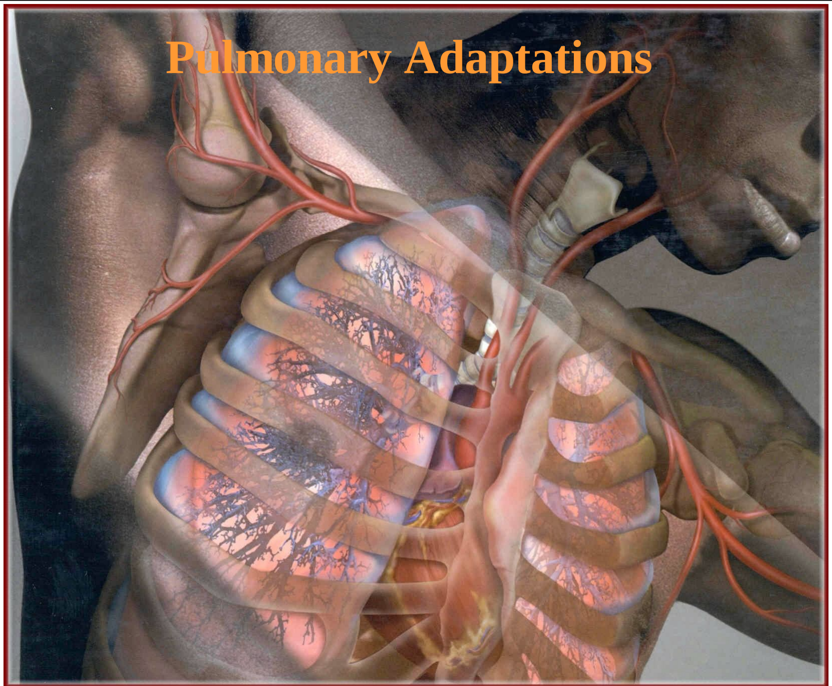
Pulmonary Adaptations



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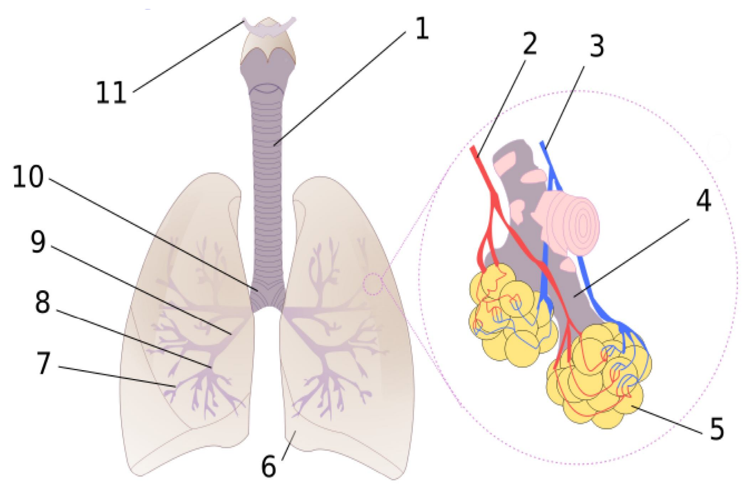
The Respiratory



1 Larynx; 2 Pulmonary arteriole; 3 Pulmonary venule; 4 Respiratory bronchiole; 5 Alveoli; 6 Lnugs; 7 Tertiary bronchiole; 8 Secondary bronchiole; 9 Prinmary bronchi; 10 RIght bronchi; 11 Trachea

Items 1, 10, 9, 8, 7 = conduting zone

Items 4 and 5 = respiratory zone

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This is a cast of the airways that conduct air to the lungs.

Why is this morphology potentially detrimental to air conductance into and from the lungs?

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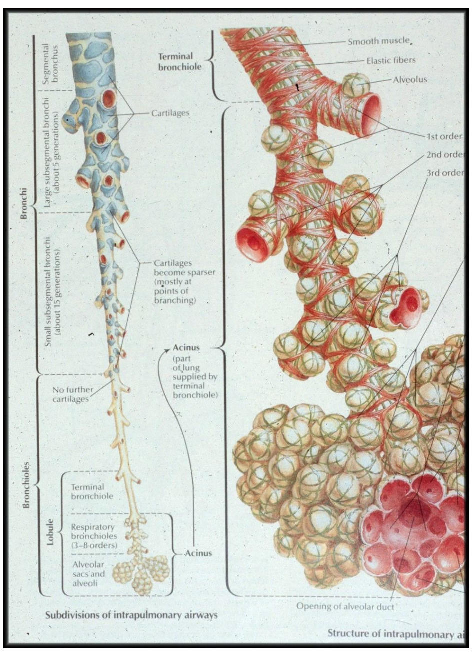

Note;
The respiratory zone has the greatest surface area and a dense capillary network.

