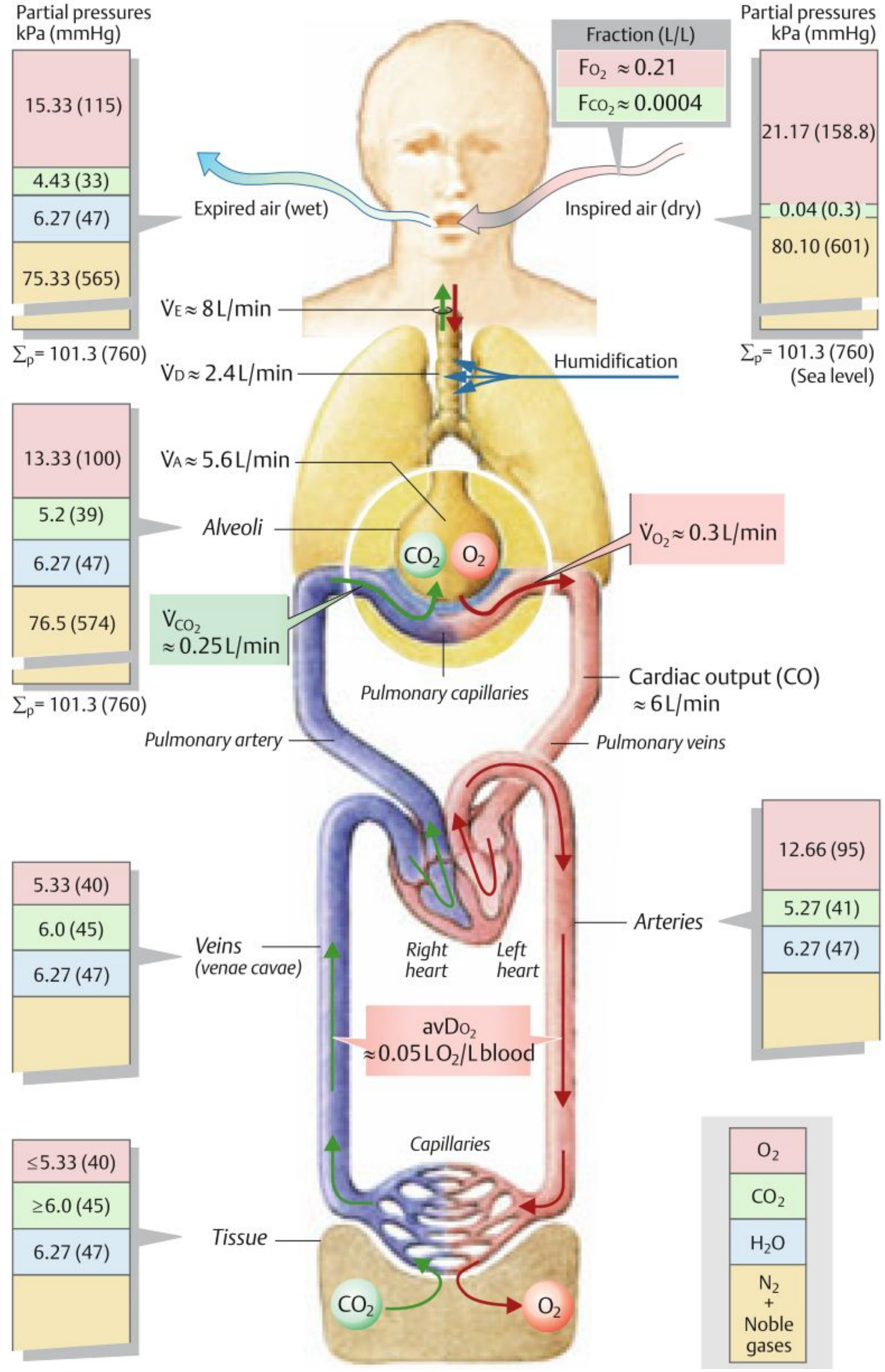
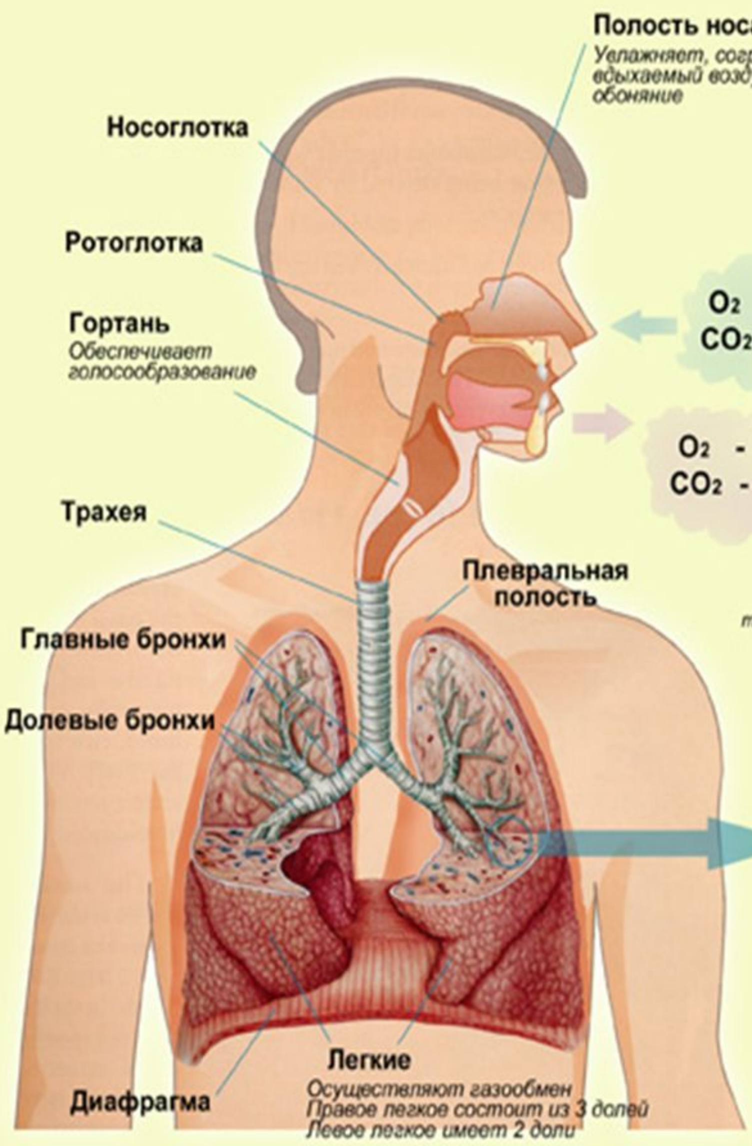
Механизм вентиляции. Газообмен в лёгких

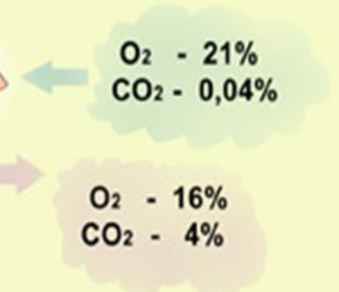

ГАЗООБМЕН МЕЖДУ ВНЕШНЕЙ СРЕДОЙ И ОРГАНИЗМОМ
АТМОСФЕРНЫЙ ВОЗДУХ
ВДОХ
ВЫДОХ
АЛЬВЕОЛЯРНЫЙ ВОЗДУХ
ТКАНИ
ВНЕШНЕЕ ДЫХАНИЕ
ПЕРЕНОС ГАЗОВ КРОВЬЮ
ТКАНЕВОЕ ДЫХАНИЕ

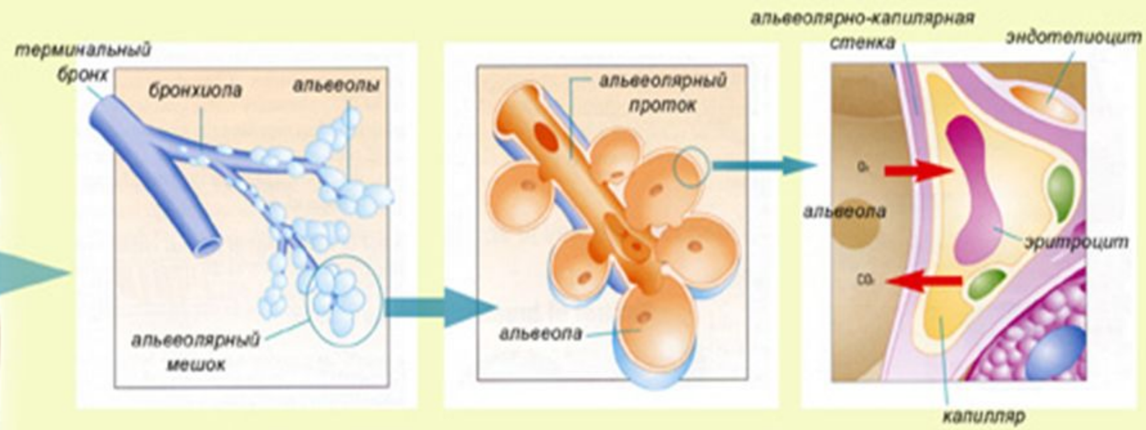


Partial pressures kPa (mmHg)
15.33 (115)
4.43 (33)
6.27 (47)
75.33 (565)
Σp = 101.3 (760)
Expired air (wet)
Fraction (L/L)
FO2 ≈ 0.21
FCO2 ≈ 0.0004
Inspired air (dry)
Partial pressures kPa (mmHg)
21.17 (158.8)
0.04 (0.3)
80.10 (601)
Σp = 101.3 (760)
(Sea level)
V̇E ≈ 8 L/min
V̇D ≈ 2.4 L/min
Humidification
13.33 (100)
5.2 (39)
6.27 (47)
76.5 (574)
Σp = 101.3 (760)
V̇A ≈ 5.6 L/min
Alveoli
CO2
O2
V̇O2 ≈ 0.3 L/min
V̇CO2 ≈ 0.25 L/min
Pulmonary capillaries
Cardiac output (CO) ≈ 6 L/min
Pulmonary artery
Pulmonary veins
5.33 (40)
6.0 (45)
6.27 (47)
Veins (venae cavae)
Right heart
Left heart
Arteries
12.66 (95)
5.27 (41)
6.27 (47)
avDO2 ≈ 0.05 L O2/L blood
Capillaries
≤5.33 (40)
≥6.0 (45)
6.27 (47)
Tissue
CO2
O2
O2
CO2
H2O
N2 + Noble gases

