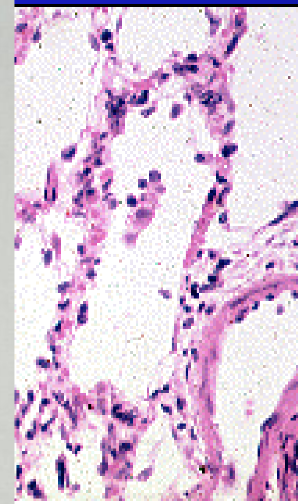
Pulmonary fibrosis

(scarring throughout the lungs)

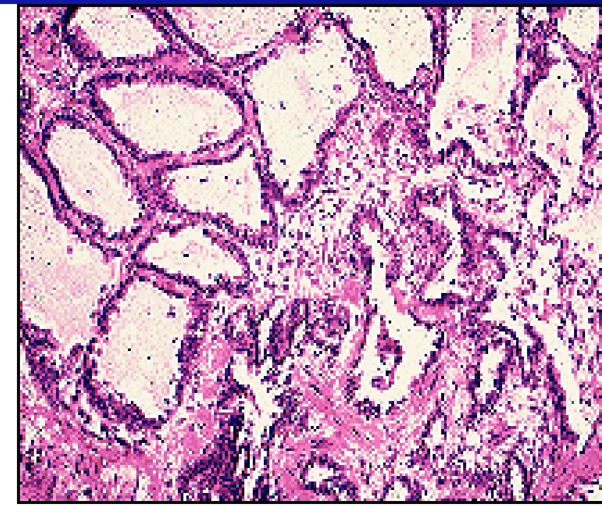








ology



Fibrotic Alveoli – Histology

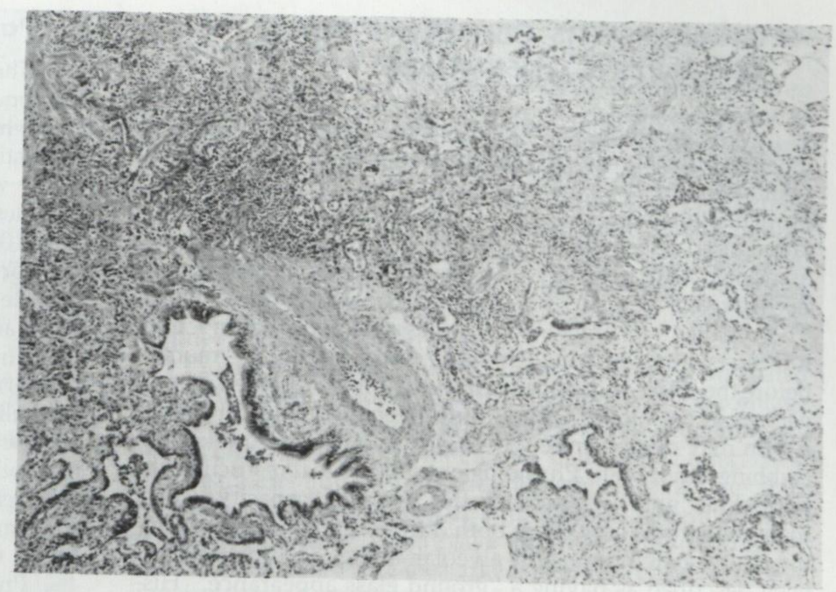
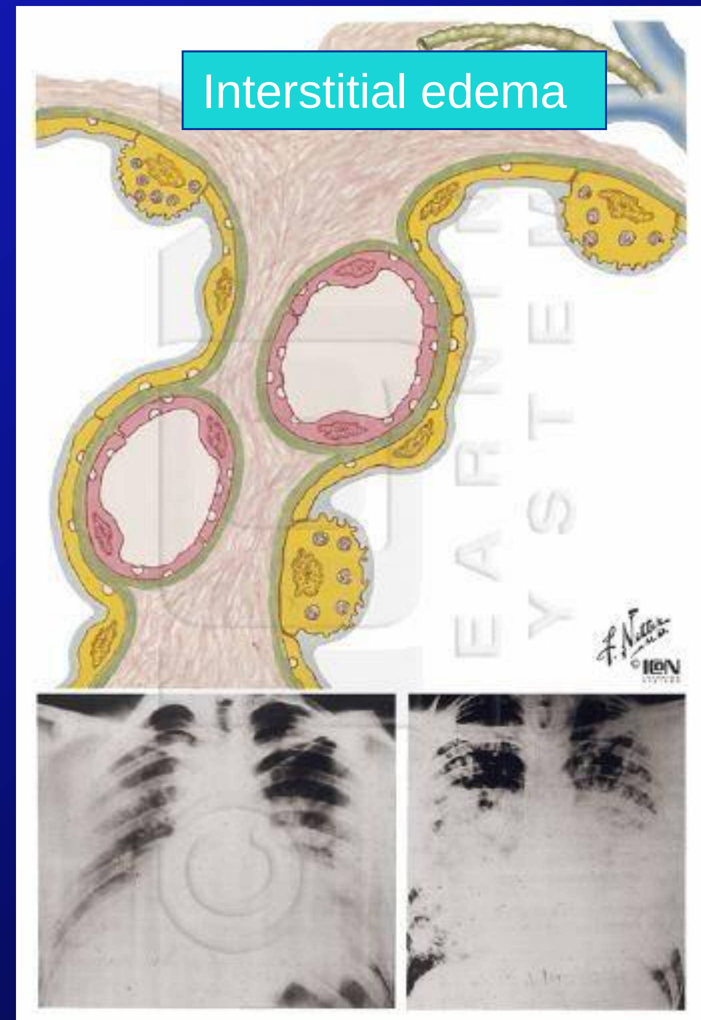


Figure 163–1. Severe pulmonary fibrosis. The majority of the lung tissue is consolidated because of a combination of air space collapse and accumulations of nondistensible fibrous tissue within the interstitium and former air spaces. Little functional gas-exchange tissue is present except for a few partially collapsed alveoli. Compare with normal lung in Figure 160–1A. Original magnification = 75×. (Courtesy of Dr. Rodney Schmidt, Pathology Department, University of Washington)

Pulmonary edema
- Heart problems
- other reasons

Pulmonary edema begins with an increased filtration through the loose junctions of the pulmonary capillaries.

As the intracapillary pressure increases, normally impermeable(tight) junctions between the alveolar cells open, permitting alveolar flooding to occur.

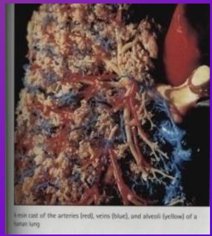


Alveolar edema

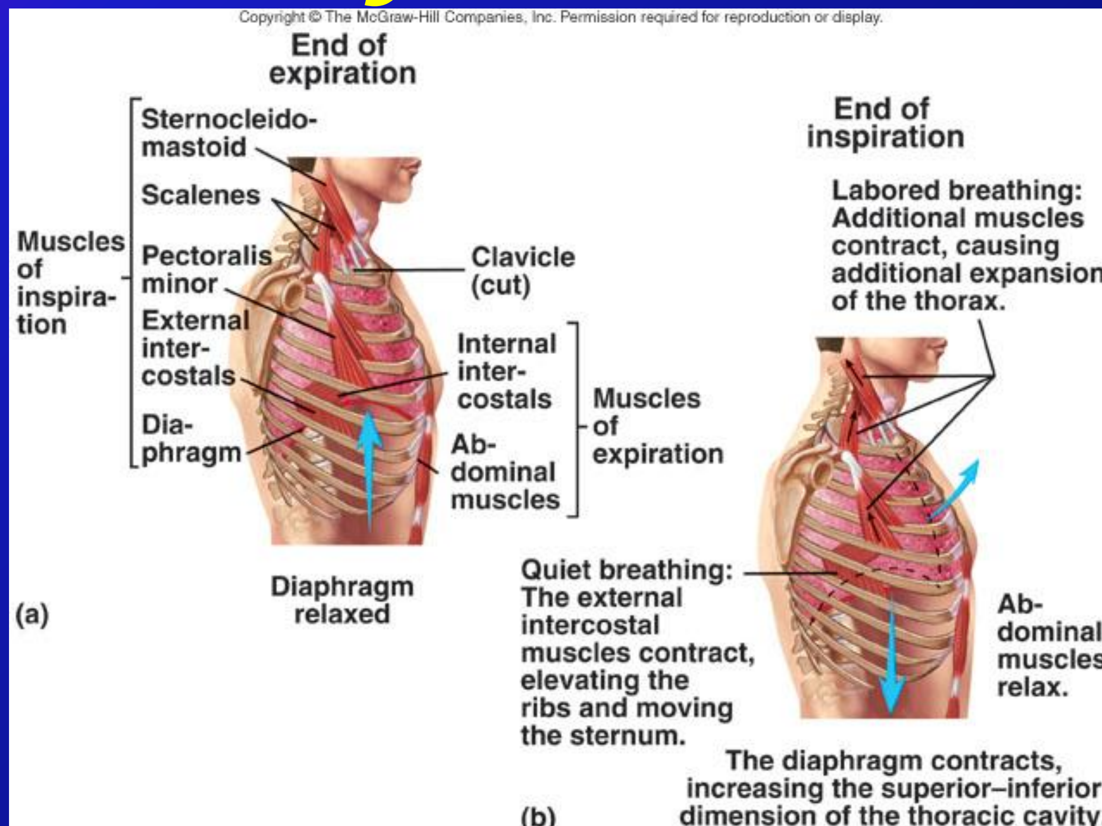
Mechanics of Breathing

and

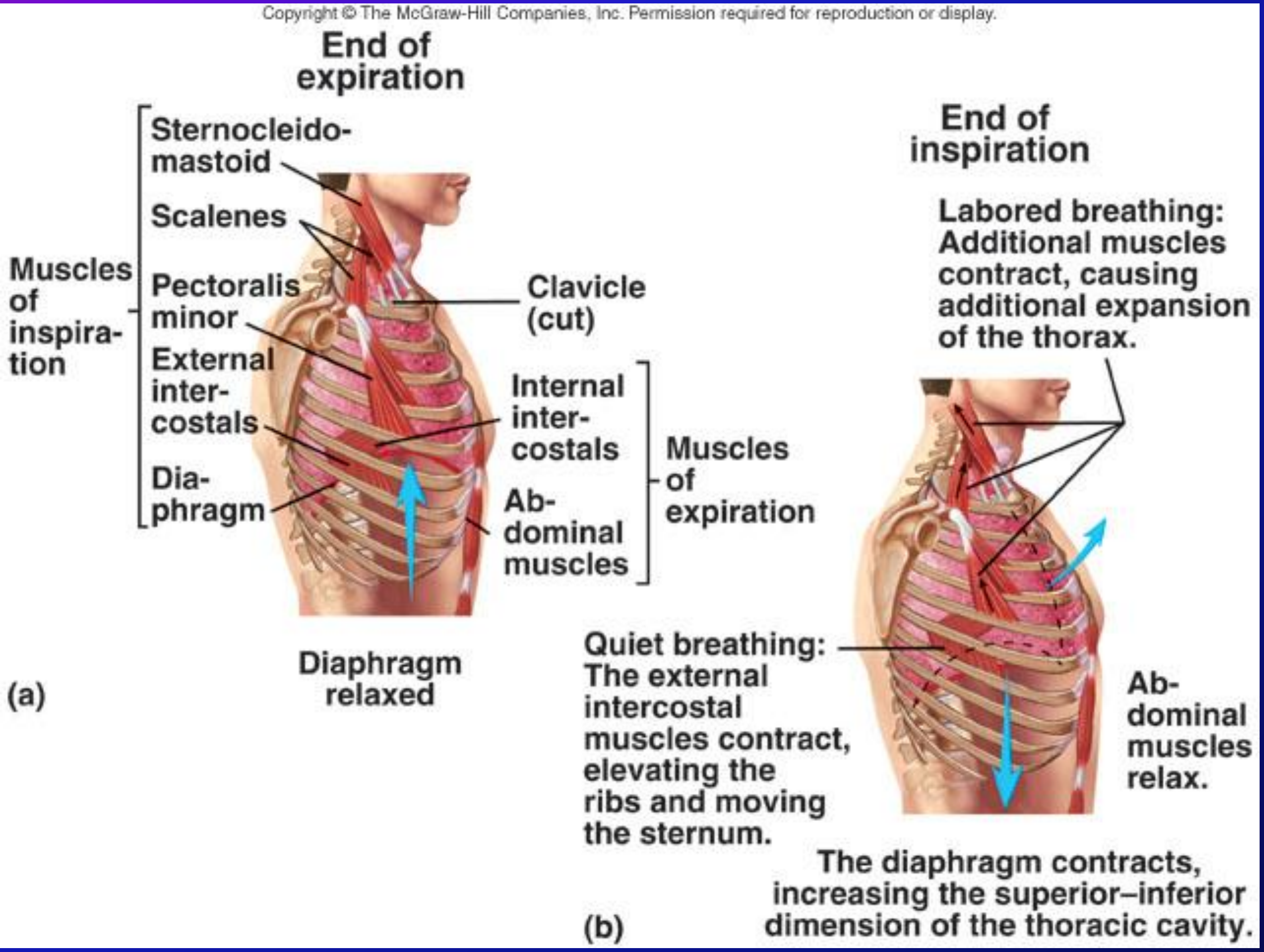
Elastic Recoil

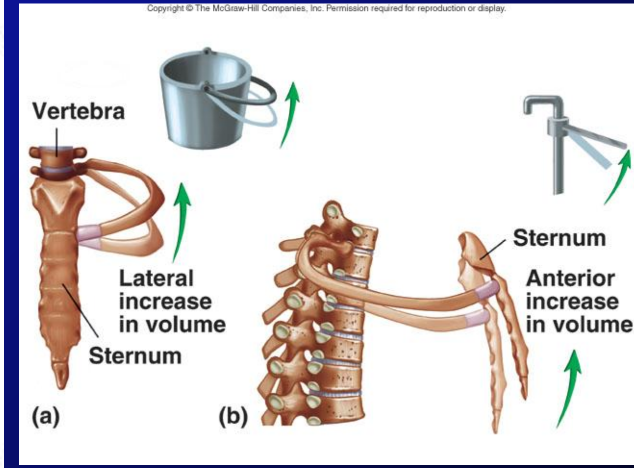


Inspiration
-always active



Muscles of Respiration





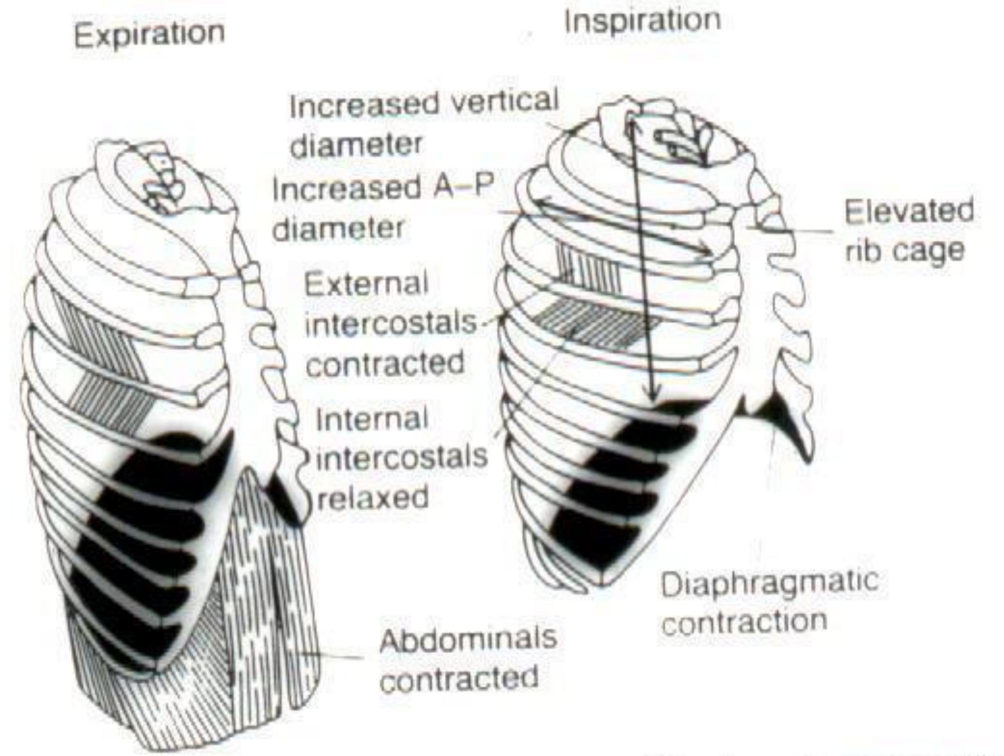
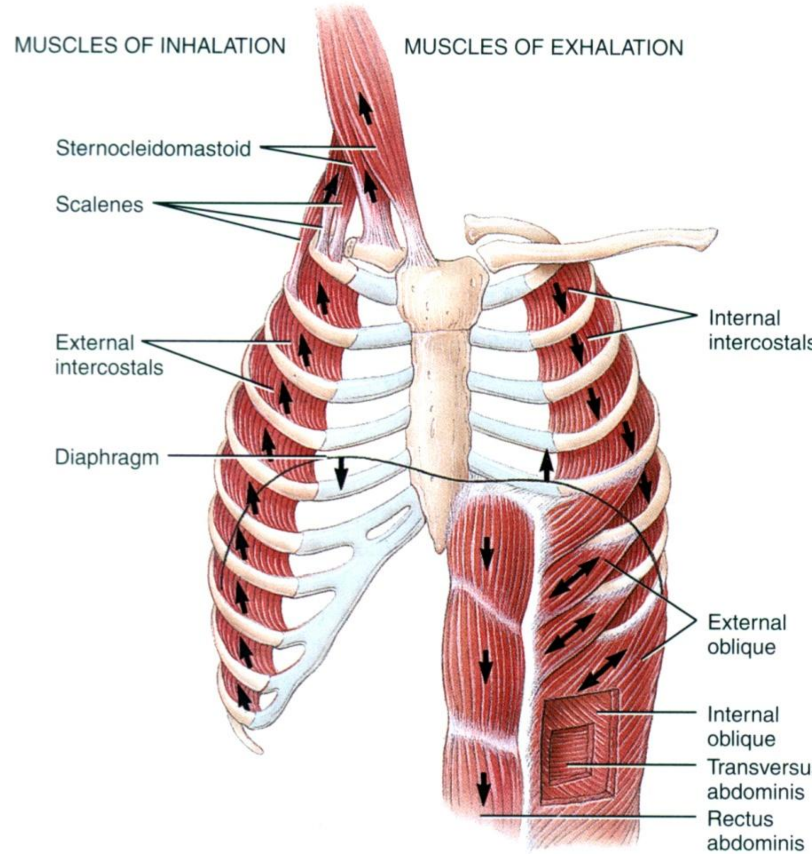
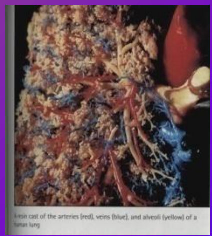


Figure 37 – 1. Expansion and contraction of the thoracic cage during expiration and inspiration, illustrating especially diaphragmatic contraction, elevation of the rib cage, and function of the intercostals.