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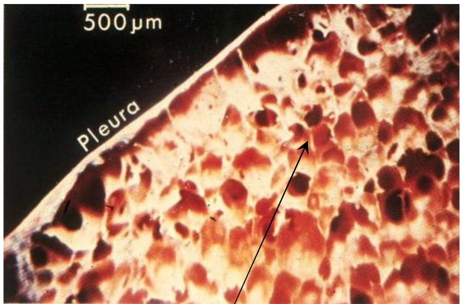

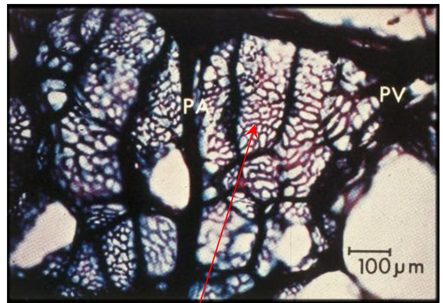

Note the density of the alveoli and their thin walls.

Note the dense capillary network that surrounds alveoli.

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Surfactant

A phospholipoprotein molecule, secreted by specialized cells of the lung, that *lines the surface of alveoli and respiratory bronchioles*. Surfactant *lowers the surface tension* of the alveoli membranes, *preventing the collapse* of alveoli during exhalation and *increasing compliance* during inspiration.

Respiration

The process of gas exchange, which for the human body involves oxygen (O_2) and carbon dioxide (CO_2).

Internal respiration - at the cellular level

External respiration - at the lung

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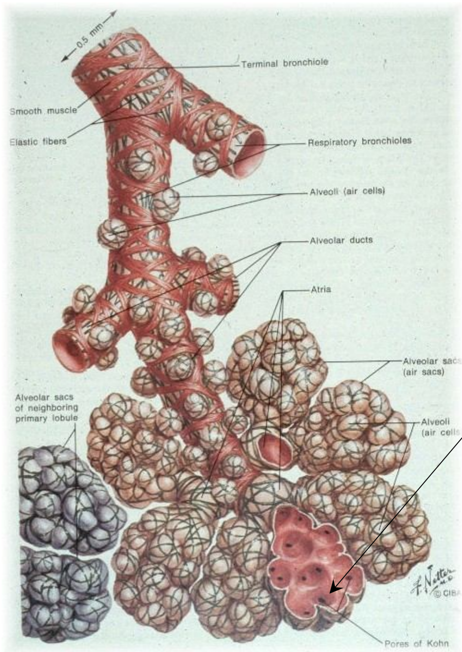


The distribution of surfactant is aided by holes that connect alveoli called Pores of Kohn.

Ventilation

The movement of air into and from the lung by the process of bulk flow.

Ventilation (V_E) (L/min) = frequency (br/min) x tidal volume (L)

For rest conditions,

V_E (L/min) = 12 (br/min) x 0.5 (L) = 6 L/min

For exercise at VO_2max,

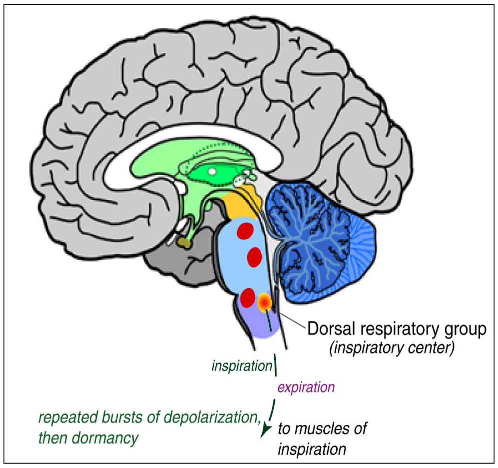
V_E (L/min) = 60 (br/min) x 3.0 (L) = 180 L/min

Compliance - *the property of being able to increase size or volume with only small changes in pressure.*

Ventilation During Rest

Inspiration is controlled by a repetitive discharge of action potentials from the *inspiratory center*.