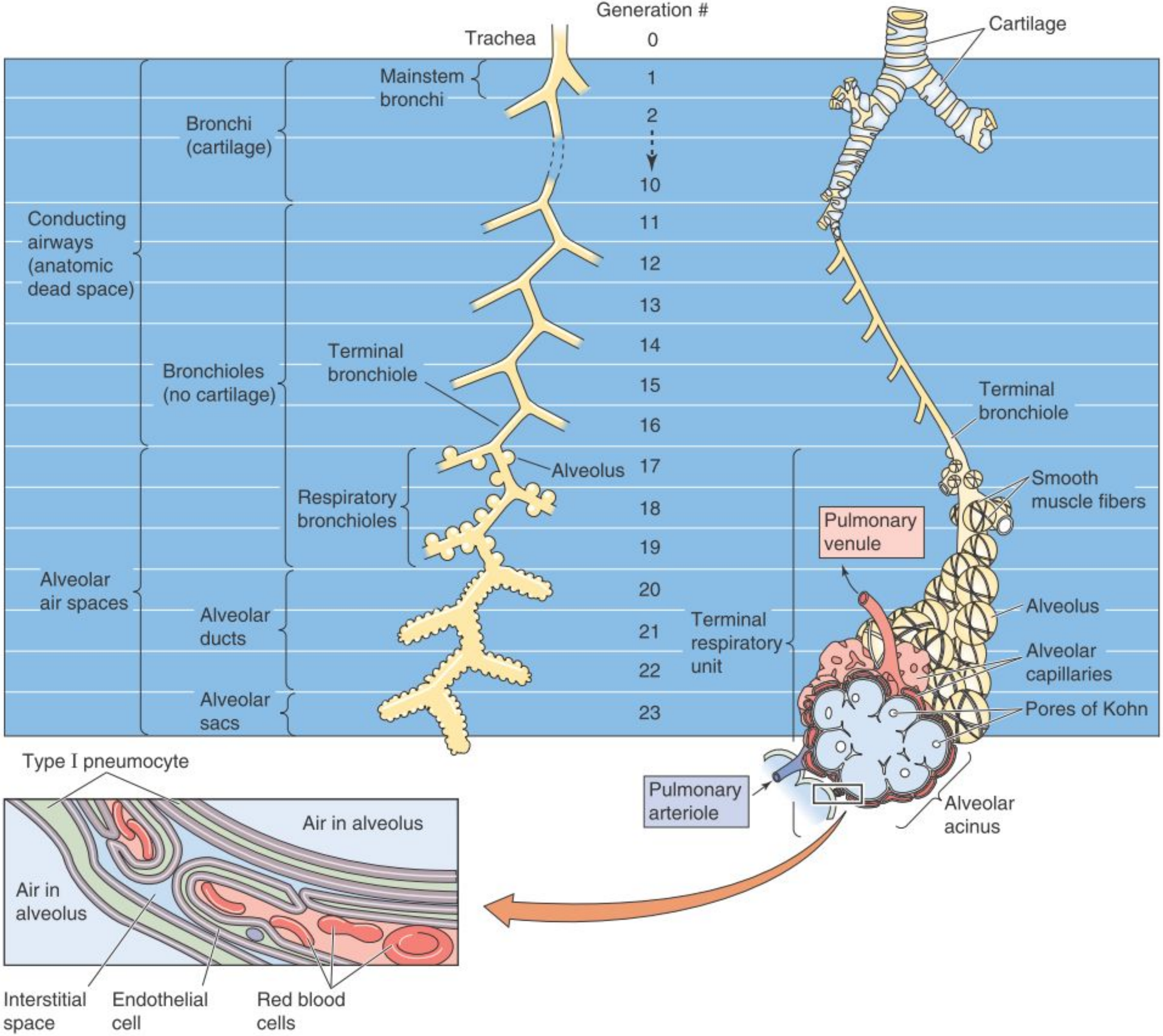
ДЫХАТЕЛЬНАЯ СИСТЕМА



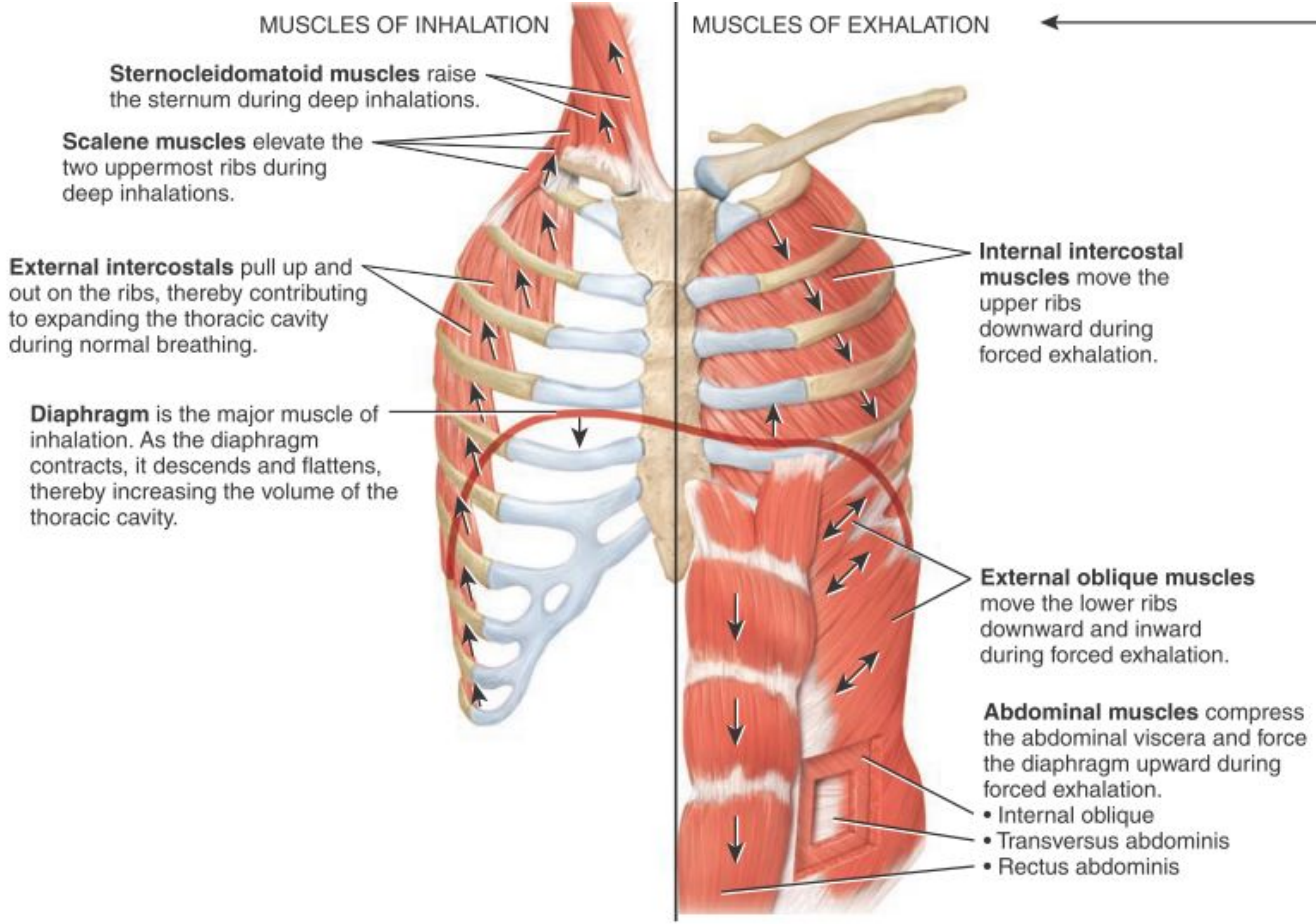


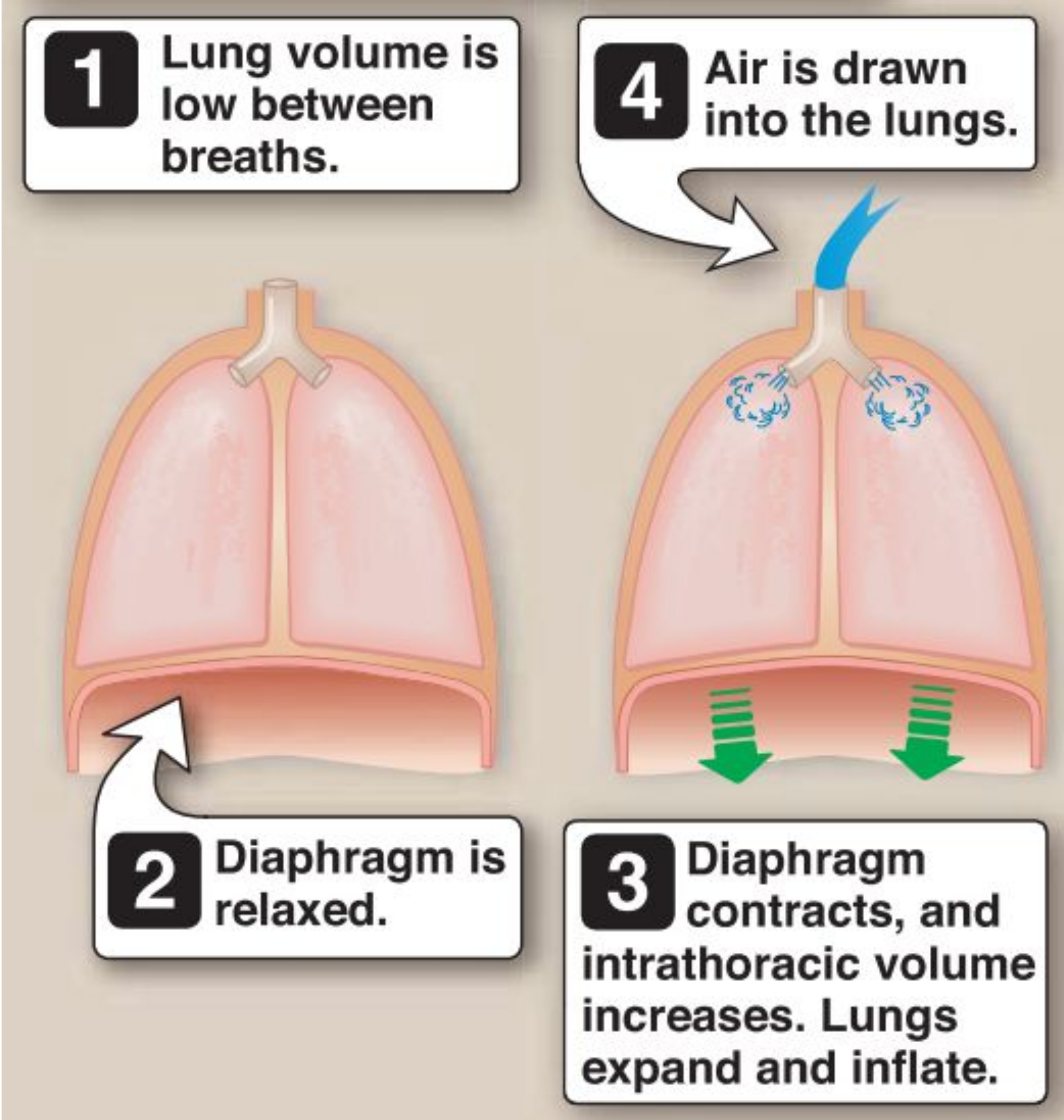


Частота дыхания в покое составляет 16 раз в минуту
За один вдох в легкие попадает около 500 мл воздуха (дыхательный объем)
Максимальное количество воздуха, которое можно вдохнуть называют жизненной емкостью легких. Она составляет от 3,5 до 5 литров



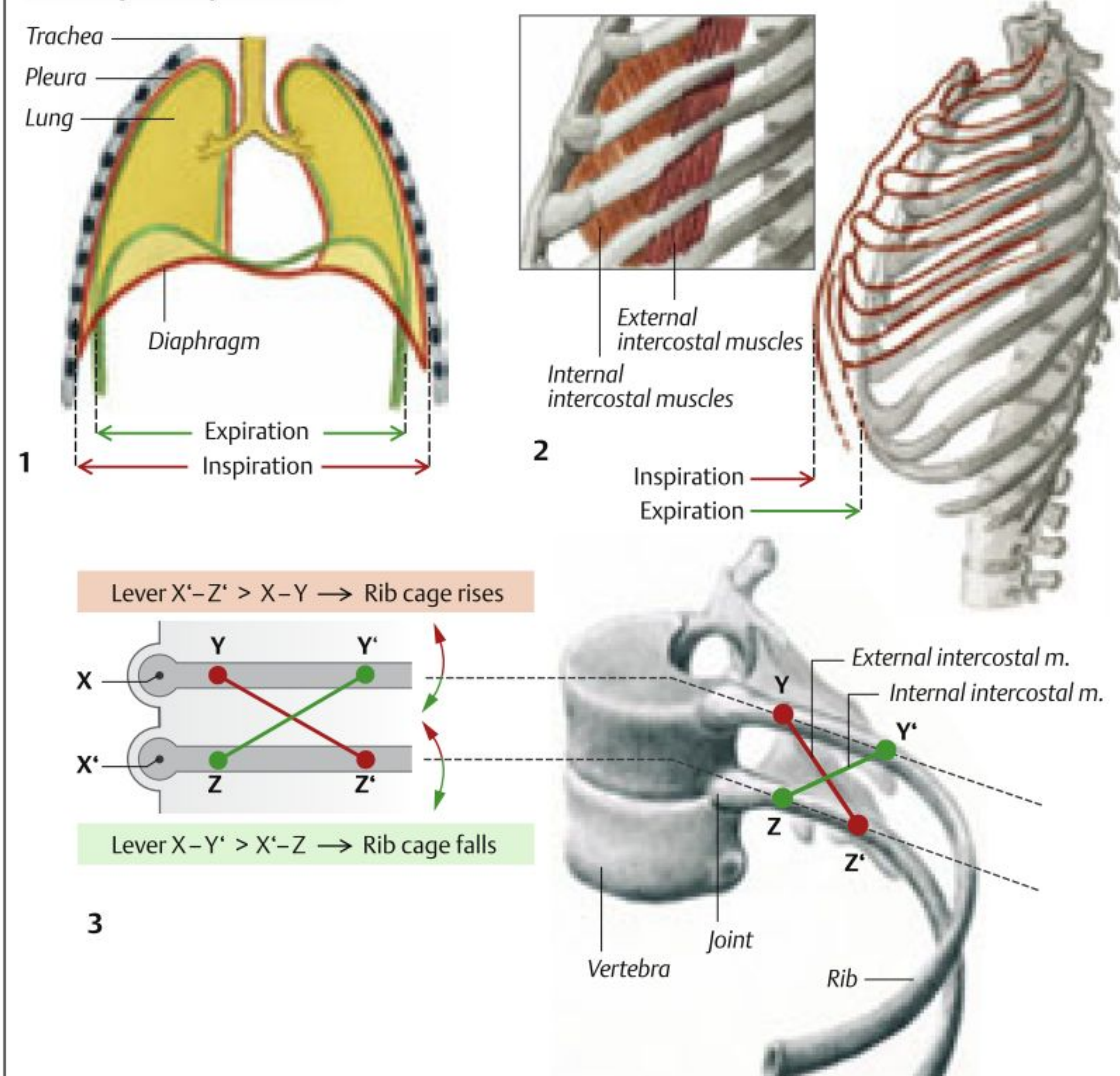
Generation #
Trachea
0
1
2
10
11
12
13
14
15
16
17
18
19
20
21
22
23
Cartilage
Mainstem bronchi
Bronchi (cartilage)
Conducting airways (anatomic dead space)
Bronchioles (no cartilage)
Terminal bronchiole
Terminal bronchiole
Alveolus
Respiratory bronchioles
Smooth muscle fibers
Pulmonary venule
Alveolar air spaces
Alveolar ducts
Alveolar sacs
Terminal respiratory unit
Alveolus
Alveolar capillaries
Pores of Kohn
Pulmonary arteriole
Alveolar acinus
Type I pneumocyte
Air in alveolus
Air in alveolus
Interstitial space
Endothelial cell
Red blood cells

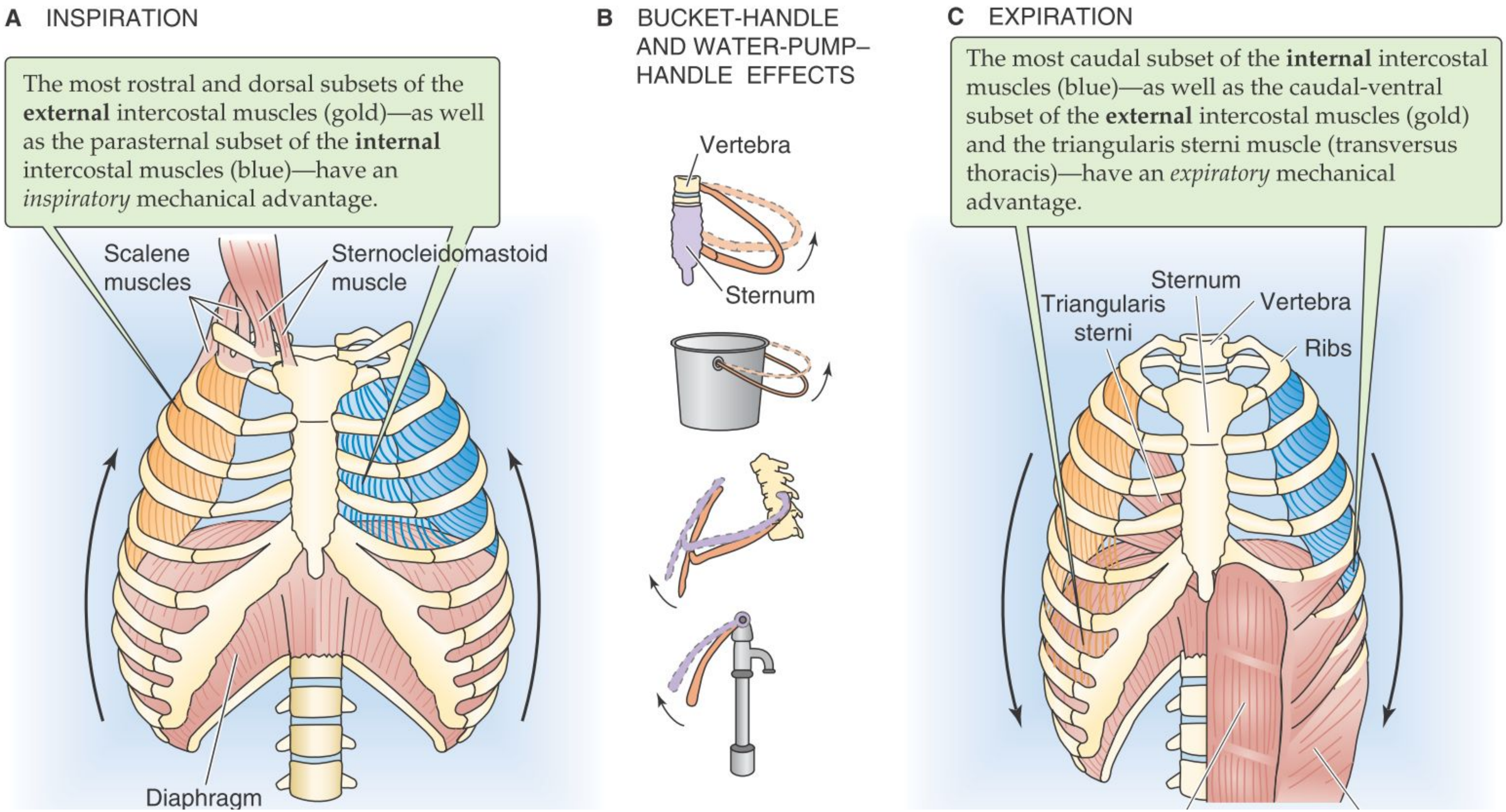

MUSCLES OF INHALATION
MUSCLES OF EXHALATION
Sternocleidomatoid muscles raise the sternum during deep inhalations.
Scalene muscles elevate the two uppermost ribs during deep inhalations.
External intercostals pull up and out on the ribs, thereby contributing to expanding the thoracic cavity during normal breathing.
Diaphragm is the major muscle of inhalation. As the diaphragm contracts, it descends and flattens, thereby increasing the volume of the thoracic cavity.
Internal intercostal muscles move the upper ribs downward during forced exhalation.
External oblique muscles move the lower ribs downward and inward during forced exhalation.
Abdominal muscles compress the abdominal viscera and force the diaphragm upward during forced exhalation.
• Internal oblique
• Transversus abdominis
• Rectus abdominis