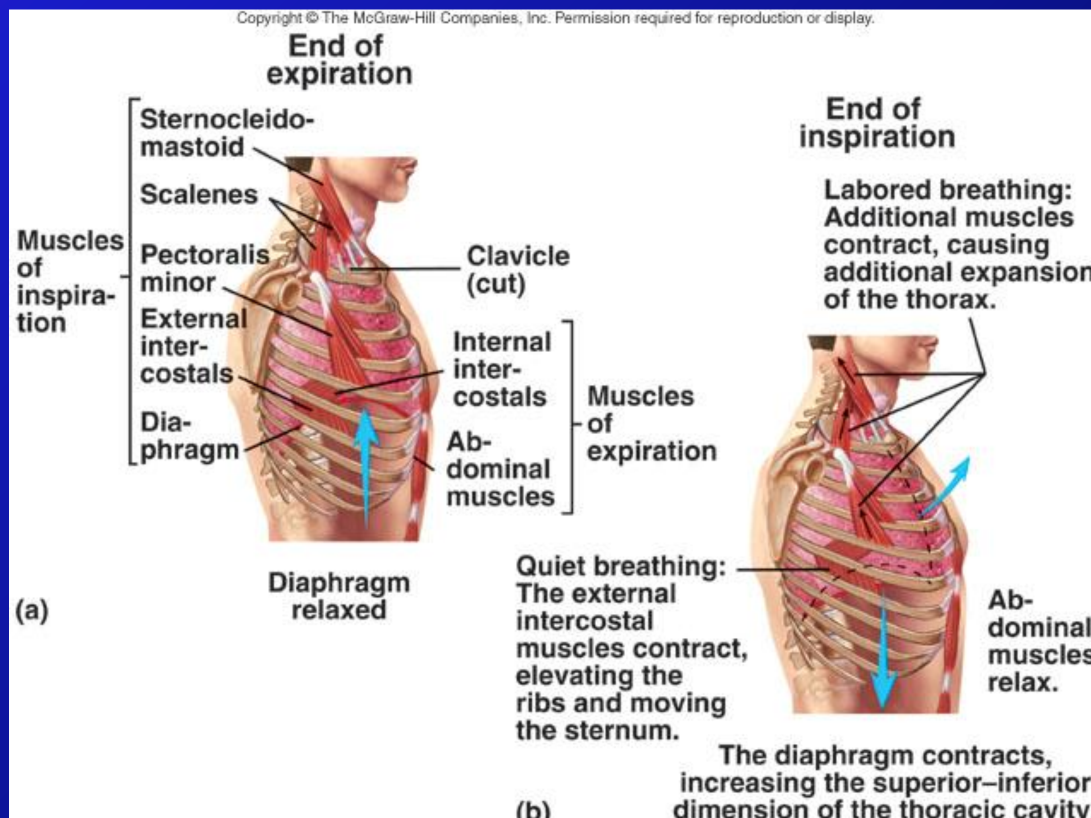
(a) Muscles of inhalation and their actions (left); muscles of exhalation and their actions (right)

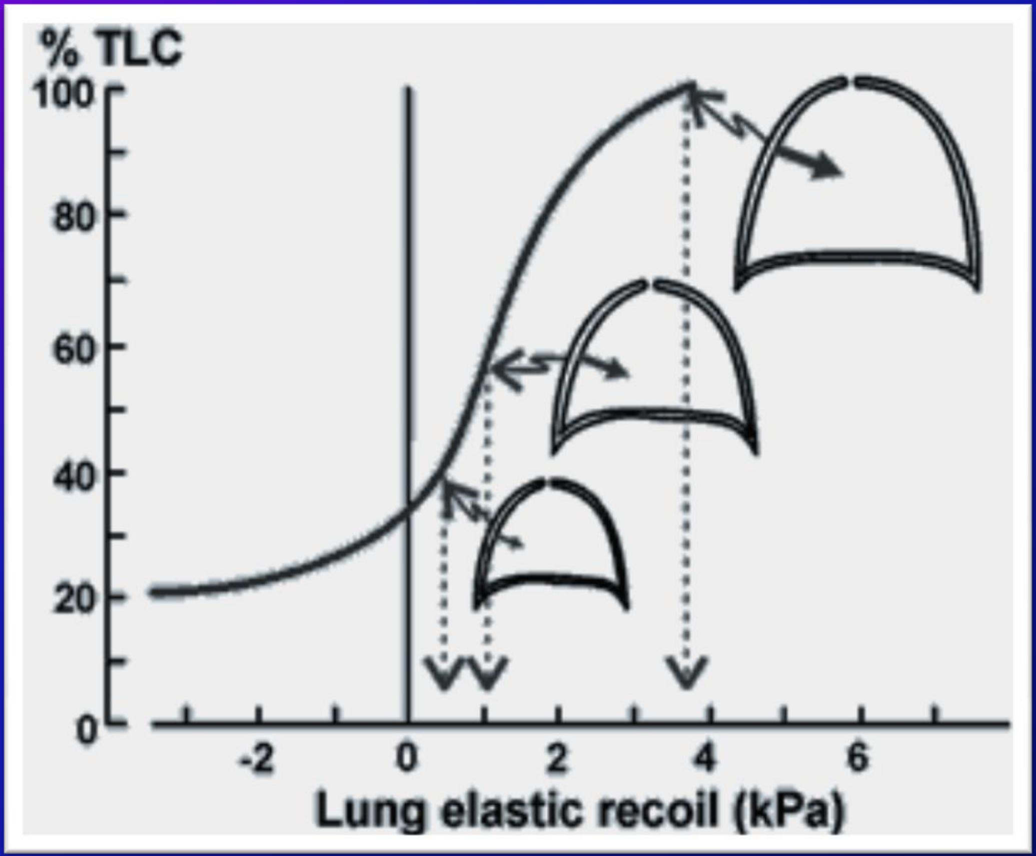


Expiration

- Quiet = passive

- Deeper = active

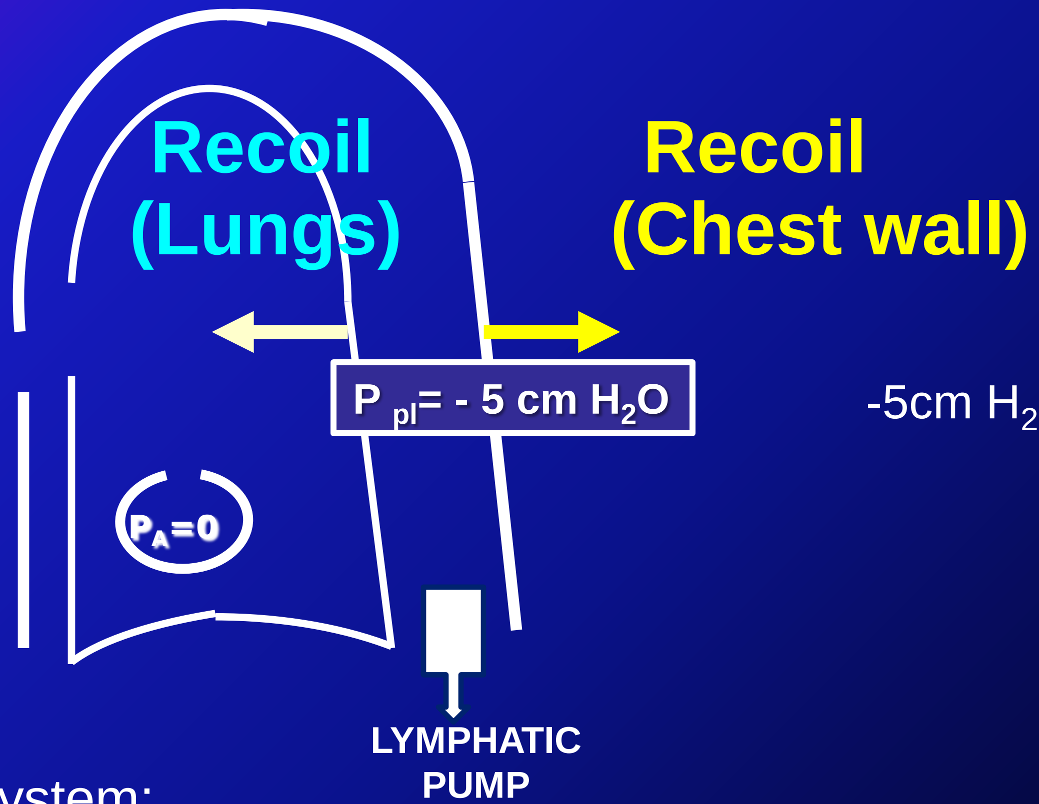




Elastic Forces → Lung (elastic) recoil

- *elastic forces of the lung tissue itself (elastic, collagen fibres)*
- *elastic forces caused by surface tension of the fluid that lines the inside walls of the alveoli*

END OF QUIET EXPIRATION



-5cm H_20 = - 4 mm Hg

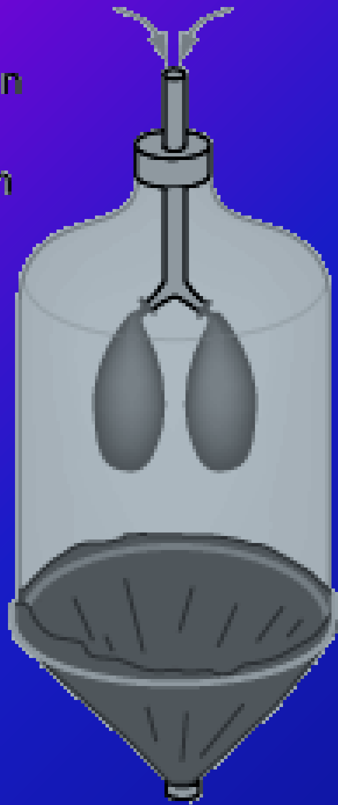
Respiratory System:

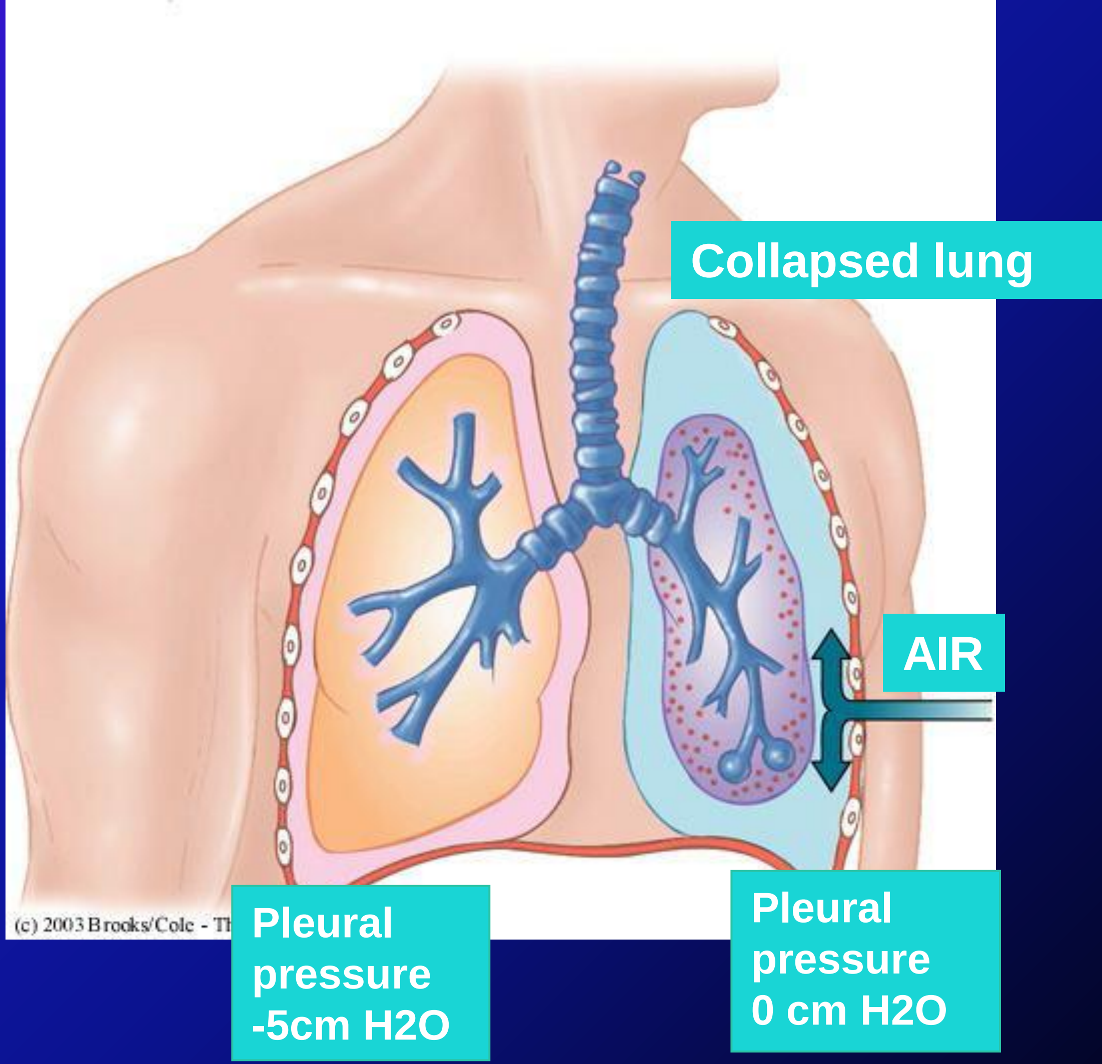
- Convenient unit for pressure is 1 cm H_2O

1 mm Hg = 13,6 mm H_2O (1,36 cm H_2O), 1 cm H_2O = 0,74 mm Hg

- Atmospheric pressure (760 mm Hg) - set as zero

Modeling lung action with balloons and an elastic diaphragm



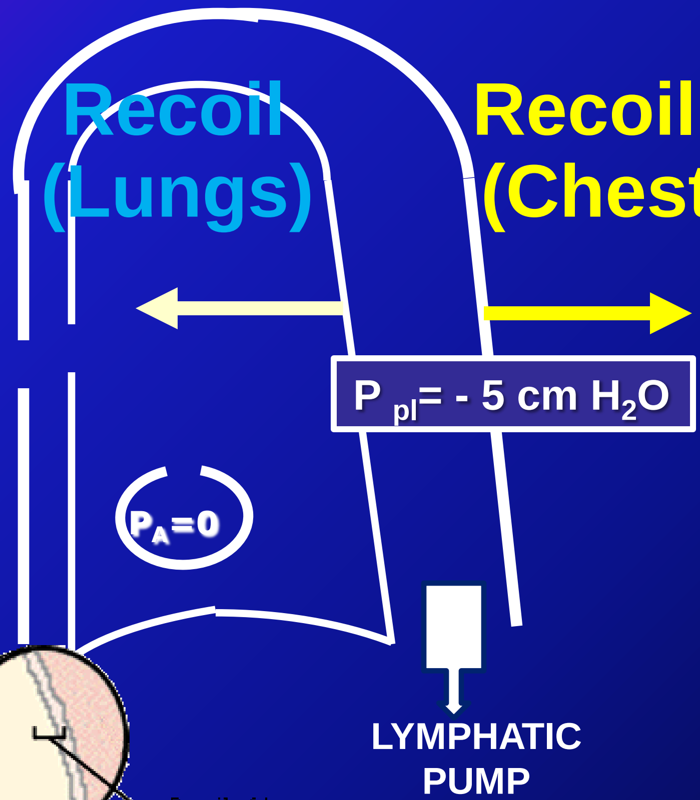


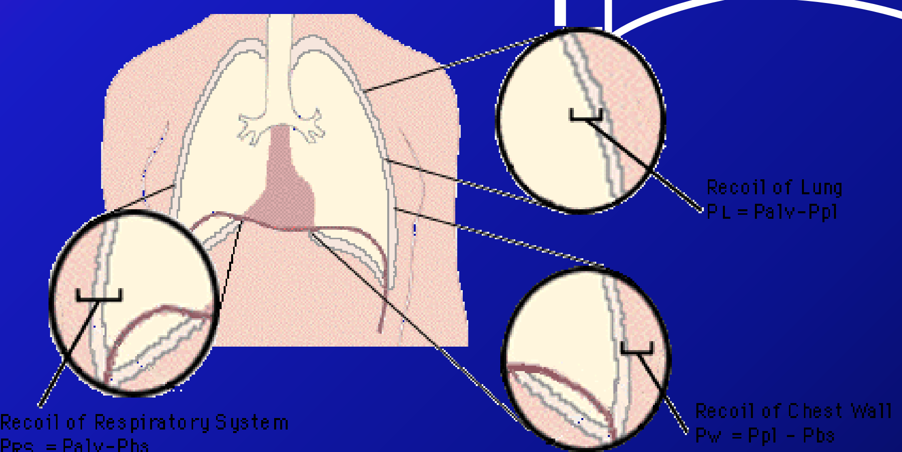
Pleural pressure

- **Negative pressure can cause alveoli to expand**

  - Pneumothorax is an opening between pleural cavity and air that causes a loss of pleural pressure

