Pathophysiology of the respiratory system I

Structural properties of airways and lungs
Respiration and gas exchange
- ventilation & diffusion & perfusion

Pulmonary mechanics
Ventilation – perfusion (in)equality

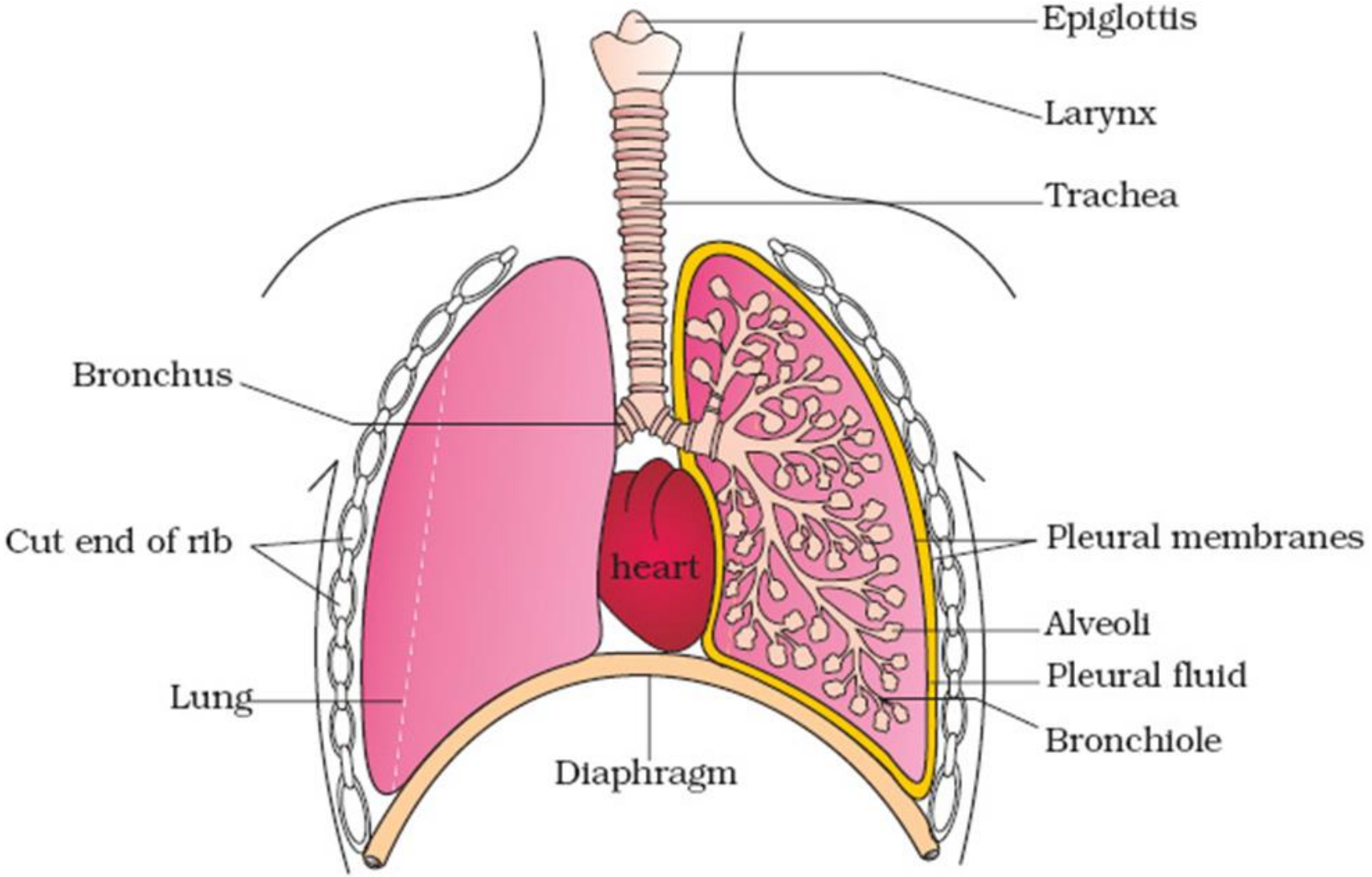
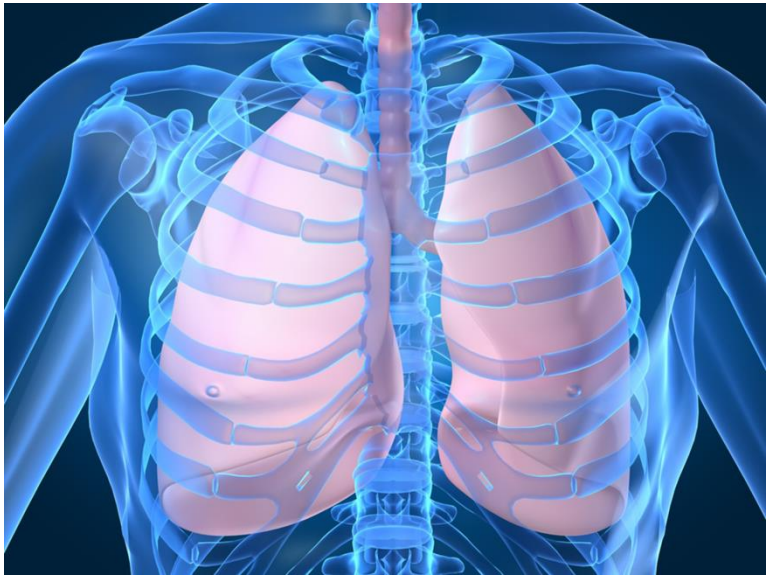


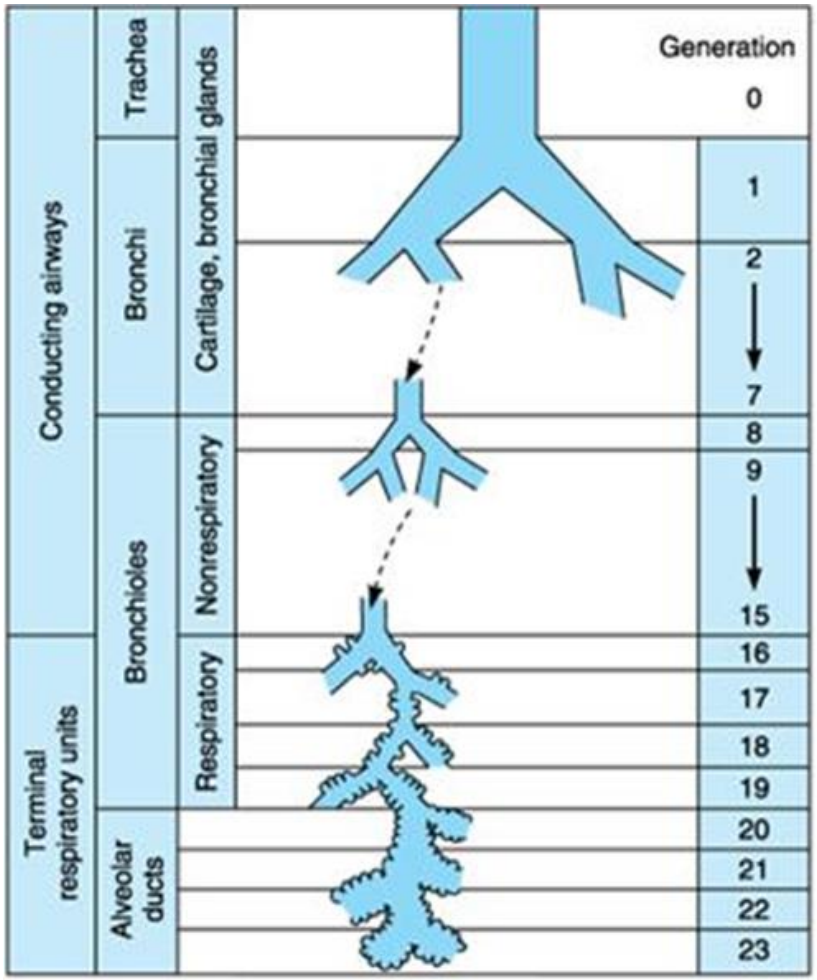
Figure 17.1 Diagrammatic view of human respiratory system (Sectional view of the left lung is also shown)

The delicate structure-function coupling of lungs

- The main role of the respiratory system is to **extract oxygen from the external environment** and **dispose of waste gases**, principally carbon dioxide
  - at the end of deep breath 80% of lung volume is air, 10% blood and 10% tissue
    - lung tissue spreads over an enormous area !
- The lungs have to provide
  - a **large surface area** accessible to the environment (~tennis court area) for gas exchange
  - alveoli walls have to present **minimal resistance to gas diffusion**
- Close contact with the external environment means lungs can be damaged by dusts, gases and infective agents
  - **host defense** is therefore a key priority for the lung and is achieved by a combination of structural and immunological means



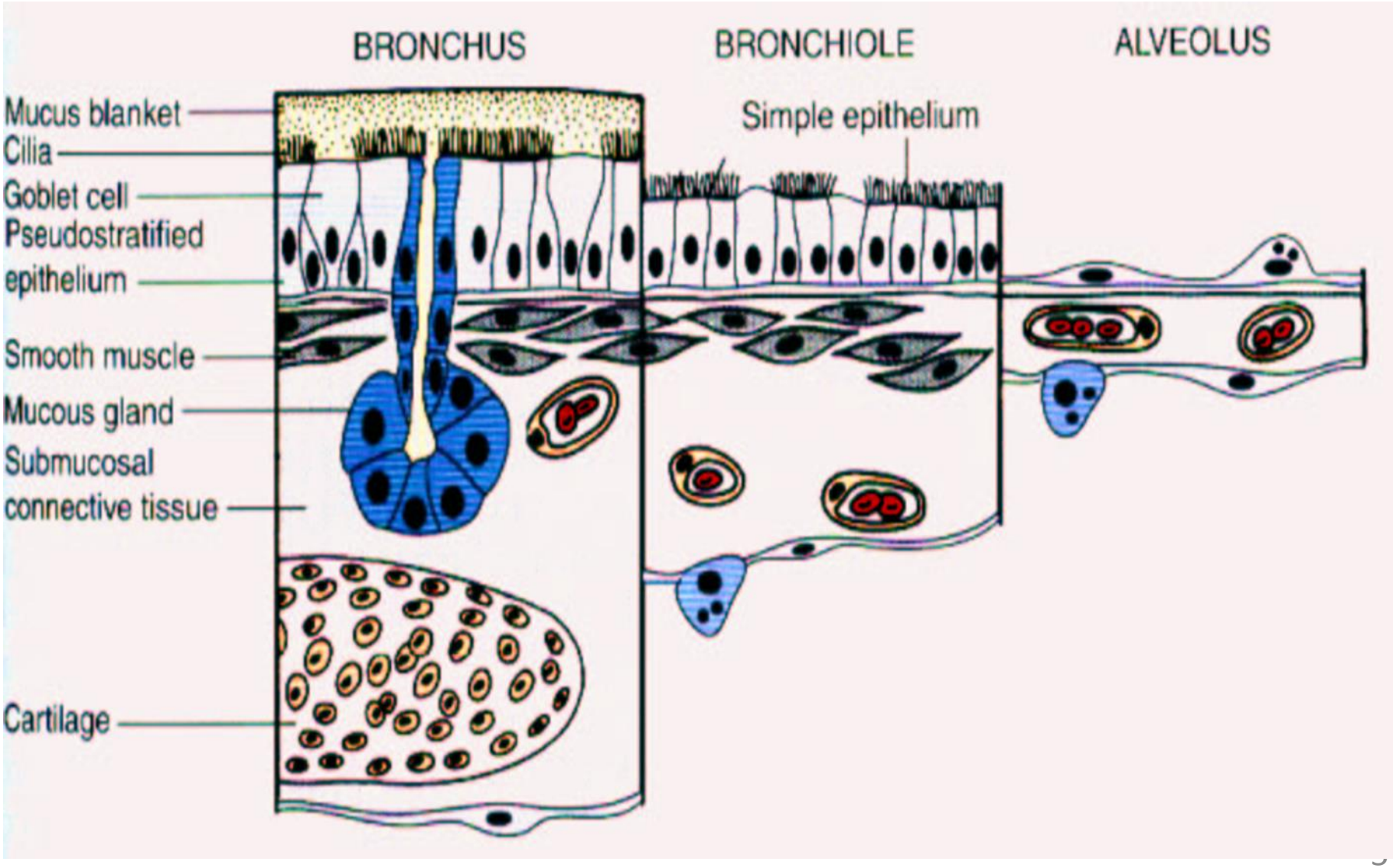
Structure of airways



Source: McPhee SJ, Ganong WF: *Pathophysiology of Disease: An Introduction to Clinical Medicine*, 5th Edition: http://www.accessmedicine.com

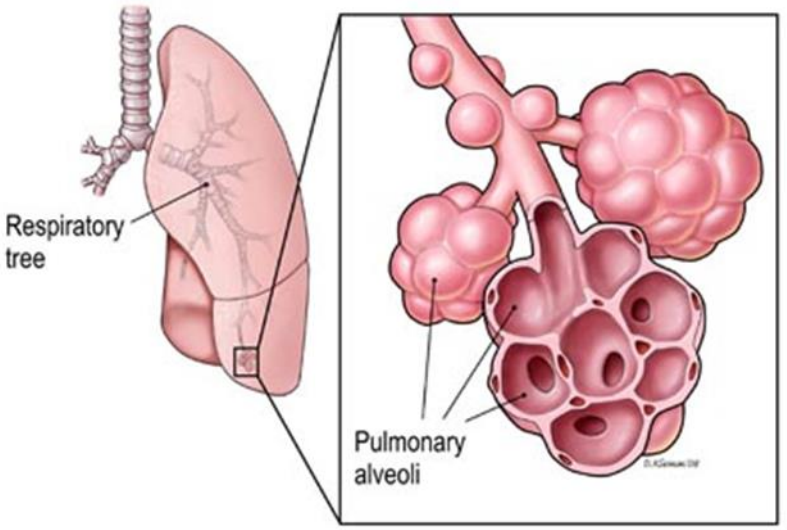
- There are about 23 (18-30) divisions (2^{23} i.e. approx. 8 millions of sacs) between the trachea and the alveoli
  - the first seven divisions, the bronchi have:
    - walls consisting of cartilage and smooth muscle
    - epithelial lining with cilia and goblet cells
    - submucosal mucus-secreting glands
    - endocrine cells - Kulchitsky or APUD (amine precursor and uptake decarboxylation) containing 5-hydroxytryptamine
  - the next 16-18 divisions the bronchioles have:
    - no cartilage
    - muscular layer progressively becomes thinner
    - a single layer of ciliated cells but very few goblet cells
    - granulated Clara cells that produce a surfactant-like substance

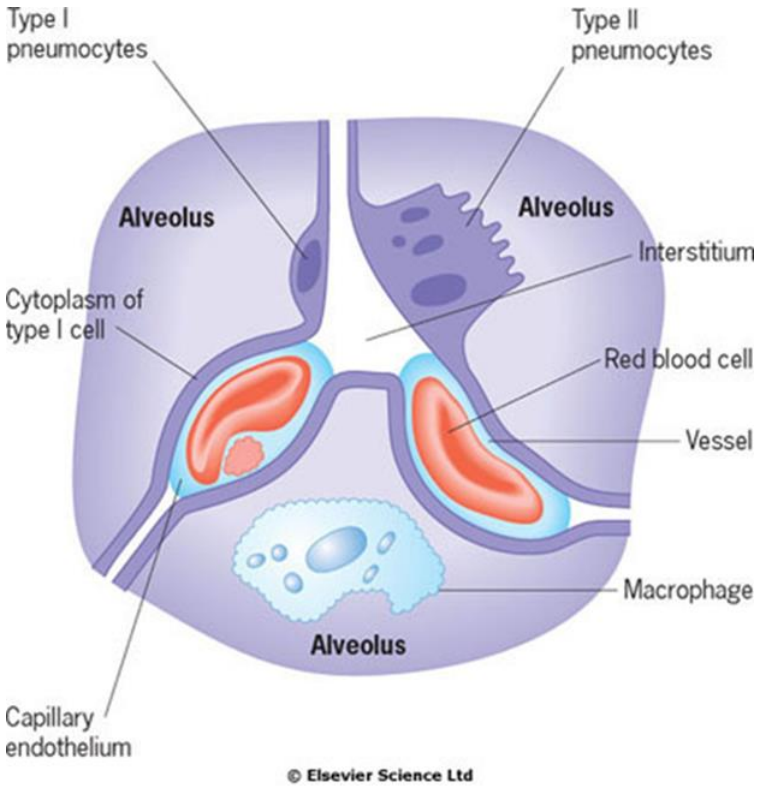
Wall structure of conducting conducting airways and alveolar region