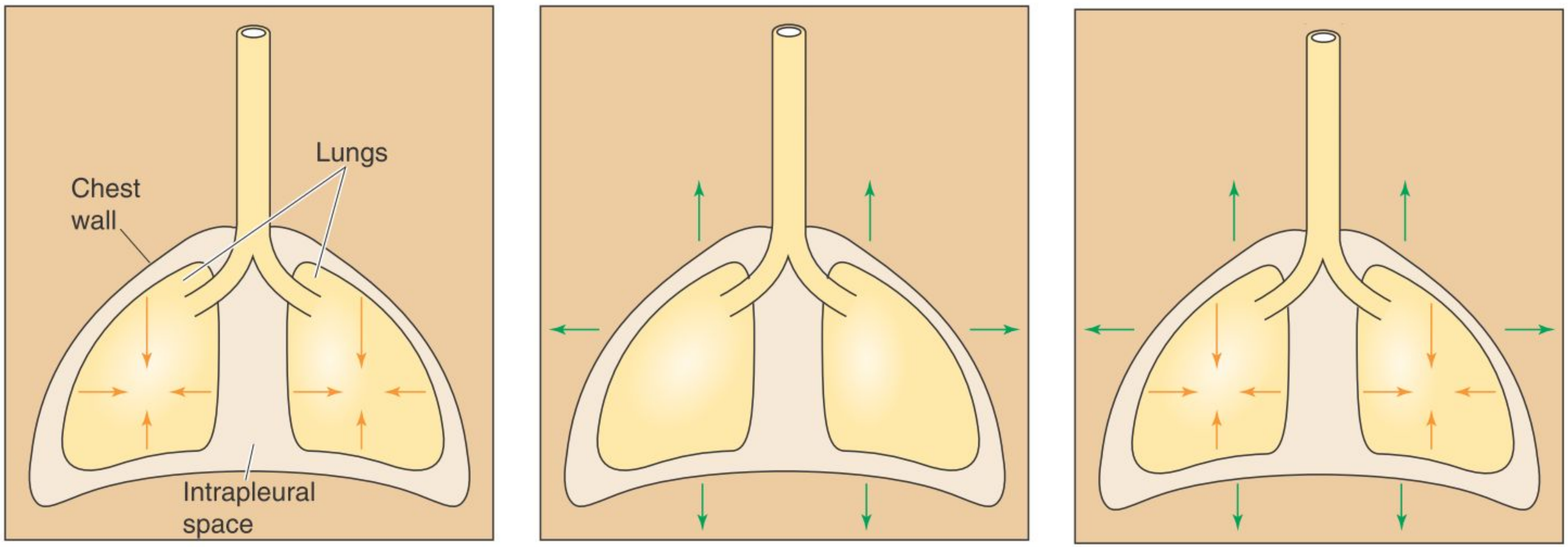


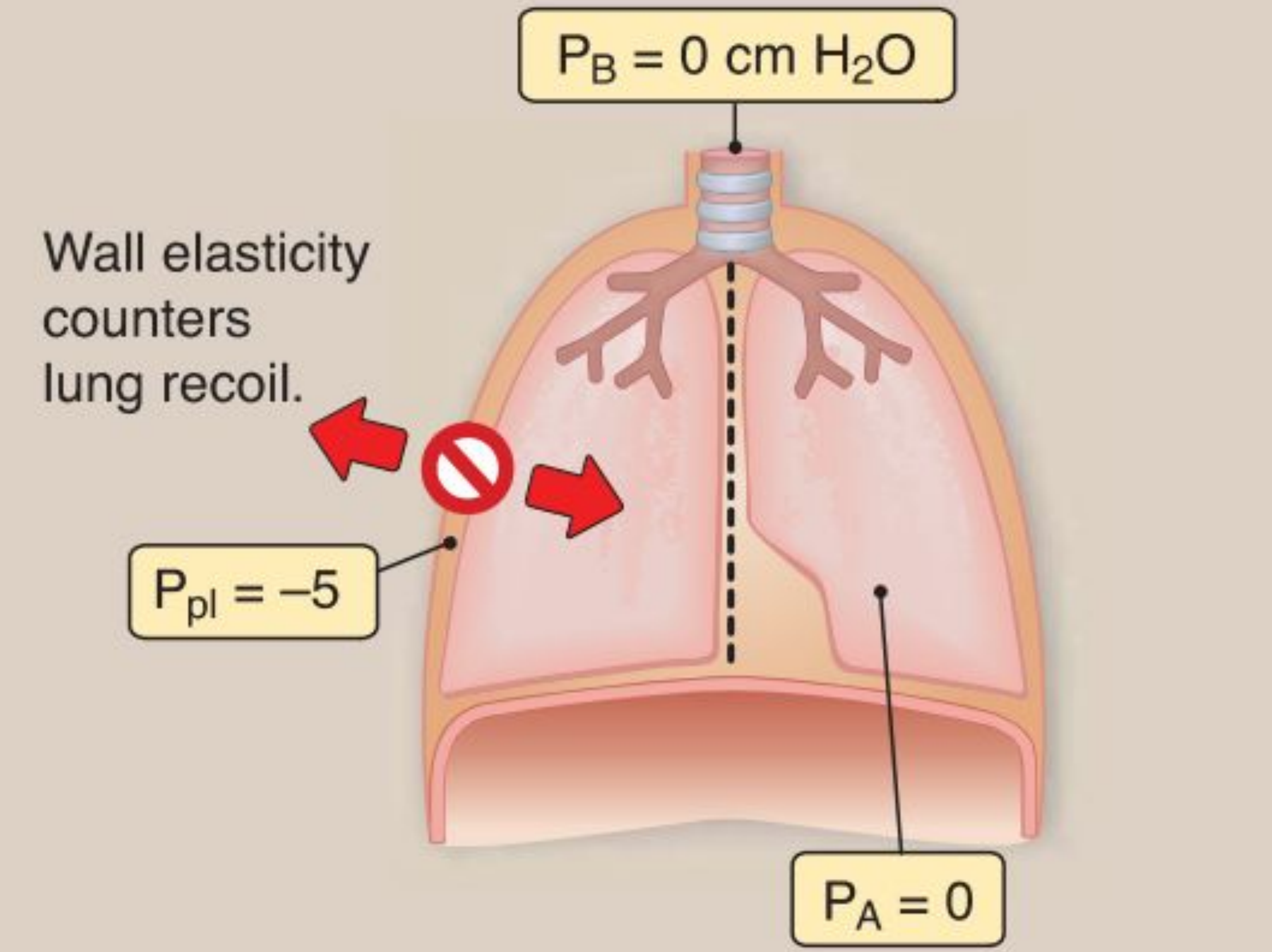
1 Lung volume is low between breaths.
4 Air is drawn into the lungs.
2 Diaphragm is relaxed.
3 Diaphragm contracts, and intrathoracic volume increases. Lungs expand and inflate.

A. Respiratory muscles



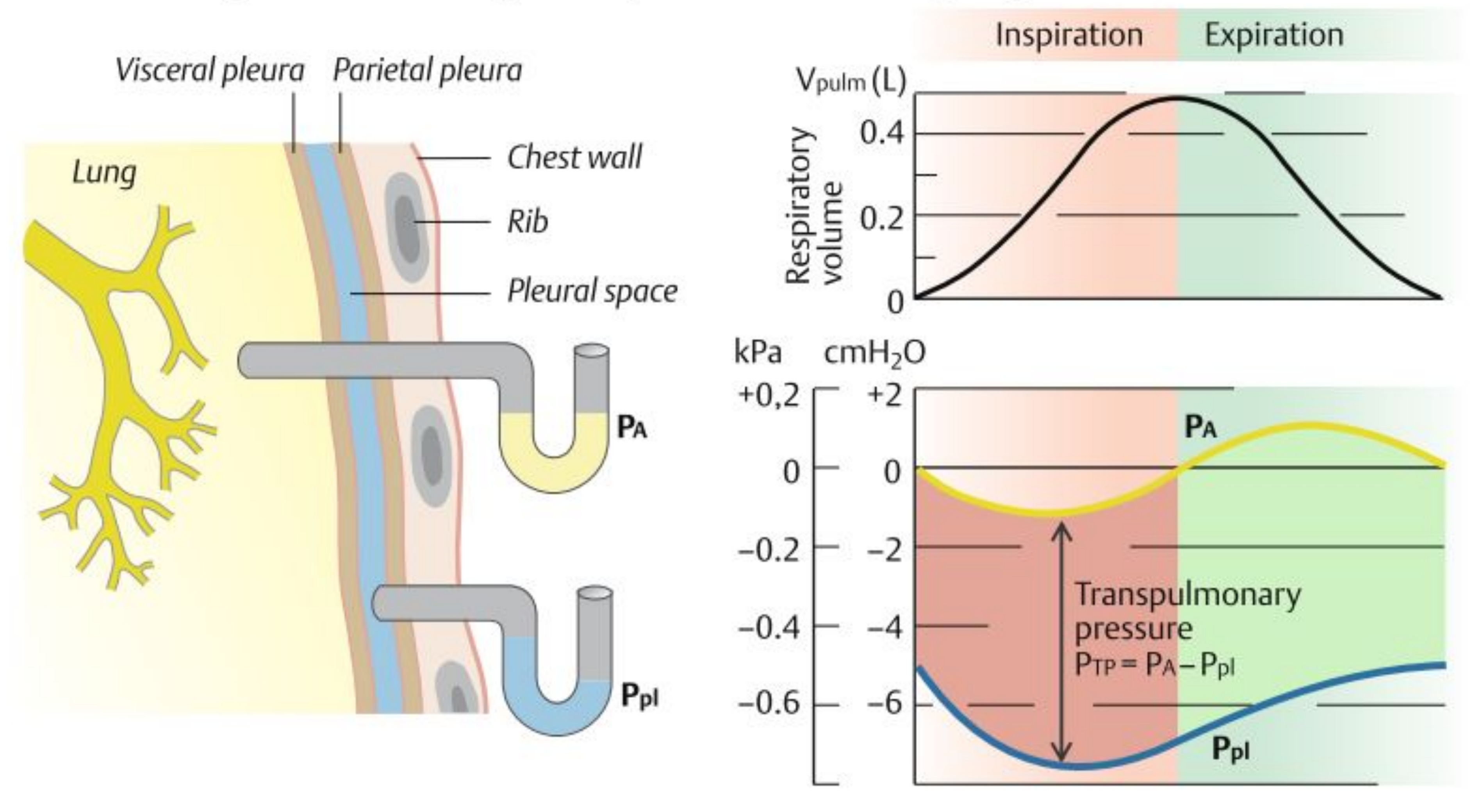

A INSPIRATION
The most rostral and dorsal subsets of the **external** intercostal muscles (gold)—as well as the parasternal subset of the **internal** intercostal muscles (blue)—have an *inspiratory* mechanical advantage.
Scalene muscles
Sternocleidomastoid muscle
Diaphragm
B BUCKET-HANDLE AND WATER-PUMP–HANDLE EFFECTS
Vertebra
Sternum
C EXPIRATION
The most caudal subset of the **internal** intercostal muscles (blue)—as well as the caudal-ventral subset of the **external** intercostal muscles (gold) and the triangularis sterni muscle (transversus thoracis)—have an *expiratory* mechanical advantage.
Sternum
Triangularis sterni
Vertebra
Ribs

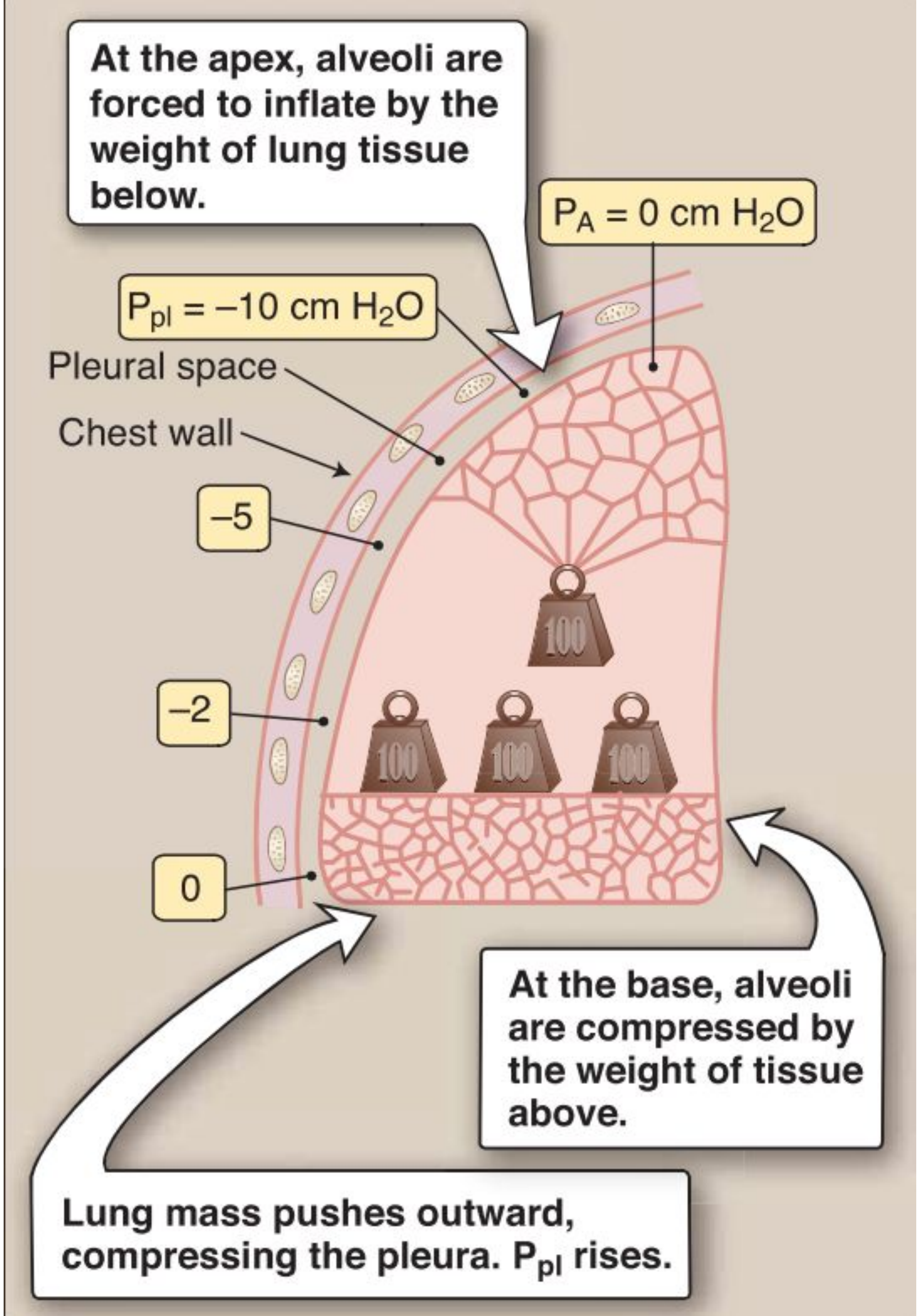

Lungs
Chest
wall
Intrapleural
space



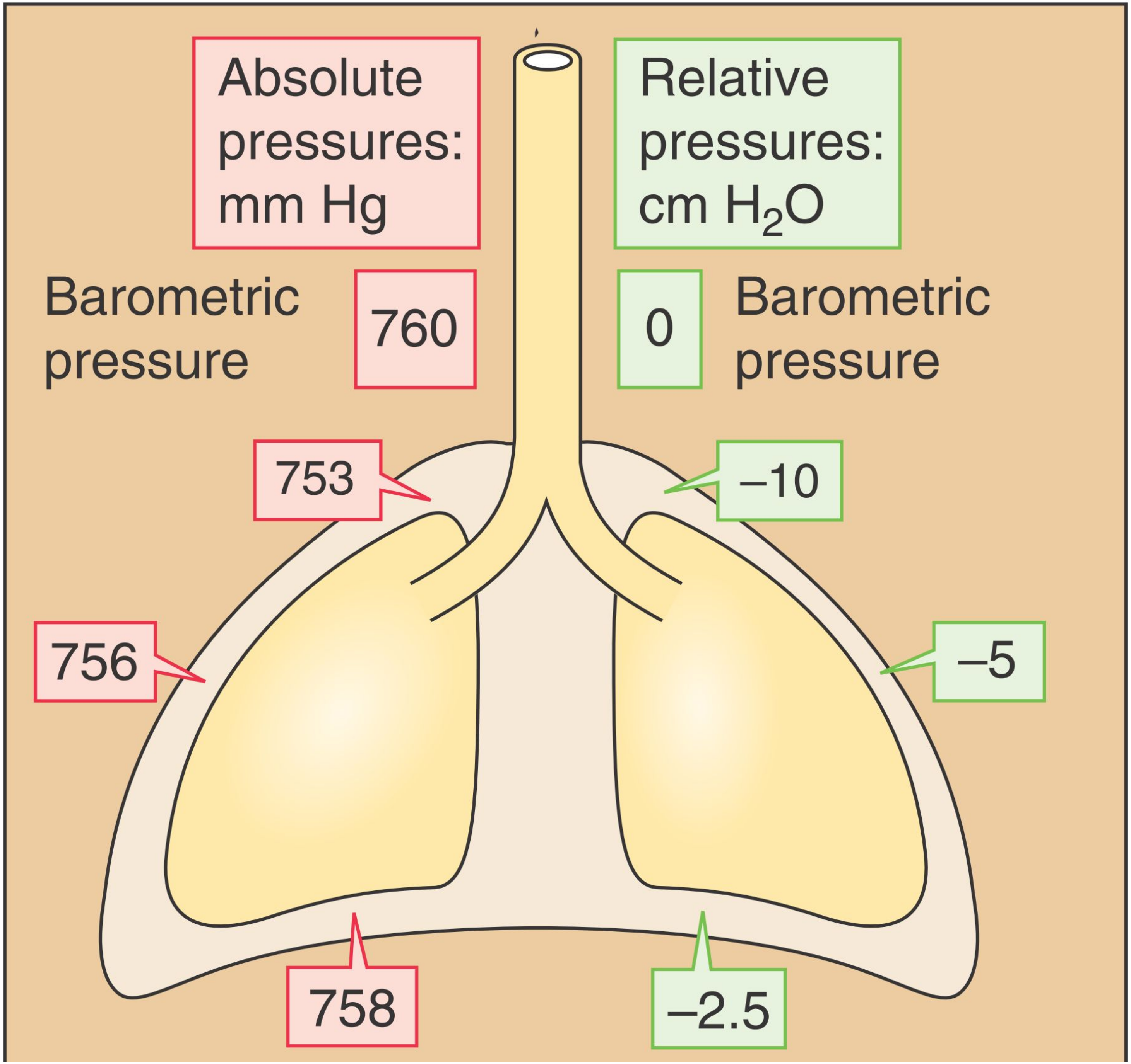
P_B = 0 cm H_2O
Wall elasticity counters lung recoil.
P_pl = –5
P_A = 0