END OF QUIET EXPIRATION





$P_{TP} = 0 – (-5\text{ cm } H_2O) = + 5\text{ cm } H_2O$

$Pw = - 5\text{ cm } H_2O – 0 = - 5\text{ cm } H_2O$

$PRS = 0 – 0 = 0$

Pressure is inversely related to volume

Boyle`s Law

The pressure of a given quantity of gas is inversely proportional to its volume (assuming a constant temperature)

INSPIRATION

Inspiratory muscles contract

↓

Thoracic cavity expands

↓

Pleural pressure ↓

(becomes more subatmospheric)

↓

Lungs expand

↓

Alveolar pressure ↓

(becomes subatmospheric)

↓

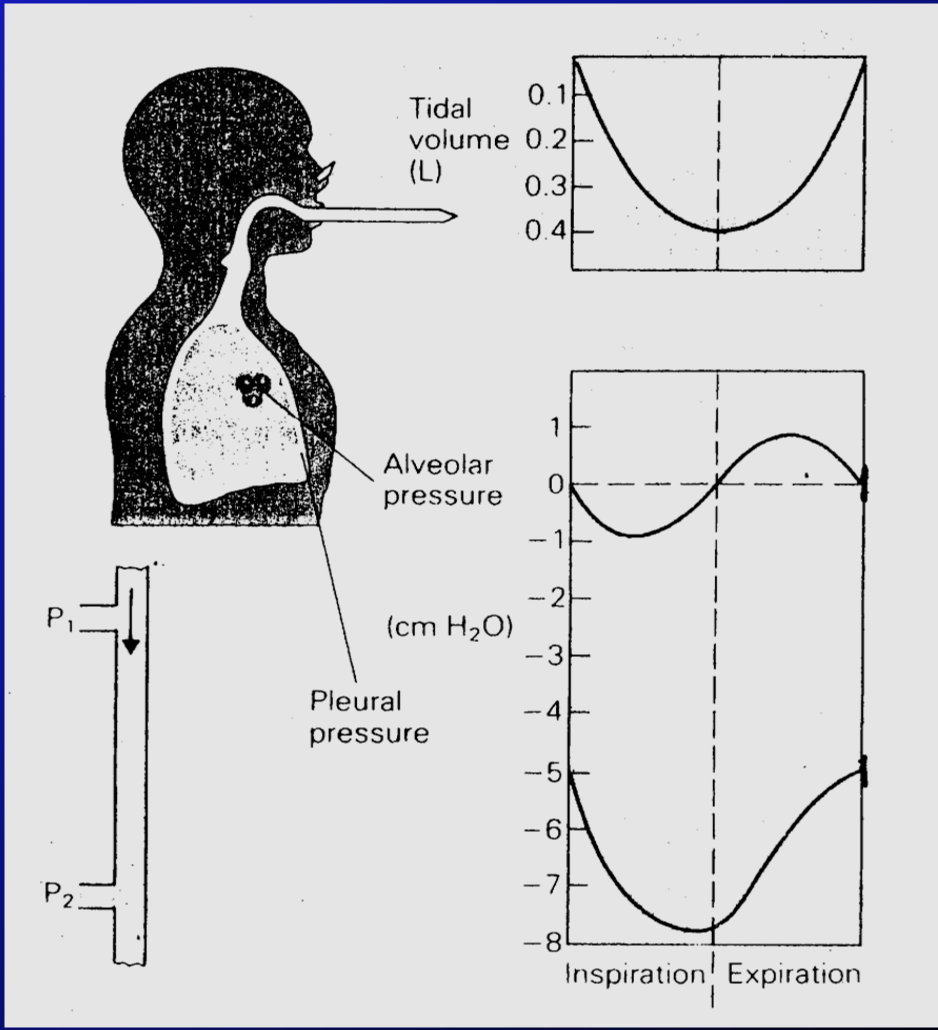
Pressure gradient in airways ↑

(lower pressure in alveoli)

↓

Air flows into the lungs

Alveolar and Pleural Pressures
during a Breathing Cycle (Quiet Breathing)



EXPIRATION

Respiratory muscles relax

↓

Thoracic cage volume ↓

↓

Pleural pressure ↑

(becomes less subatmospheric)

↓

Size of lungs ↓

↓

Alveolar pressure ↑

(exceeds atmospheric level)

↓

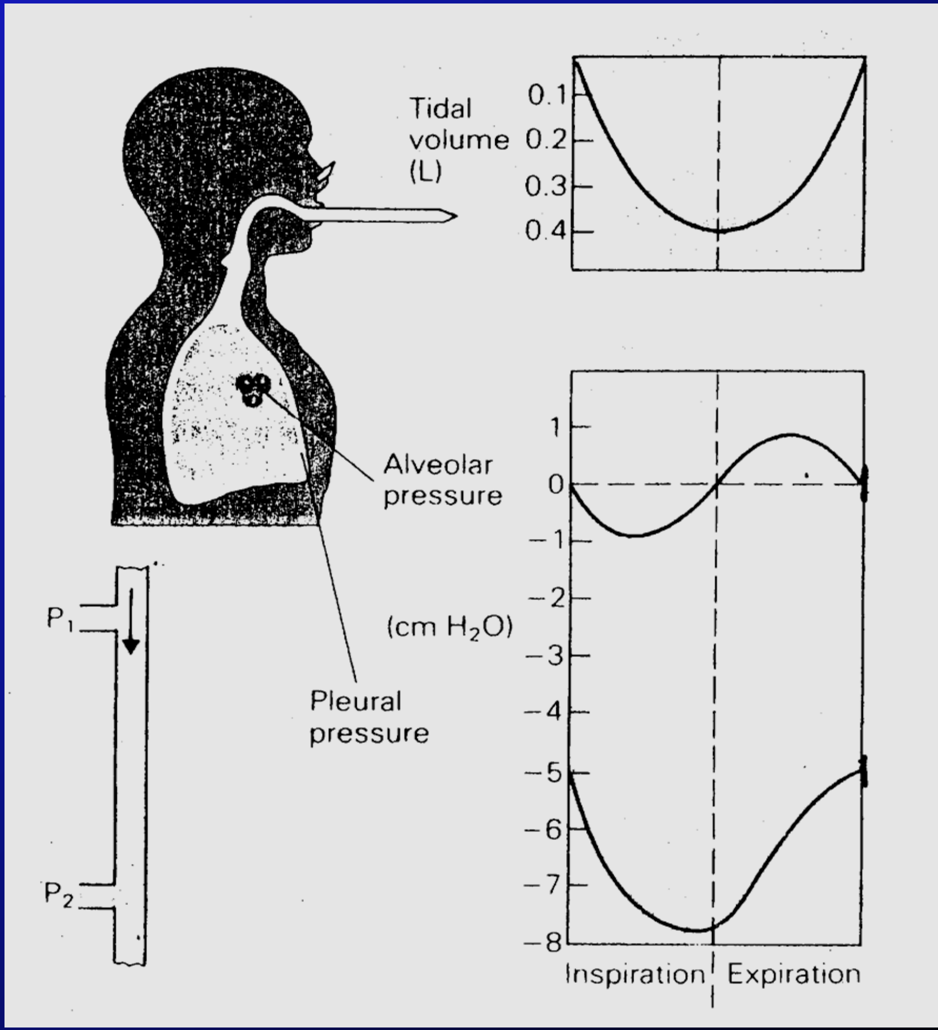
Pressure gradient in airways ↑

(lower pressure in upper airways)

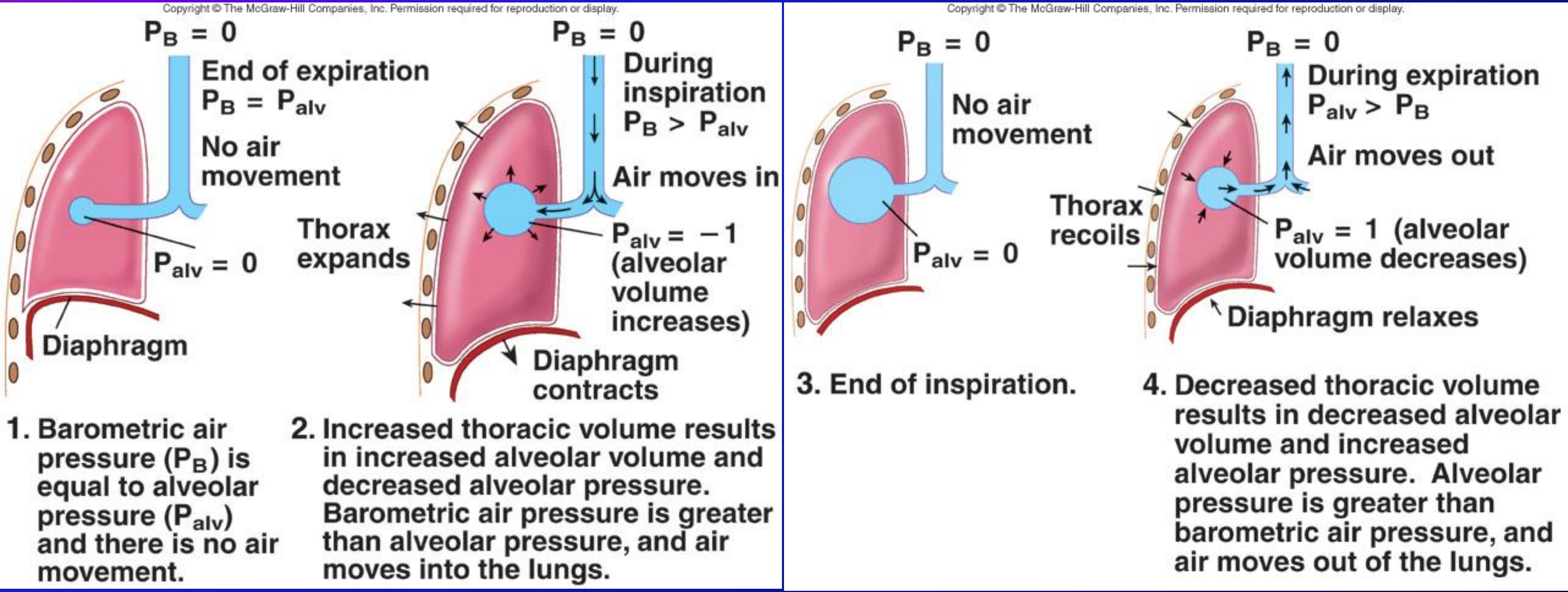
↓

Air flows out of the lungs

Alveolar and Pleural Pressures
during a Breathing Cycle (Quiet Breathing)



Alveolar Pressure Changes



- Air moves from area of higher pressure to area of lower pressure
- <u>**No air movement → AWR = 0**</u>

Compliance (C)

- describes distensibility of the lung and chest wall
- reflex the easy with which an object can be deformed

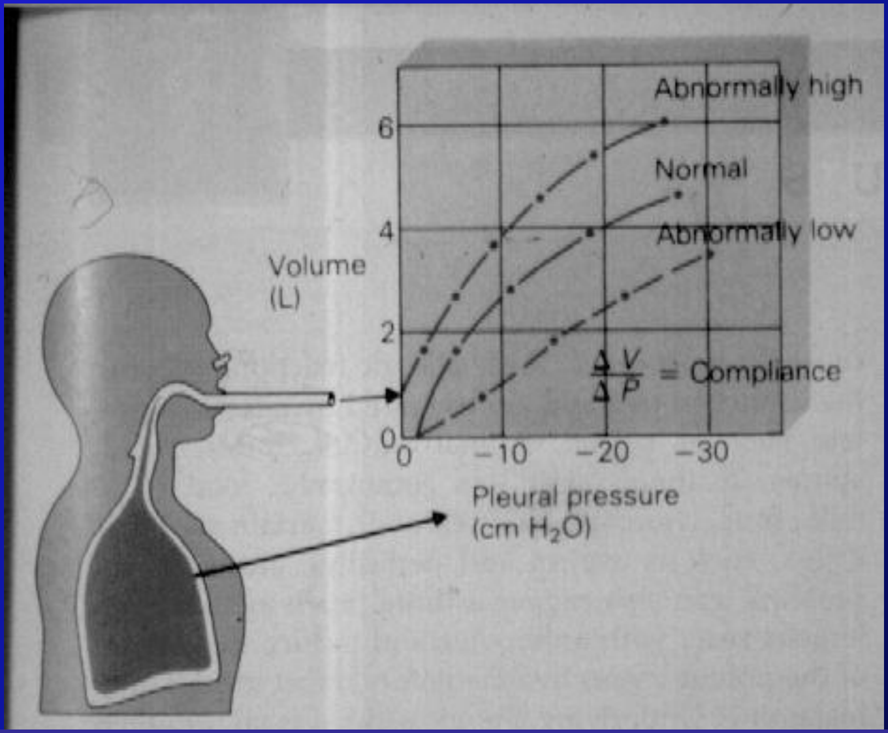
Elastance (E)

reflex the opposition of an object to deformation by an external force

Compliance of the Lungs (an index of lung distensibility)