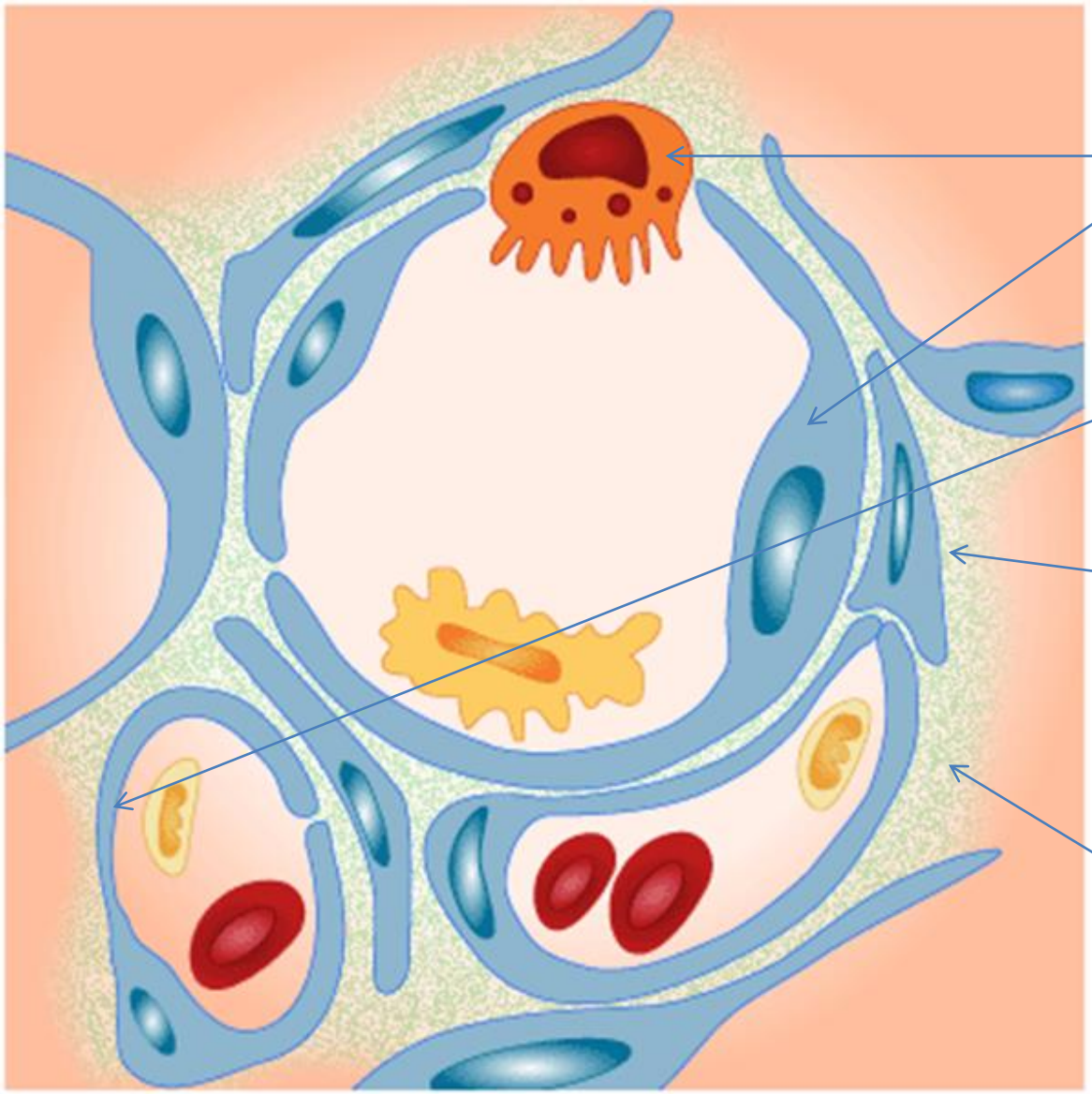
Alveoli

- There are approximately 300-400 million alveoli in each lung with the total surface area is 40 - 80m^2
- Cell types of the epithelial lining
  - type I pneumocytes
    - an extremely thin cytoplasm, and thus provide only a thin barrier to gas exchange, derived from type II pneumocytes
    - connected to each other by tight junctions that limit the fluid movements in and out of the alveoli
    - easily damageable, but cannot divide!
  - type II pneumocytes
    - slightly more numerous than type I cells but cover less of the epithelial lining
    - the **source of type I cells** and **surfactant**
  - macrophages





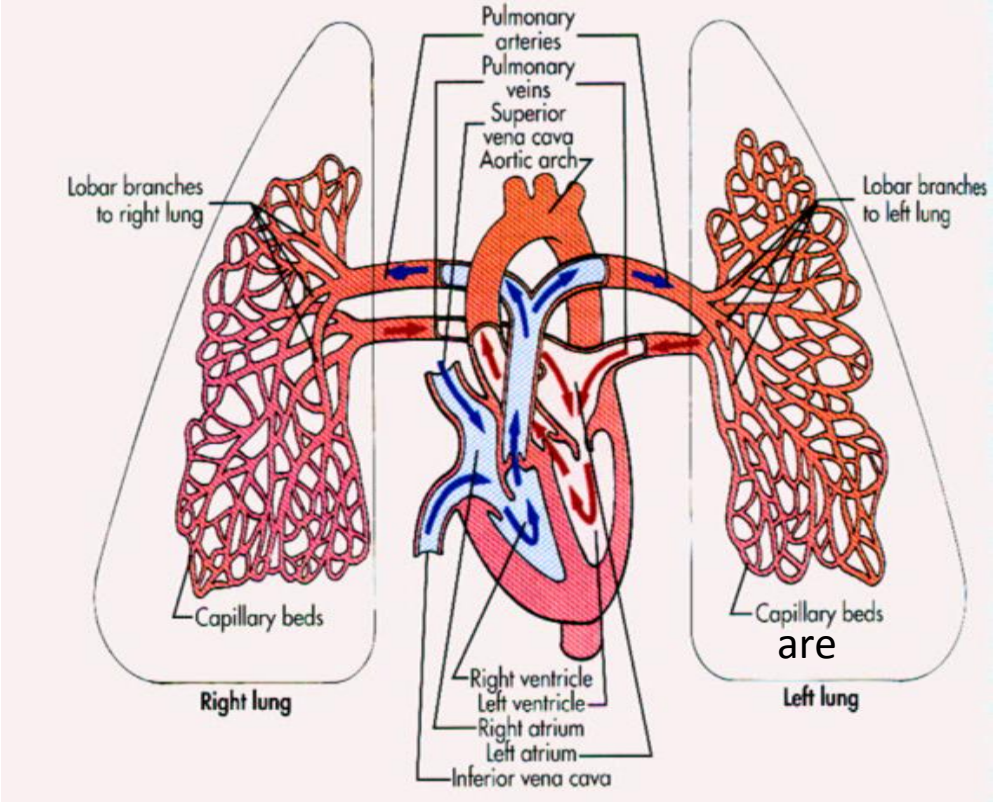
Alveolo - capillary barrier



- Alveolar epithelia
  - type I and II cells
- Capillary endothelium
  - non-fenestrated
- Intersticium
  - cells (very few!)
    - fibroblasts
    - contractile cells
    - immune cells (intersticial macrophages, mast cells, …)
  - ECM
    - elastin and collagen fibrils

Pulmonary vasculature and lymphatics

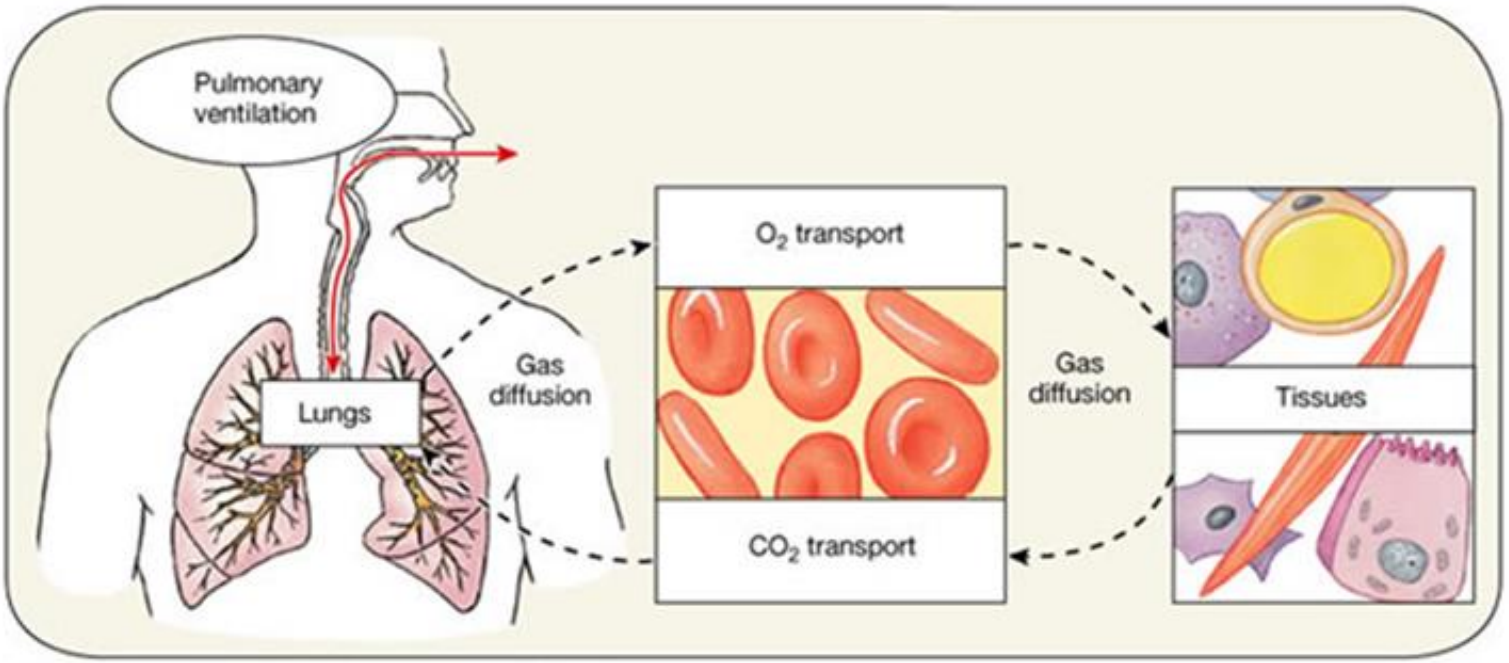
- Lungs are the only organ through which **all the blood** (CO) has to pass!!!
- Lungs have a **dual blood supply**
  - deoxygenated blood from the right ventricle via the pulmonary artery
  - systemic (nutritional) supply throughout the bronchial circulation
    - arises from the descending aorta
    - bronchial arteries supply tissues down to the level of the respiratory bronchiole
    - bronchial veins drain into the pulmonary vein, forming part of the **physiological shunt** observed in normal individuals
- Drainage is provided by the four main pulmonary veins (into the left atrium)
- Lymphatics start in the interstitial space between the alveolar cells and the capillary endothelium of the pulmonary arterioles
  - the tracheobronchial lymph nodes arranged in five main groups:
    - paratracheal, superior tracheobronchial, subcarinal, bronchopulmonary and pulmonary

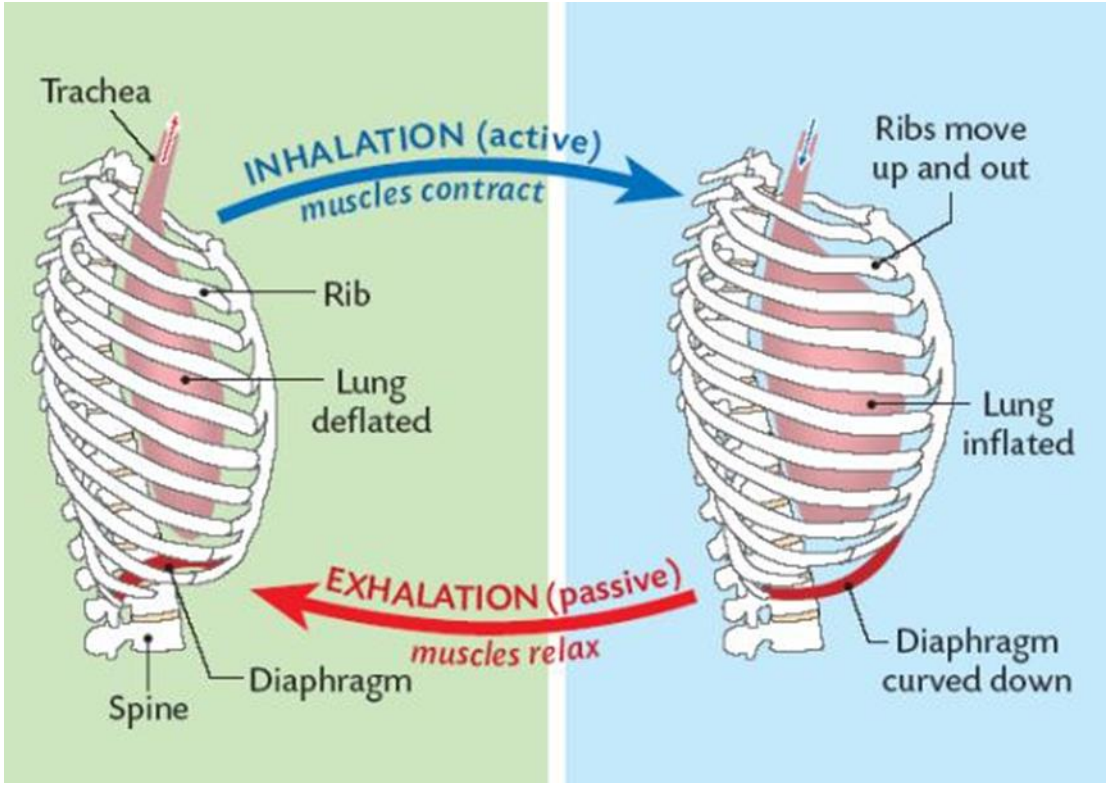


are

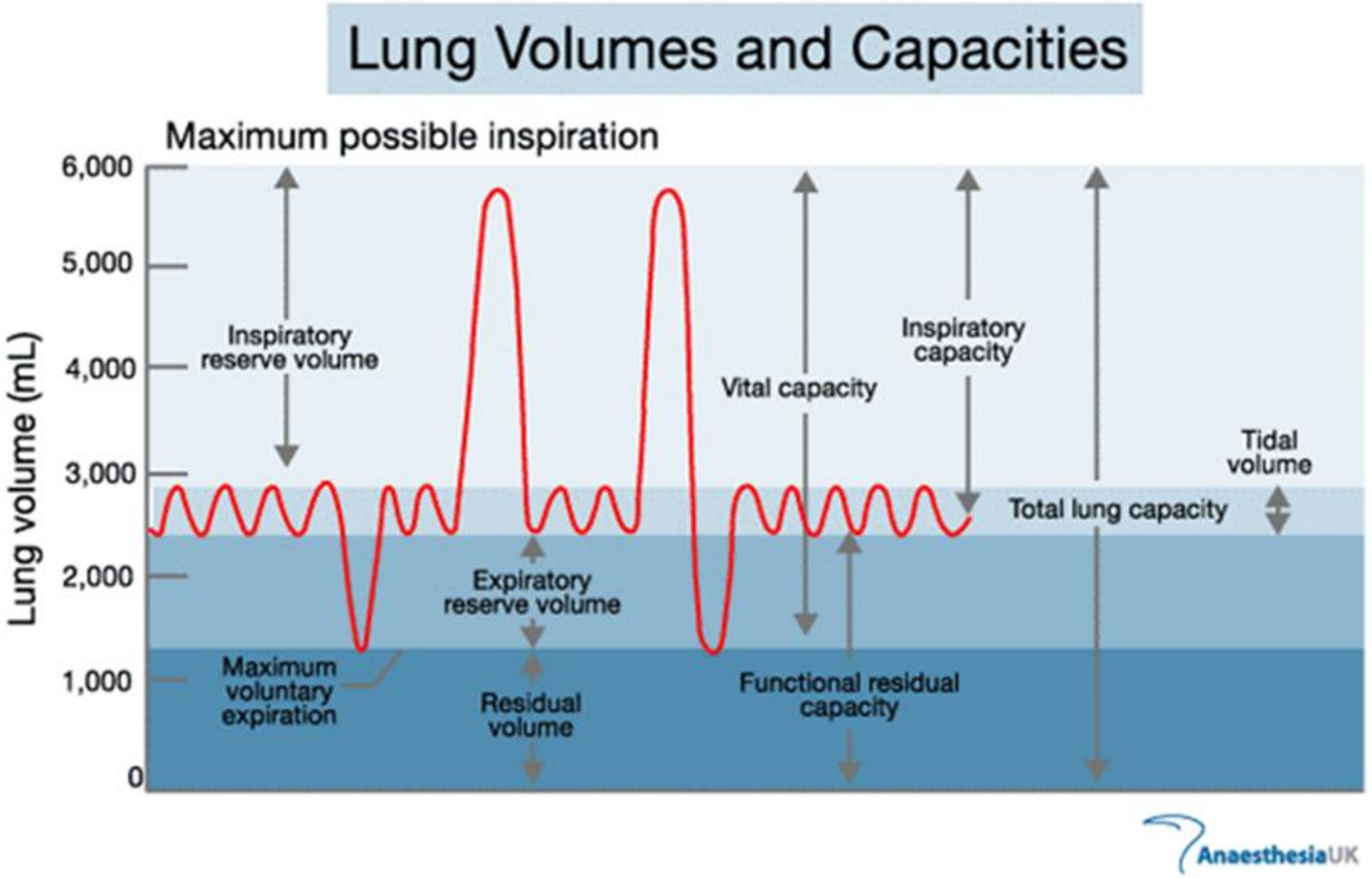
Respiration and gas exchange in the lungs