B. Alveolar pressure P_A and pleural pressure P_{pl} during respiration

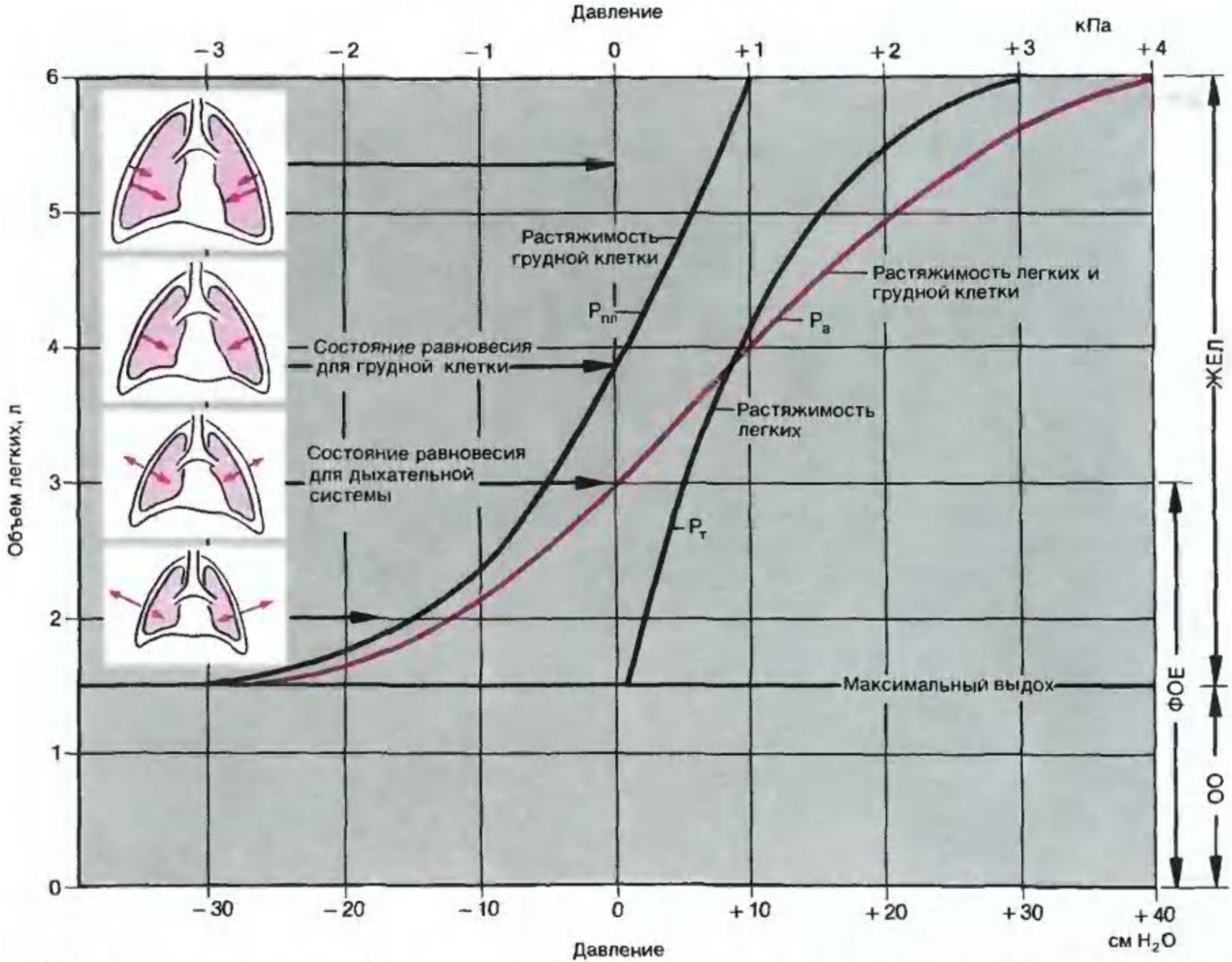




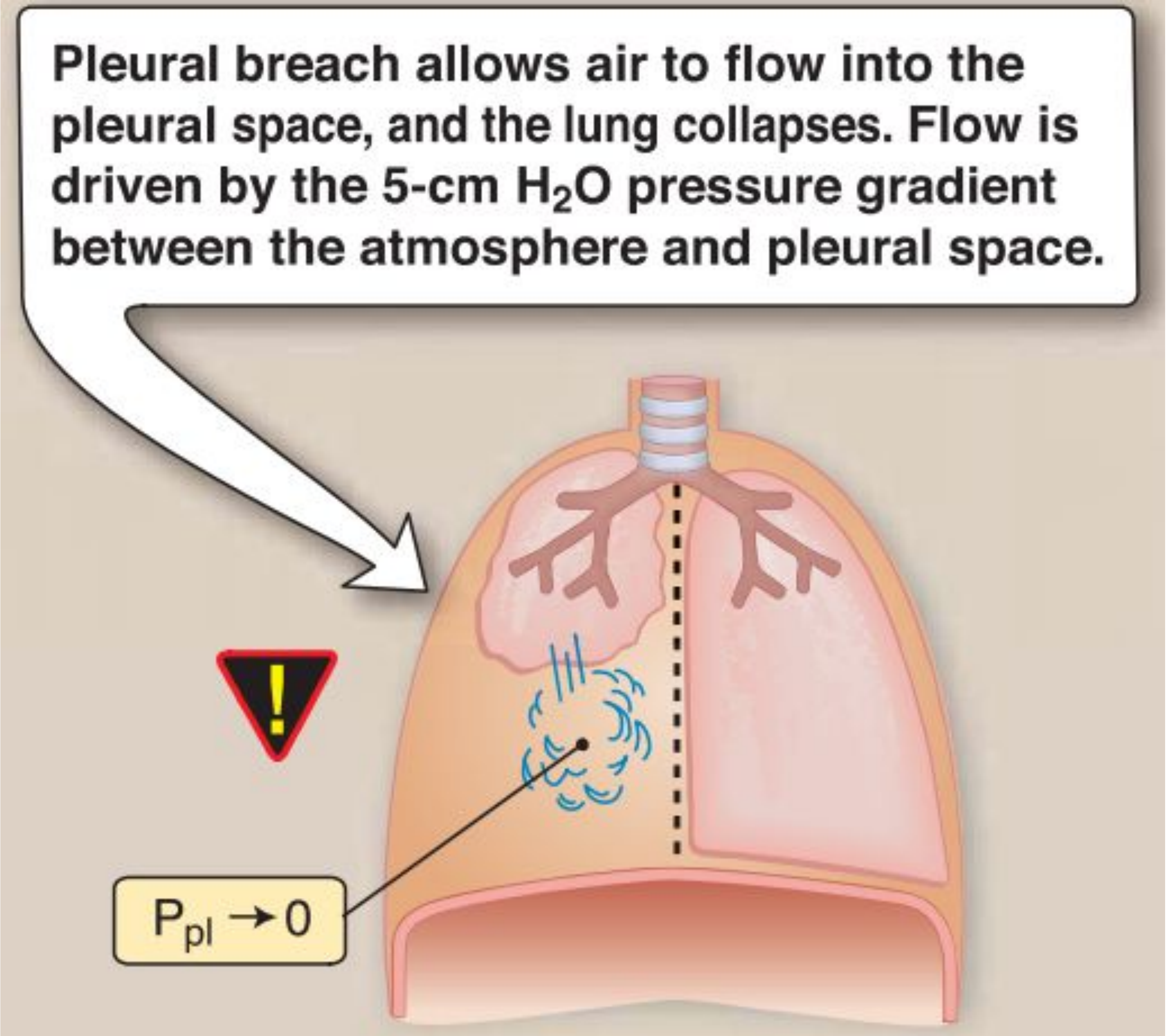
At the apex, alveoli are forced to inflate by the weight of lung tissue below.
$P_A = 0$ cm H_2O
$P_{pl} = -10$ cm H_2O
Pleural space
Chest wall
–5
–2
0
100
100
100
100
At the base, alveoli are compressed by the weight of tissue above.
Lung mass pushes outward, compressing the pleura. P_{pl} rises.

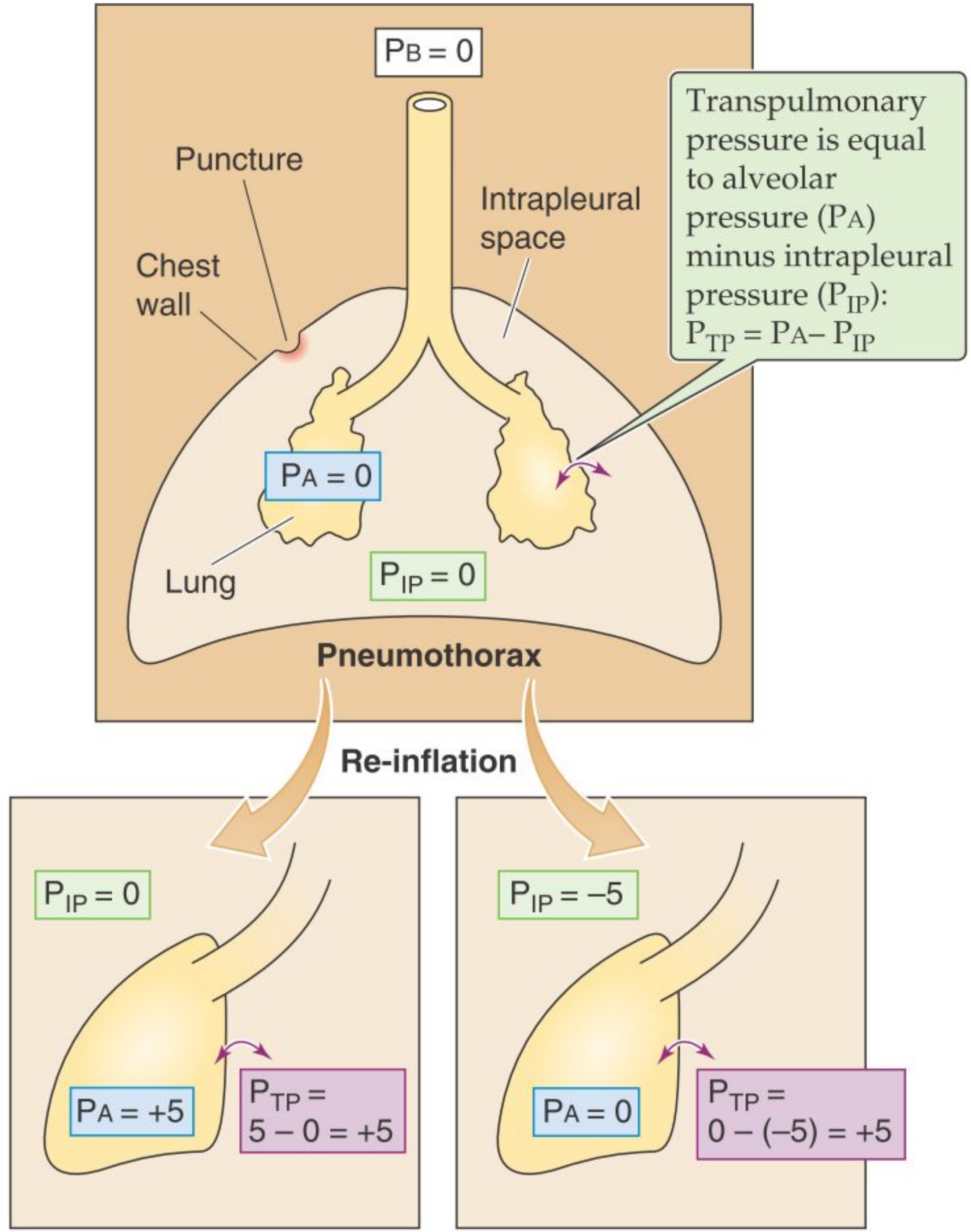


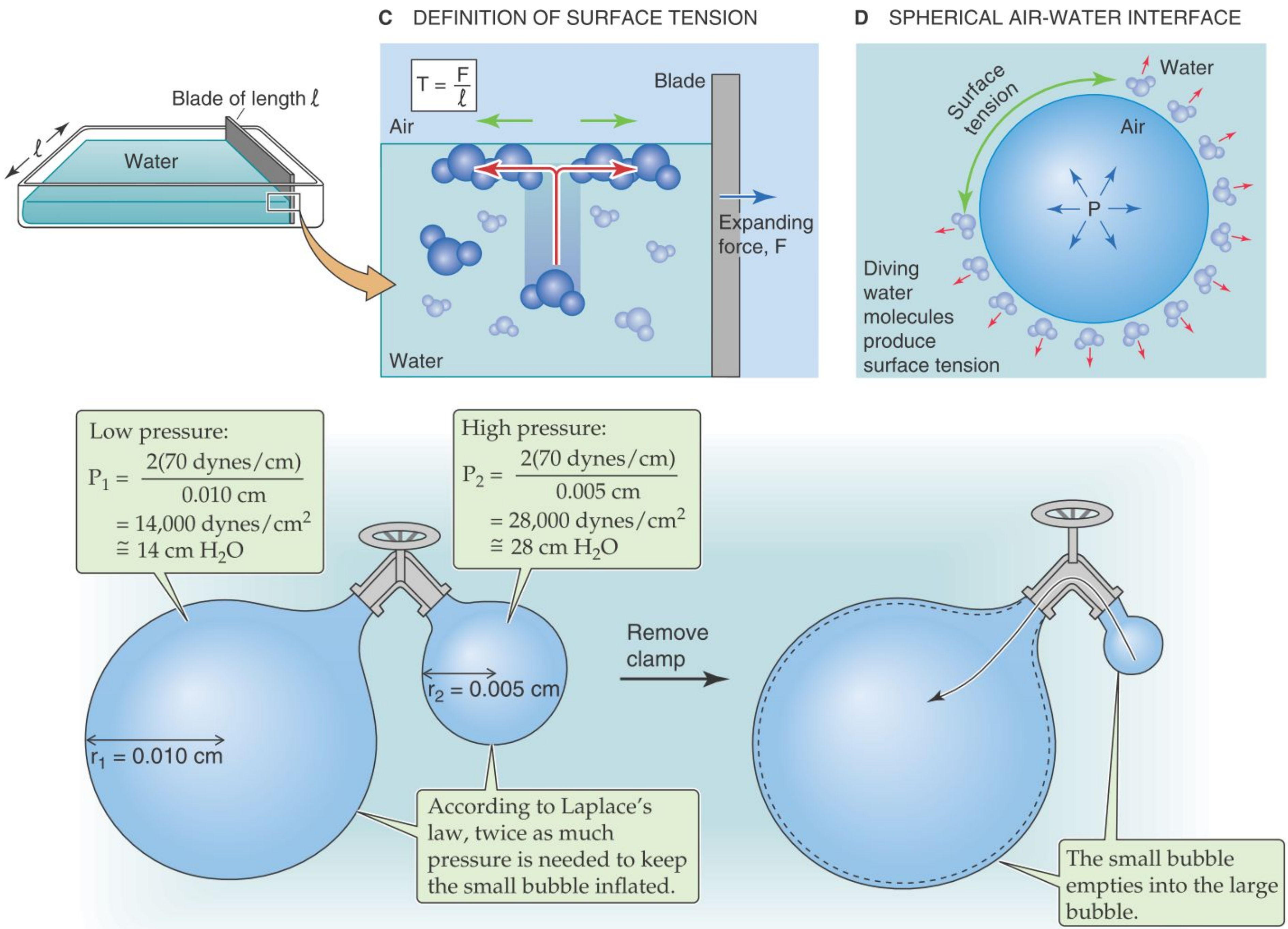
Absolute pressures: mm Hg
Relative pressures: cm H_2O
Barometric pressure
760
0
Barometric pressure
753
–10
756
–5
758
–2.5