$C_L = \Delta V/\Delta P$ **(200 - 230 ml/ 1 cm H_2O)**

lung volume change / unit intrapleural pressure change



- a slope of pressure - volume curve

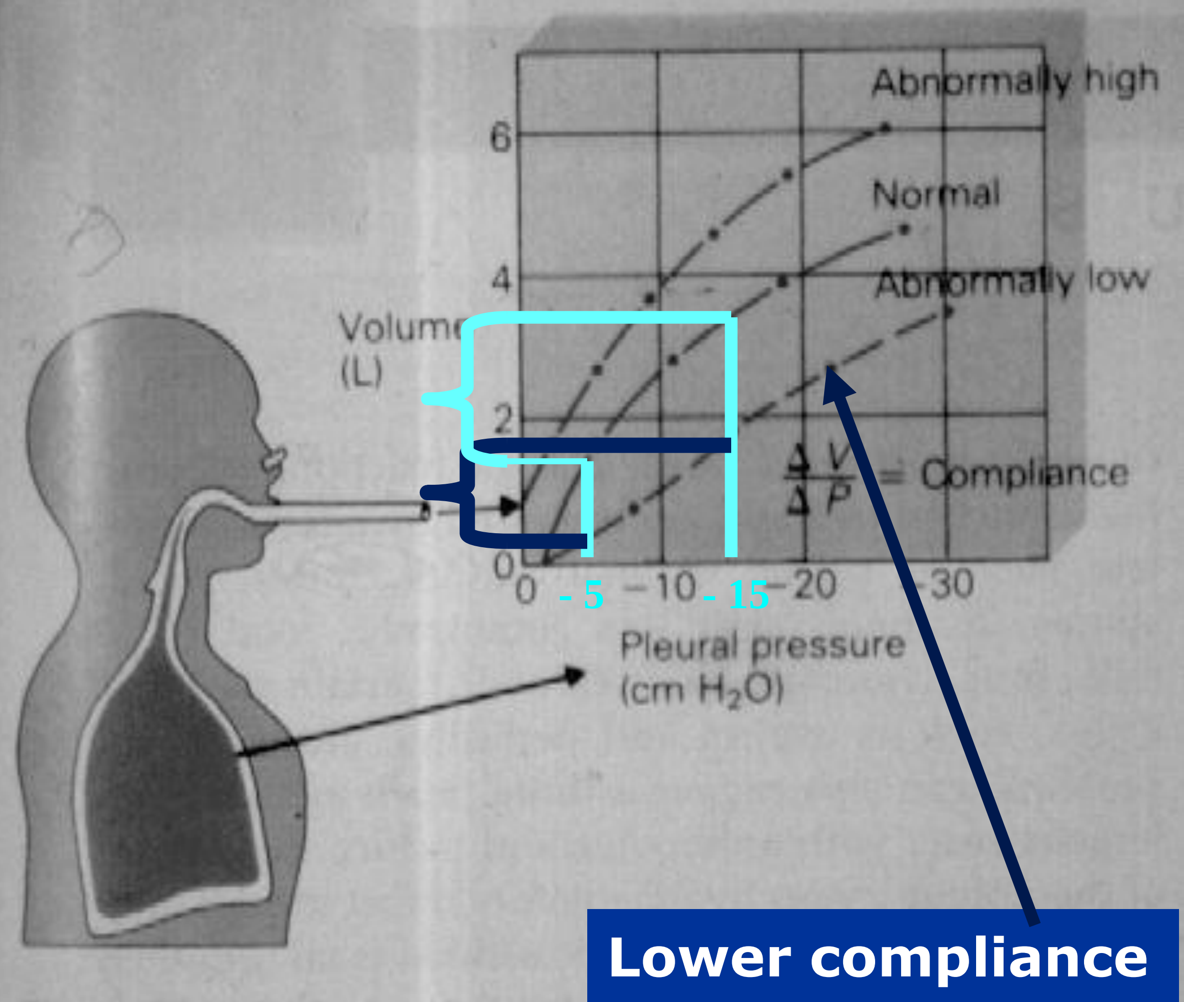
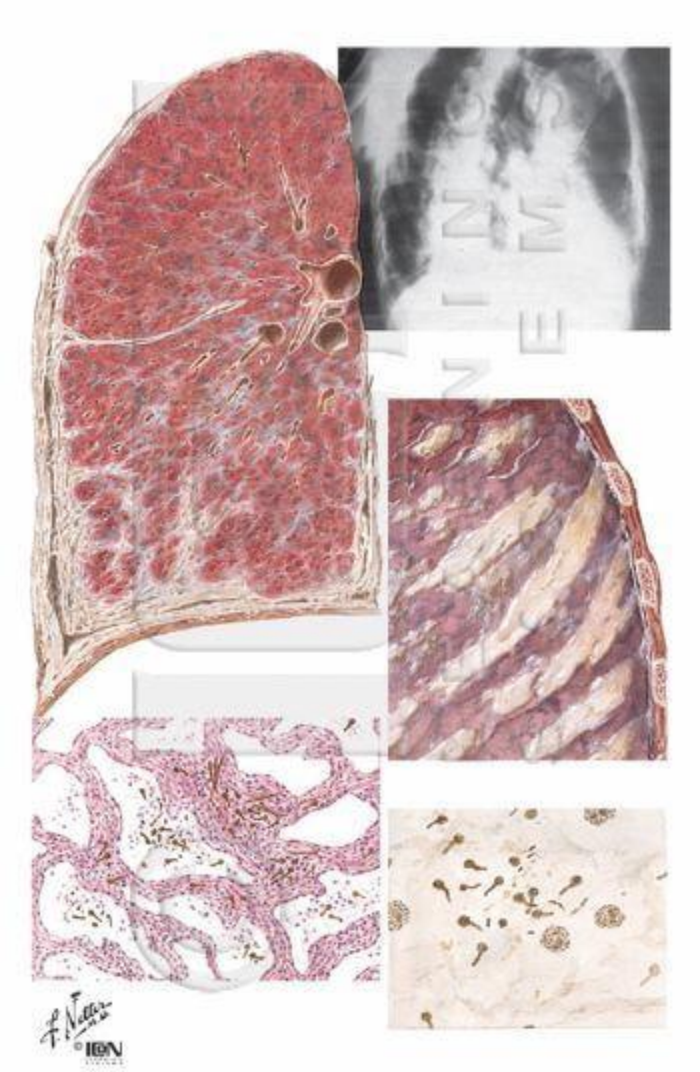


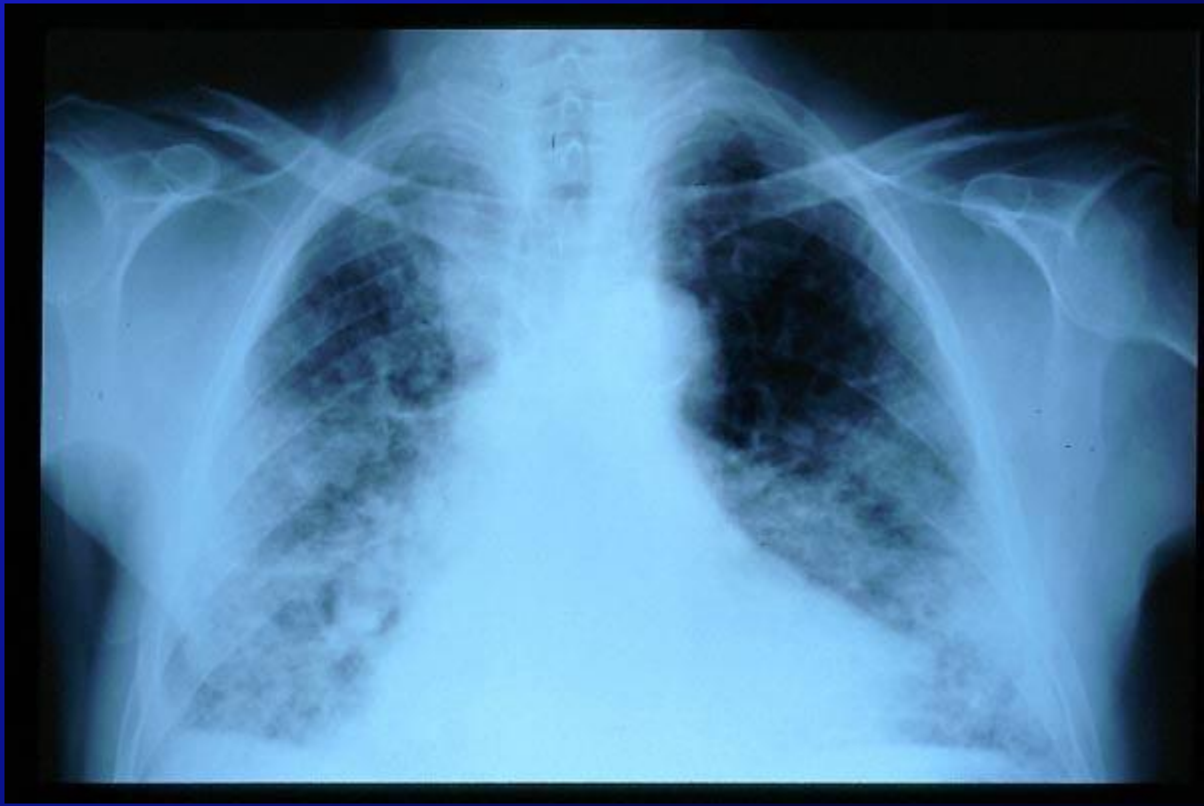
Figure 20–18

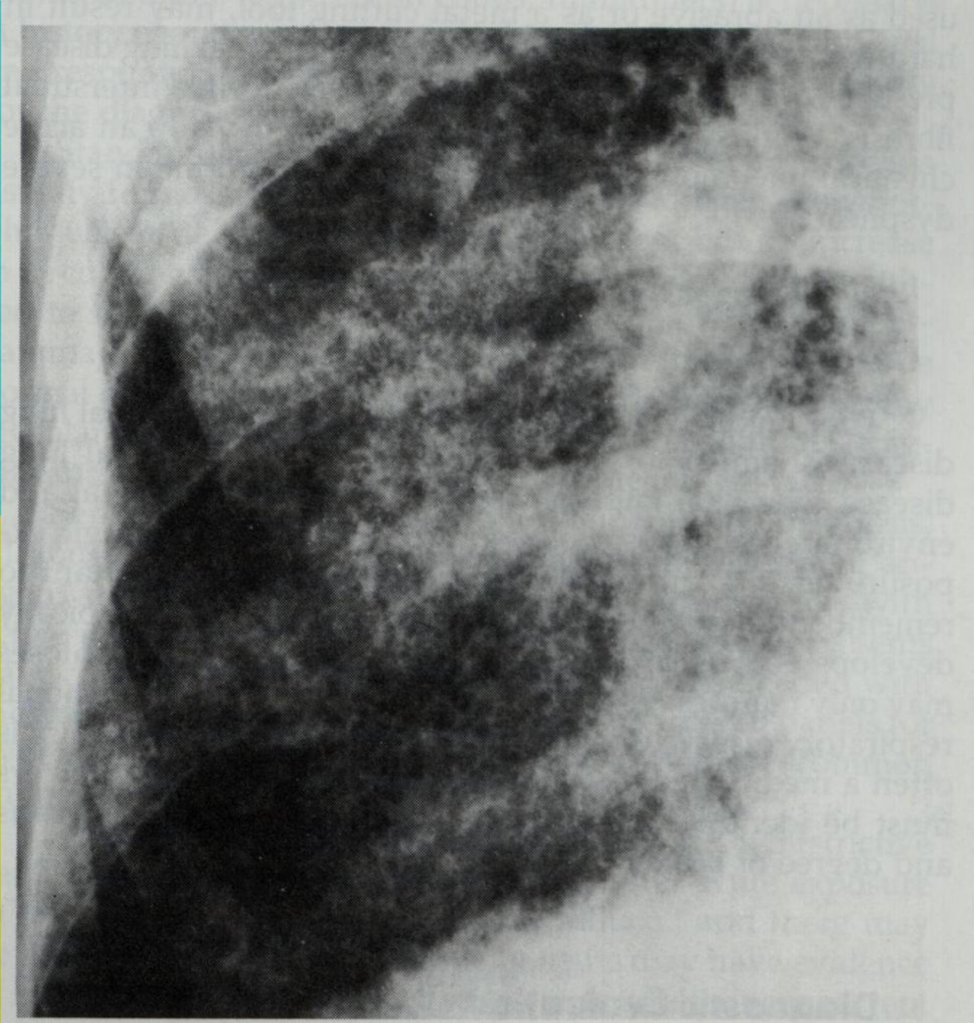
Lung pressure-volume curve and compliance. A lung with a slope greater than normal would have an abnormally high compliance. A lung with a slope smaller than normal would have an abnormally low compliance.

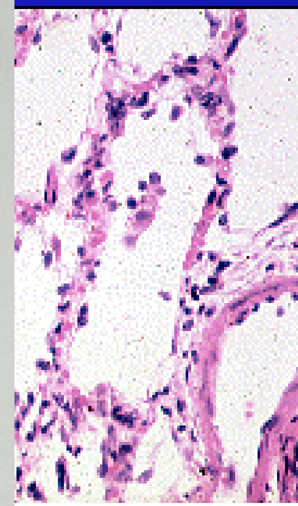
Pulmonary fibrosis

(scarring throughout the lungs)

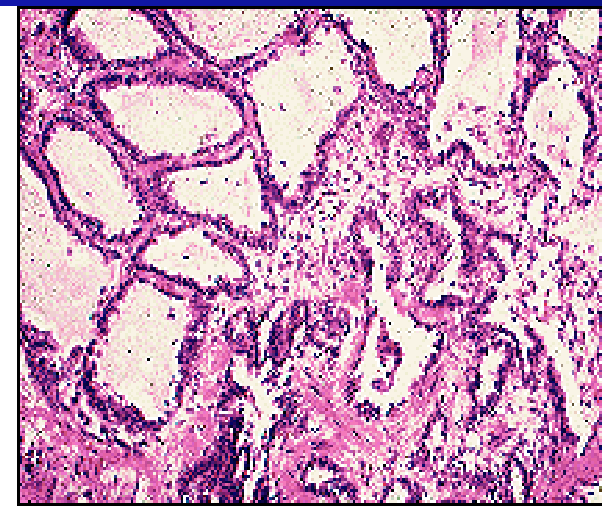








ology



Fibrotic Alveoli – Histology

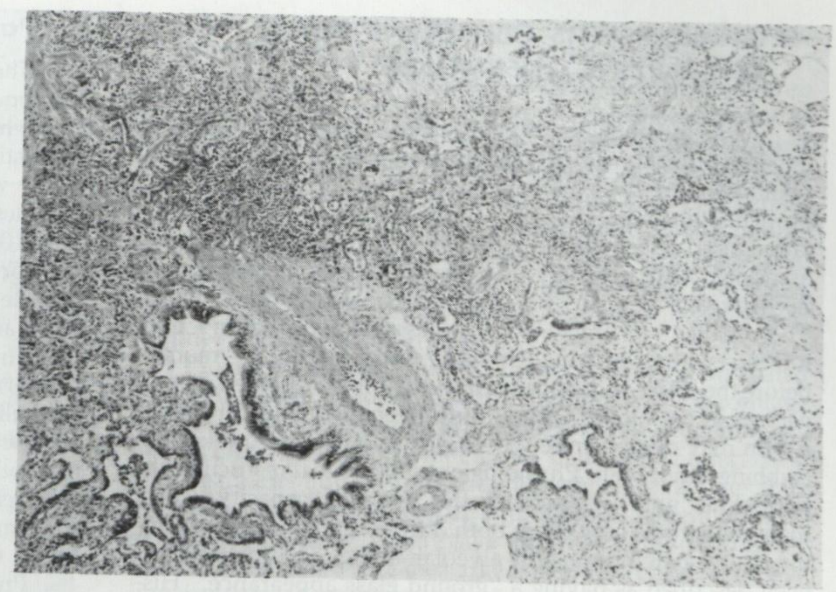
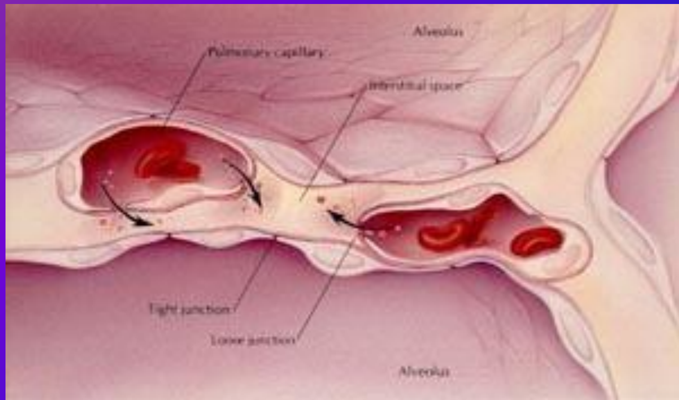
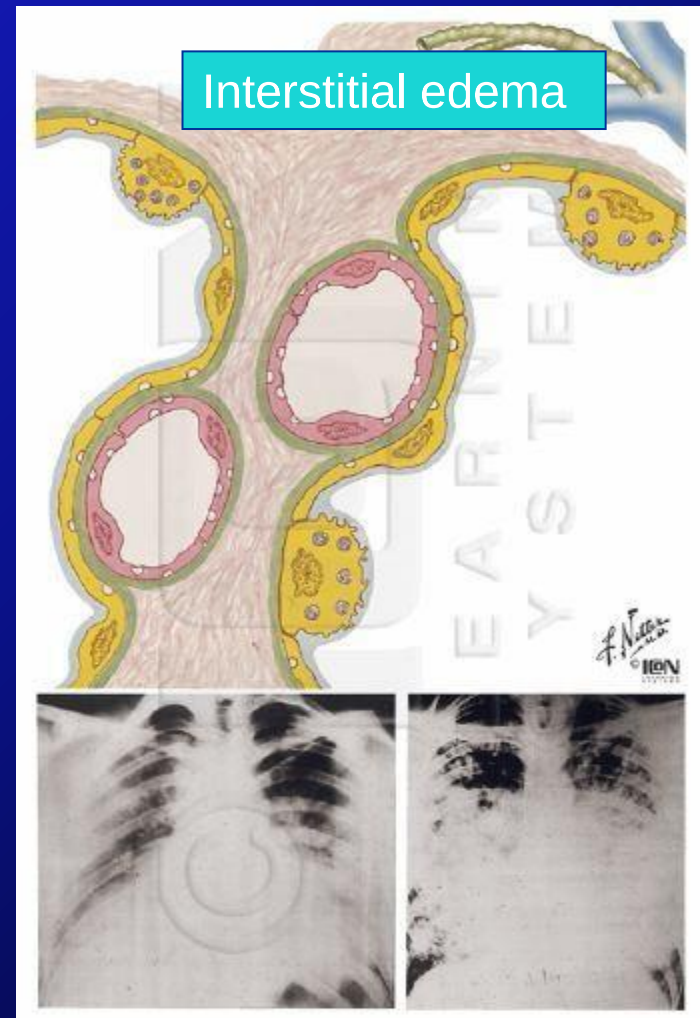


Figure 163–1. Severe pulmonary fibrosis. The majority of the lung tissue is consolidated because of a combination of air space collapse and accumulations of nondistensible fibrous tissue within the interstitium and former air spaces. Little functional gas-exchange tissue is present except for a few partially collapsed alveoli. Compare with normal lung in Figure 160–1A. Original magnification = 75×. (Courtesy of Dr. Rodney Schmidt, Pathology Department, University of Washington)



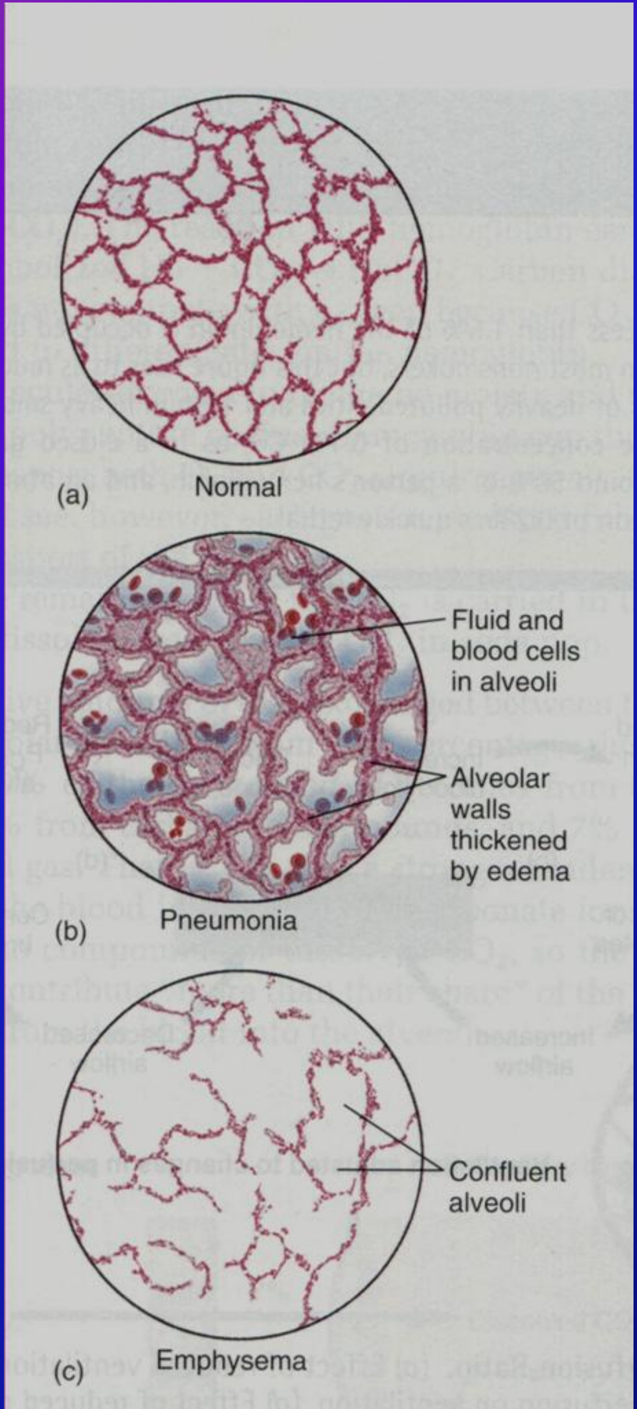
Pulmonary edema
- **Heart problems**
- other reasons

Pulmonary edema begins with an increased filtration through the loose junctions of the pulmonary capillaries.