Expiration involves the *passive recoil* of the diaphragm.



Minimal regulation from chemoreceptors occurs during normal acid-base conditions.

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Alveolar Ventilation

The volume of "fresh" air that reaches the respiratory zone of the lung.

Alveolar Ventilation (V_A) (L/min)

V_A = frequency (br/min) x (tidal volume - 0.15) (L)

For normal breathing conditions,

V_A = 12 (br/min) x (1.0 - 0.15) (L)

= 12 x 0.85 = 10.2 L/min

For rapid shallow breathing conditions,

V_A = 60 (br/min) x (0.2 - 0.15) (L) **(8.2b)**

= 60 x 0.05 = 3.0 L/min

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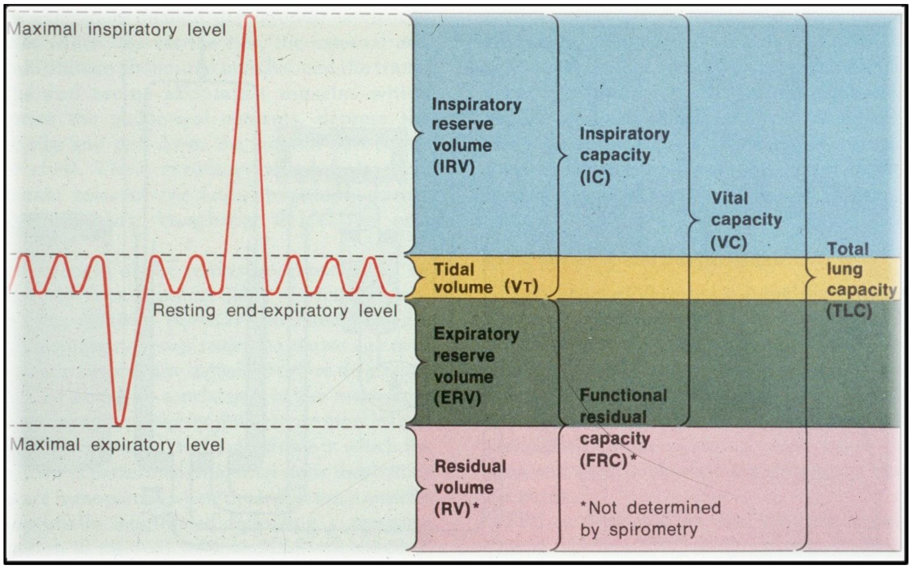
Lung Volumes and Capacities



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Measurement	Abbreviation	Description
Can be measured from spirometry		
Tidal volume	V_T	Volume of air inhaled and exhaled each breath
Inspiratory reserve volume	IRV	Maximum volume of air that can be inhaled after a normal resting end tidal inspiration
Expiratory reserve volume	ERV	Maximum volume of air that can be exhaled after a normal resting end tidal expiration
Inspiratory capacity	IC	Sum of IRV + V_T
Expiratory capacity	EC	Sum of ERV + V_T
Vital capacity	VC	Maximum volume or air exhaled after reaching IC = IC + ERV
Forced vital capacity	FVC	Same as for VC, but with forced rapid exhalation
Forced expiratory volume in 1 s	FEV1	Maximum volume of air that can be expired in 1 s when starting at IC
Maximal voluntary ventilation	MVV	Maximum rate of ventilation that can be attained with voluntary effort
Cannot be measured from spirometry		
Residual volume	RV	Volume of air remaining in the lungs at ERV.
Functional residual capacity	FRC	Sum of RV + ERV
Total lung capacity	TLC	Sum of V_T + IRV + ERV + RV