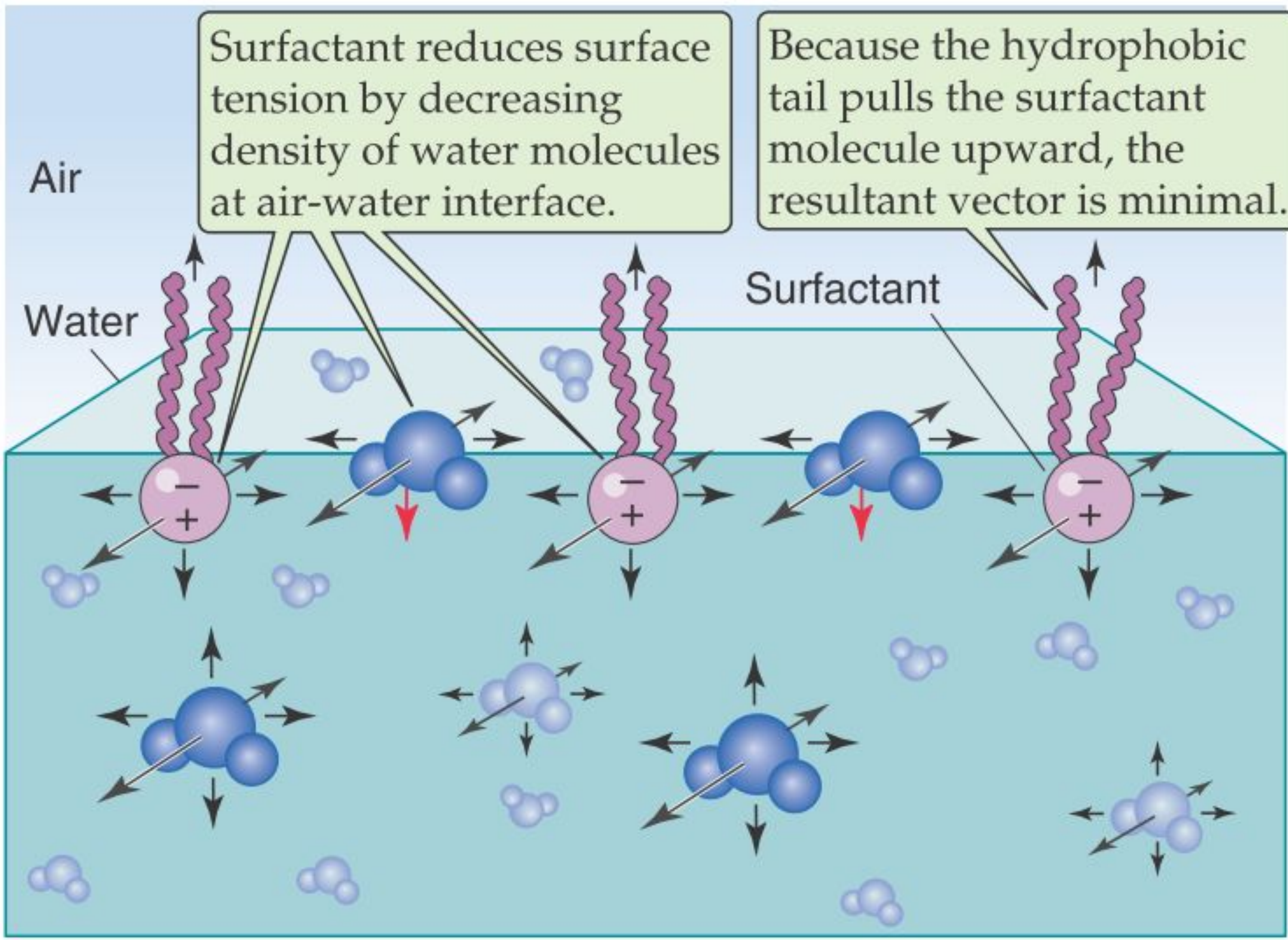


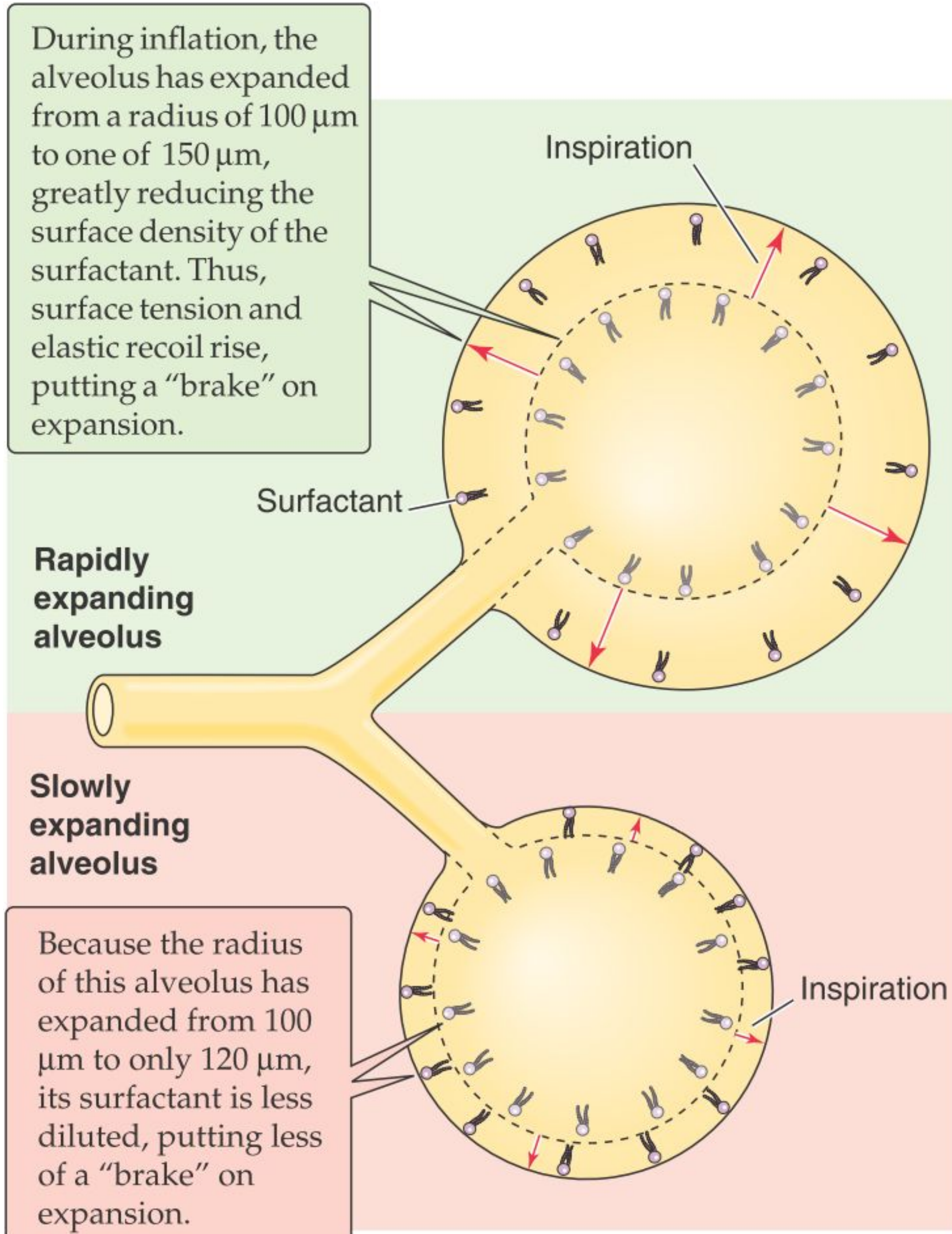
Давление
кПа
−3
−2
−1
0
+1
+2
+3
+4
6
5
4
3
2
1
0
Объем легких, л
Растяжимость грудной клетки
Растяжимость легких и грудной клетки
$P_{пл}$
P_a
Состояние равновесия для грудной клетки
Растяжимость легких
Состояние равновесия для дыхательной системы
$P_т$
Максимальный выдох
ЖЕЛ
ФОЕ
ОО
−30
−20
−10
0
+10
+20
+30
+40
см H_2O
Давление

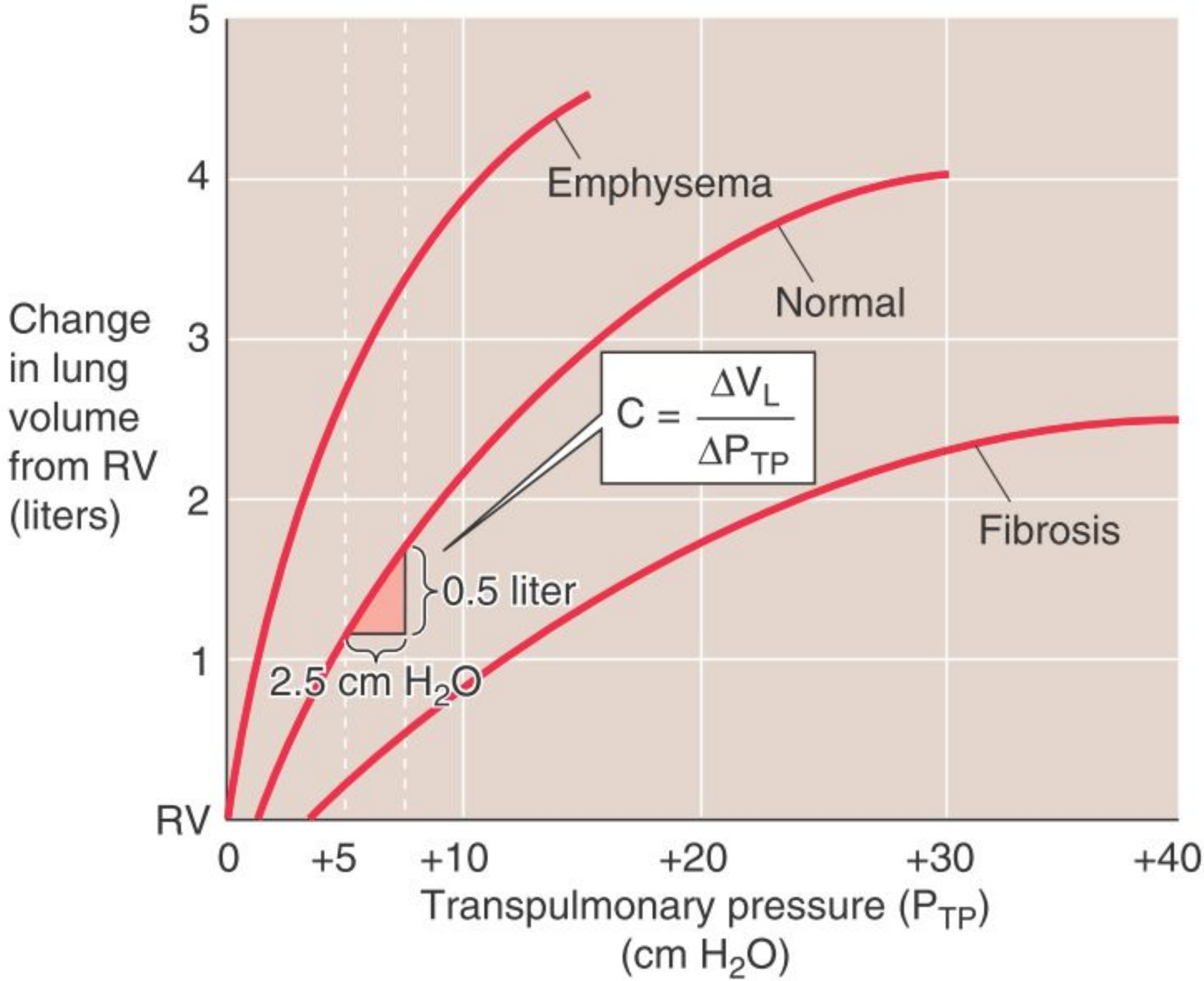

Pleural breach allows air to flow into the pleural space, and the lung collapses. Flow is driven by the 5-cm H_2O pressure gradient between the atmosphere and pleural space.
!
$P_{pl} \rightarrow 0$


PB = 0
Puncture
Chest wall
Intrapleural space
Transpulmonary pressure is equal to alveolar pressure (PA) minus intrapleural pressure (PIP):
PTP = PA– PIP
PA = 0
Lung
PIP = 0
Pneumothorax
Re-inflation
PIP = 0
PA = +5
PTP = 5 – 0 = +5
PIP = –5
PA = 0
PTP = 0 – (–5) = +5


C DEFINITION OF SURFACE TENSION
D SPHERICAL AIR-WATER INTERFACE
Blade of length ℓ
ℓ
Water
T = F/ℓ
Blade
Air
Water
Expanding force, F
Surface tension
Water
Air
P
Diving water molecules produce surface tension
Low pressure:
P1 = 2(70 dynes/cm) / 0.010 cm
= 14,000 dynes/cm2
≅ 14 cm H2O
High pressure:
P2 = 2(70 dynes/cm) / 0.005 cm
= 28,000 dynes/cm2
≅ 28 cm H2O
r2 = 0.005 cm
r1 = 0.010 cm
Remove clamp
According to Laplace's law, twice as much pressure is needed to keep the small bubble inflated.
The small bubble empties into the large bubble.

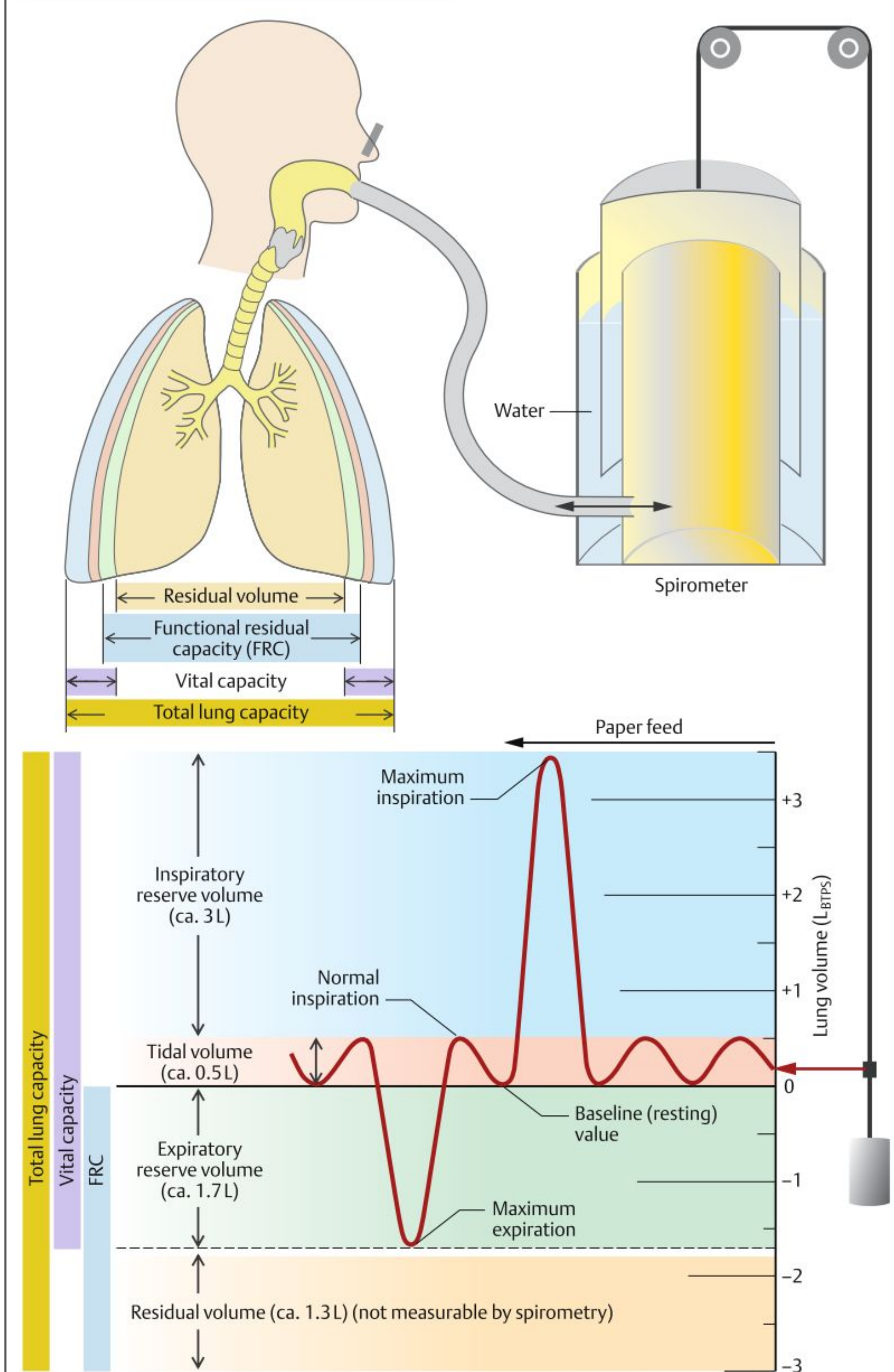

Surfactant reduces surface tension by decreasing density of water molecules at air-water interface.
Because the hydrophobic tail pulls the surfactant molecule upward, the resultant vector is minimal.
Air
Water
Surfactant