As the intracapillary pressure increases, normally impermeable(tight) junctions between the alveolar cells open, permitting alveolar flooding to occur.

Alveolar edema



↓ compliance:

- **Pulmonary congestion**
- **Interstitial pulmonary fibrosis**
- **Alveolar filling processes**

  (pneumonia, alveolar edema)
- **Respiratory distress syndrome**

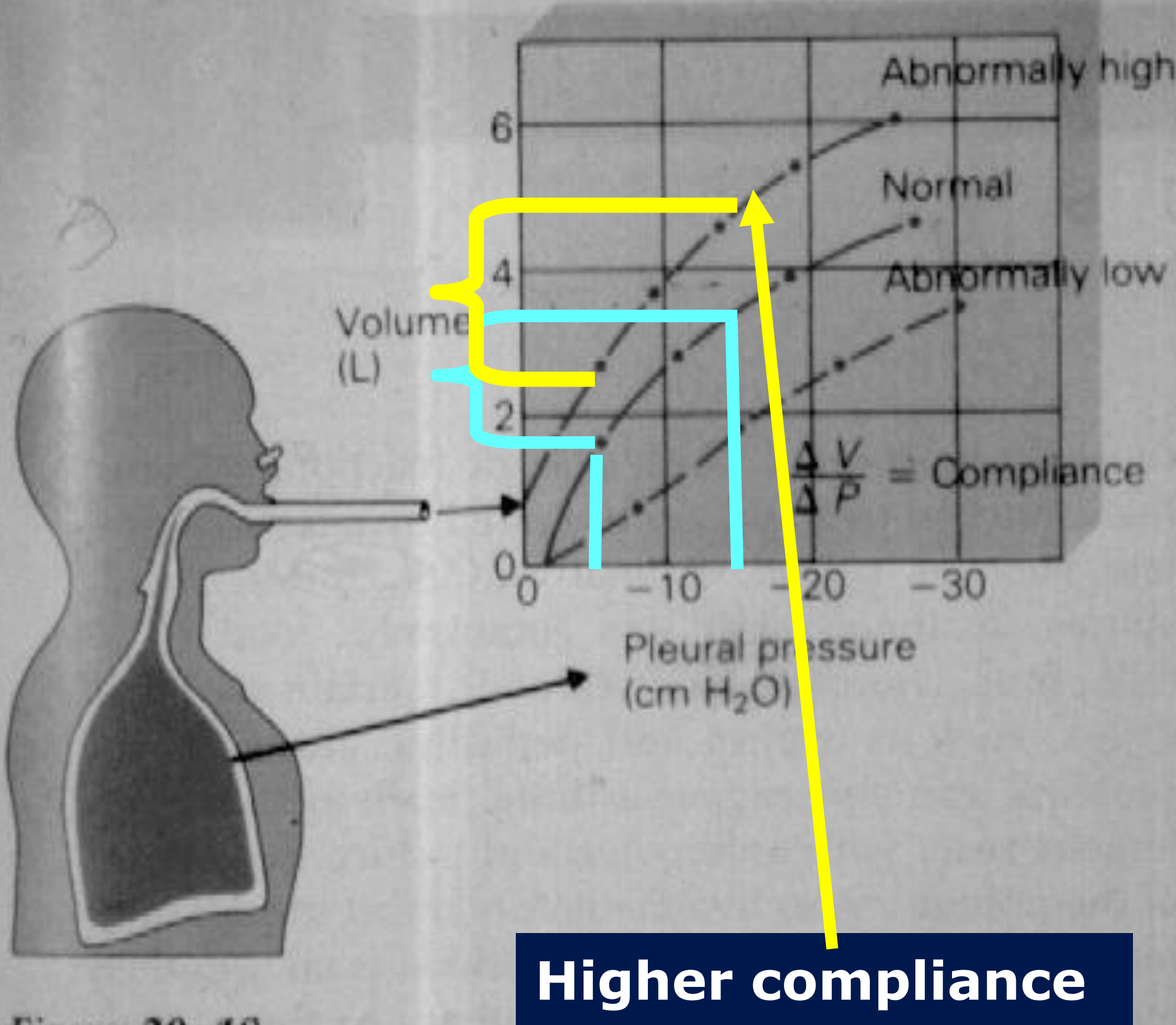
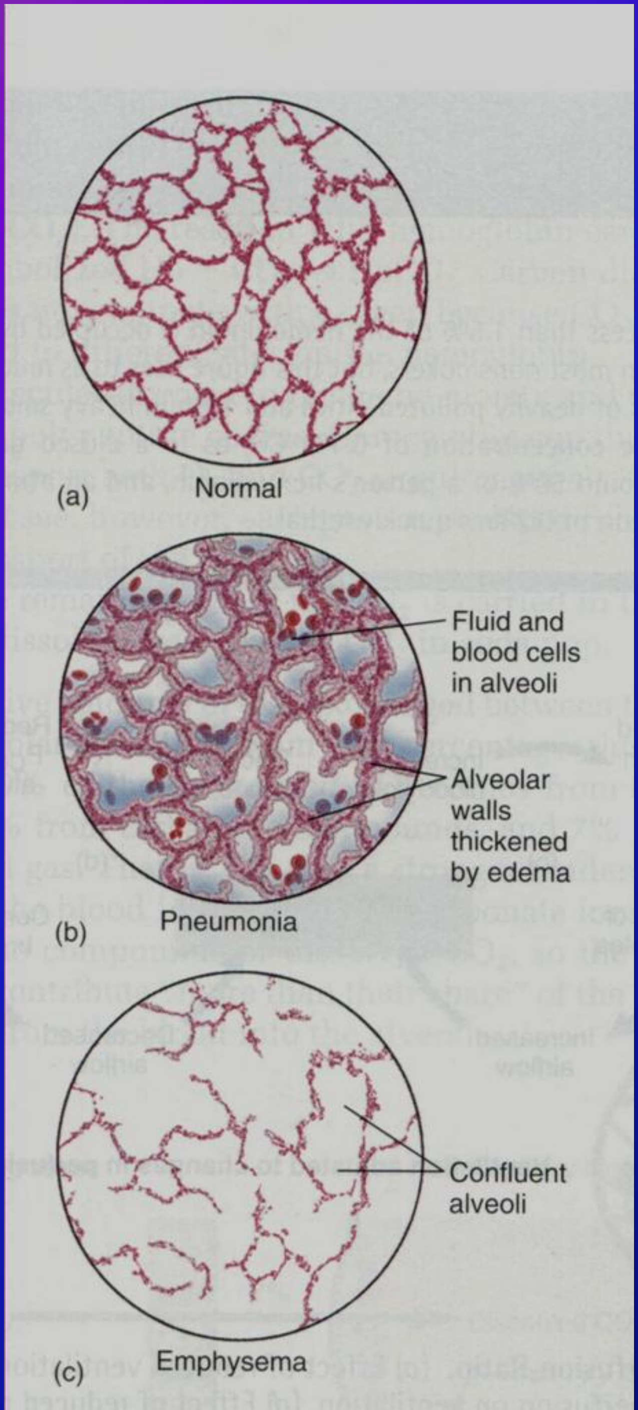


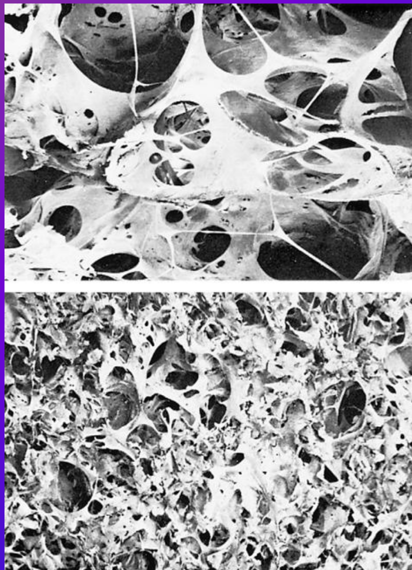
Figure 20–18

Lung pressure-volume curve and compliance. A lung with a slope greater than normal would have an abnormally high compliance. A lung with a slope smaller than normal would have an abnormally low compliance.



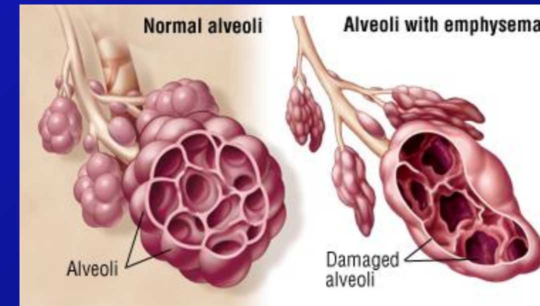
↑ compliance:

- emphysema
- age

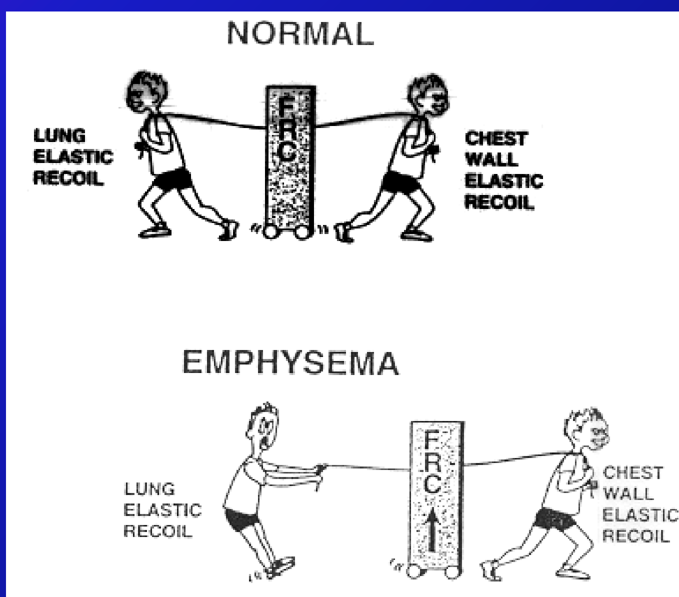


Emphysema

Destruction of elastic fibers



- Lung recoil?
- Lung compliance?
- AWR?



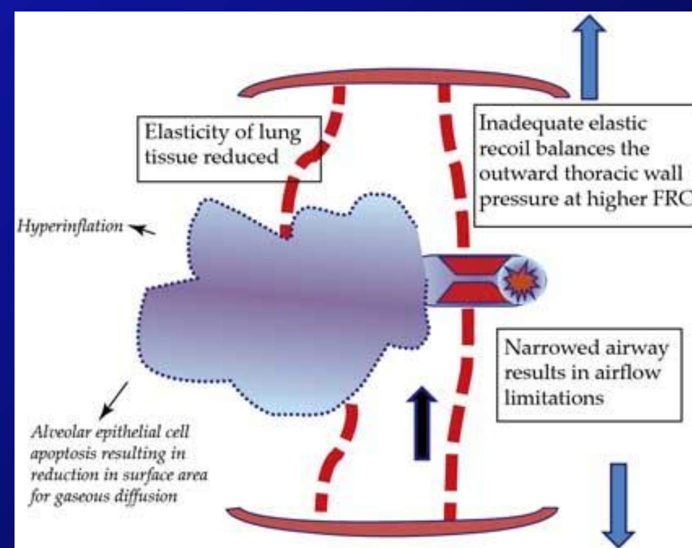


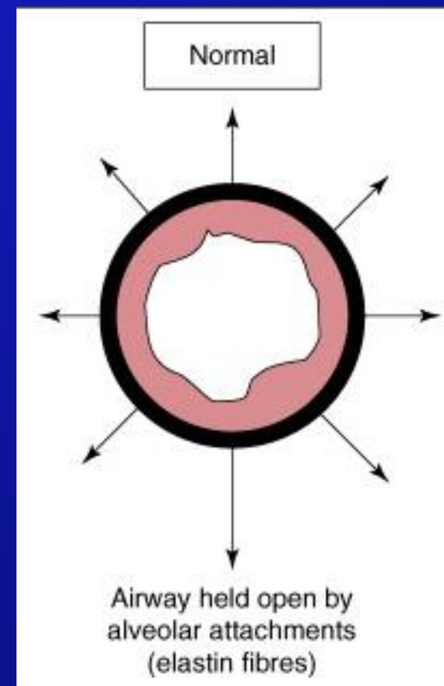
Fig. 3 : Pathophysiological Changes occurring in the Lungs of COPD patients

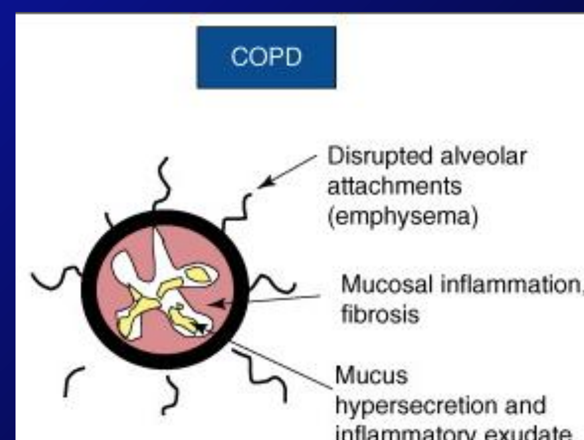
Emphysema

- ↓ lung recoil
- ↑ lung compliance

- ↓ radial traction (airways)

- Less negative intrapleural pressure
  (during expiration may be positive and higher than atmospheric!)





Lungs:

- Ventilation
- Perfusion
- Gas Exchange - Diffusion

Our lungs are NOT uniform !!!

(Upright Position)

Distribution of Ventilation

In the lower parts of the lungs ventilation is ……….
than in the upper ones

Details – please wait for the lecture

Our lungs are NOT uniform !!!