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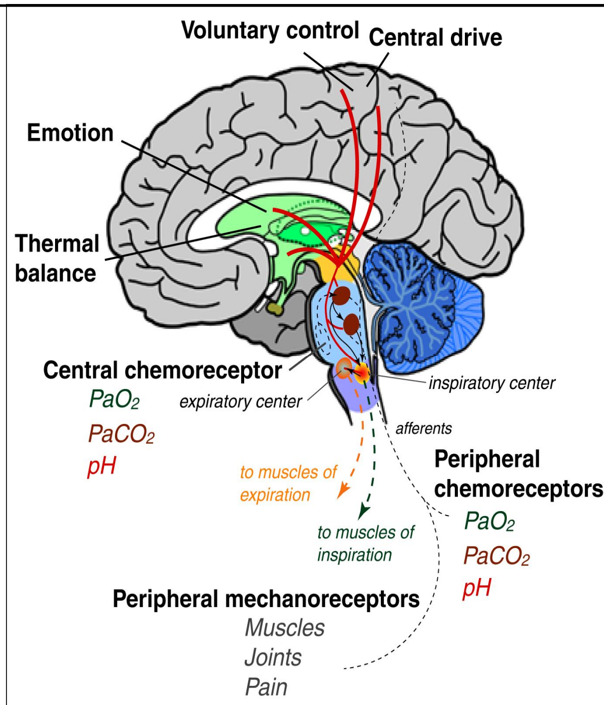
Control of Ventilation During Exercise



Diffusion of Gases

The gases of respiration (O_2 and CO_2) diffuse down pressure gradients that exist between,

a. pulmonary blood and the alveoli

b. systemic capillary blood and cells

	Sea Level P_B=760 mmHg P_B-47=713 * 0.9906 = 706.3			5,280 ft (1,610 m) P_B=620 mmHg P_B-47=573 * 0.9906 = 567.6
Gas	Air Fraction	Alveolar Fraction	$P_A$gas (mmHg)	$P_A$gas (mmHg)
Nitrogen	**0.78084**	0.7868	561	447
Oxygen	**0.209476**	**0.1472**	**104**	84
Carbon Dioxide	**0.000314**	0.0566	**40**	32

The data of alveolar partial pressures at any barometric pressure (altitude) can be calculated from memorizing the bold values.

The factors that govern the directionality and magnitude of gas diffusion are?

What Determines Gas Exchange?

The factors that govern the directionality and magnitude of gas diffusion are,

- the gas diffusion capacity
- **the gas partial pressure gradient**
- characteristics of the medium through which diffusion occurs (hydration, thickness, cross sectional area)

The fact that alveolar and blood gas partial pressures approximately reach equilibrium within the lung enables researchers to estimate arterial blood gas partial pressures from alveolar partial pressures!

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Gas Partial Pressures in Atmospheric and Alveolar Air

Gas	Air* Fraction	Air* Partial Pressure	Alveolar Fraction^	Alveolar Partial Pressure
H_2O	0	0	----	47
O_2	0.2095	159.0	0.1459	104
CO_2	0.0003	0.3	0.0561	40
N_2	0.7808	600.6	0.7980	569

* assumes dry air at sea level, P_B=760 mmHg
^ note that the water vapor pressure is removed to calculate alveolar gas fractions