- **ventilation** = mechanical process
  - breathing in narrower meaning
- **diffusion** = chemical process
  - through alveolo-cappilary barrier
- **perfusion** = circulatory process
  - circulation of blood in lungs



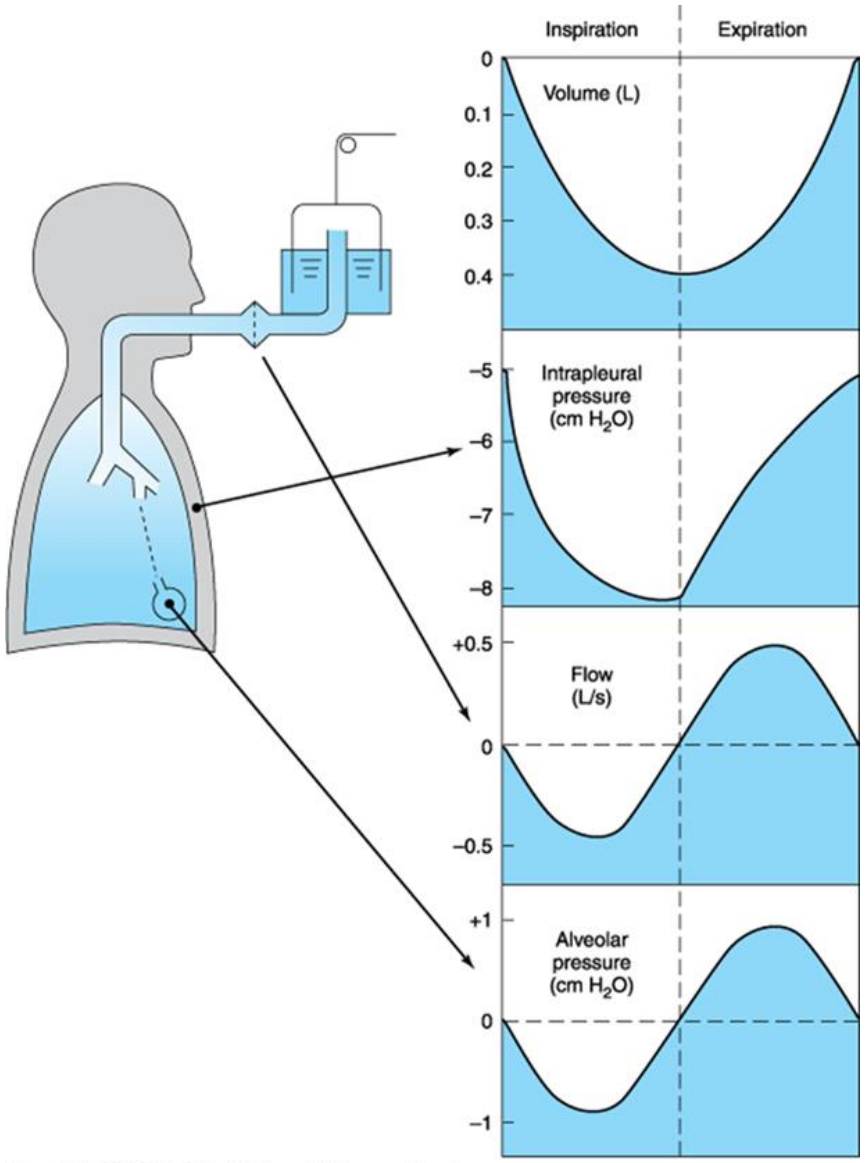


(1) VENTILATION & PULMONARY MECHANICS



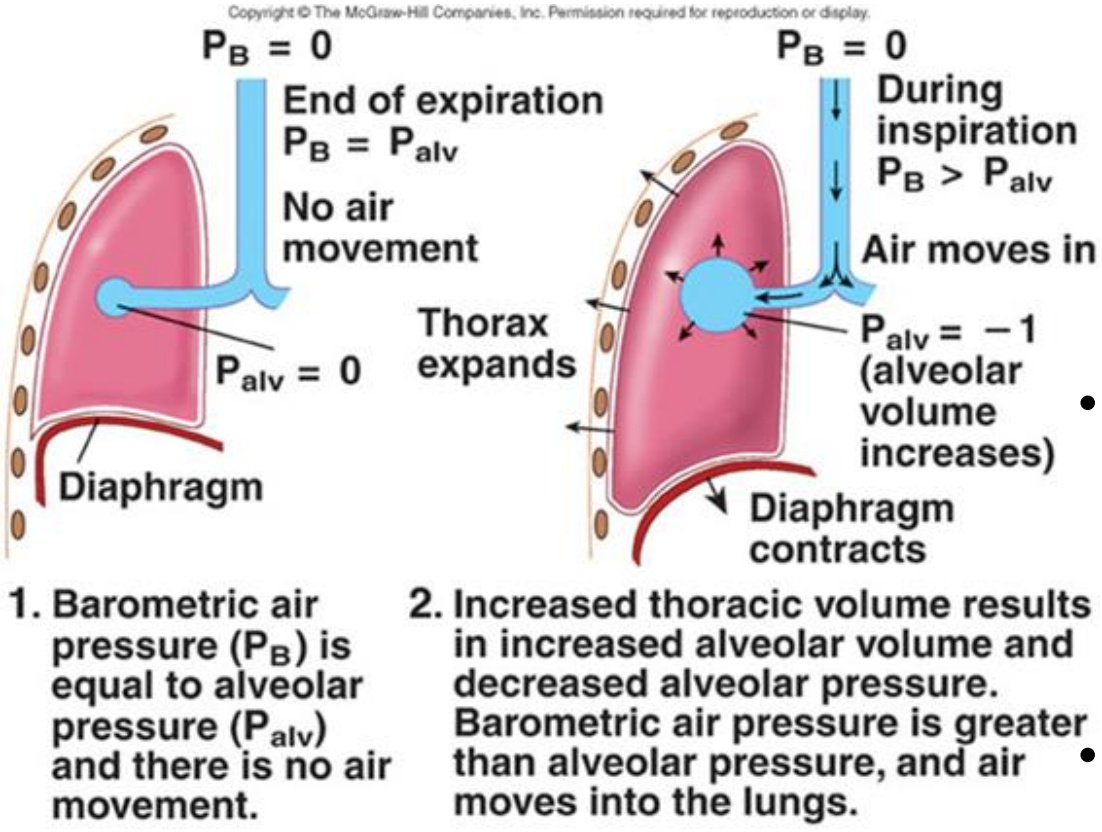
set by opposing recoil forces of the chest and lungs and the effort of respiratory muscles

Mechanika dýchání



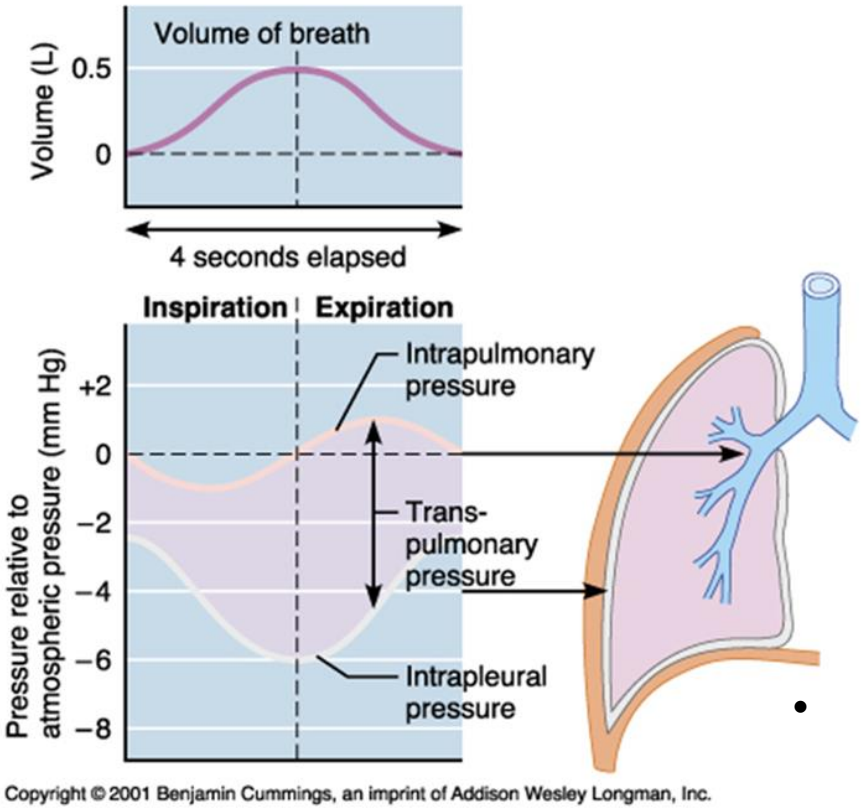
- tlaky a tlakové gradienty
  - tlak na povrchu těla (P_{bs}), většinou totožný s atmosferickým (P_{ao})
  - tlak v alveolu (P_{alv})
  - „elastický“ tlak vyvíjený parenchymem plic a povrchovým napětím (P_el)
  - tlak v pleurální dutině (P_{pl})
  - transpulmonální tlak = tlakový rozdíl mezi alveolem a pleurální dutinou (P_L)
    - $P_L = P_{alv} - P_{pl}$
  - transtorakální tlak = rozdíl mezi alveoly a tělesným povrchem (P_{rs}), určuje zda probíhá inspirium nebo expirium
    - $P_{rs} = P_{alv} - P_{bs}$

Ventilation



- pressure necessary to distend lungs has to overcome two kinds of resistances
  - **DYNAMIC = airway resistance** (in the convection part of airways)
  - **STATIC = elastic recoil** (in the respiratory part of airways and lung parenchyma)
- energy requirements for respiratory muscles to overcome these two resistances is normally quite low (2-5% of a total O_2 consumption)
- but increases dramatically when resistance increases (up to 30%) → subjective perception as a **dyspnea**

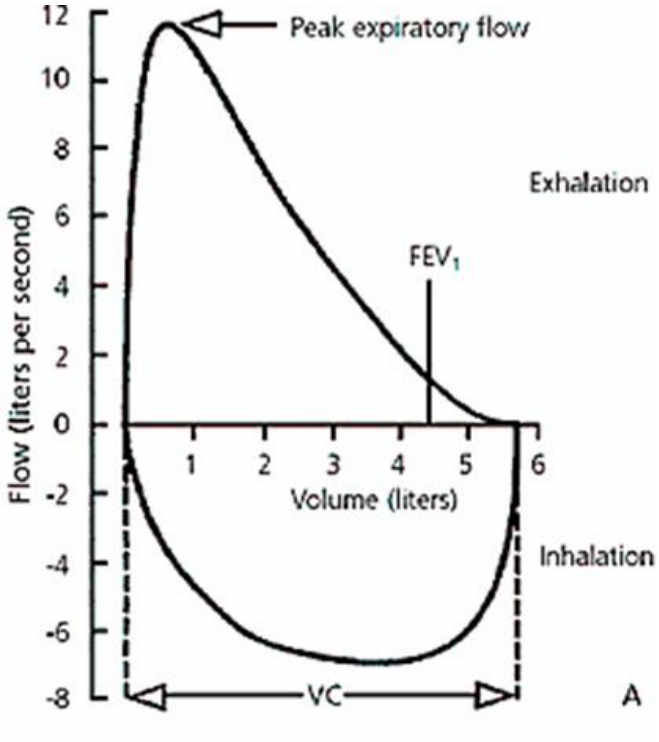
Ventilation (breathing) as a mechanical process



- Inspiration
  - an active process that results from the descent of the **diaphragm** and movement of the ribs upwards and outwards under the influence of the **intercostal muscles**
    - in resting healthy individuals, contraction of the diaphragm is responsible for most inspiration
  - respiratory muscles are similar to other skeletal muscles but are less prone to fatigue
    - weakness may play a part in respiratory failure resulting from neurological and muscle disorders and possibly with severe chronic airflow limitation
  - inspiration against increased resistance may require the use of the accessory muscles of ventilation
    - sternocleidomastoid and scalene muscles
- Expiration
  - follows passively as a result of gradual lessening of contraction of the intercostal muscles, allowing the lungs to collapse under the influence of their own elastic forces (**elastic recoil**)
  - forced expiration is also accomplished with the aid of accessory muscles
    - abdominal wall

Airflow

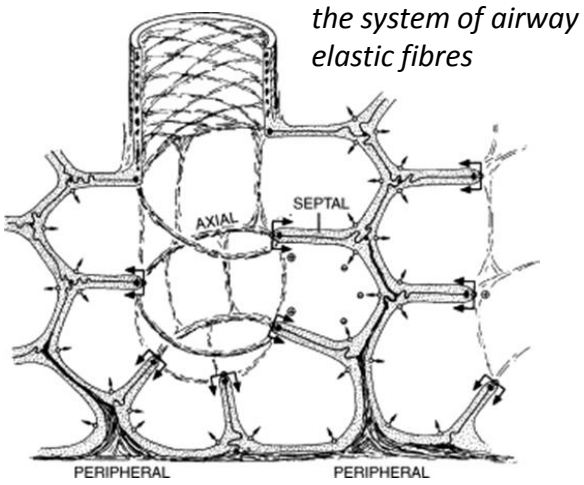
- Movement of air through the airways results from a **difference between the pressure in the alveoli and the atmospheric pressure**
  - alveolar pressure (P_{ALV}) is equal to the elastic recoil pressure (P_{EL}) of the lung plus the pleural pressure (P_{PL})
  - positive P_{ALV} occurs in expiration and a negative pressure occurs in inspiration
- During quiet breathing the sub-atmospheric pleural pressure throughout the breathing cycle slightly distends the airways
  - during vigorous expiratory efforts (e.g. cough) the central airways are compressed by positive pleural pressures exceeding 10 kPa
  - the airways do not close completely because the driving pressure for expiratory flow (alveolar pressure) is also increased
- When there is no airflow (i.e. during a pause in breathing) the tendency of the lungs to collapse (the positive P_{EL}) is exactly balanced by an equivalent negative P_{PL}