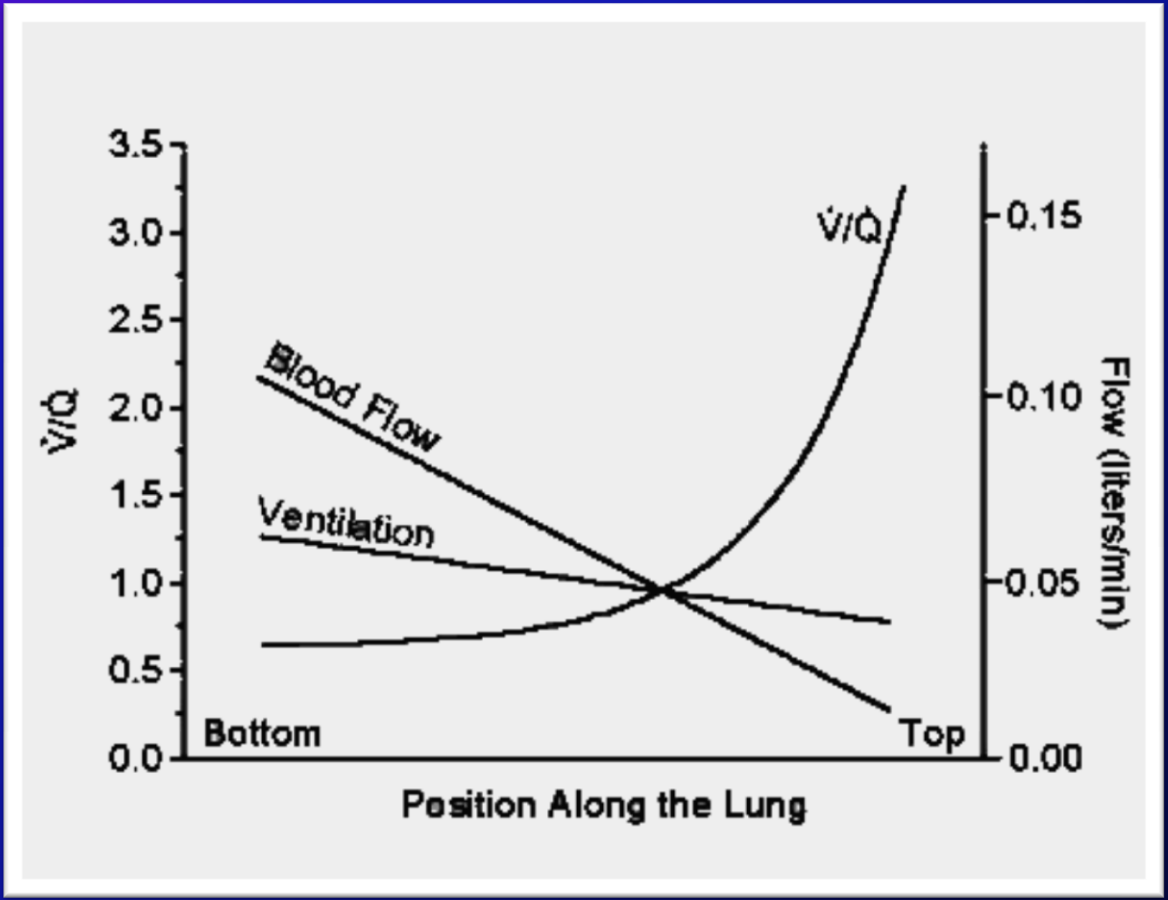
(Upright Position)

Distribution of Perfusion

In the lower parts of the lungs perfusion is ……….
than in the upper ones

Details – please wait for the lecture

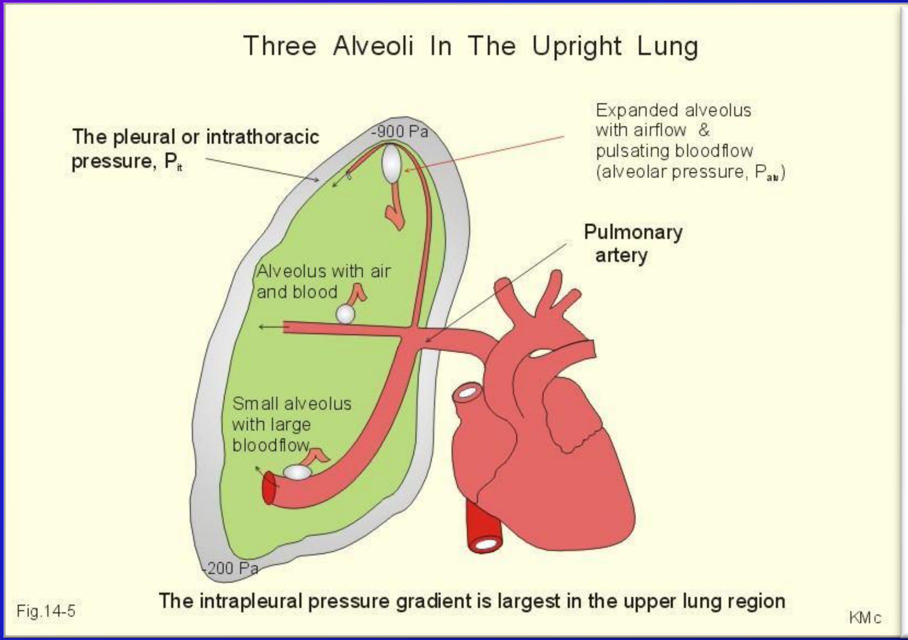
Ventilation- Perfusion Imbalance

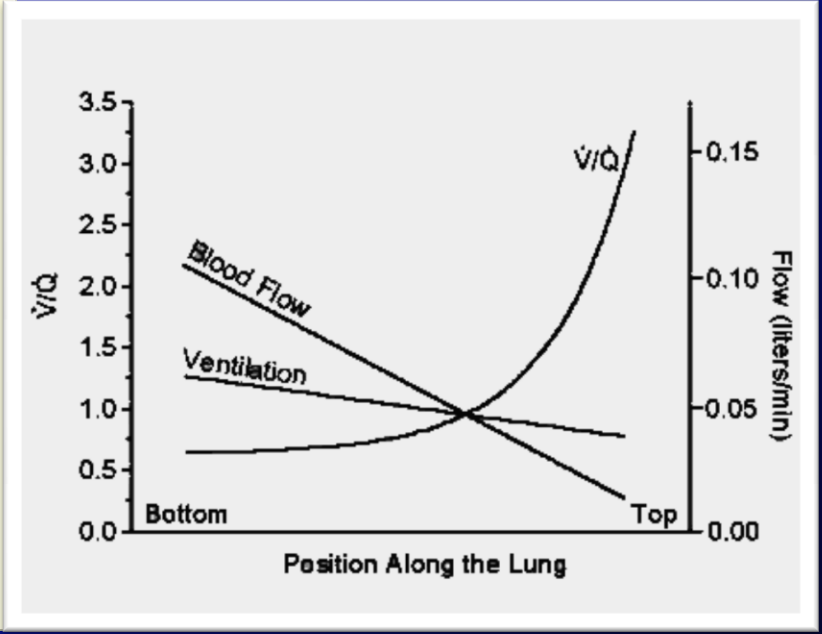


VENTILATION / PERFUSION RATIO

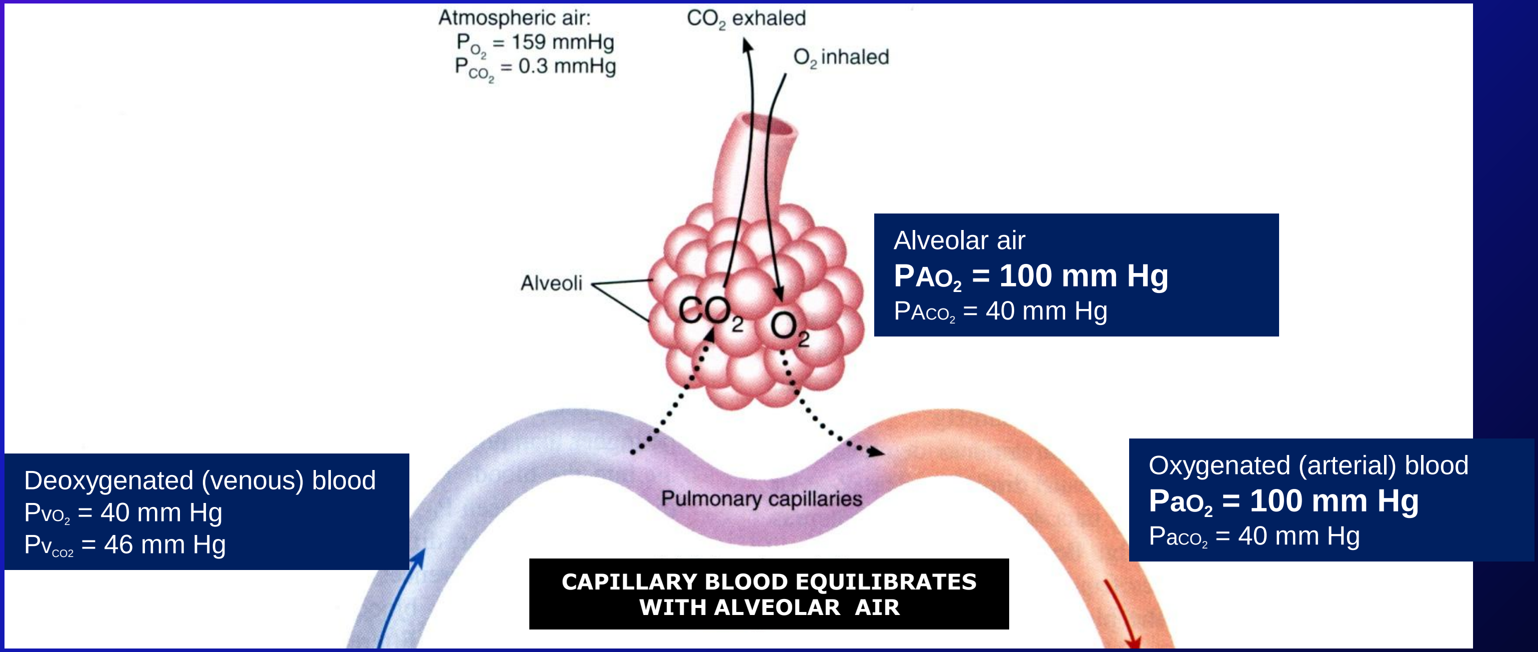
$$\dot{V}_A / \dot{Q}$$

Pulmonary Ventilation, Circulation, and Ventilation/Perfusion ratio





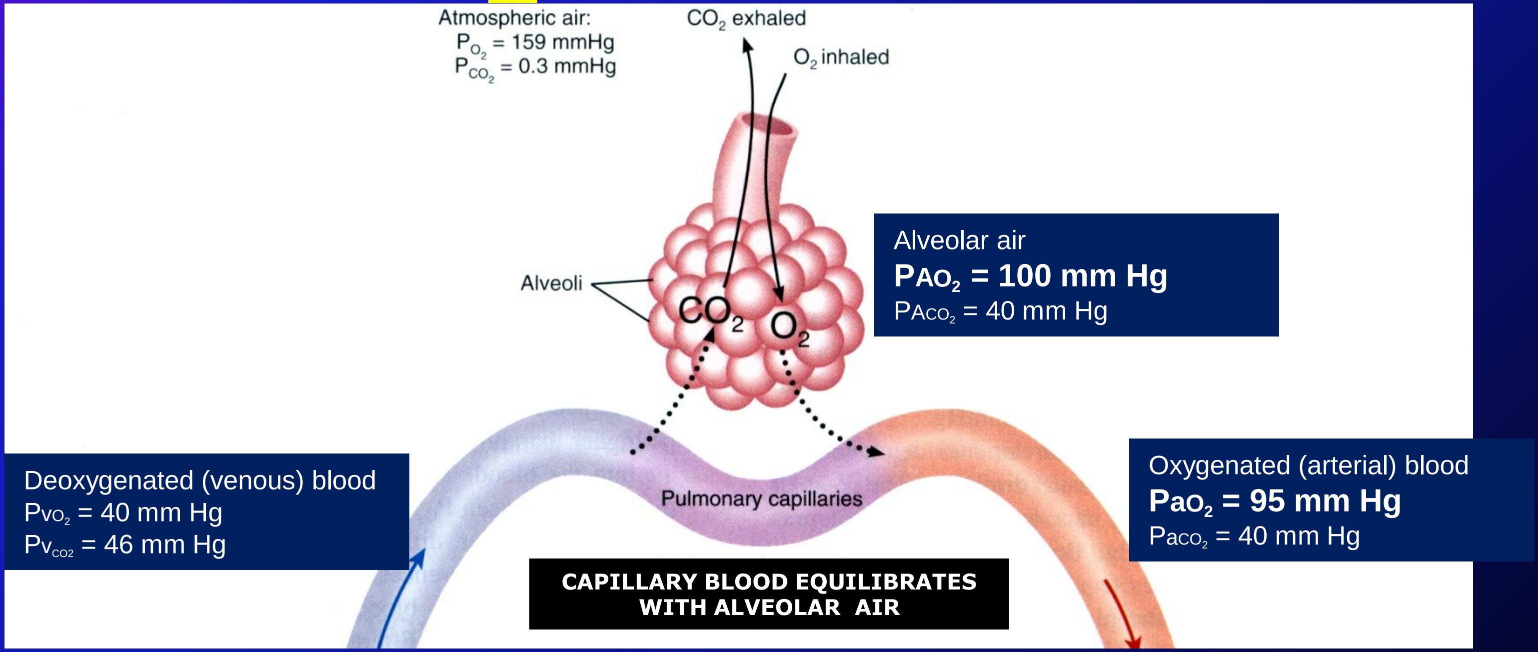
V_A / Q = 1 /ideal/ - matching



Ventilation – perfusion relationship can be measured
by calculating alveolar – arterial PO2 difference

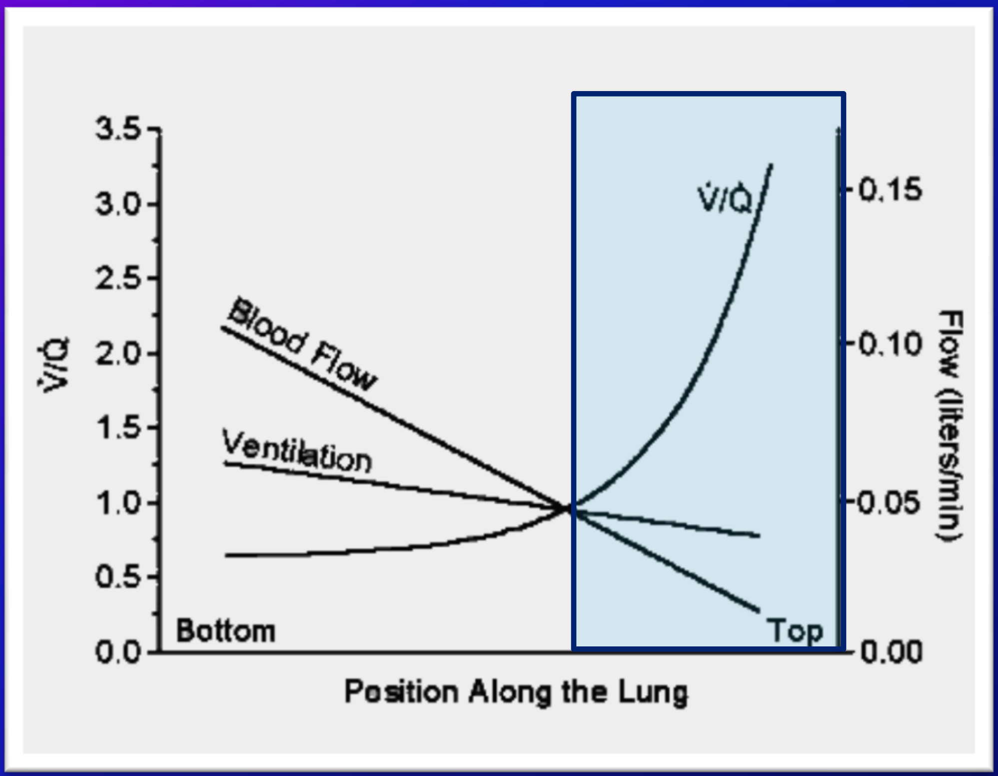
V_A = 4.2 L/min   Q = 5 L/min

V_A / Q = 0,84



Ventilation – perfusion relationship can be measured by calculating alveolar – arterial PO2 difference

Ventilation- Perfusion Imbalance

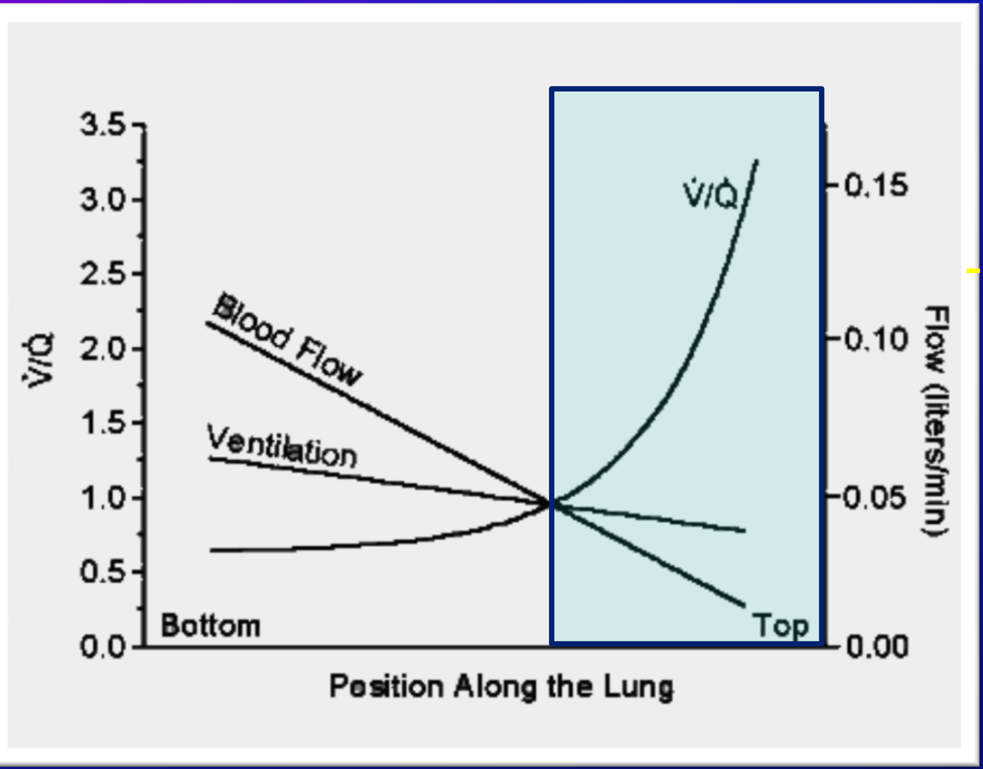


↑ V_A/Q

Upper portions of lungs

- Blood flow and ventilation are much less than in the lower parts
- Blood flow is decreased considerably more than is ventilation