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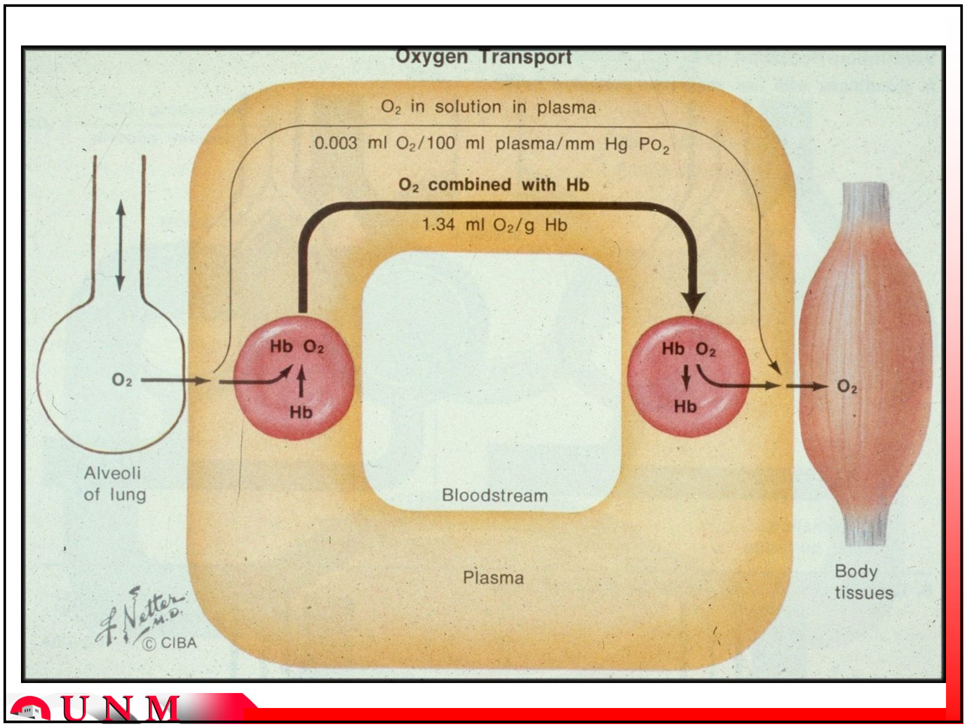
Oxygen Transport
O2 in solution in plasma
0.003 ml O2/100 ml plasma/mm Hg PO2
O2 combined with Hb
1.34 ml O2/g Hb
Hb O2
Hb
O2
Alveoli of lung
Bloodstream
Plasma
Body tissues
© CIBA
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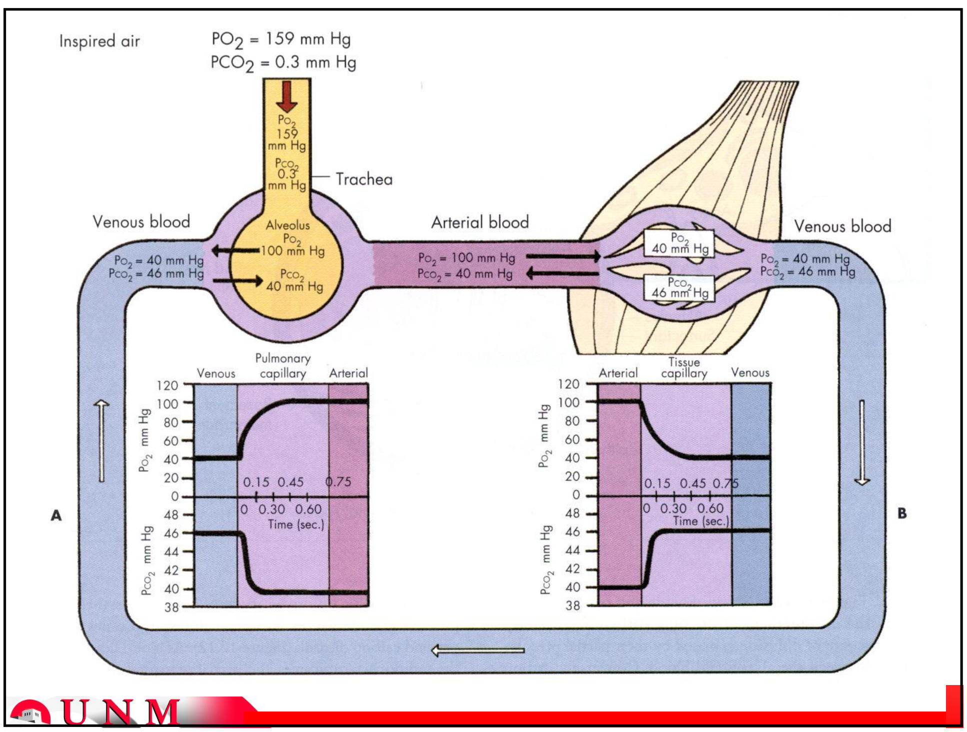
Inspired air
PO2 = 159 mm Hg
PCO2 = 0.3 mm Hg
Trachea
Venous blood
Arterial blood
Alveolus
Po2 = 100 mm Hg
Pco2 = 40 mm Hg
Po2 = 40 mm Hg
Pco2 = 46 mm Hg
Venous
Pulmonary capillary
Arterial
Tissue capillary
Time (sec.)
A
B
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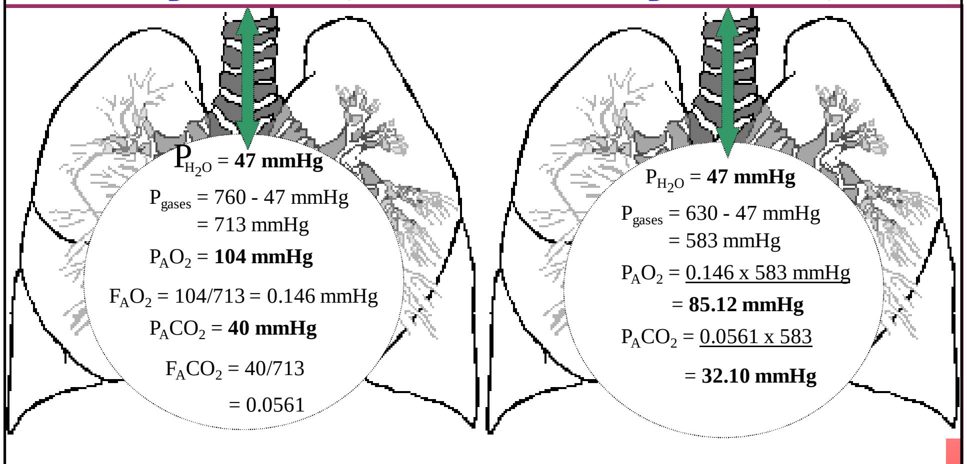
Sea Level	Albuquerque
P_B = 760 mmHg	P_B = 630 mmHg