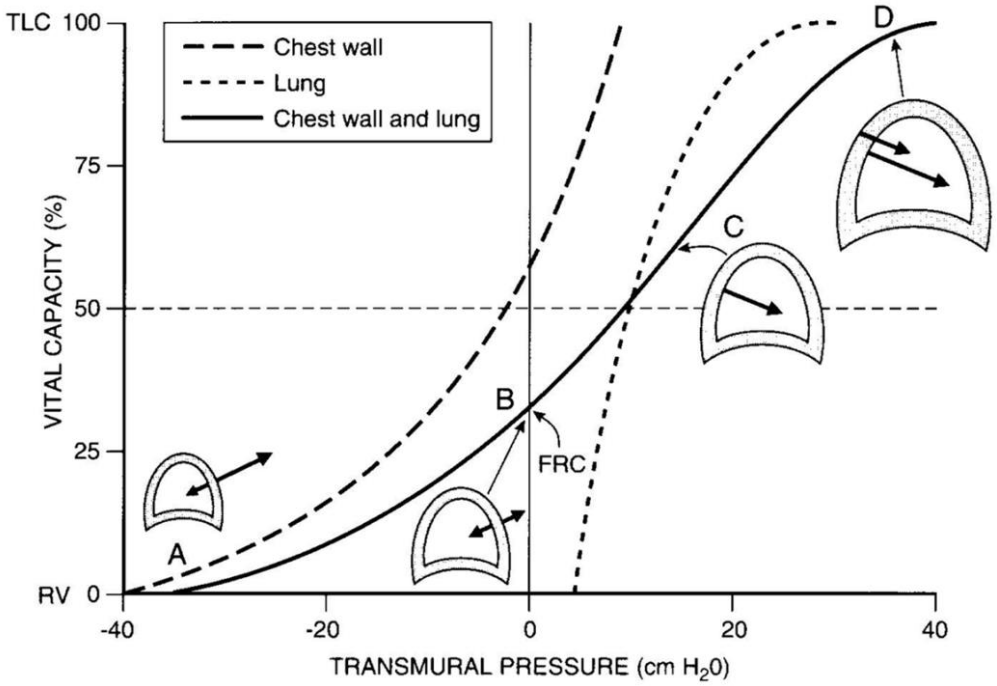


The relationship between maximal flow rates on expiration and inspiration is demonstrated by the maximal flow-volume (MFV) loops

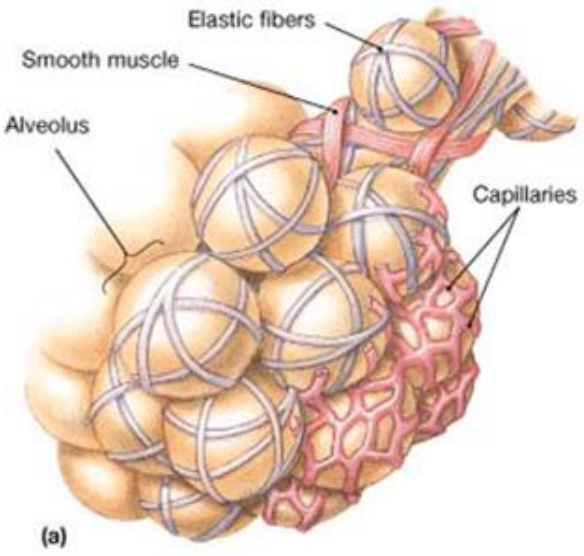
Elastic properties of the lung

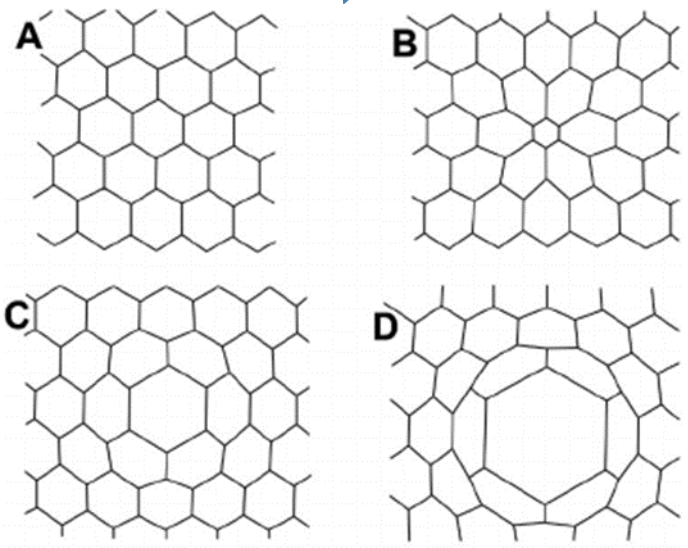
- lungs have an inherent elastic property that causes them to tend to collapse generating a negative pressure within the pleural space
  - the strength of this retractive force relates to the volume of the lung; for example, at higher lung volumes the lung is stretched more, and a greater negative intrapleural pressure is generated
  - at the end of a quiet expiration, the retractive force exerted by the lungs is balanced by the tendency of the thoracic wall to spring outwards
    - at this point, respiratory muscles are resting and the volume of the lung is known as the **functional residual capacity** (FRC)

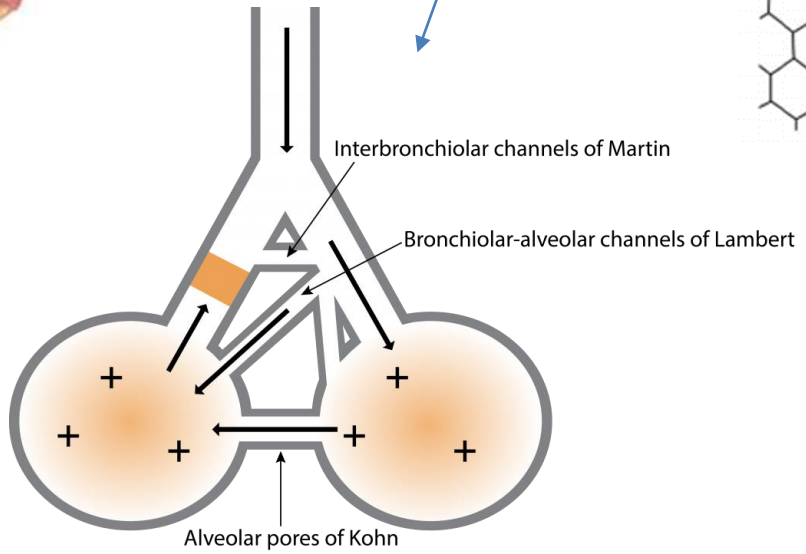


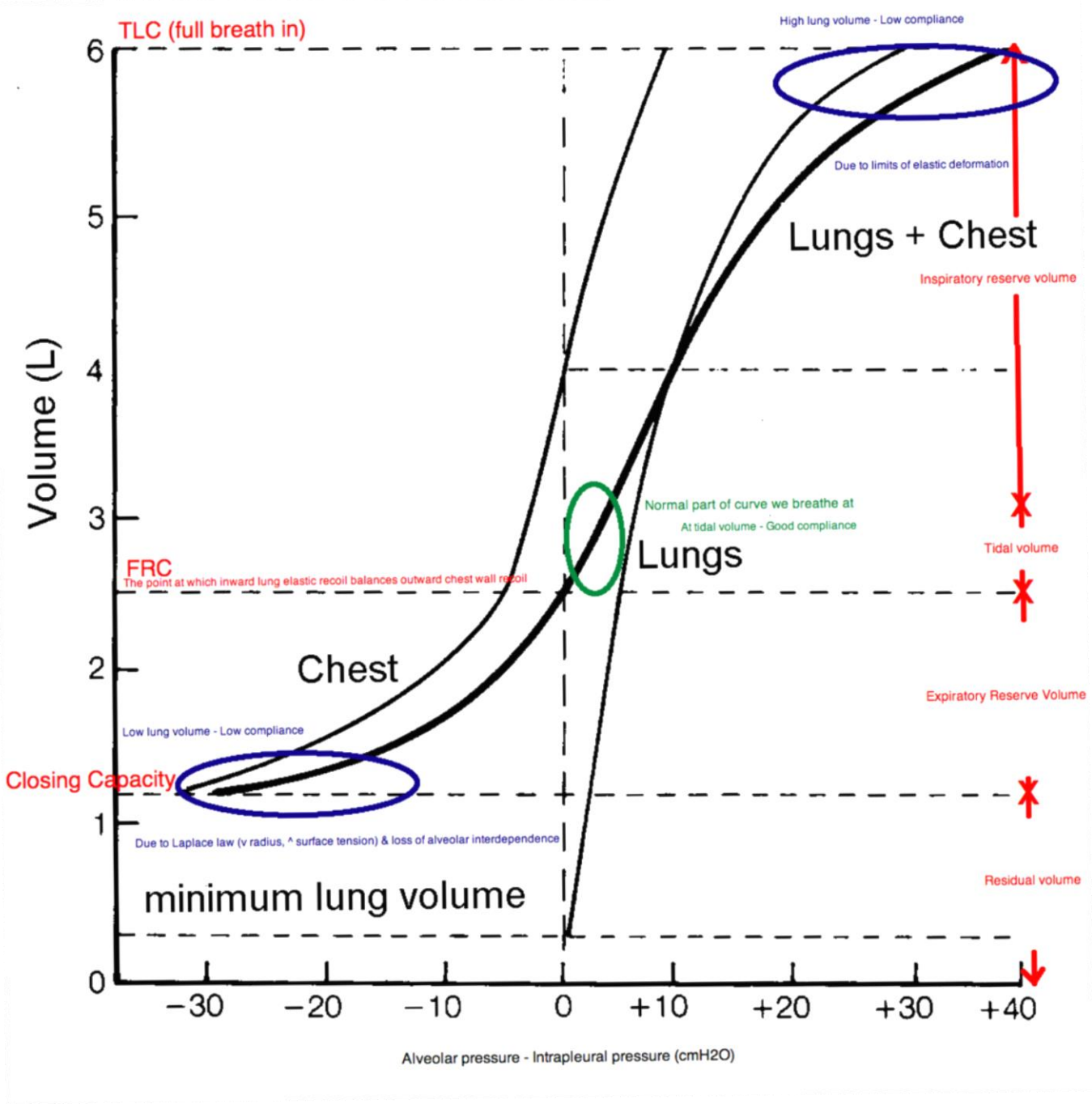


Anatomical – functional considerations explain alveolar stability (due to **alveolar interdependence** and **collateral ventilation**)



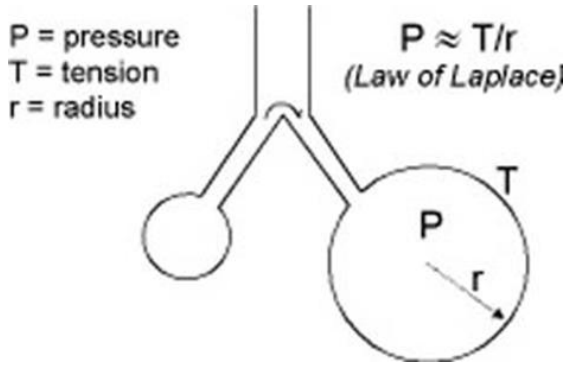




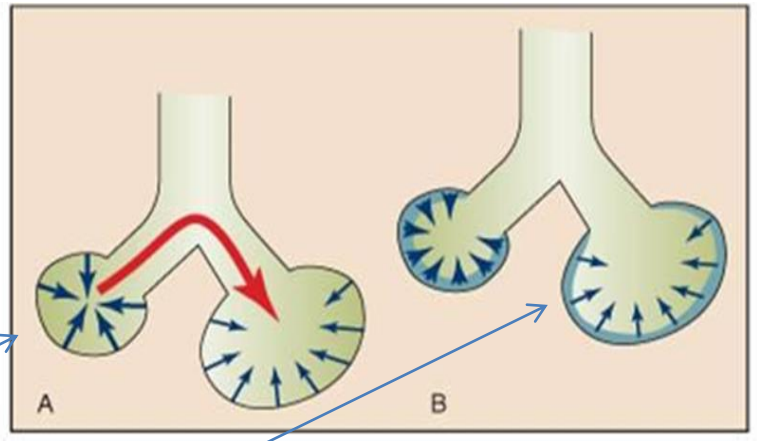

TLC (full breath in)
High lung volume - Low compliance
Due to limits of elastic deformation
Lungs + Chest
Inspiratory reserve volume
Volume (L)
6
5
4
3
2
1
0
Normal part of curve we breathe at
At tidal volume - Good compliance
Lungs
Tidal volume
FRC
The point at which inward lung elastic recoil balances outward chest wall recoil
Chest
Expiratory Reserve Volume
Low lung volume - Low compliance
Closing Capacity
Due to Laplace law (v radius, ^ surface tension) & loss of alveolar interdependence
Residual volume
minimum lung volume
−30
−20
−10
0
+10
+20
+30
+40
Alveolar pressure - Intrapleural pressure (cmH2O)

Elastic recoil is determined by two kinds of forces

- **lung compliance** ("distensibility") = **connective tissue**
  - a measure of the relationship between this retractive force and lung volume
  - defined as the change in lung volume brought about by unit change in transpulmonary (intrapleural) pressure (L/kPa)

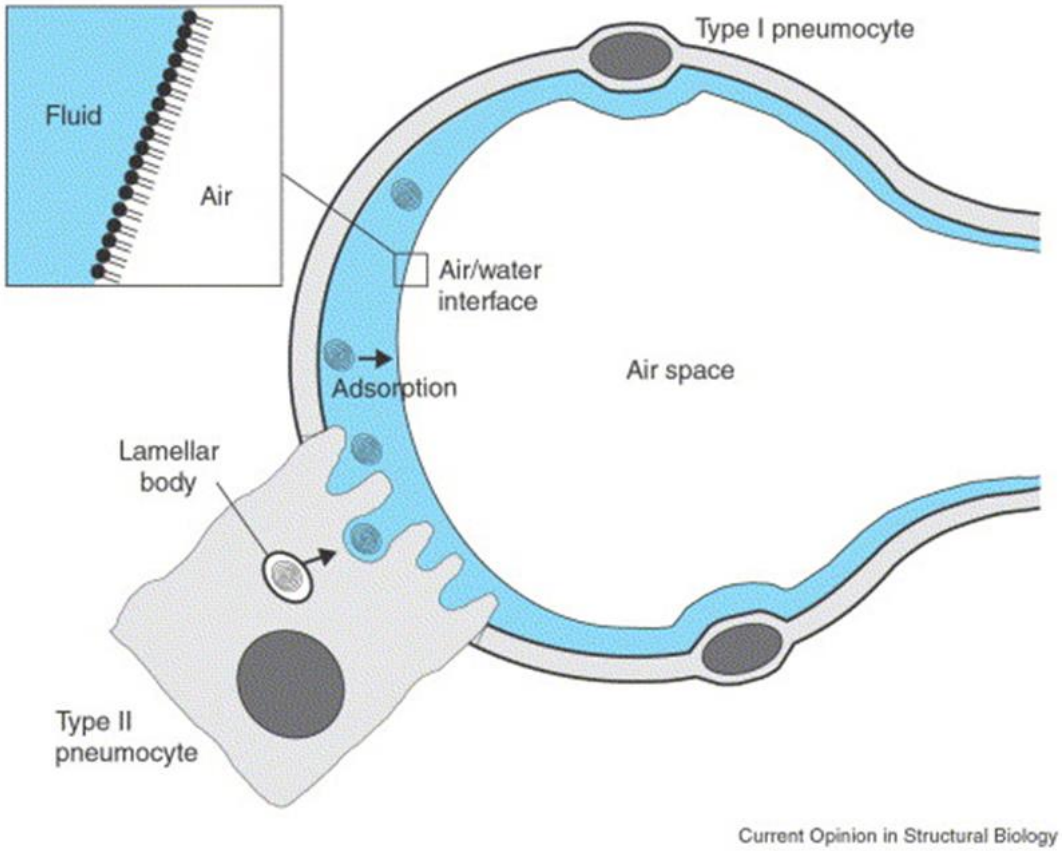


- **surface tension** produced by the layer of fluid that lines the alveoli
  - determined by the cohesive (binding together) forces between molecules of the same type
    - on the inner surface of the alveoli is fluid that can resist lung expansion
    - there would be a lot of surface tension because there is an air-water interface in every alveolus
    - if surface tension remained constant, decreasing r during expiration would increase P and smaller alveolus would empty into large one (A)
  - this collapsing tendency is offset by pulmonary surfactant which significantly lowers surface tension (B)