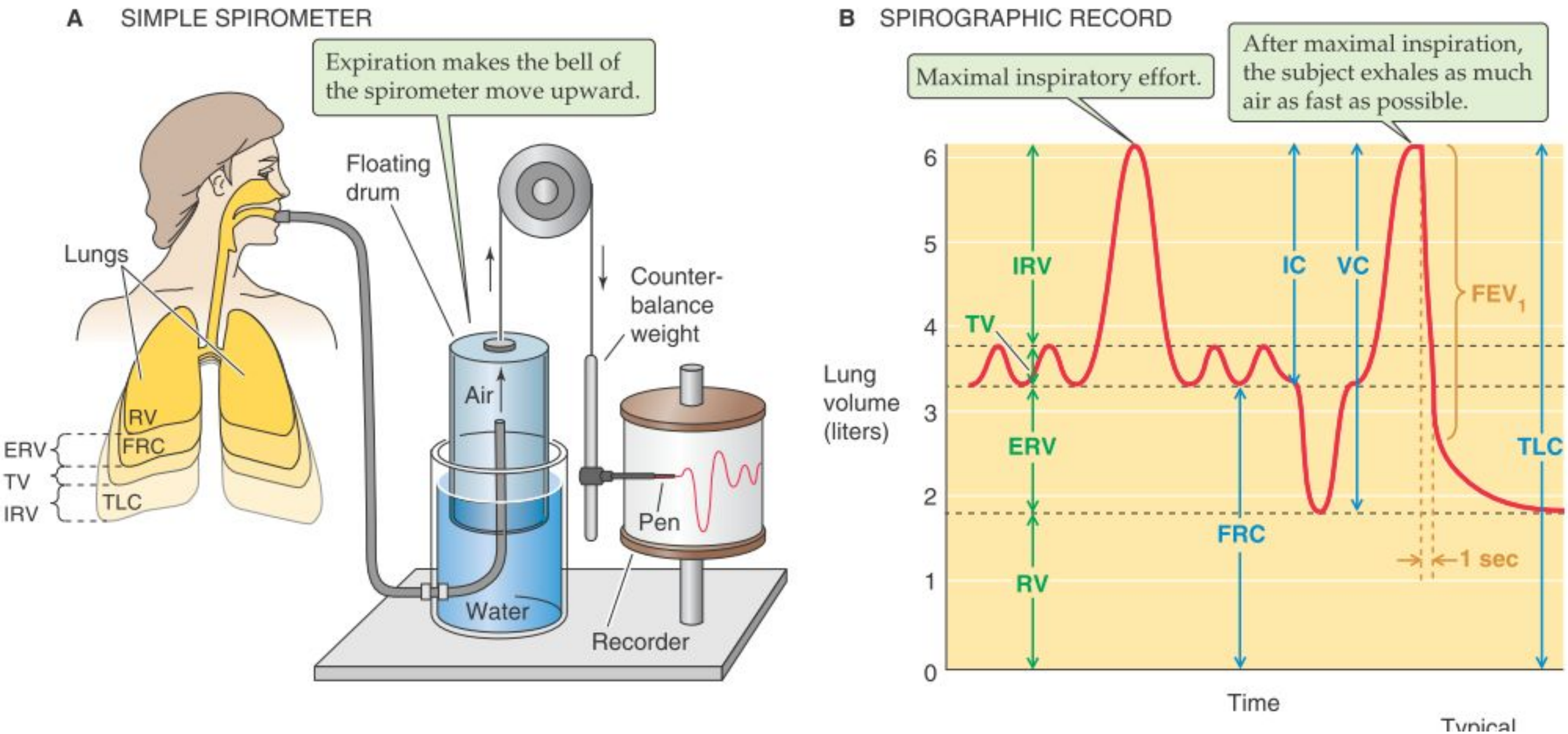

During inflation, the alveolus has expanded from a radius of 100 µm to one of 150 µm, greatly reducing the surface density of the surfactant. Thus, surface tension and elastic recoil rise, putting a "brake" on expansion.
Inspiration
Surfactant
Rapidly expanding alveolus
Slowly expanding alveolus
Because the radius of this alveolus has expanded from 100 µm to only 120 µm, its surfactant is less diluted, putting less of a "brake" on expansion.
Inspiration



Change in lung volume from RV (liters)
5
4
3
2
1
RV
0
+5
+10
+20
+30
+40
Transpulmonary pressure (P_{TP}) (cm H_2O)
Emphysema
Normal
Fibrosis
$C = \frac{\Delta V_L}{\Delta P_{TP}}$
0.5 liter
2.5 cm H_2O

A. Lung volumes and their measurement

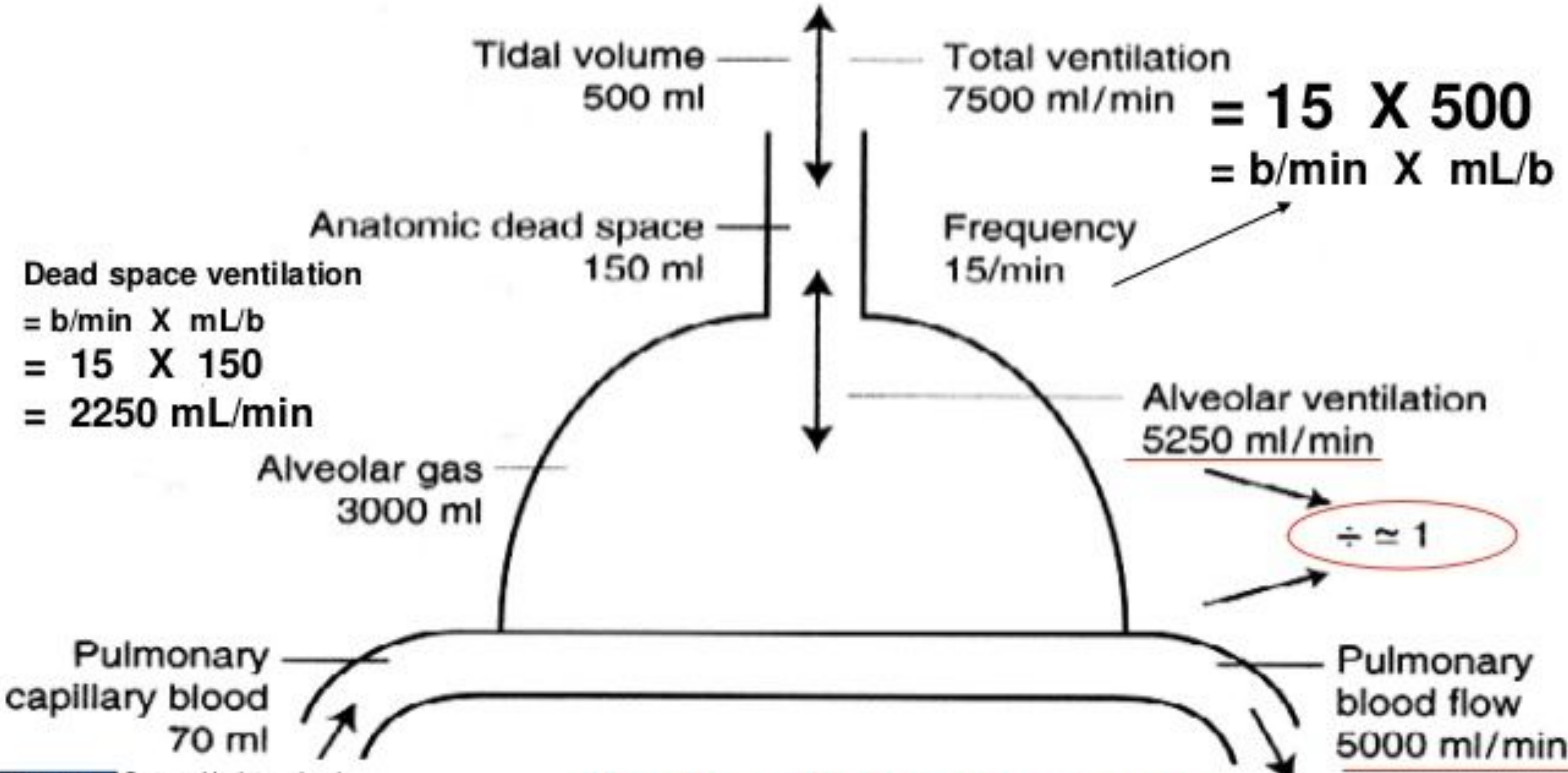




A SIMPLE SPIROMETER
Expiration makes the bell of the spirometer move upward.
Floating drum
Lungs
Counter-balance weight
Air
RV
FRC
ERV
TV
IRV
TLC
Pen
Water
Recorder
B SPIROGRAPHIC RECORD
Maximal inspiratory effort.
After maximal inspiration, the subject exhales as much air as fast as possible.
6
5
4
3
2
1
0
Lung volume (liters)
IRV
TV
ERV
RV
FRC
IC
VC
FEV1
TLC
1 sec
Time

	FEV_1	FVC	FEV_1: FVC (%)
Normal	~4.0	~5.0	>70
Obstructive	~1.3	~3.1	<70
Restrictive	~2.8	~3.1	>70

Alveolar ventilation	= Total ventilation	- Dead space ventilation
b/min X mL/b	= b/min X mL/b	- b/min X mL/b
17 X 350	= 15 X 500	- 15 X 150
5250 ml/min	= 7500 ml/min	- 2250 ml/min



= 15 X 500

= b/min X mL/b

Dead space ventilation

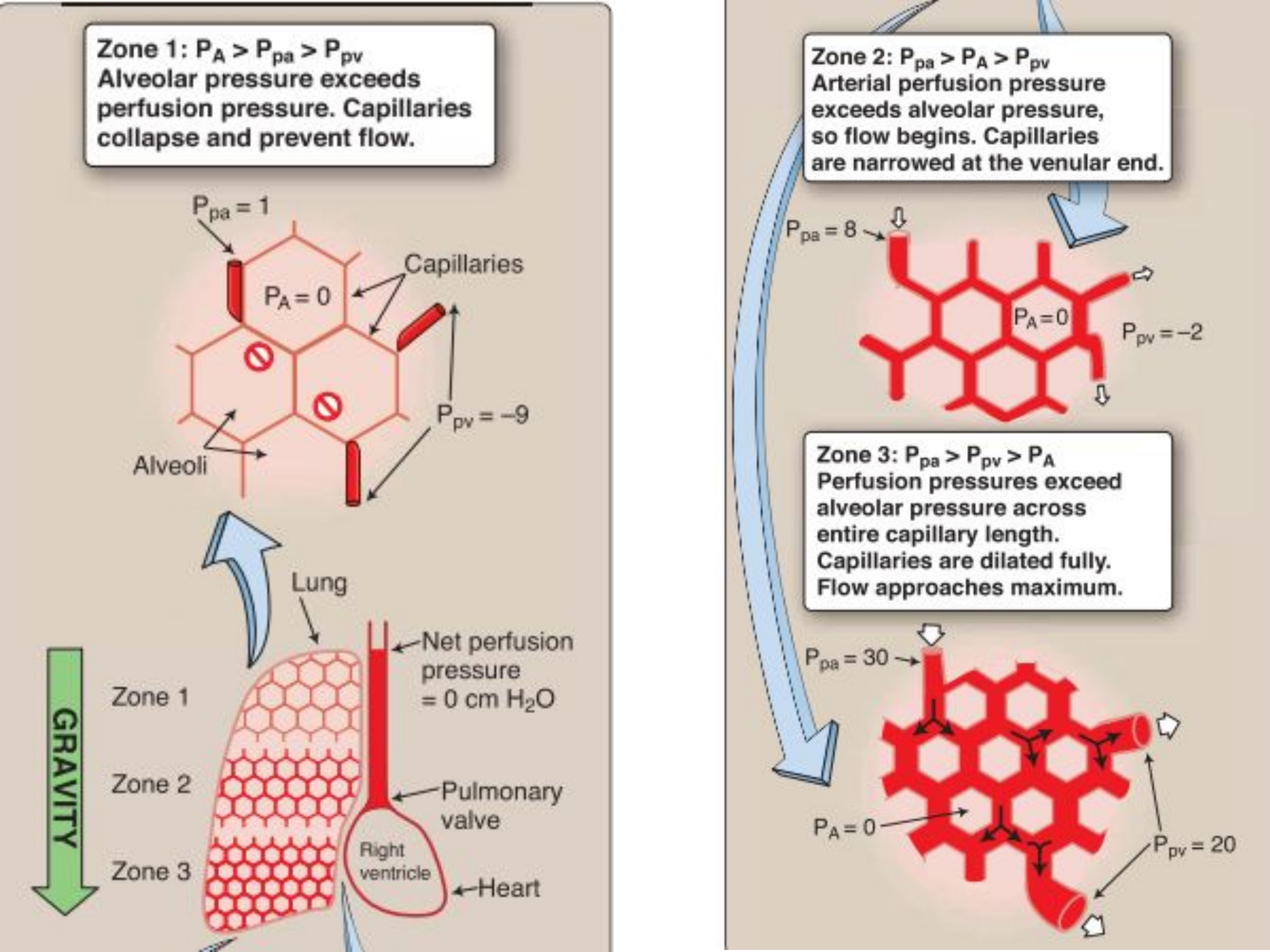
= b/min X mL/b

= 15 X 150

= 2250 mL/min

Source Undetermined

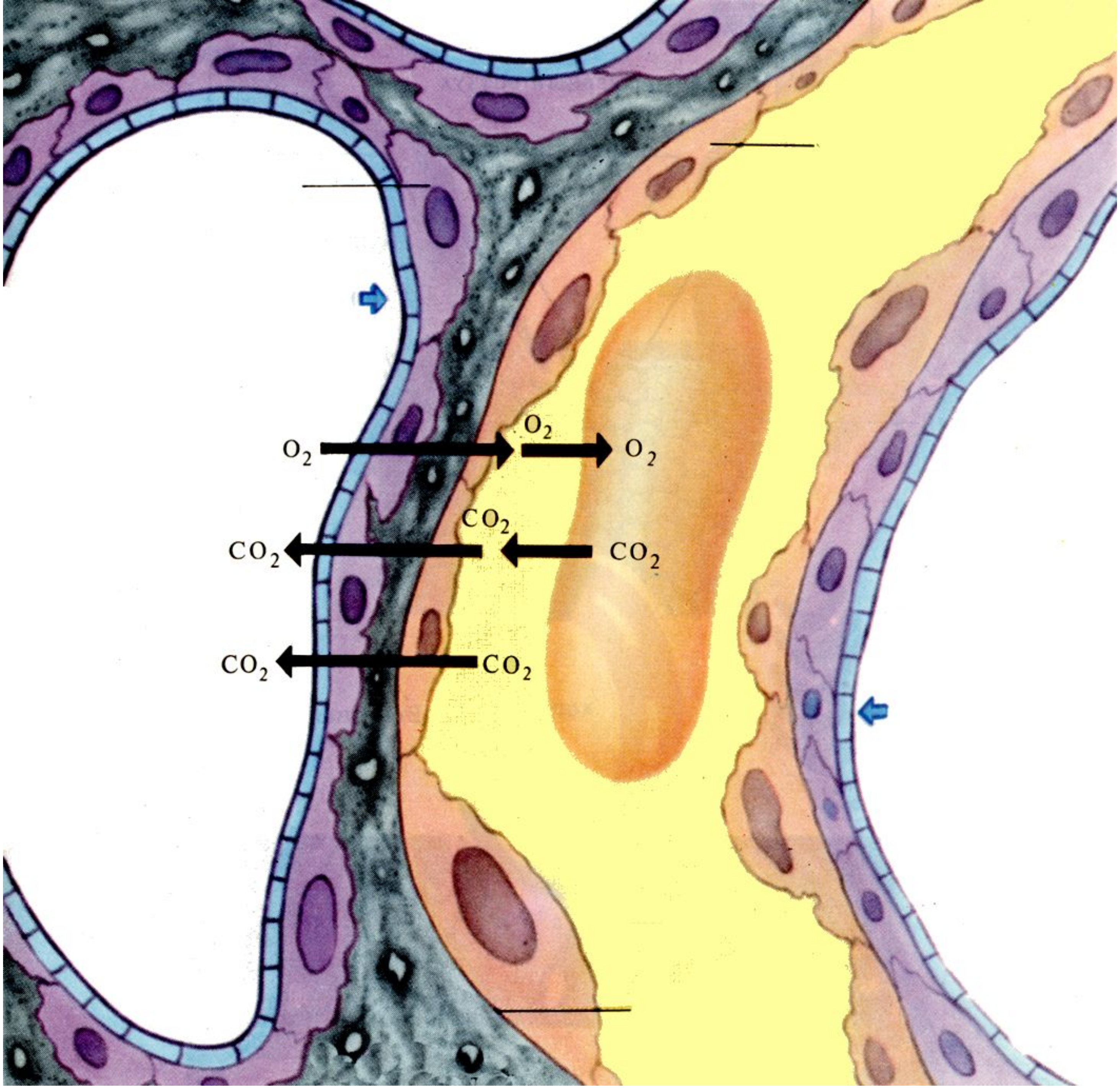
Alveolar ventilation is approximately equal to pulmonary blood flow (cardiac output).