Note the decreases in alveolar O_2 fractions from atmospheric air to alveolar air

Note that estimating F_AO_2 as 0.146 enables you to estimate P_AO_2 for any given barometric pressure condition

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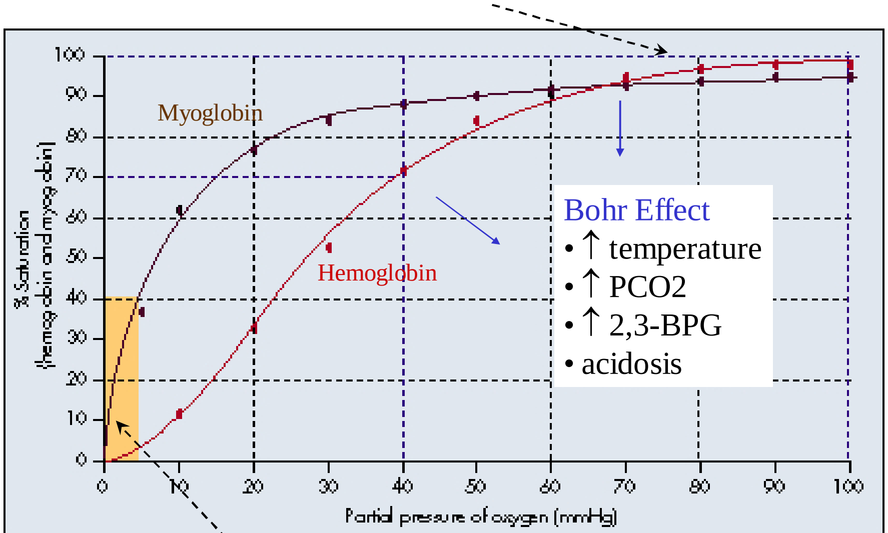
Oxy-hemoglobin Dissociation Curve

Note the relatively flat region of the curve btwn 80-100mmHg



Note the small range of PO_2 in muscle during exercise when intramuscular PO_2 may↓ to less than 5 mmHg.

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Exchange of gas at the cellular level

(i.e., systemic capillary blood and muscle cells)

In addition to the Bohr and Haldane effects, unloading of oxygen is also aided by the molecule **myoglobin**.

Myoglobin is found within skeletal muscle fibers and is similar to hemoglobin in that it contains a *heme prosthetic group* that can *bind oxygen*.

When PaO2 drops **below 60 mmHg**, myoglobin has a higher affinity for oxygen than does hemoglobin.

This allows for a unidirectional transfer of O2 from hemoglobin (blood) to the myoglobin (muscle fiber).

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Transport of Oxygen in the Blood

Oxygen is transported in blood bound to **hemoglobin** (Hb). 1 gram of Hb can maximally bind 1.34 mL of oxygen (1.34 mL O_2/g Hb @ 100% saturation).