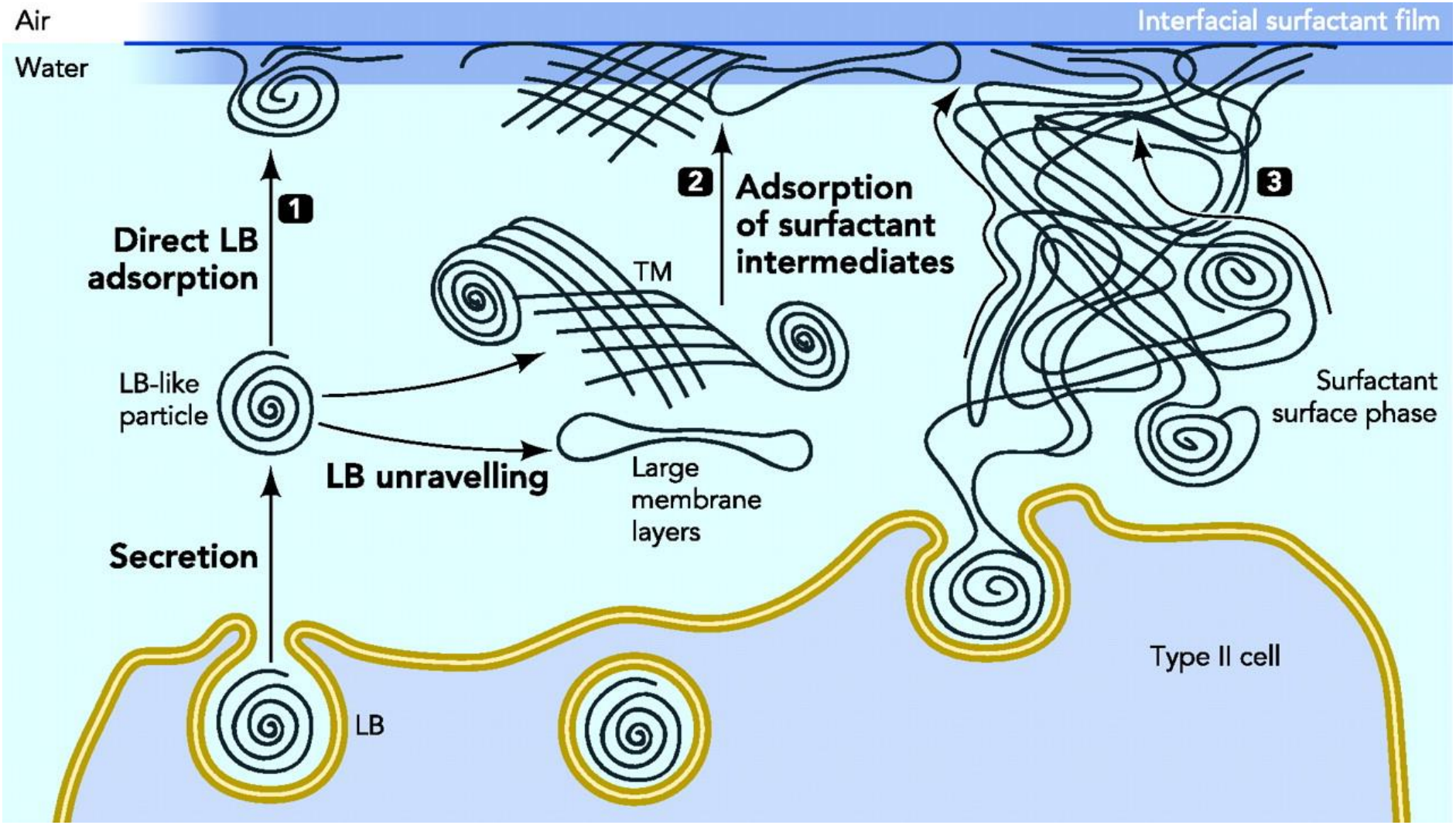


Pulmonary surfactant

- Complex mixture of lipids and proteins at the alveolar cell surface (liquid – gas interface) reducing surface tension
  - superficial layer made of phospholipids (dipalmitoyl lecithin)
  - deeper layer (hypophase) made of proteins (SP-A, -B, -C, -D)
- Surfactant maintains lung volume at the end of expiration
- Continually recycles
  - influenced by many hormones incl. glucocorticoids
    - lung maturation in pre-term newborns



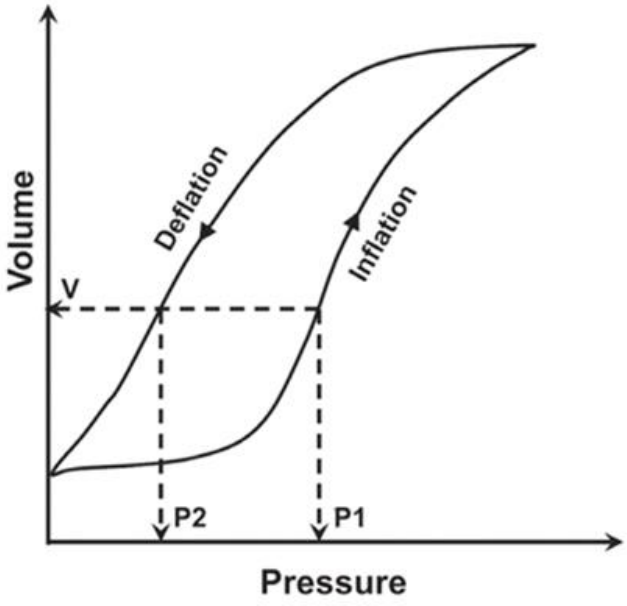
Pulmonary surfactant adsorption to the interface and surface film formation : Processes that may contribute to transport of surface active surfactant species to the interface include 1) direct cooperative transfer of surfactant from secreted lamellar body-like particles (LB) touching the interface, 2) unravelling of secreted LB to form intermediate structures such as tubular myelin (TM) or large surfactant layers that have the potential to move and transfer large amounts of material to the interface, and 3) rapid movement of surface active species through a continuous network of surfactant membranes (so-called surface phase) connecting secreting cells with the interface.

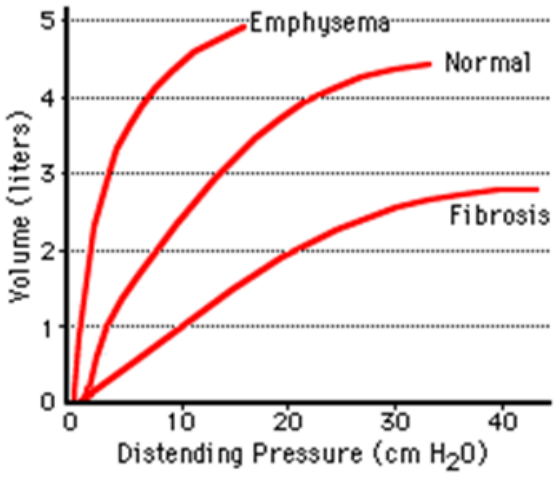


Perez-Gil J , Weaver T E Physiology 2010;25:132-141

Abnormalities of elastic properties

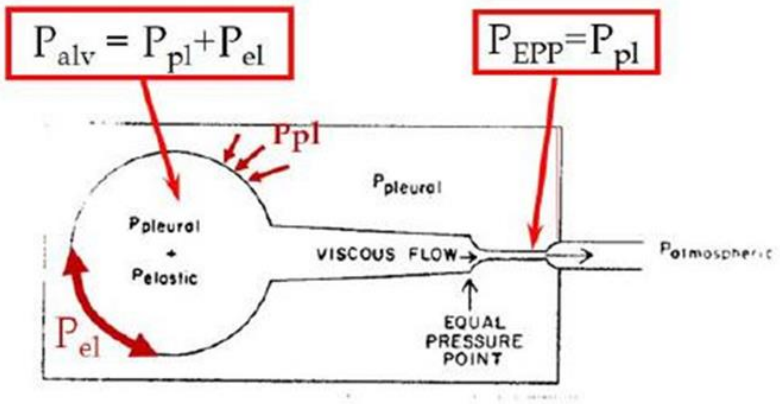
- change of lung compliance
  - ↑ in pulmonary **emphysema**, aging (↑ TLC, ↑ FRC, ↑ RV)
  - ↓ in **interstital disease** (↓TLC, ↓ FRC, ↓ RV), e.g. pulmonary fibrosis or bronchopneumonia
- lack of surfactant (↓TLC, ↓ FRC, ↓ RV)
  - infant or adult **respiratory distress syndrome** (IRDS or ARDS, resp.), i.e. lung collapse
  - lung **edema** (damages surfactant)
- diseases that affect the movement of the thoracic cage and diaphragm
  - marked obesity
  - diseases of the thoracic spine
    - ankylosing spondylitis and kyphoscoliosis
  - neuropathies
    - e.g. the Guillain-Barré syndrome)
  - injury to the phrenic nerves
  - myasthenia gravis

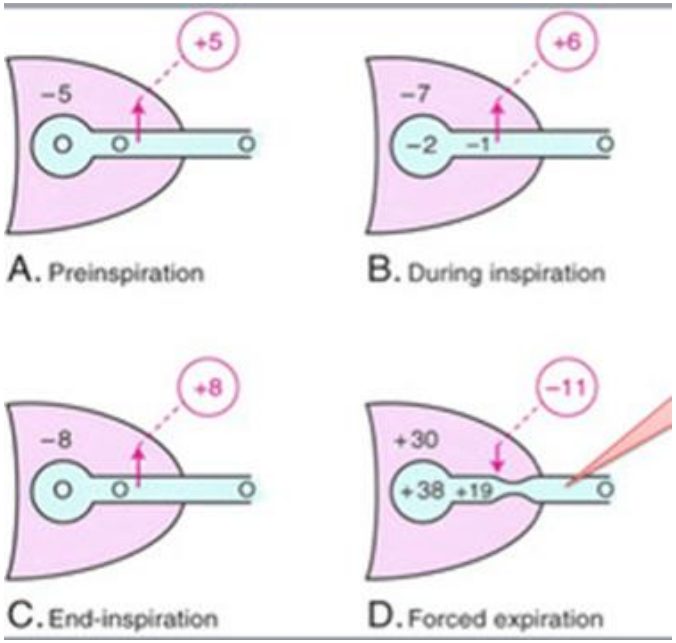




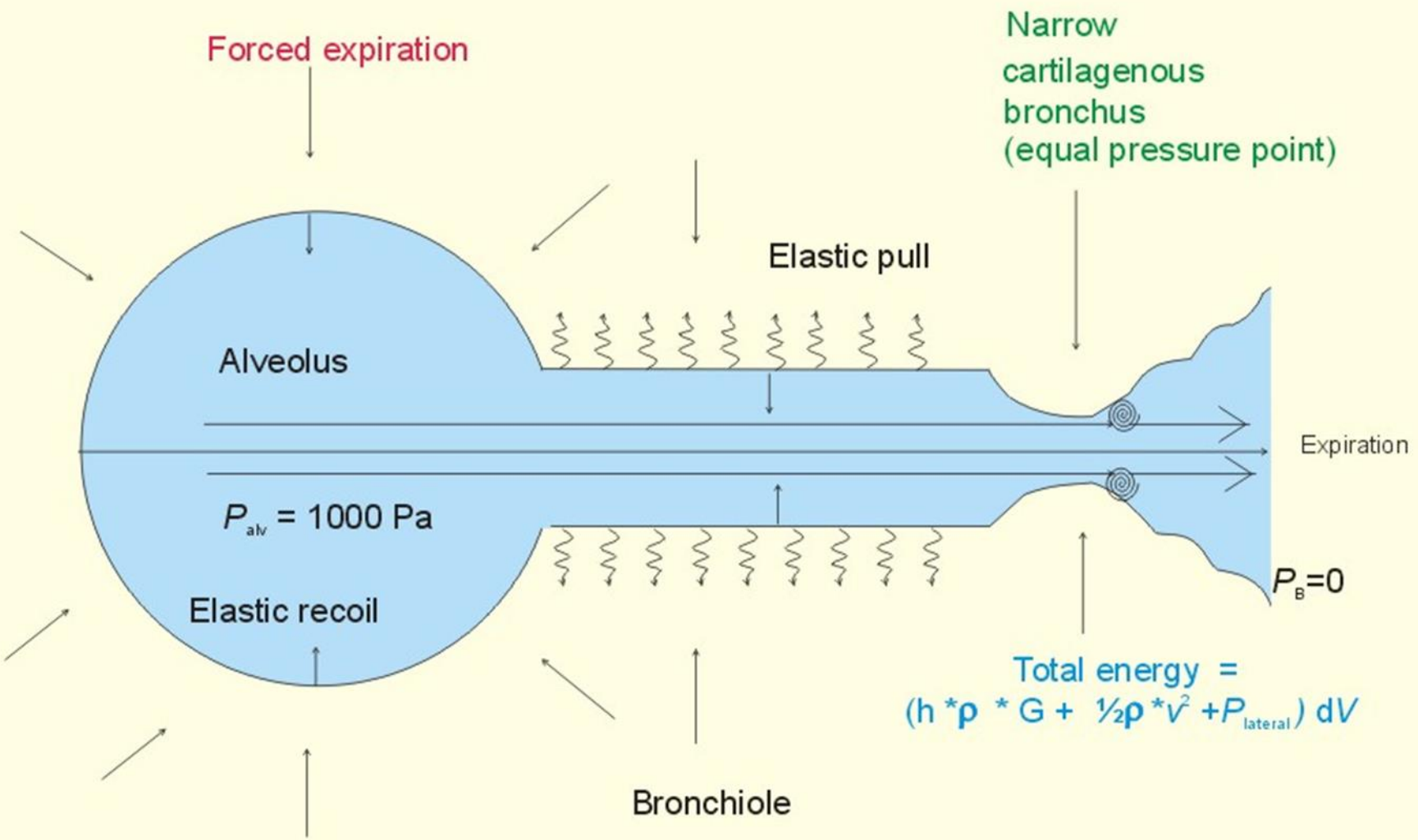
Forced expiration - dynamic compression

- In forced expiration, the driving pressure raises both the P_{ALV} and the P_{PL}
  - between the alveolus and the mouth, a point will occur (C) where the airway pressure will equal the intrapleural pressure, and airway compression will occur
  - however, this compression of the airway is temporary, as the transient occlusion of the airway results in an increase in pressure behind it (i.e. upstream) and this raises the intra-airway pressure so that the airways open and flow is restored
    - the airways thus tend to vibrate at this point of 'dynamic compression'