Ventilation- Perfusion Imbalance



↑ V_A/Q

TOP

Inadequate perfusion in relation to ventilation

- Gas exchange more efficient

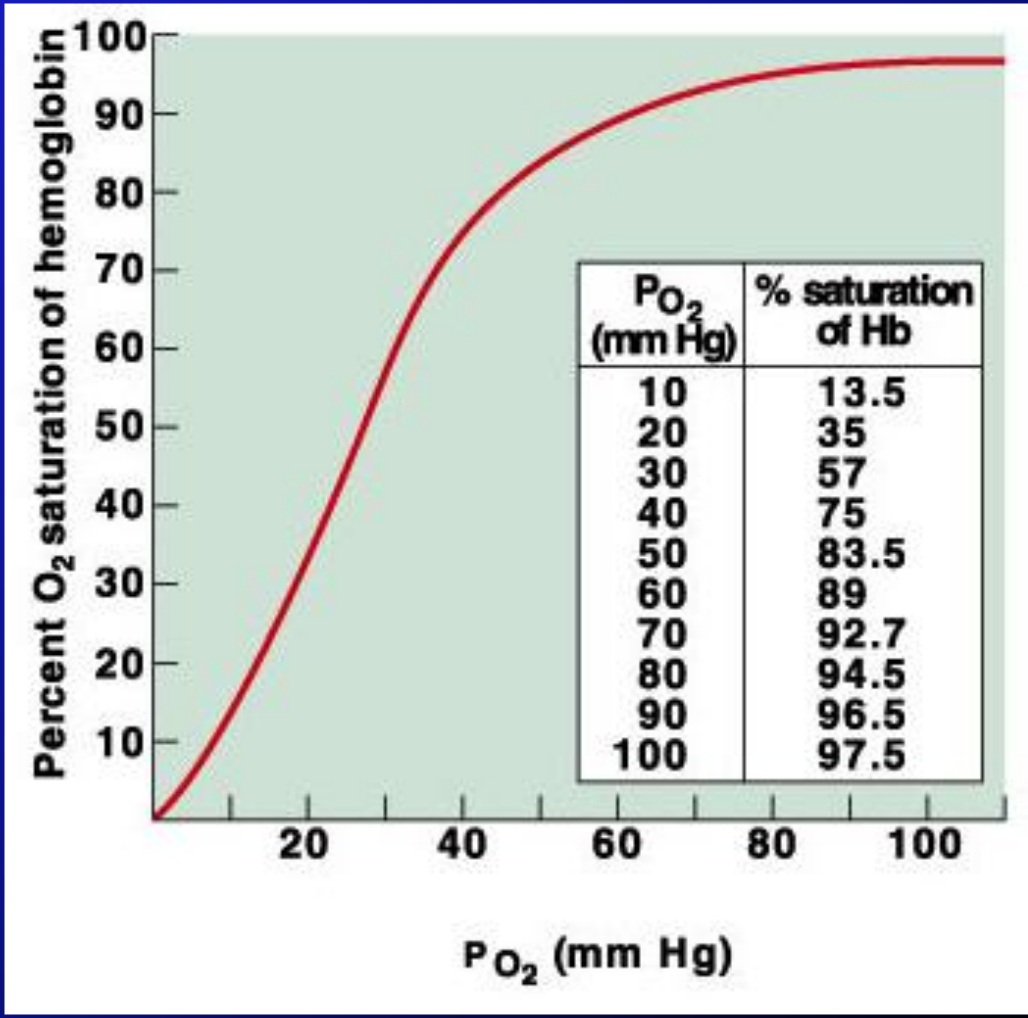
↑PO_2 ↓PCO_2

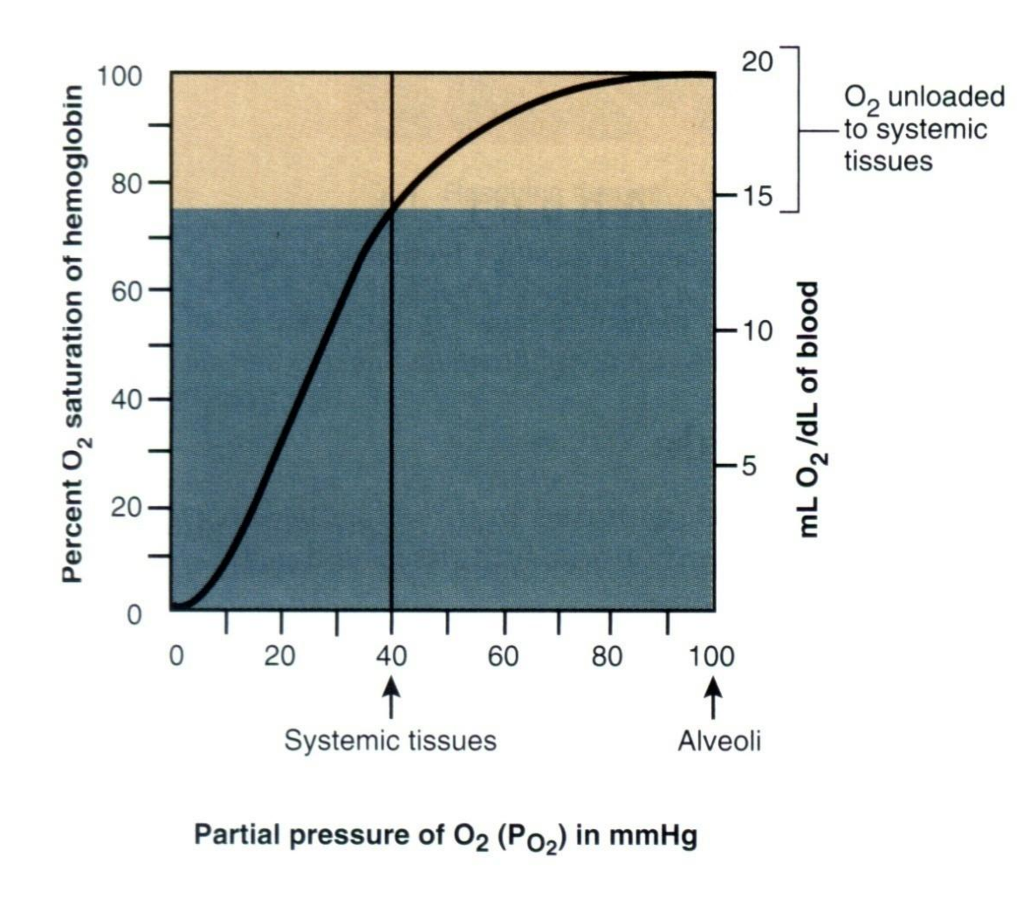
- Slight increase in O_2 content in blood leaving this region
- Minor distribution to the total amount of blood (low blood flow)

Oxygen-Hemoglobin Dissociation Curve at Rest

Oxygen is transported
- by hemoglobin (98.5%)
- dissolved in plasma (1.5%)

Oxygen-hemoglobin dissociation curve shows that hemoglobin is almost completely saturated when PO_2 is 80 mm Hg or above.
At lower partial pressures, the hemoglobin releases oxygen





100
80
60
40
20
0
Percent O_2 saturation of hemoglobin
20
15
10
5
mL O_2/dL of blood
O_2 unloaded to systemic tissues
0
20
40
60
80
100
Systemic tissues
Alveoli
Partial pressure of O_2 (P_{O_2}) in mmHg

↑ V_A/Q

Over ventilated / Under perfused alveoli

Pathology:

Obstruction (embolism) of pulmonary artery,

Compression (tumor, fluid, gas) of pulmonary artery,

Loss of capillary bed (emphysema), shock

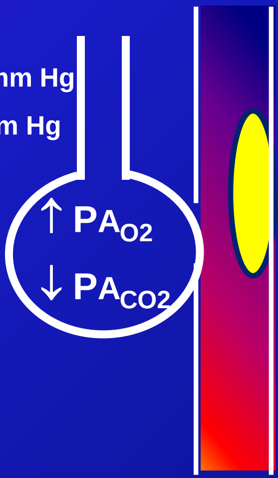
Ventilated / Unperfused alveoli

Q=0

V/Q=infinity

P_{IO_2}= 150 mm Hg

P_{ICO_2}= 0 mm Hg



Mixed venous blood

P_{VO_2}= 40 mm Hg

P_{VCO_2}= 46 mm Hg

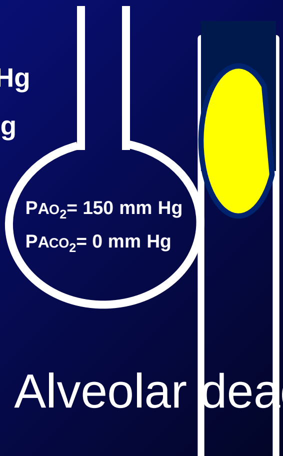
Blood „leaving" the alveolus

↑ Pa_{O_2}

↓Pa_{CO_2} - hypocapnia

P_{IO_2}= 150 mm Hg

P_{ICO_2}= 0 mm Hg



Alveolar dead space

Dead space *– a volume of the respiratory system that is ventilated but does not exchange gasses with pulmonary capillary blood:*

- **Alveolar (functional) dead space**
  (Areas of the lung with increased ratios)

  +

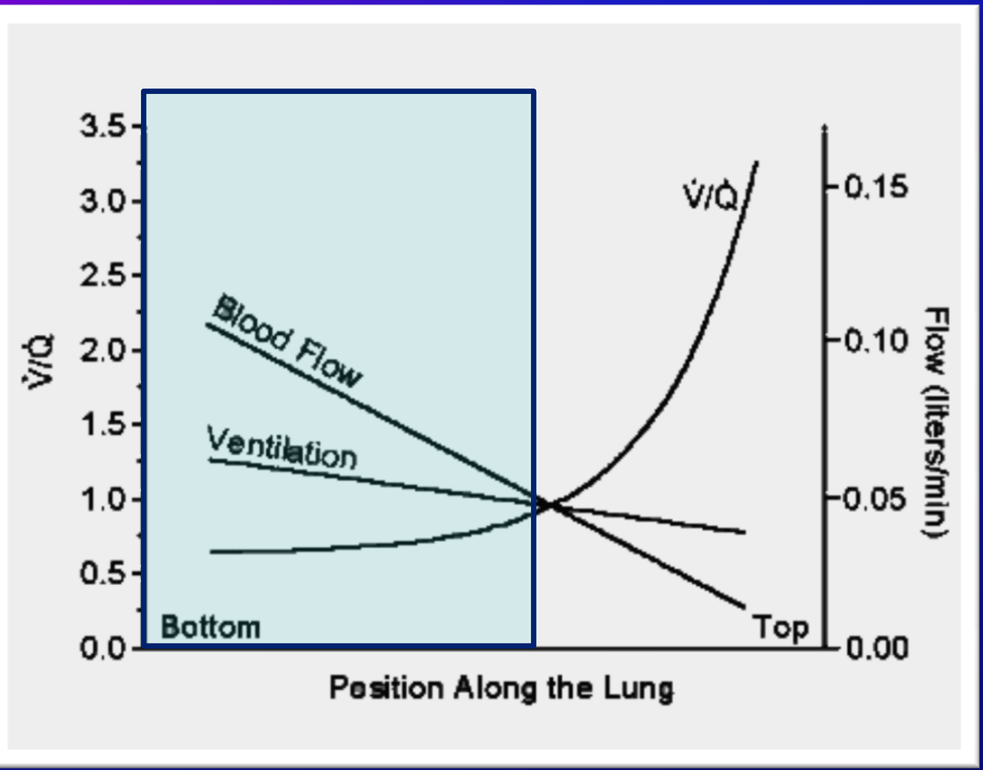
- **Anatomic dead space**

  =

Physiologic dead space

(Wasted ventilation)

Ventilation- Perfusion Imbalance



↓ V_A/Q

Bottom

- **Inadequate ventilation in relation to perfusion**
- **Gas exchange less efficient**

$\downarrow PO_2$ $\uparrow PCO_2$

- A certain fraction of venous blood passing through the pulmonary capillaries does not become oxygenated (**Intrapulmonary shunt)**
- A decrease in **Po_2 and So_2** in blood leaving this region

Shunt – *blood that bypasses from systemic veins to systemic arteries without exchanging gas with alveolar air:*

- **Intrapulmonary shunts**

  (areas of the lung with decreased ratios)

- **Anatomic shunts** :

  - Bronchopulmonary venous anastomoses

    (bronchial circulation supplies: airways, supporting tissues, pulmonary arteries, veins)

  - Intracardiac thebesian veins

Uneven matching of alveolar ventilation and alveolar blood flow – a major cause of **systemic hypoxemia** in patients with cardiopulmonary diseases.

↓ V_A/Q

Under ventilated / Over perfused alveoli

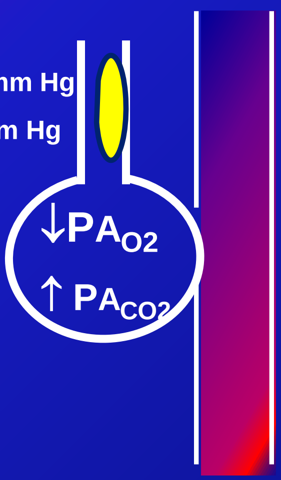
Pathology:

Narrowing of airways (asthma, bronchitis, emphysema)

Compresion of airways (tumor, edema, fluid)

PI_{O_2}= 150 mm Hg

PI_{CO_2}= 0 mm Hg



Mixed venous blood

P_{O_2}= 40 mm Hg

P_{CO_2}= 46 mm Hg

Blood „leaving" the alveolus

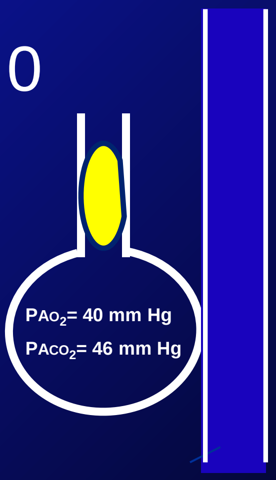
<u>↓ Pa_{O_2} (hypoxemia)</u>

↑Pa_{CO_2} - hypercapnia

Unventilated / Perfused alveoli

V=0

V/Q= 0



Mixed venous blood

P_{O_2}= 40 mm Hg

P_{CO_2}= 46 mm Hg

Blood „leaving" the alveolus

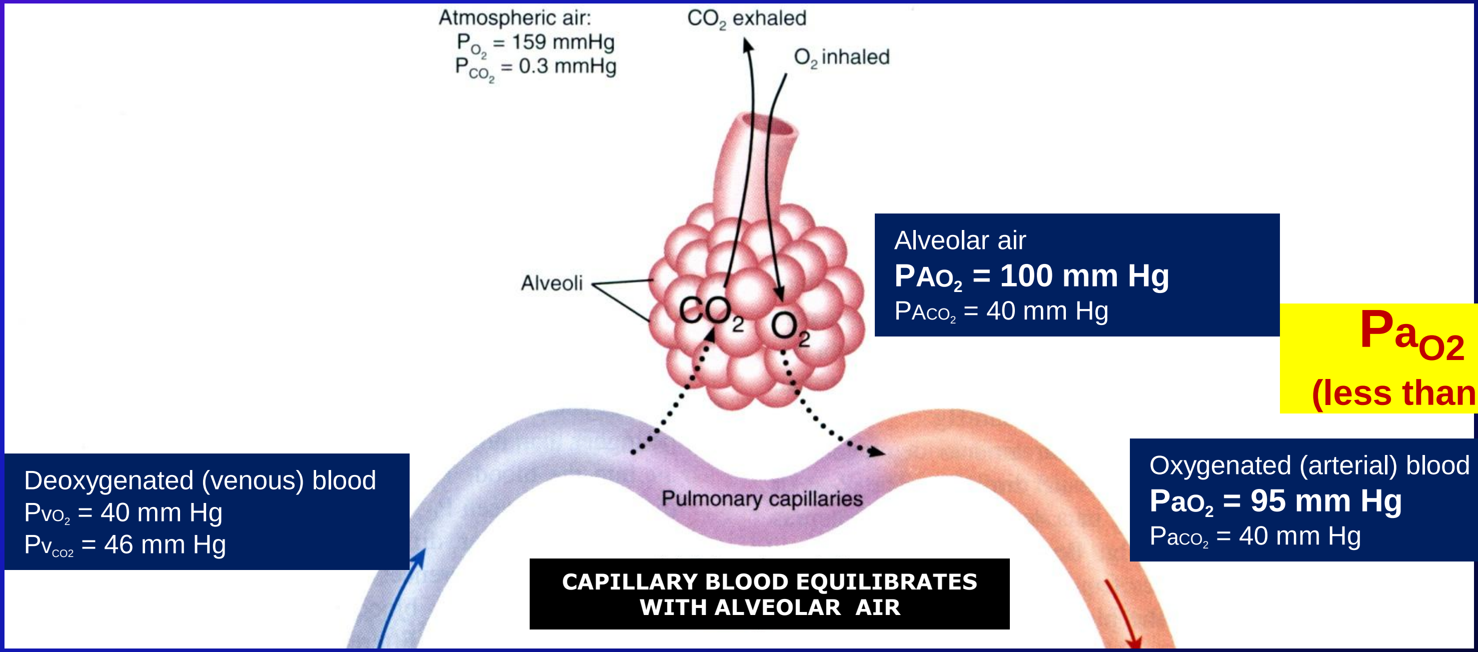
Pa_{O_2}= 40 mm Hg

Pa_{CO_2}= 46 mm Hg

Venous admixture – Intrapulmonary shunt

V_A = 4.2 L/min   Q = 5 L/min

V_A / Q = 0,84



Alveolar air
PAo_2 = 100 mm Hg
$PAco_2$ = 40 mm Hg

Pa_{O2} <PA_{O2}
(less than 20 mm Hg)