Table 8.1: Examples of hemoglobin (Hb) and oxygen carrying capacity conditions (98% saturation and pH = 7.4)

Population/Condition	*[Hb]*	*mL O_2/L*
Males	14.0	183.8
Females	12.0	157.6
Blood Doping	18.0	236.4
Anemia	< 10.0	< 131.3

[Hb] = g/100 mL

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The oxygen content (CaO_2) of blood can be calculated;

CaO_2 = [Hb] x O_2/g Hb x Hb-O_2 saturation

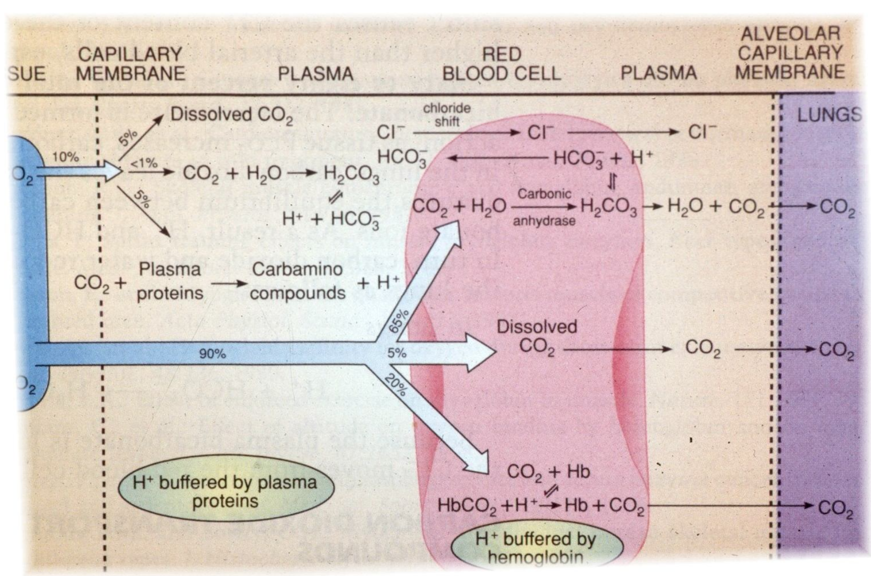
= 150 g/L x 1.34 mL O_2/g x 0.98

= 197 mL O_2/L

Another small source of oxygen in blood is the volume of *oxygen dissolved in plasma*. However, due to the low solubility of oxygen,this value is small and approximates,

dissolved O_2 = 0.003 mL / 100 mL blood / mmHg PO_2

~ 0.3 mL / 100 mL at sea level (PaO_2 ~ 100 mmHg)



Carbonic anhydrase

$$CO_2 + H_2O \rightarrow H_2CO_3 \rightarrow H^+ + HCO_3^-$$

Carbonic acid Bicarbonate

Buffering

When acid is produced from metabolism, the liberated proton can bind with bicarbonate, eventually forming CO_2, which is then expired by the lung.

Carbonic anhydrase

$$CO_2 + H_2O \leftarrow H_2CO_3 \leftarrow H^+ + HCO_3^-$$

Carbonic acid Bicarbonate

The bicarbonate-carbon dioxide system relies on ventilation for proper function as a buffer system.

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Carbonic anhydrase

$$\uparrow CO_2 + H_2O \leftarrow H_2CO_3 \leftarrow H^+ + HCO_3^-$$

Carbonic acid **Bicarbonate**

It is this increased production of carbon dioxide from the bicarbonate buffering of acid that accounts for the increase in **RER above 1.0** during intense exercise.

Remember, the *respiratory exchange ratio (RER)* is calculated by;