Dynamic Airway Collapse

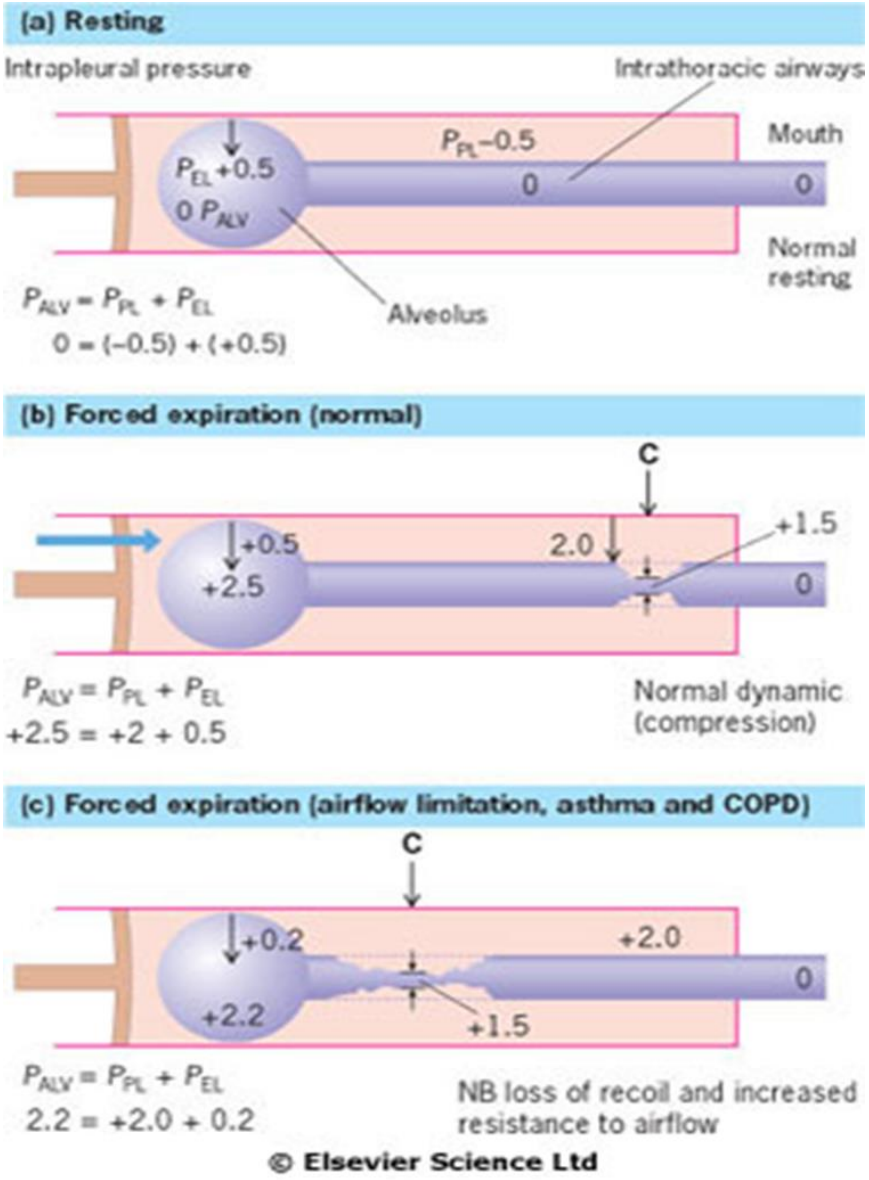


Expiratory effort --- Increased kinetic energy --- Reduced lateral pressure --- Dynamic Airway Collapse

Fig. 13-5

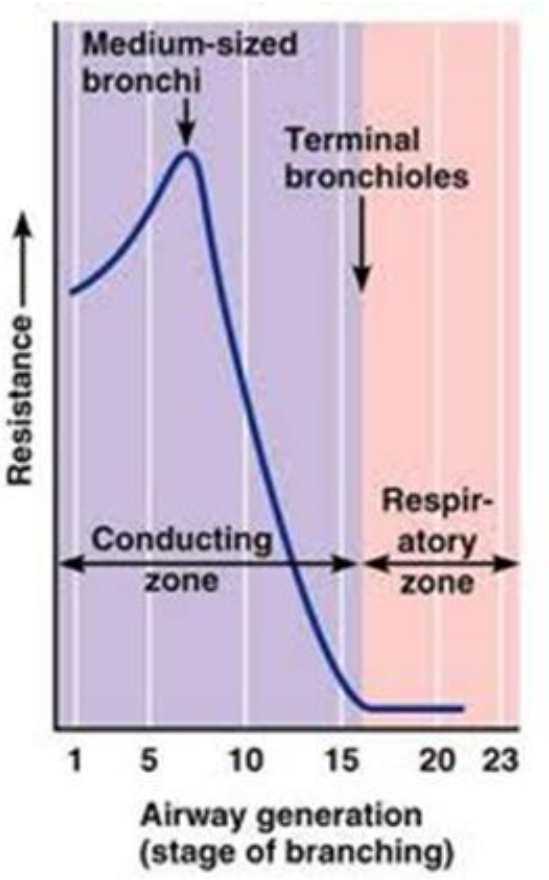
KMc

Dynamic compression in various situations



- The respiratory system is represented as a piston with a single alveolus and the collapsible part of the airways within the piston
  - C, compression point; PALV, alveolar pressure; PEL, elastic recoil pressure; PPL, pleural pressure.
  - (a) at rest at functional residual capacity
  - (b) forced expiration in normal subjects
  - (c) forced expiration in a patient with COPD

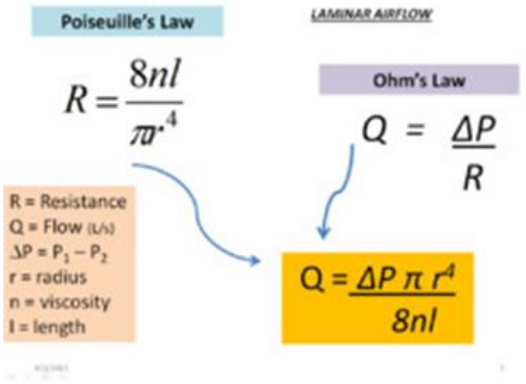
Airflow pattern as a result of change in airway diameter & resistance

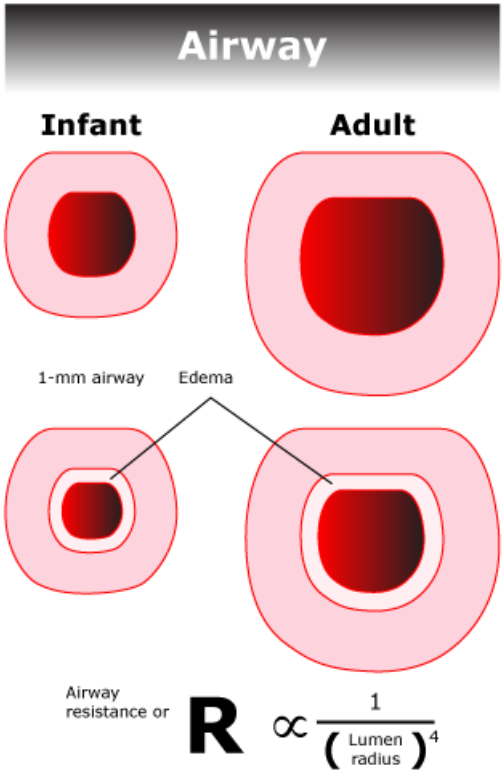


- From the trachea to the periphery, the airways become smaller in size (although greater in number)
  - the cross-sectional area available for airflow increases as the total number of airways increases
  - the flow of air is greatest in the trachea and slows progressively towards the periphery (as the velocity of airflow depends on the ratio of flow to cross-sectional area)
    - in the terminal airways, gas flow occurs solely by diffusion
- The **resistance to airflow** is very low (0.1-0.2 kPa/L in a normal tracheobronchial tree), **steadily decreasing from the medium size to small airways**
- Airway tone is under the control of the autonomic nervous system
  - bronchomotor tone is maintained by **vagal efferent nerves**
  - many **adrenoceptors** on the surface of bronchial muscles respond **to circulating catecholamines**
    - sympathetic nerves do not directly innervate them!

Airway resistance

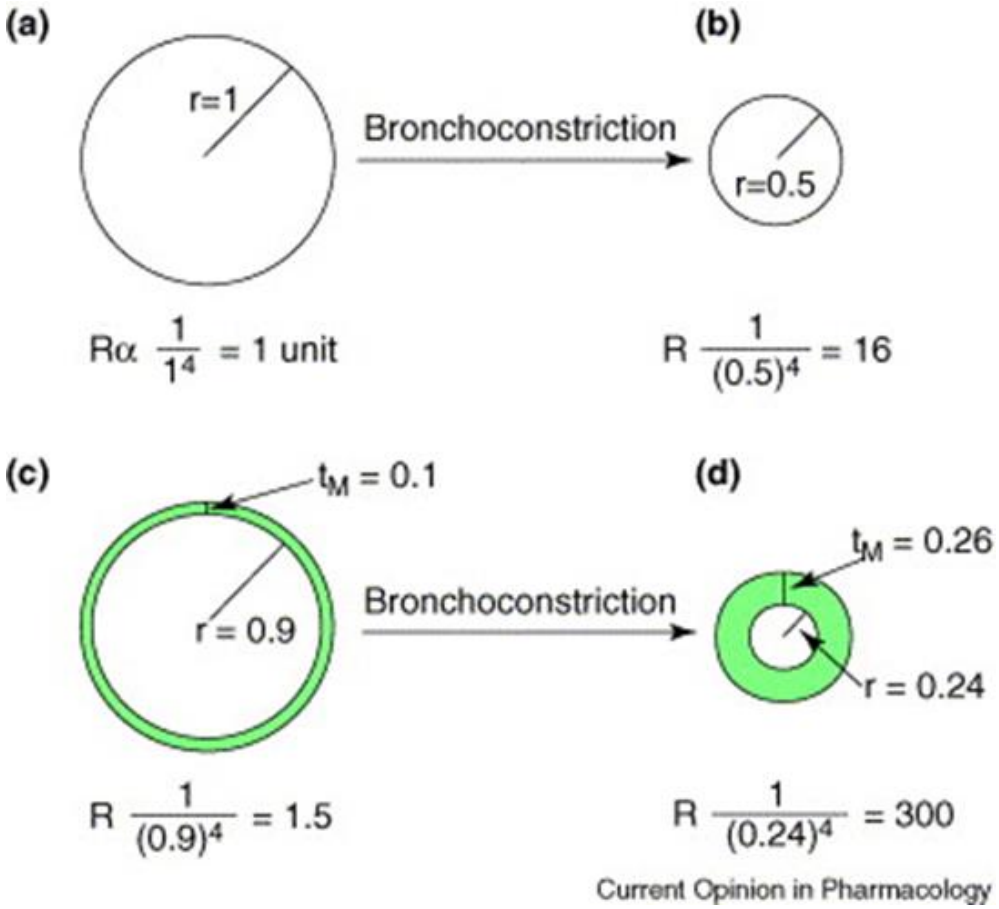
- Ohm´s law:
  - flow is inversely proportional to resistance
- Poiseuille’s law:
  - determinants od resistance
- This means that the most important variable here is the **radius**
- Overcoming increased resistance requires **forced expiration**





	Infant	Adult
Airway diameter	4 mm	8 mm
Airway diameter with edema	3 mm	7 mm
Airway resistance	↑ 16 x	↑ 3 x
Cross-sectional area	↓ 75 percent	↓ 44 percent

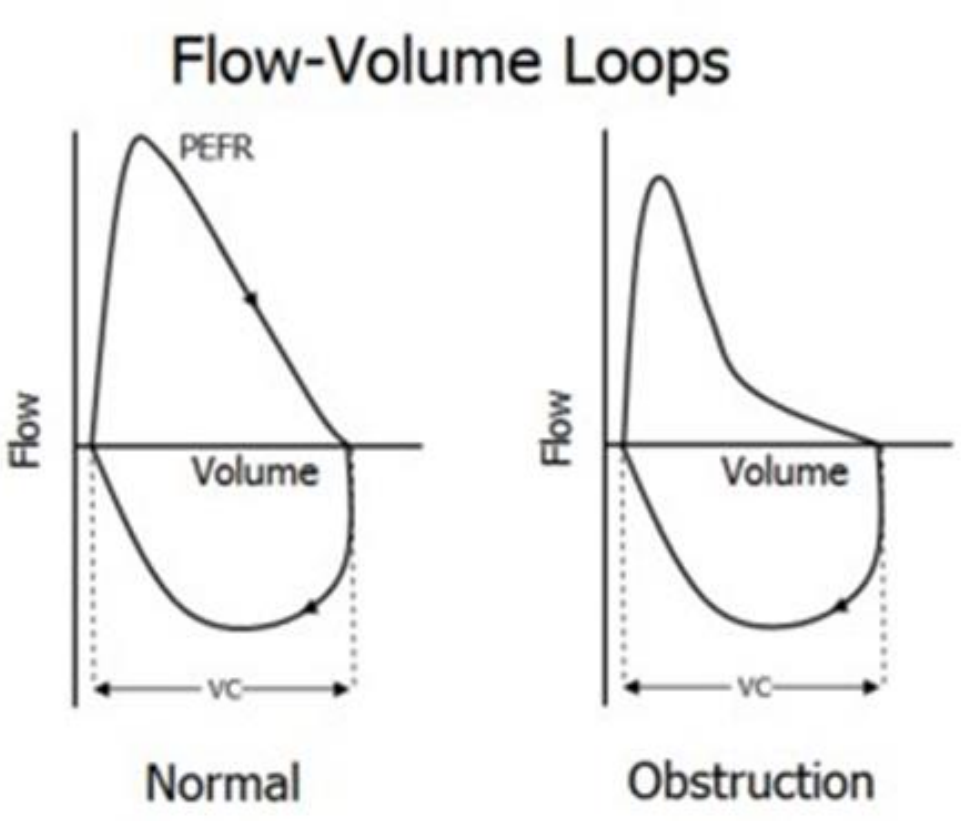
Airflow resistance - bronchoconstriction

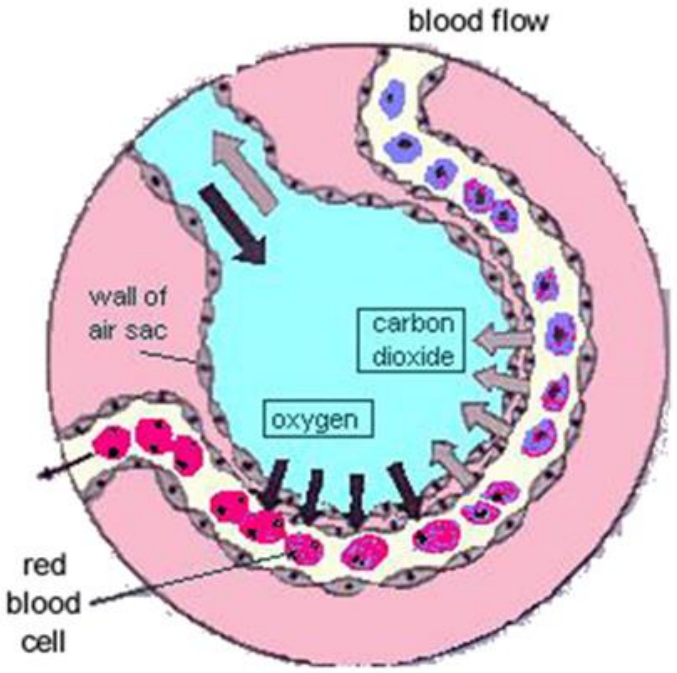


- theoretical amplifying effect of luminal mucus on airflow resistance in asthma. **(a)** According to Poiseuille's law, resistance to flow (R) is proportional to the reciprocal of the radius (r) raised to the fourth power. **(b)** Without luminal mucus, bronchoconstriction to reduce the airway radius by half increases airflow resistance 16-fold. **(c)** A small increase in mucus thickness (t_M), which reduces the radius of the airway by only one-tenth, has a negligible effect on airflow in the unconstricted airway (compare with panel **a**). **(d)** With bronchoconstriction, the same amount of luminal mucus markedly amplifies the airflow resistance of this airway

Airflow obstruction

- In patients with severe COPD, limitation of expiratory flow occurs even during tidal breathing at rest
- To increase ventilation these patients have to breathe at higher lung volumes and also allow more time for expiration by increasing flow rates during inspiration, where there is relatively less flow limitation
- Thus patients with severe airflow limitation have a prolonged expiratory phase to their respiration