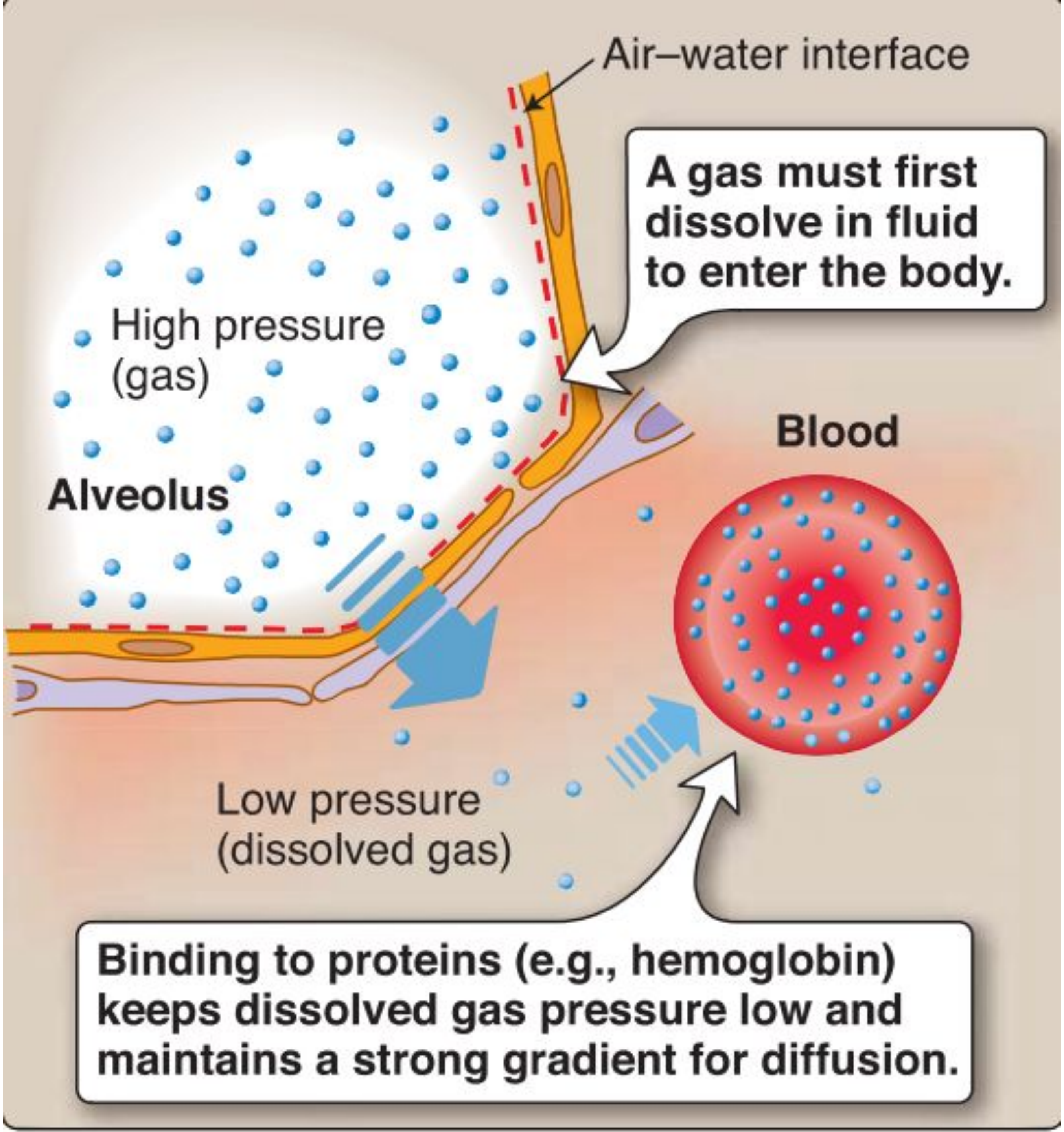
Zone 1: $P_A > P_{pa} > P_{pv}$
Alveolar pressure exceeds perfusion pressure. Capillaries collapse and prevent flow.
$P_{pa} = 1$
Capillaries
$P_A = 0$
$P_{pv} = -9$
Alveoli
Lung
Net perfusion pressure = 0 cm H_2O
Zone 1
Zone 2
Zone 3
GRAVITY
Pulmonary valve
Right ventricle
Heart
Zone 2: $P_{pa} > P_A > P_{pv}$
Arterial perfusion pressure exceeds alveolar pressure, so flow begins. Capillaries are narrowed at the venular end.
$P_{pa} = 8$
$P_A = 0$
$P_{pv} = -2$
Zone 3: $P_{pa} > P_{pv} > P_A$
Perfusion pressures exceed alveolar pressure across entire capillary length. Capillaries are dilated fully. Flow approaches maximum.
$P_{pa} = 30$
$P_A = 0$
$P_{pv} = 20$

Т а б л и ц а 12.2. **Состав атмосферного воздуха и газовой смеси легких (%)**

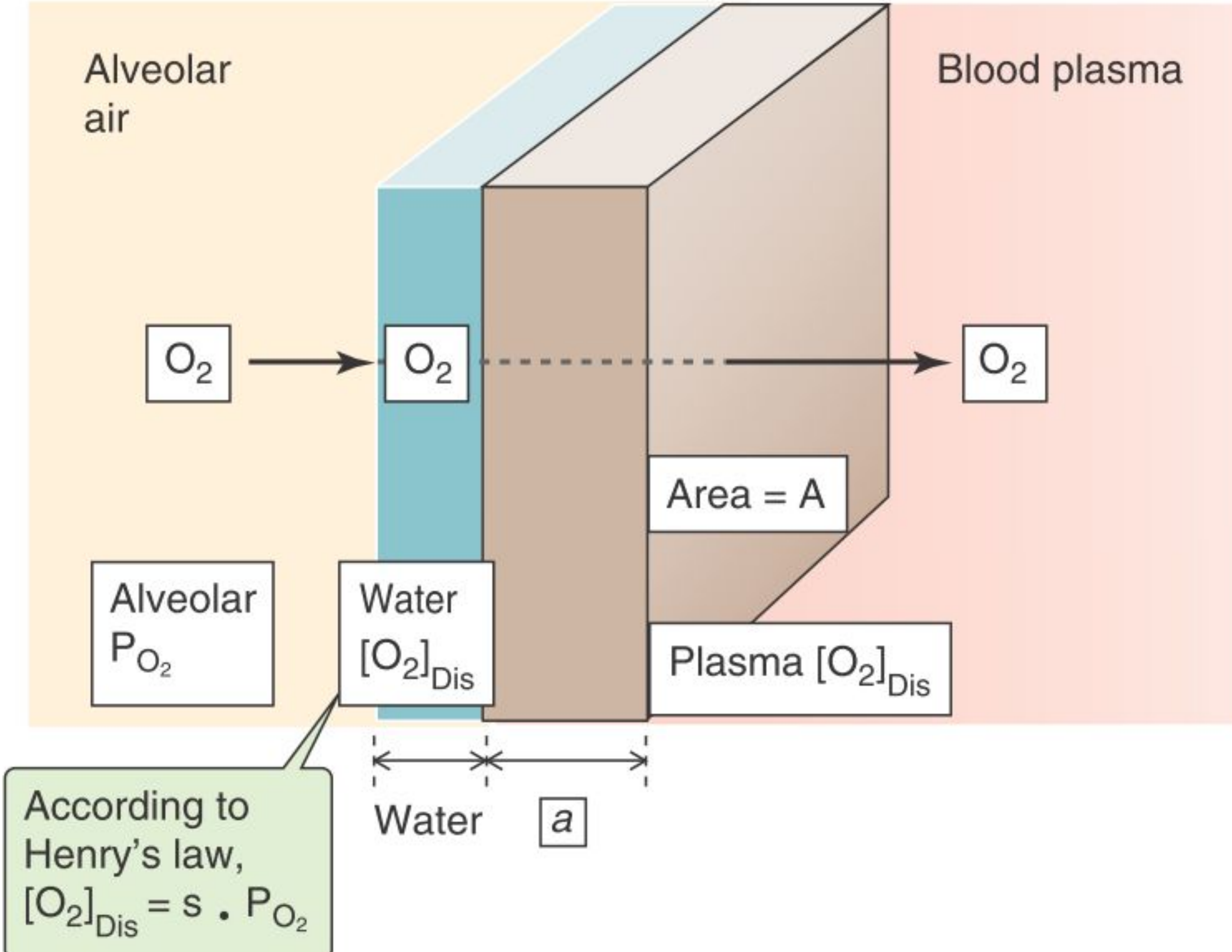
Компонент	Атмосферный воздух	Выдыхаемая смесь газов	Альвеолярная смесь газов
O_2	20,93	16,0	14,0
CO_2	0,04	4,0	5,5
Азот и инертные газы	78,5	74,9	74,5
Пары воды	0,5	5,5	5,6

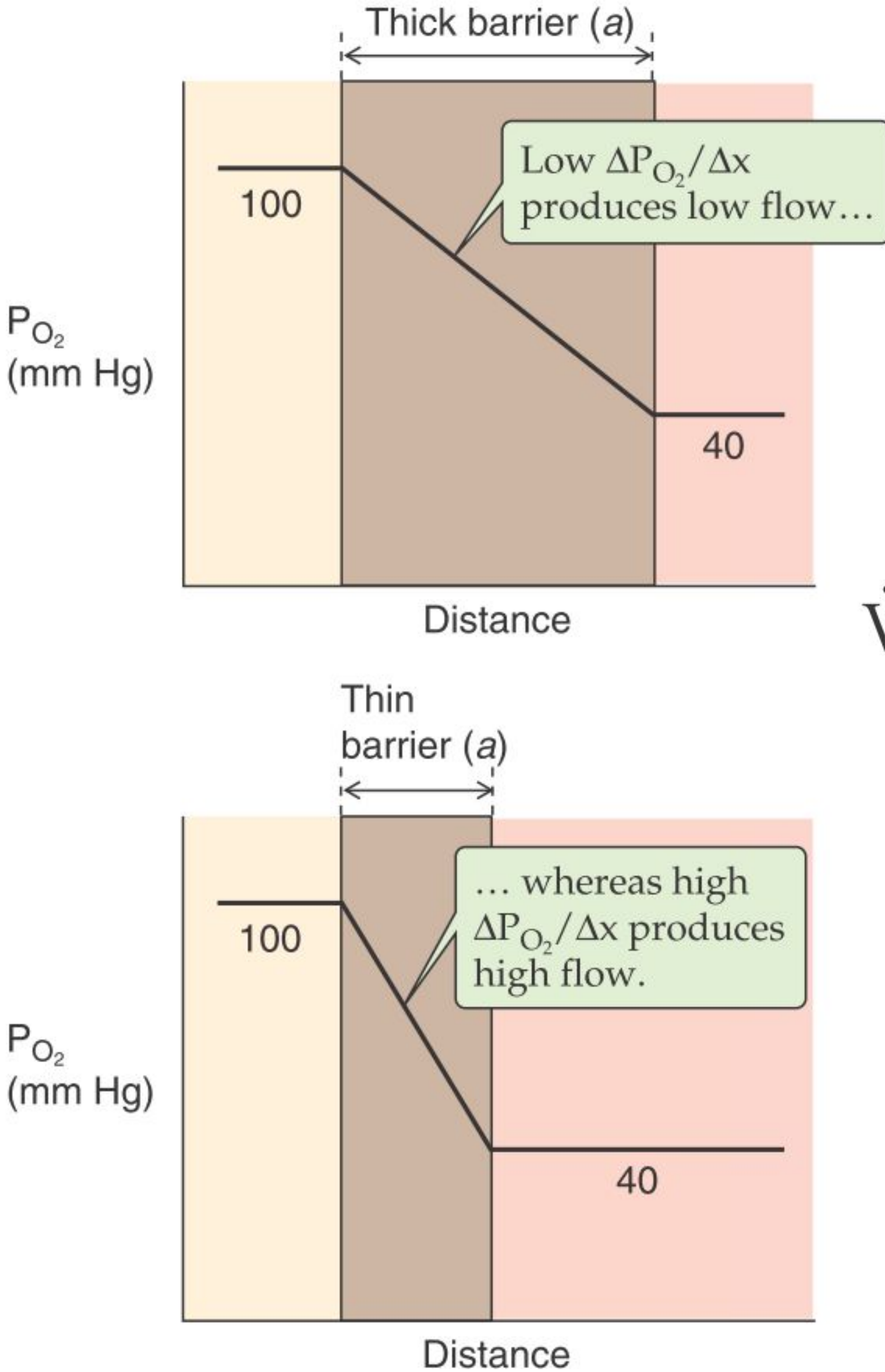


O_2
O_2
O_2
CO_2
CO_2
CO_2
CO_2
CO_2

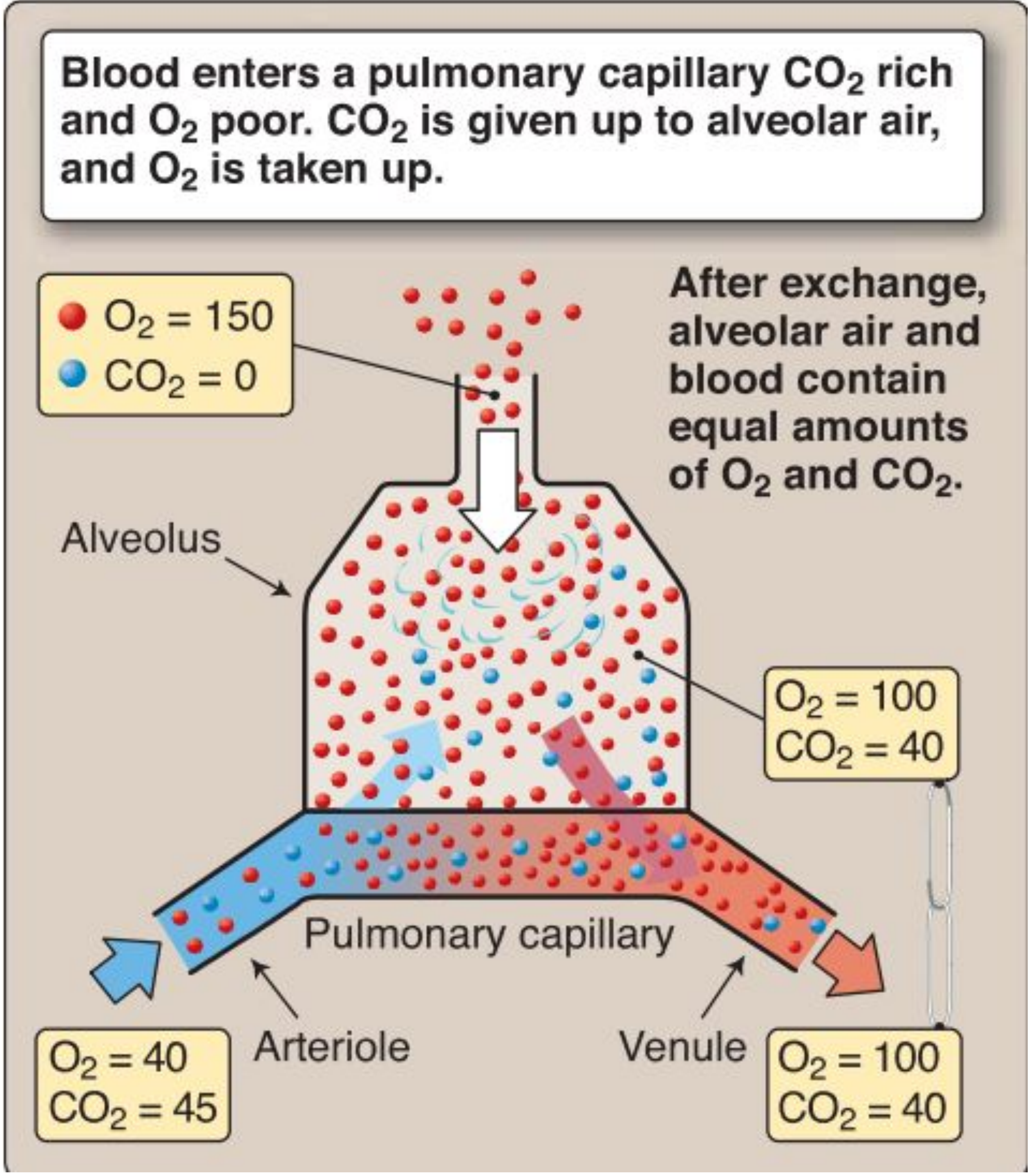

Air–water interface
A gas must first dissolve in fluid to enter the body.
High pressure (gas)
Alveolus
Blood
Low pressure (dissolved gas)
Binding to proteins (e.g., hemoglobin) keeps dissolved gas pressure low and maintains a strong gradient for diffusion.