Deoxygenated (venous) blood
Pvo_2 = 40 mm Hg
Pv_{co2} = 46 mm Hg

Oxygenated (arterial) blood
Pao_2 = 95 mm Hg
$Paco_2$ = 40 mm Hg

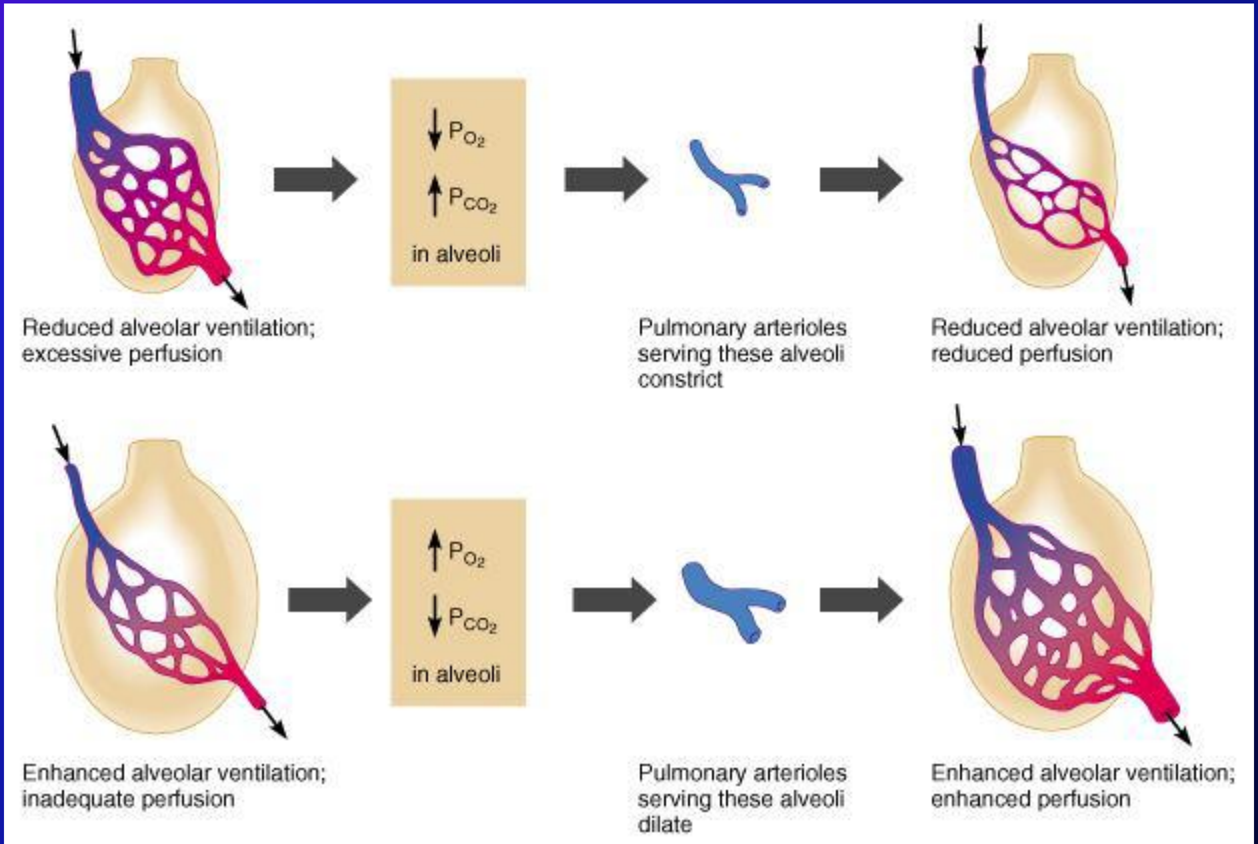
CAPILLARY BLOOD EQUILIBRATES WITH ALVEOLAR AIR

- Areas of the lung with low ˙V/˙Q ratios cannot compensate for areas of the lung with high ˙V/˙Q ratios, the ˙V/˙Q ratio abnormalities result in lower arterial P_{O2} and lead to A-a gradient for oxygen

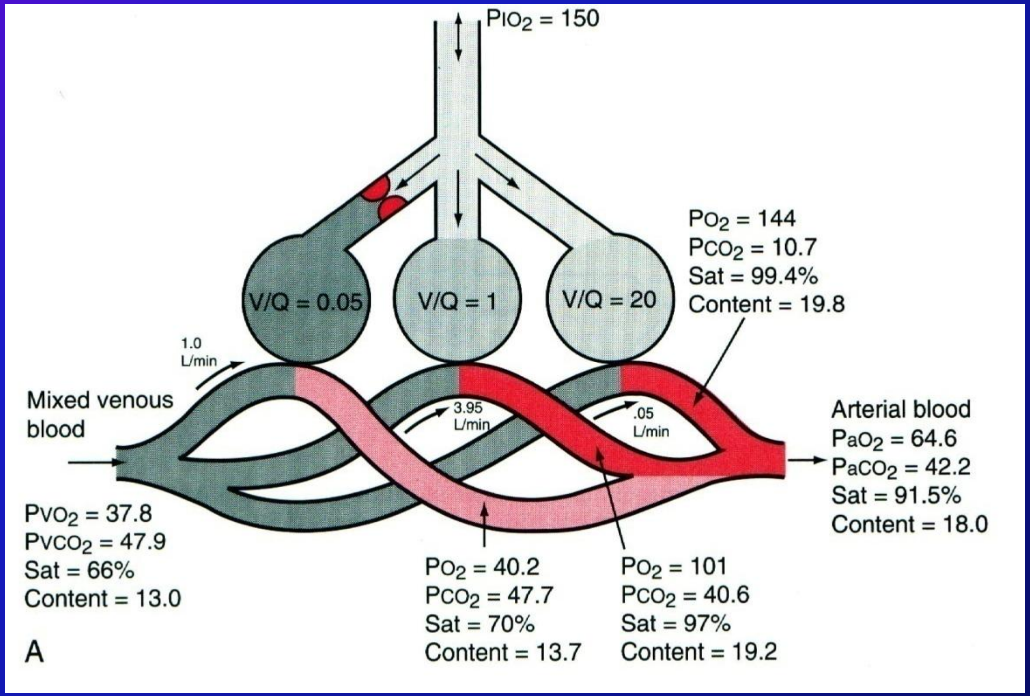
Ventilation – perfusion relationship can be measured by calculating alveolar – arterial P_{O2} difference

Ventilation- Perfusion Relationship

Compensation for V/Q mismatching:



Ventilation- Perfusion Relationship



Compensation for V/Q mismatching:

↓ V/Q:

↓ PO_2 (alveolar air) - vasoconstriction
- blood shifted away from poorly ventilated region (directed to other portions of lungs)

↑ PCO_2 - bronchodilation

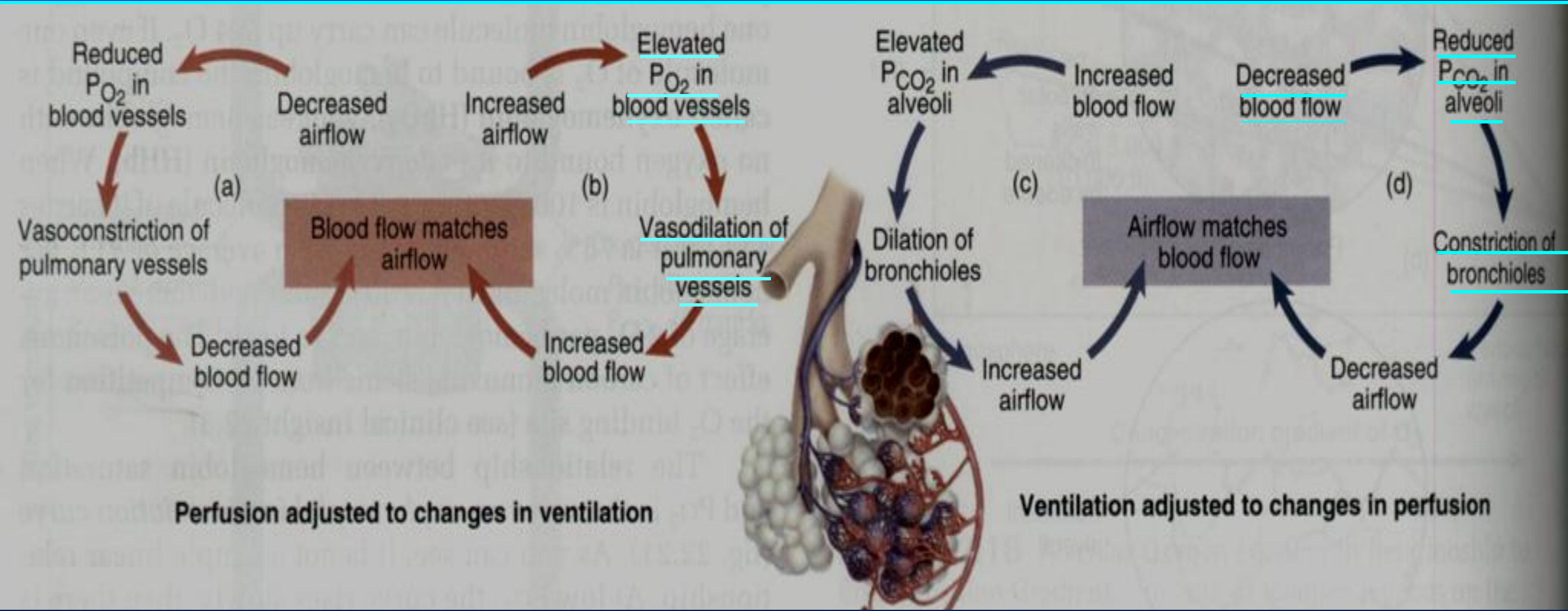
↑ V/Q:

↑ PO_2 - vasodilation

↓Pco_2 - bronchoconstriction – airflow shifted away from poorly perfused region (directed to other portions of lungs)

PATHOLOGY:

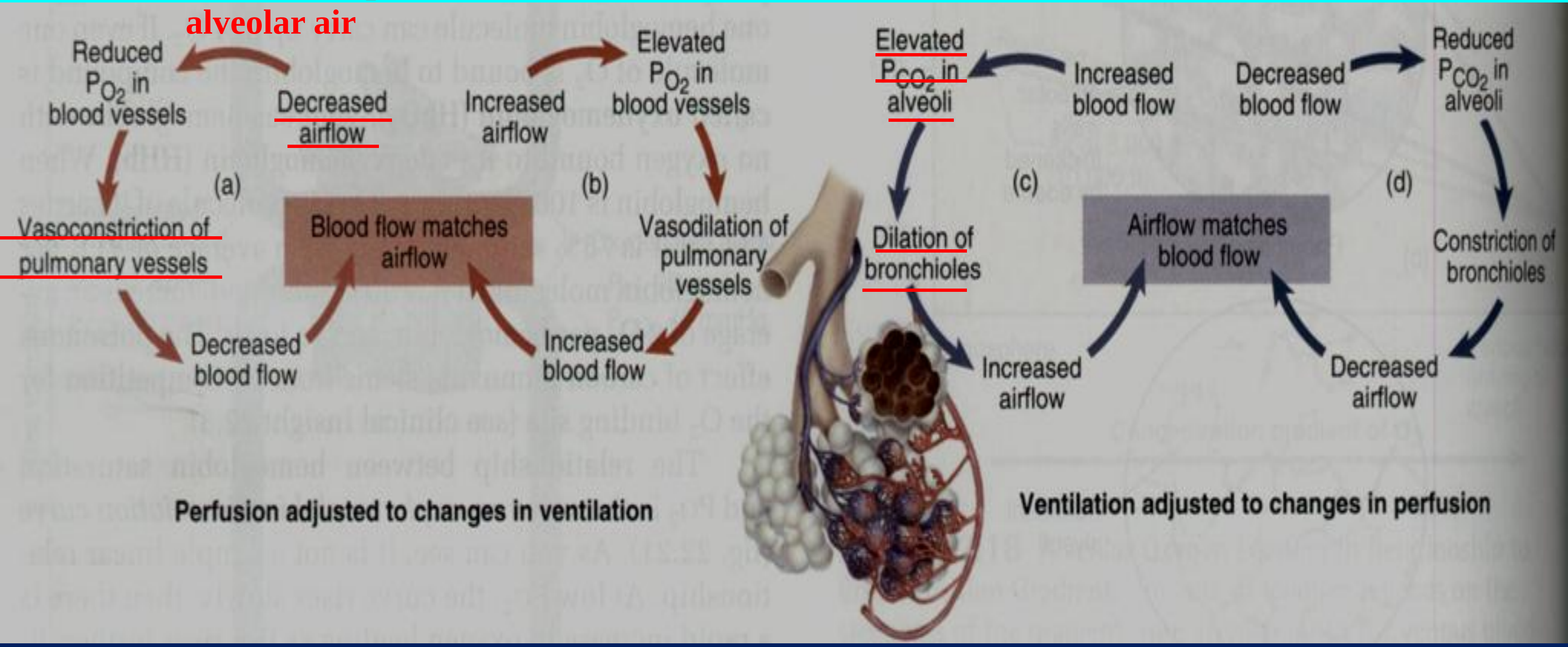
- **OBSTRUCTION OF PULMONARY ARTERY (EMBOLISM)**
- **LOSS OF CAPILLARY BED (EMPHYSEMA)**



↓ blood flow: ↓ P_{CO_2} - bronchoconstriction - airflow directed to other portions of lungs to ↓ dead space volume,

PATHOLOGY: AIRWAY OBSTRUCTION, TUMOR

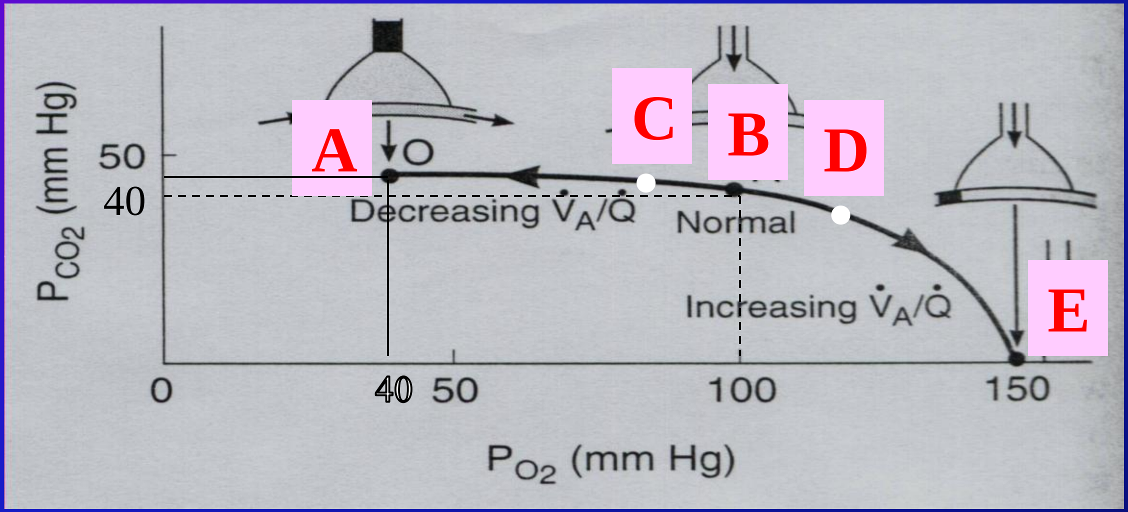
Reduced PO_2 in alveolar air



↓ airflow - ↓ PO_2 (alveolar air) - vasoconstriction - blood directed to other portions of lungs to ↓ venous admixture

↑ $P\ CO_2$ - bronchodilation

Choose the point on the PO_2 - PCO_2 diagram that best described the condition



1. The inspired P_{O2} and P_{CO2} of an individual breathing room air at sea level (TBP = 760 mm Hg).

2. The P_{O2} and P_{CO2} of blood in the right atrium.

3. The P_{O2} and P_{CO2} in an individual alveolus with an ideal ventilation/perfusion ration.

4. The P_{O2} and P_{CO2} of blood leaving an alveolus in which ventilation is somewhat reduced by the accumulation of bronchial secretion.

5.The P_{O2} and P_{CO2} of an alveolar unit at the base of the lung when in the erect position.

6. The P_{O2} and P_{CO2} of an alveolar unit at the apex of the lung when in the erect position.

7. The P_{O2} and P_{CO2} of an alveolus downstream to a tumor that partially occludes the blood vessel

Regulation of Respiration

→ **see** ***Lecture***