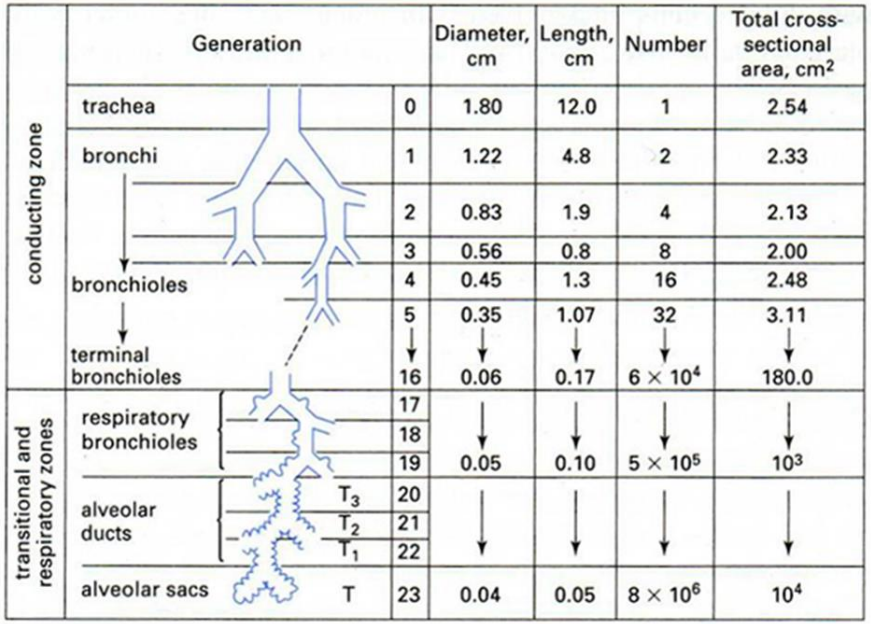




VÝMĚNA PLYNŮ V PLICÍCH & POMĚR VENTILACE-PERFÚZE

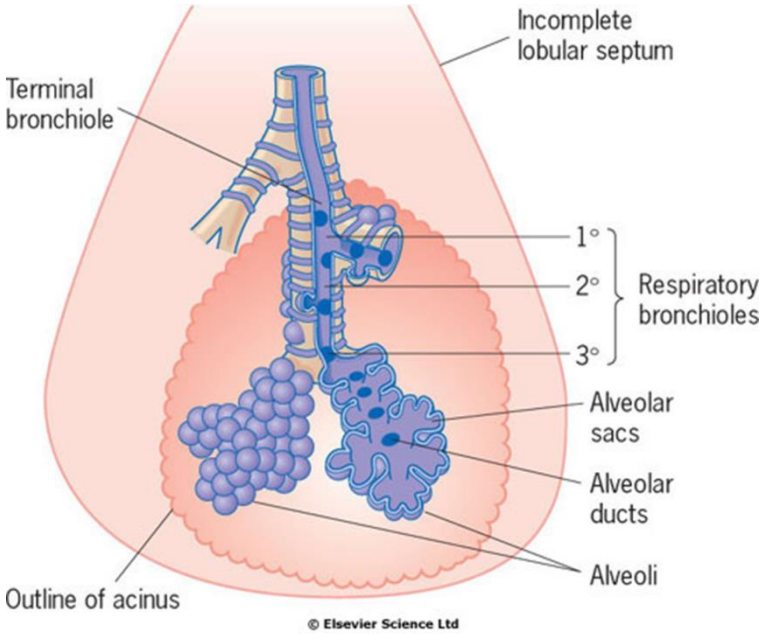
Functional classification of airways

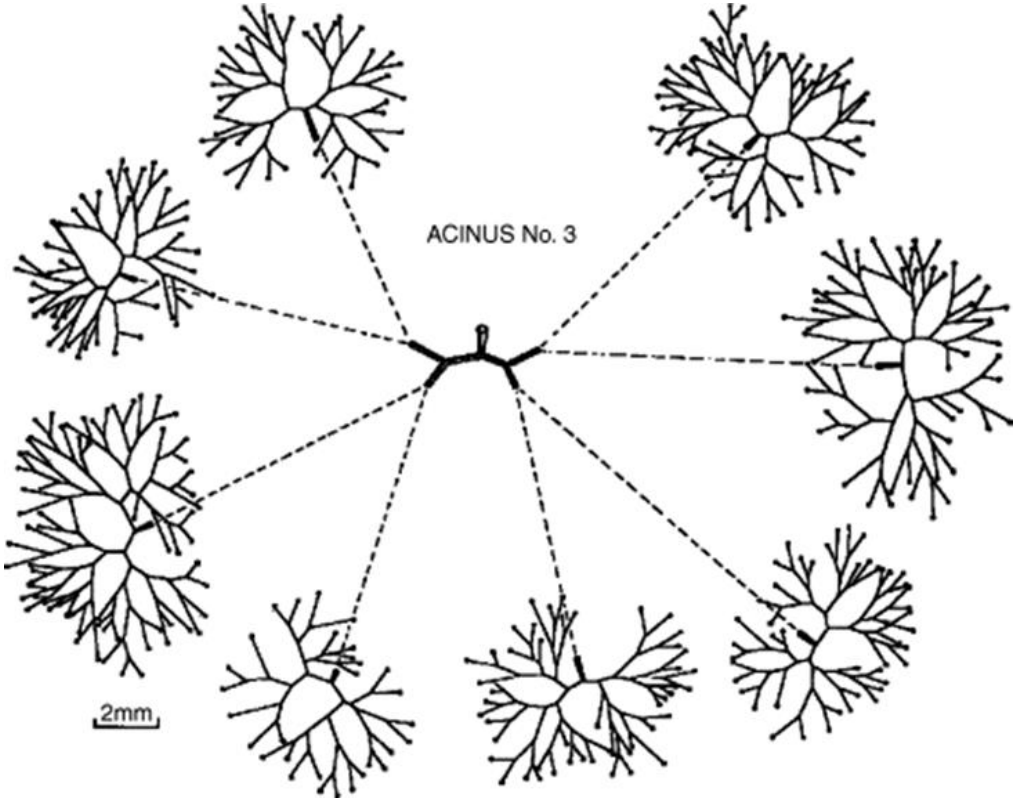
- Conducting airways (= **anatomical dead space**)
  - nose (mouth)
  - larynx
  - trachea
  - main bronchi & bronchioles
  - gas conduction, warming
- Acinar airways (= **respiratory space**)
  - respiratory bronchioles
  - alv. ducts & sacs
  - alveoli
  - gas exchange
- Pulmonary acinus
  - the functional 3-D unit – a part of the parenchyma in which all airways have alveoli attached to their wall and thus participating in gas exchange



	Generation		Diameter, cm	Length, cm	Number	Total cross-sectional area, cm^2
conducting zone	trachea	0	1.80	12.0	1	2.54
	bronchi	1	1.22	4.8	2	2.33
		2	0.83	1.9	4	2.13
		3	0.56	0.8	8	2.00
	bronchioles	4	0.45	1.3	16	2.48
	terminal bronchioles	5 ↓ 16	0.35 ↓ 0.06	1.07 ↓ 0.17	32 ↓ 6×10^4	3.11 ↓ 180.0
transitional and respiratory zones	respiratory bronchioles	17 18 19	↓ 0.05	↓ 0.10	↓ 5×10^5	↓ 10^3
	alveolar ducts	T_3 20 T_2 21 T_1 22	↓	↓	↓	↓
	alveolar sacs	T 23	0.04	0.05	8×10^6	10^4

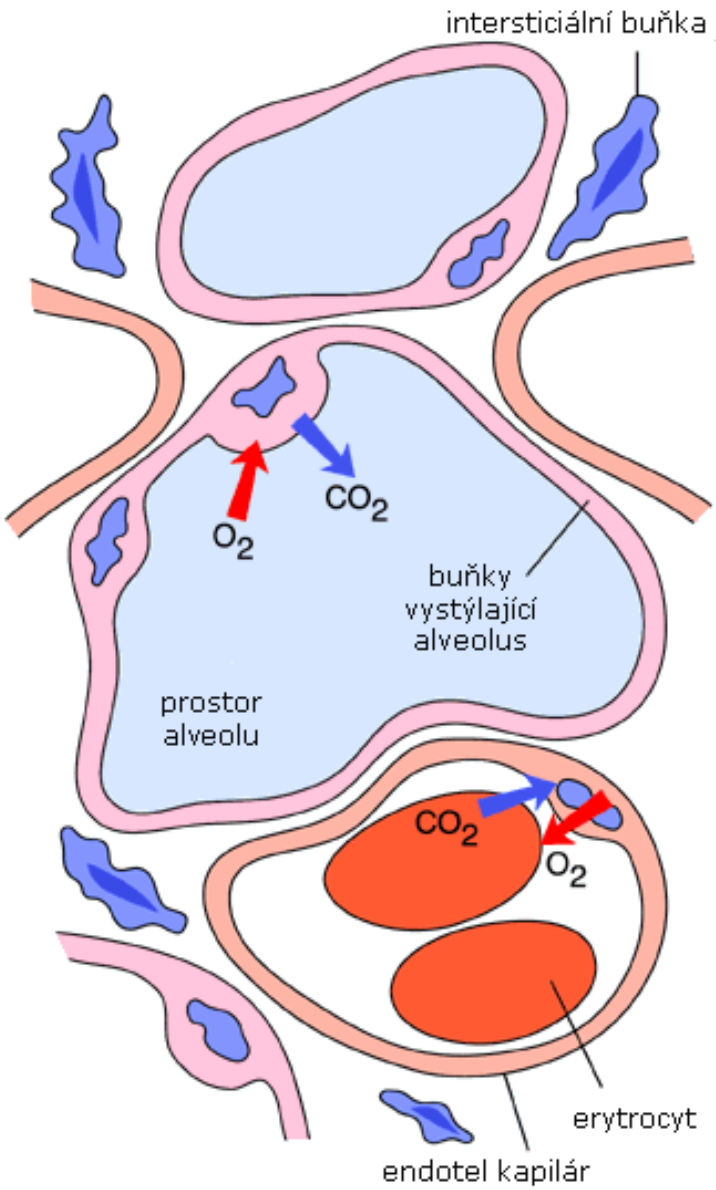
Koncept acinu





- 3-D struktura následující po terminálním bronchiolu
  - 3 úrovně větvení resp. bronchiolu a násl. cca 8 větvení alveolárních duktů,
  - každý plicní lalůček (anatomický pojem) tak vyplňuje 10 - 30 acinů
  - vzhledem k tomu, že kyslík (pouze) difunduje (neproudí) a tedy mění svůj koncentrační gradient směrem k periferii acinu, je tento koncept důležitý pro pochopení **ventilačně – perfúzní nerovnováhy**

Výměna plynů v plicích

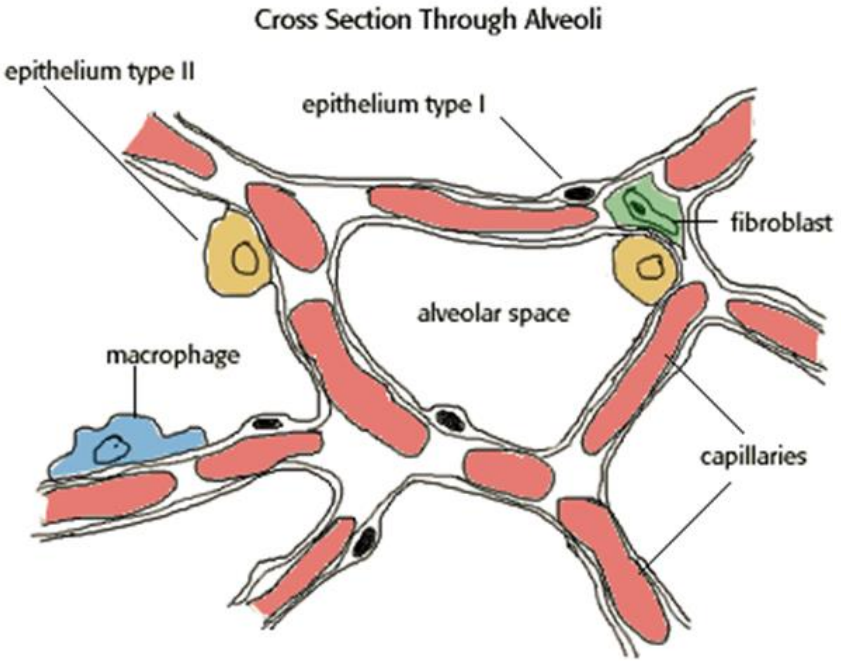


- hlavní funkce dýchacího systému – **výměna plynů mezi okolím a krví** – je podřízena časově variabilním nárokům organismu na O_2
  - udržovány v optimálním rozmezí zejm. regulací intenzity ventilace
- nároky jsou určeny spotřebou **ATP** a jeho nahrazováním **mitochondriemi** (ox. fosforylací)
- alveolo-kapilární výměna plynů probíhá z alv. prostoru do krve **prostou difuzí** přes stěnu alveolu, plicní intersticium a stěnu kapilár
- hnací silou dodávky O_2 (a recipročně CO_2) je postupný pokles jeho parciálního tlaku, tj. **koncentrační gradient** mezi vdechovaným vzduchem, krví a tkáněmi:
  - parciální tlak = tlak, který by plyn měl pokud by byl ve směsi sám

Výměna plynů v plicích

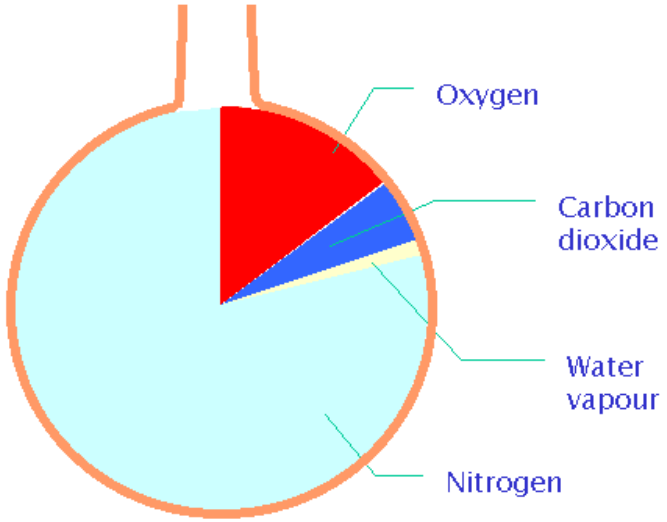
- důvody poklesu PO_2:
  - difuze v acinárních cestách a postupný pokles gradientu
  - kompetice s CO_2 v alveolu (do výše atm. tlaku)
    - alveolární rovnice plynů
  - rozpustnost = < 100% difuze přes alveolo-kapilární membránu
  - fyziologický pravo-levý zkrat
    - míchání okysličené a neokysličené krve (aa. bronchiales a vv. coronarie)
  - fyziologicky malá část Hb jako Met-Hb a COHb
  - postupné spotřebovávání v průběhu acinu

$$P_{AO_2} = P_{IO_2} - (P_{aCO_2}/R)$$



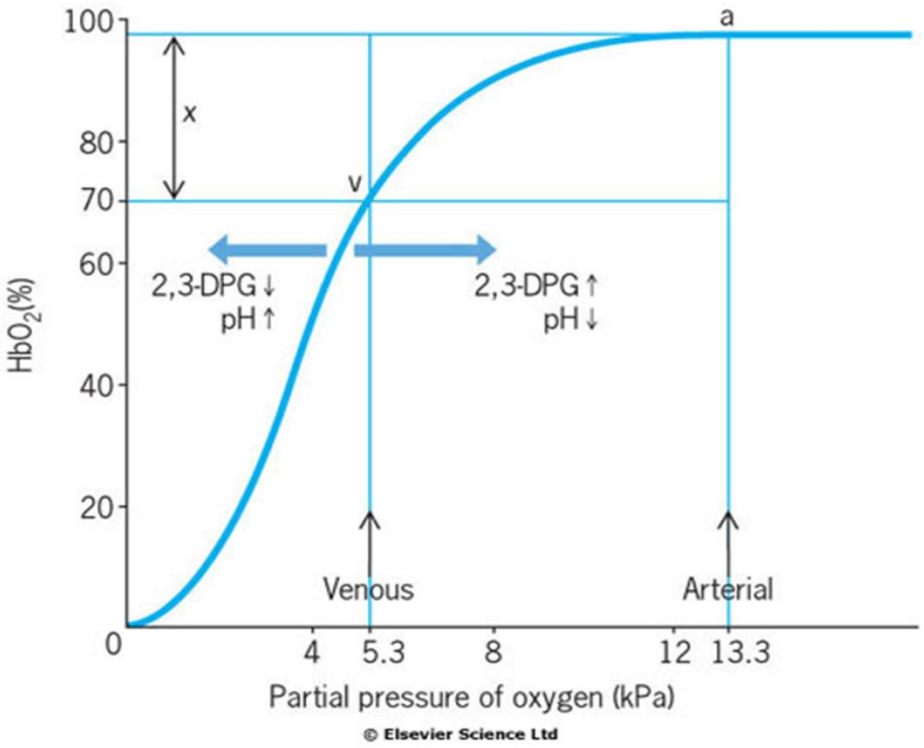
Kvantitativně

- (1) vdechovaný **atmosférický** vzduch
  - 21% O_2, 0.03% CO_2, 78% N_2, vodní páry 0.6% a zbytek tvoří další plyny (argon, helium, ..)
    - atmosferický tlak je 760 mmHg (101 kPa)
    - parc. tlak O_2 (PO_2): 0.21 x 760 = 160 mmHg
    - analogicky PCO_2 = 0.3mmHg
- (2) **alveolární** vzduch (směs vdechovaného a vydechovaného vzduchu)
  - PAO_2 = 100mmHg (13.3kPa), $PACO_2$ = 40 mmHg (5.3kPa)
    - parc. tlak O_2 v alveolu je o něco nižší něž v atmosféře kvůli většímu zastoupení CO_2 v alveolu (vydechovaný vzduch)
- (3) **arteriální** krev
  - PaO_2 = 90mmHg (12kPa), $PaCO_2$ = 45 mmHg
    - difuze kyslíku není 100% a navíc existuje fyziologický zkrat
- (4) **venózní** krev
  - PvO_2 = 30 - 50mmHg