$$\mathbf{VCO_2 / VO_2}$$

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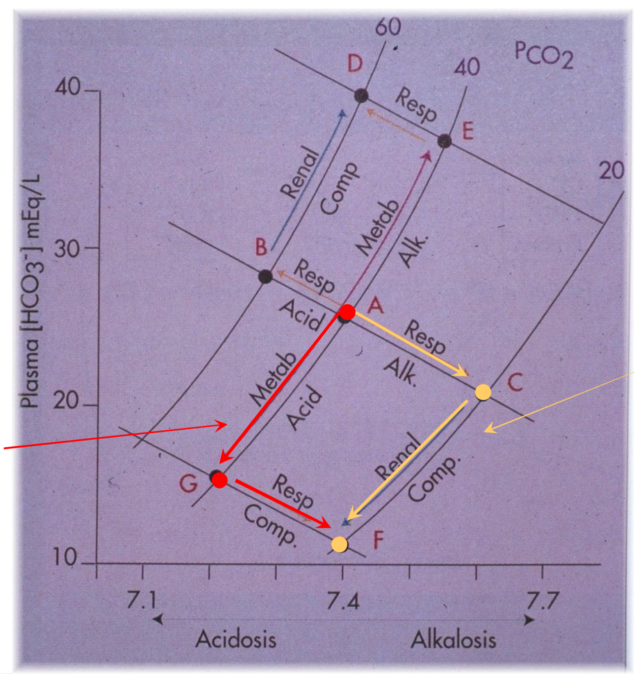
Transport of Carbon Dioxide in the Blood

The volume of CO_2 in the blood is approximately 10-fold greater than O_2.

Transport Location	Form	Percentage
Plasma	Dissolved	5
(<10%)	$CO_2 + H_2O \rightarrow H_2CO_3 \rightarrow H^+ + HCO_3^-$	<1
	Bound to proteins	5
Red Blood Cell	$CO_2 + H_2O \rightarrow H_2CO_3 \rightarrow H^+ + HCO_3^-$	65
(90%)	Dissolved	5
	Bound to hemoglobin	20

Note, this is typical of intense exercise



Note, this is typical of acute altitude exposure

Acidosis

Quantified by the pH scale, where pH equals the negative logarithm of the hydrogen ion concentration ($[H^+]$)

$$pH = -\log [H^+] \quad \text{or} \quad [H^+] = 10^{-pH}$$

Normal blood pH is ~7.4 = $[H^+]$ = 0.00000004 M

The main determinants of blood pH are;

- Balance of proton release/consumption
- Buffer capacity
- $PaCO_2$
- Renal excretion of electrolyes, protons and bases
- Ventilation
- Concentration of HCO_3^- and other bases or acids

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Acute Adaptations of Pulmonary Function During Exercise

After the onset of exercise there is;

- a rapid ↑ in ventilation
  (proportional to intensity)
- a similar rapid ↑ in pulmonary blood flow
- an improved V_E vs Q relationship in the lung
  (both ventilation & perfusion become more evenly distributed)
- ↑ lung compliance
- airway dilation and ↓ resistance to air flow
  (enlargement of trachea, dilation of bronchi & bronchioles)

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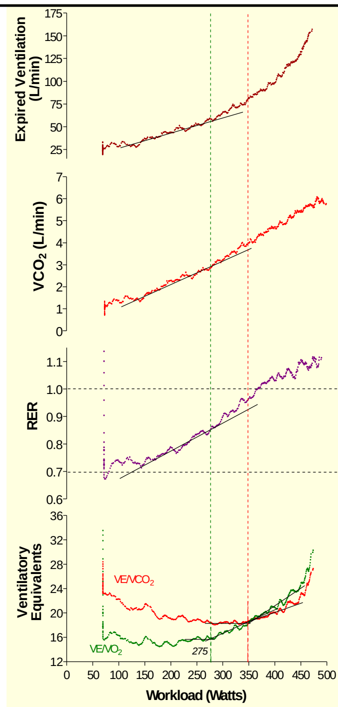
Ventilatory Threshold

Exercise intensity at which there is a deviation from linearity in *ventilation* and an increase in *VE/VO*$_2$.

The abrupt increase in acidosis and subsequent increase in PaCO2, disproportionately increases ventilation above that of oxygen use.



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Mechanics of Ventilation

As ventilation increases, both tidal volume and breathing frequency increase, with an eventual plateau seen in tidal volume.

As ventilation and intensity increase;

- ↑ air remaining in lung after expiration
- ↑ inspiratory pleural pressure
- ↑ work of breathing

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Exercise-Induced Hypoxemia

A lowering of partial pressure of oxygen (PaO_2) (hypoxia) resulting in a reduced CaO_2 (hypoxemia) during exhausting exercise in *highly endurance-trained individuals*, even at sea level.

- decreased pulmonary transit time
- decreased / uneven diffusion capacities in lung
- venoarterial shunts
- ventilation-perfusion inequalities
- inadequate hyperventilation

Note, the decrement in SaO_2 is not totally dependent on the magnitude of VO_2max