B ALVEOLAR WALL

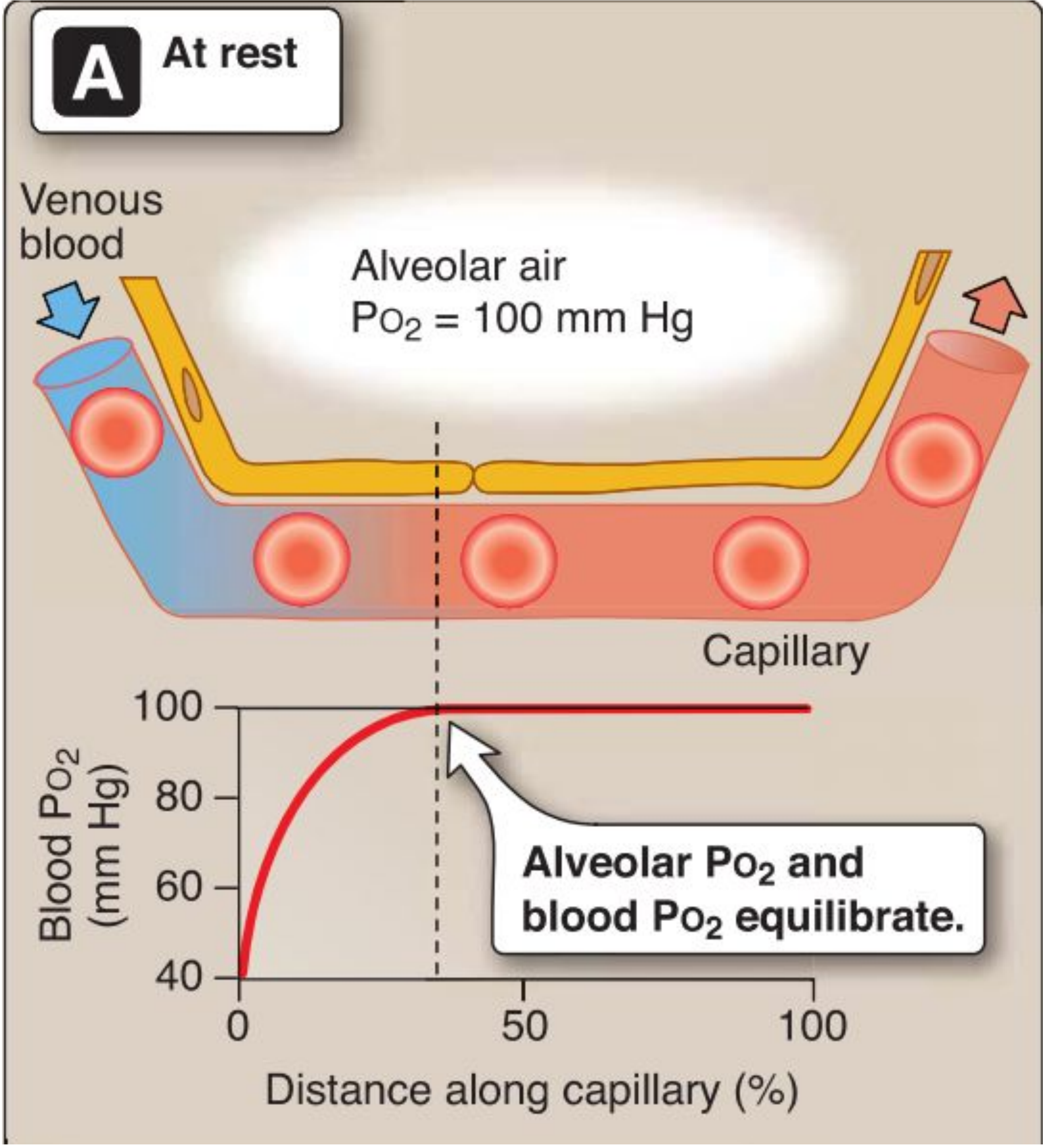




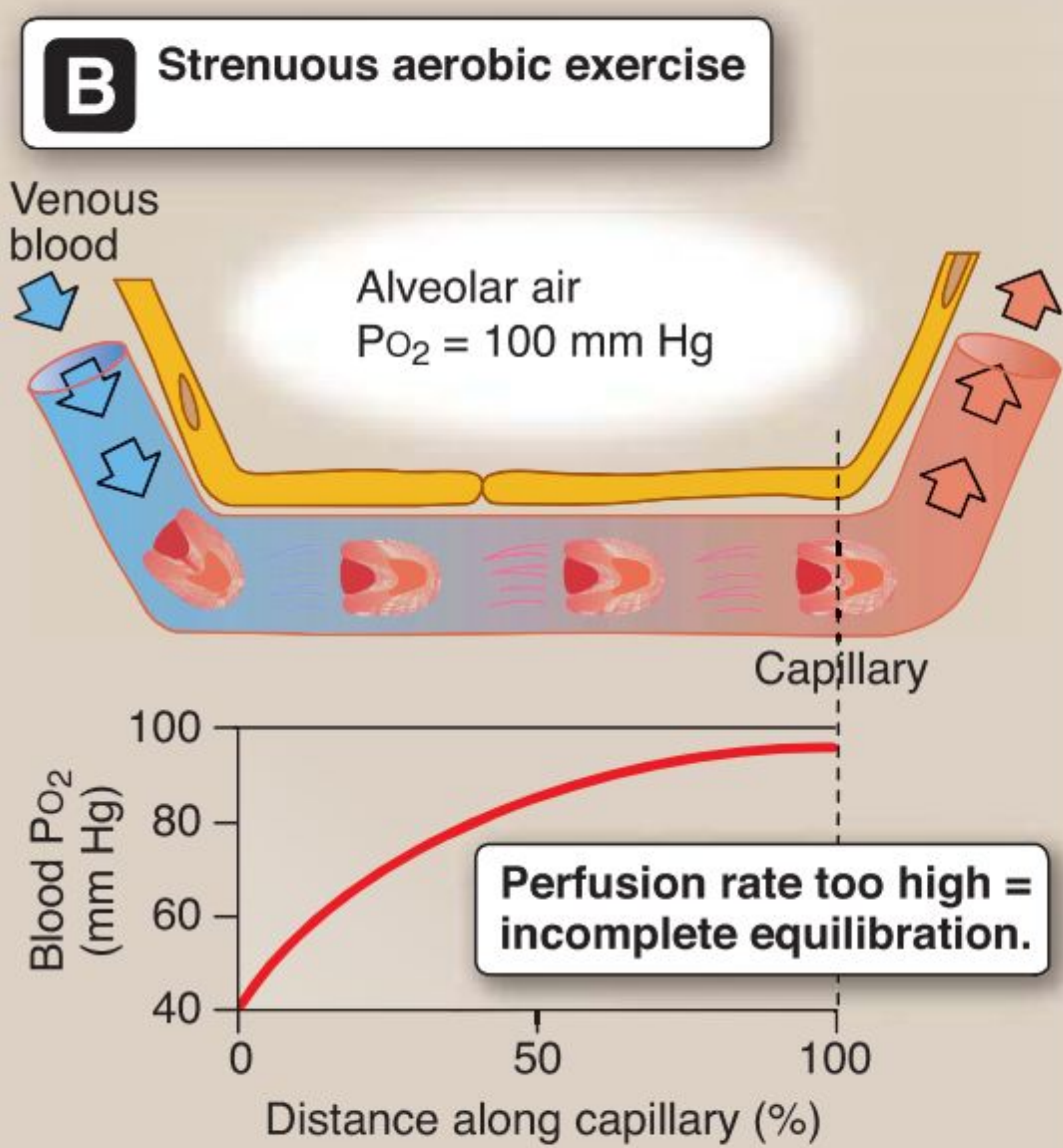
$$\dot{V}_{net} = \underbrace{\left[k \frac{A \cdot s}{a\sqrt{MW}} \right]}_{D_L} (P_1 - P_2)$$

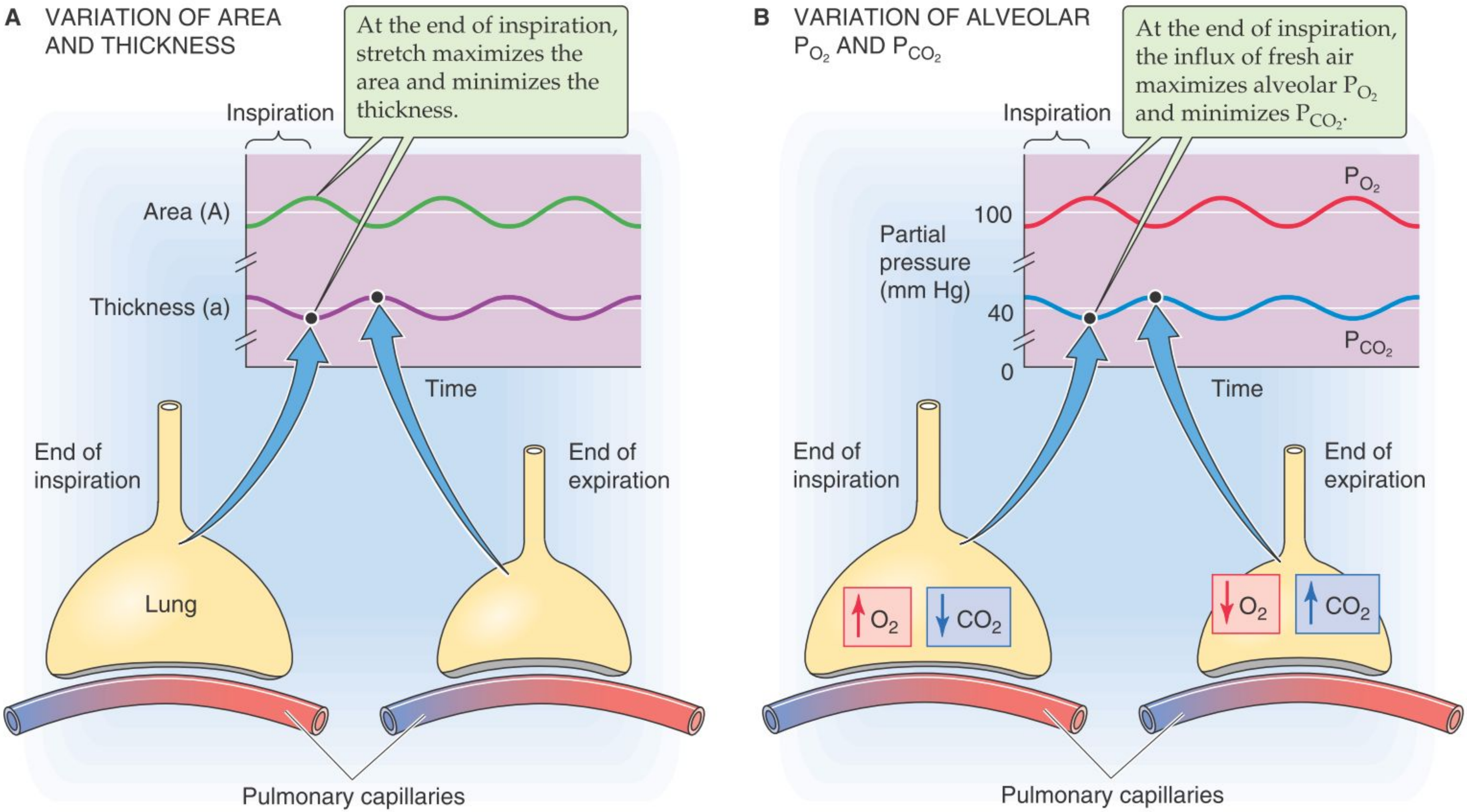

Blood enters a pulmonary capillary CO2 rich and O2 poor. CO2 is given up to alveolar air, and O2 is taken up.
O2 = 150
CO2 = 0
After exchange, alveolar air and blood contain equal amounts of O2 and CO2.
Alveolus
O2 = 100
CO2 = 40
Pulmonary capillary
O2 = 40
CO2 = 45
Arteriole
Venule
O2 = 100
CO2 = 40

Location	O_2 (mm Hg)	CO_2 (mm Hg)
External air	160	0
Conducting airways (during inhalation)	150	0
Alveoli	100	40
Pulmonary capillary	100	40
Systemic artery	95*	40
Pulmonary artery	40	45



A
At rest
Venous blood
Alveolar air
Po2 = 100 mm Hg
Capillary
100
80
60
40
Blood Po2 (mm Hg)
0
50
100
Distance along capillary (%)
Alveolar Po2 and blood Po2 equilibrate.


B
Strenuous aerobic exercise
Venous blood
Alveolar air
P_{O_2} = 100 mm Hg
Capillary
Blood P_{O_2} (mm Hg)
100
80
60
40
0
50
100
Distance along capillary (%)
Perfusion rate too high = incomplete equilibration.


A VARIATION OF AREA AND THICKNESS
At the end of inspiration, stretch maximizes the area and minimizes the thickness.
Inspiration
Area (A)
Thickness (a)
Time
End of inspiration
End of expiration
Lung
Pulmonary capillaries
B VARIATION OF ALVEOLAR P_{O_2} AND P_{CO_2}
At the end of inspiration, the influx of fresh air maximizes alveolar P_{O_2} and minimizes P_{CO_2}.
Inspiration
P_{O_2}
100
Partial pressure (mm Hg)
40
0
P_{CO_2}
Time
End of inspiration
End of expiration
O_2
CO_2
O_2
CO_2
Pulmonary capillaries

The changes in partial pressures of oxygen and carbon dioxide drive the diffusion of these gases in external and internal respiration. The partial pressures of various gases in the atmosphere are listed for comparison.

Partial pressures in atmosphere:	
Nitrogen (P_{N_2})	597.4 mmHg (78.6%)
Oxygen (P_{O_2})	158.8 mmHg (20.9%)
Carbon dioxide (P_{CO_2})	0.3 mmHg (0.04%)
Other gases ($P_{other\ gases}$)	3.5 mmHg (0.46%)
Total:	760.0 mmHg (100%)