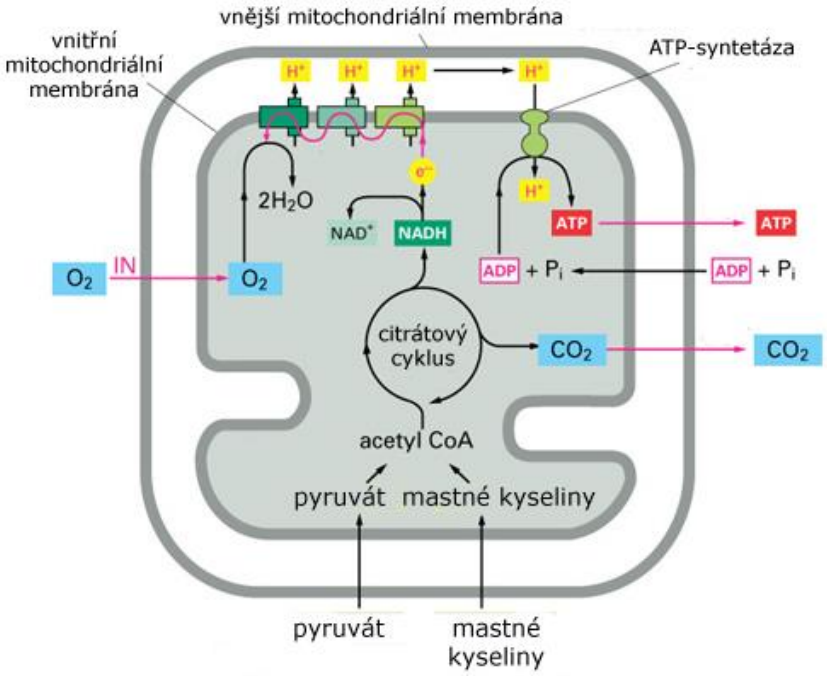
	vzduch (P)	alveolární (PA)	arteriální (Pa)	venózní (Pv)
O_2	21kPa/150mmHg	13.3 kPa/100mmHg	12kPa/90mmHg	5.3kPa/40mmHg
CO_2	0.03kPa/0.3mmHg	5.3kPa/40mmHg	5.3kPa/40mmHg	6.0kPa/45mmHg

Transport plynů krví



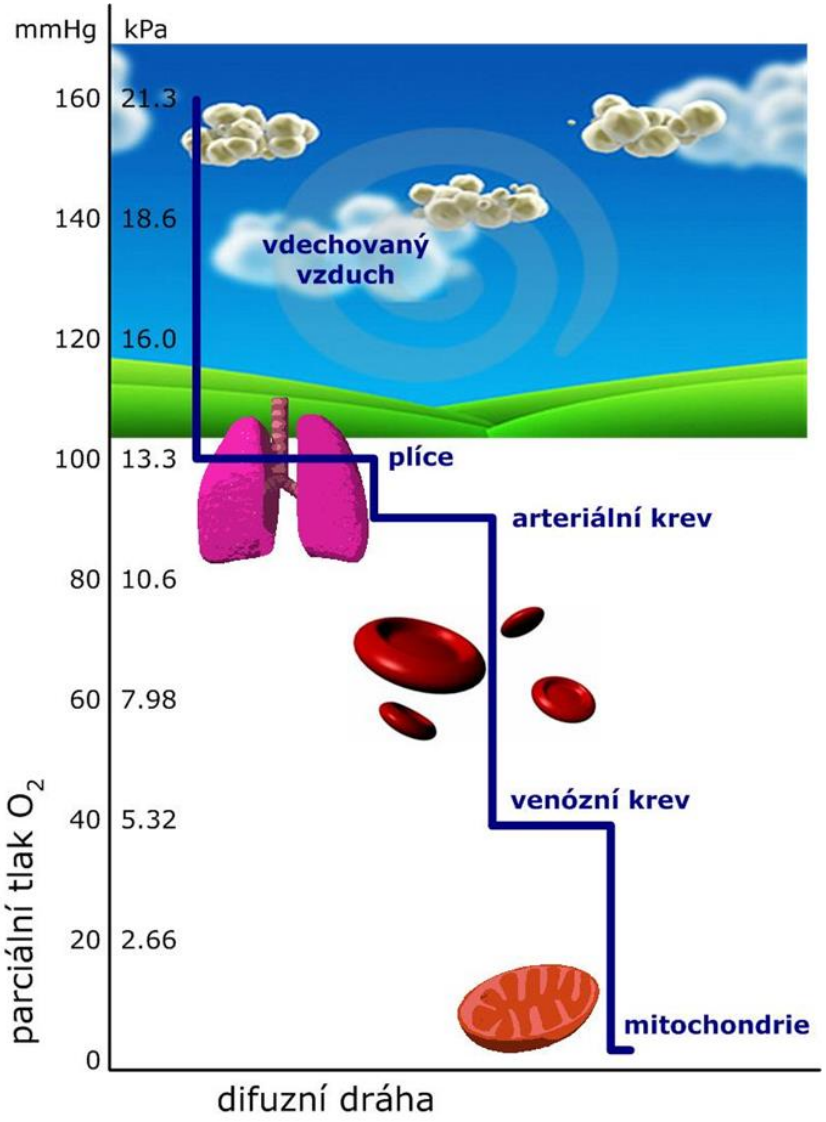
- krví je kyslík (97-98% ve vazbě na Hb a 2-3% jako fyzikálně rozpuštěný) dodáván do všech částí těla, kde difunduje do tkání
  - při fyziologickém PaO_2 (90mmHg/12kPa) a fyziologickém hemoglobinu je téměř 100% saturace
    - a do poklesu PaO_2 na 12kPa saturace významně neklesá
      - saturace měřena pulzní oxymetrií
- rozhodující je množství v mitochondriích
  - pro dostatečnou produkci ATP je nutné pO_2 v tkáních > 0.13kPa (1mmHg) = kritická tenze kyslíku
- organizmus potřebuje kyslík:
  - cca 250ml/min → 350l/den v klidu
  - při zátěži mnohem více

Význam kyslíku v organizmu



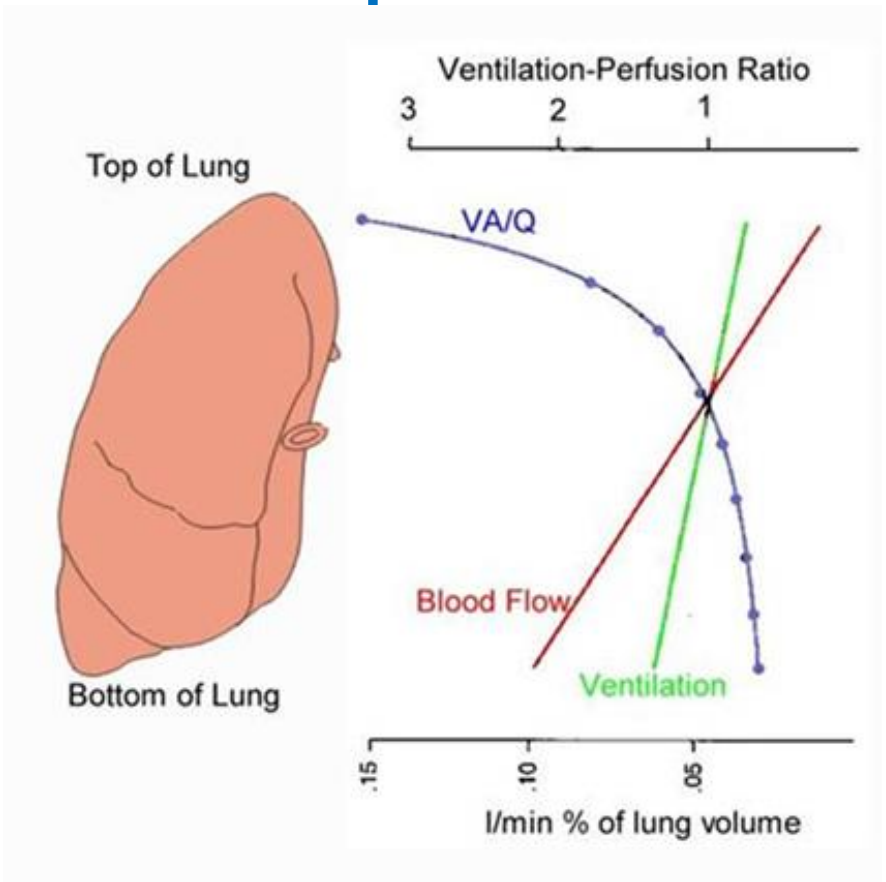
- v těle neexistují větší zásoby kyslíku
  - stačí cca na 5min
  - dýchání a dodávka kyslíku tkáním je proto nepřetržitý děj
  - jeho úplné přerušení znamená
    - ohrožení života (<5min)
      - reverzibilní ztráta zraku za cca 7s, bezvědomí za cca 10s
    - klinickou smrt (~5-7min), event. smrt mozku
    - smrt organizmu (>10min)
- 85-90% využito v aerobním metabolizmu při výrobě ATP na
  - udržení iontových gradientů
  - svalová kontrakce
  - syntézy
- pro zbytek procesů je pokles pO_2 méně kritický
  - hydroxylace steroidů
  - detoxikace (hydroxylace) cizorodých látek v játrech
  - syntéza oxidu dusnatého ($\rightarrow$ vazodilatace)
  - degradace hemu hemoxygenázou

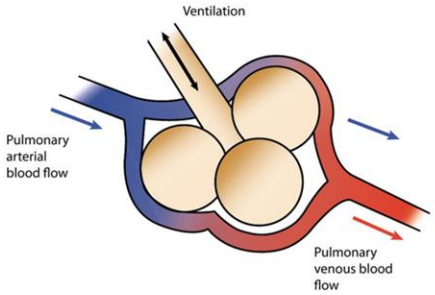
Sumárně: plíce jako součást „O_2 dráhy“

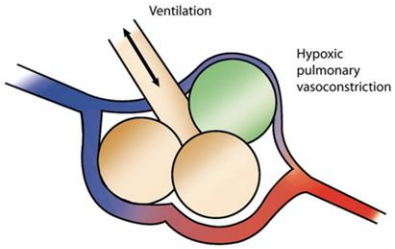


Ventilace a perfúze plic

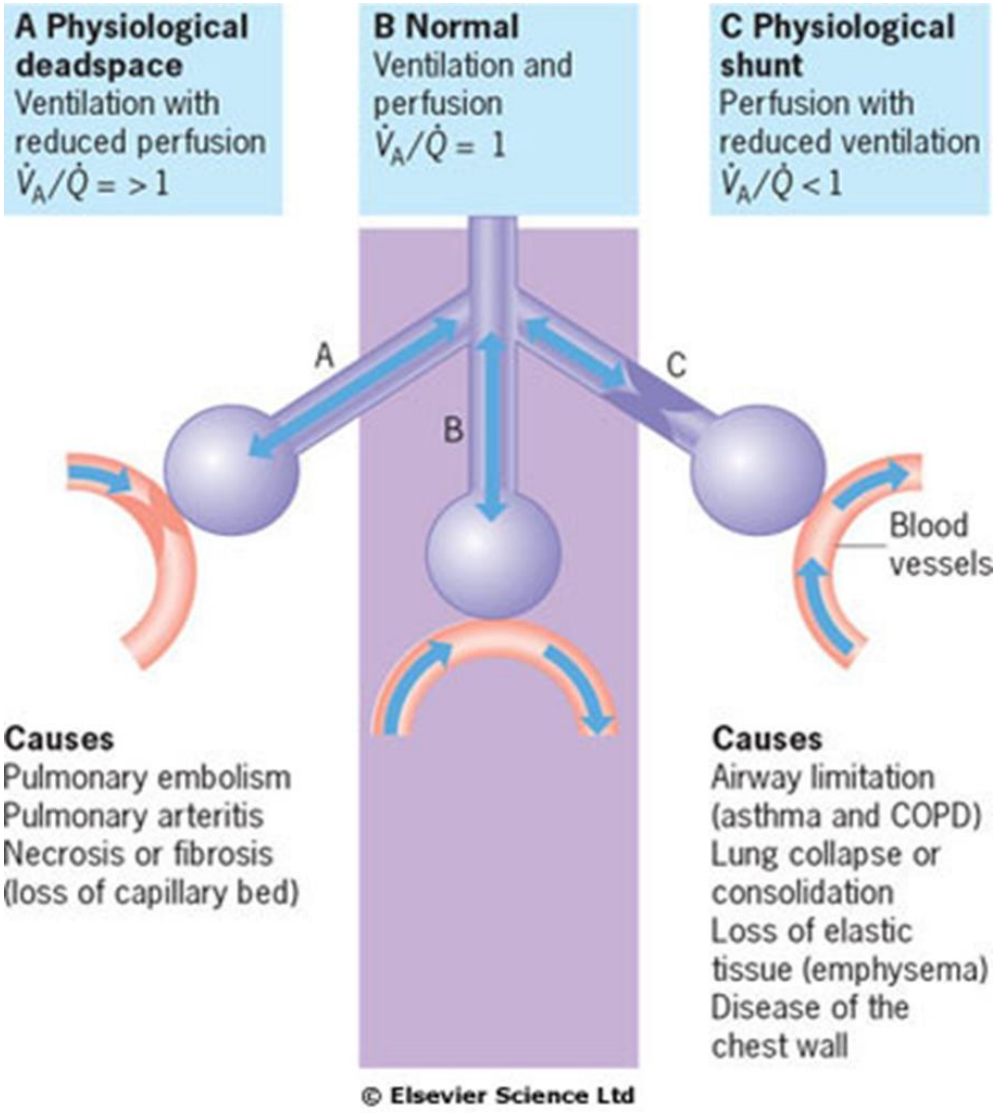
- vztah mezi ventilací a perfuzí plic je variabilní
  - do jisté míry i u zdravých lidí
    - rozdíly mezi apexem a bazí plíce
      - apex: ventilace alveolů s redukovanou perfuzí (tzv. fyziologický mrtvý prostor, $V_A/Q = 3.3$)
      - báze: perfuze alveolů s redukovanou ventilací (fyziologický zkrat, $V_A/Q = 0.7$)
- ventilačně perfuzní (V_A/Q) nepoměr se významně zvyšuje u některých plicních nemocí a zodpovídá za jejich projevy
  - ↑ V_A/Q poměru (tj. ↑ **mrtvého prostoru**)
    - např. plicní embolie
  - ↓ V_A/Q poměru (tj. ↑ **plicního zkratu**)
    - obstrukční nemoci plic
    - kolaps plíce
- optimalizace ↓ V_A/Q - **vazokonstrikční reflex**
  - cévy okolo méně ventilované části plíce se kontrahují
  - ale!!! viz důsledky obstr. nemocí







Ventilation-perfusion inequality



more detail next time!!!


I'M HAVING TROUBLE BREATHING
LYNCH