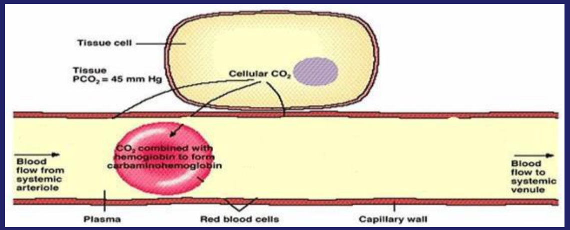
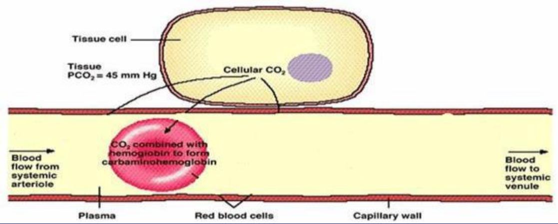


Respiration II:

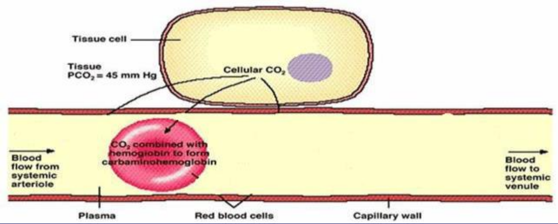
Gas exchange and transport



Composition of the atmosphere

$$P_{tot} = \sum_{i=1}^{n} F_i \times P_i$$

Gas	ppm	%	Partial Pressure in atmosphere (mmHg)	Partial Pressure in Alveolus (mmHg)
O_2	209,500	20.9	158.84	105
CO_2	420.66	0.042	0.421	47
N_2	78,840	78.1	593.56	
H_2O	25,000	0-4	30.4	

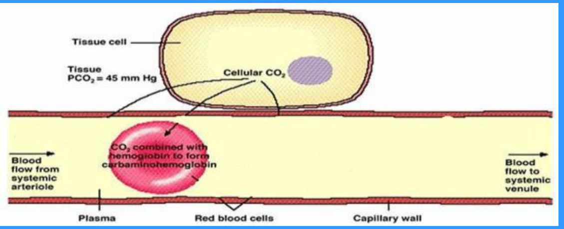


Gas Exchange: some physics

Partial Pressure: the concentration of a gas in a volume of gas is often expressed as its partial pressure (common units: mmHg).

Boyle's Law: $$P_{tot} = \sum_{i=1}^{n} F_i \times P_i$$

	Gas	Mole fraction (dry air)	Partial pressure (P_i) (mmHg)
P_{tot}=760mmHg	O_2	0.209	158.84
	CO_2	0.00042	0.312
	N_2	0.781	593.56
	Total		752.52

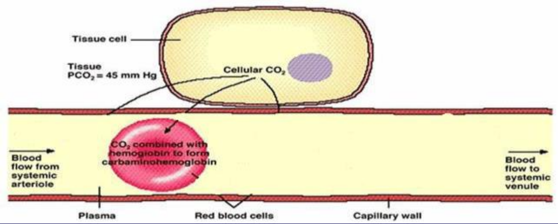


Gasses in Water

Henry's Law: The volume of a gas in water is approximately proportional to its partial pressure in the air in equilibrium with the water. The constant of proportionality (α) is "henry's constant", also called solubility or the Bunsen solubility coefficient, and is empirically determined. It is a function of temperature, other dissolved solutes, etc.

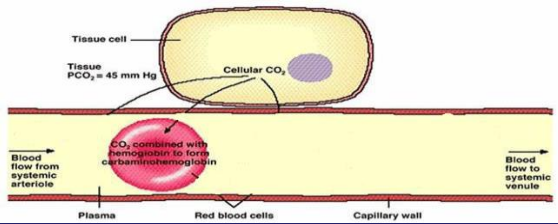
$$V_g = \alpha \frac{P_g}{P_{atm}} V_{H_2O}$$

Gas	Solubility in Water (ml gas/L water) (at 0^{o}C)	Volume in Water V_g / V_{H_2O} (ml/L)
O_2	34.1	7.12
CO_2	1019	0.307
N_2	16.9	13.2



Air and Water as Respiratory Media

Quantity		Water	Air	Ratio W/A
O_2 conc L/L		0.007	0.209	1:30
Density (Kg/L)		1.000	0.0013	800:1
Viscosity (cP)		1	0.02	50:1
Heat cap. (Cal $L^{-1}\ ^{o}C^{-1}$)		1000	0.31	3000:1
Heat cond. (cal $s^{-1} cm^{-1}\ ^{o}C^{-1}$)		0.0014	0.000 057	25:1
Diffusion Coeff ($cm^2\ s^{-1}$)	O_2	0.000 025	0.198	1:8000
	CO_2	0.000 018	0.155	1:9000
Liters medium/Liter O_2		143	4.8	30:1



Oxygen transport in blood

Dissolved oxygen in plasma: Solubility at 37^0C and one atmosphere (760 mmHg) is about 2.4 ml per 100 mL.

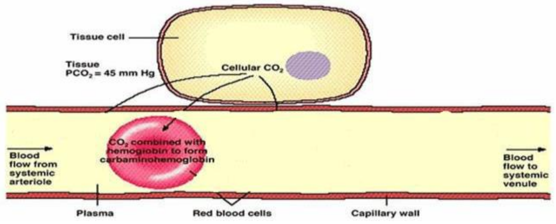
P_{O2} in the alveolus and arteries is only about 100mmHg.

Thus, the amount of dissolved oxygen in plasma is about 0.3 ml per 100 ml blood. (0.3 volume percent)

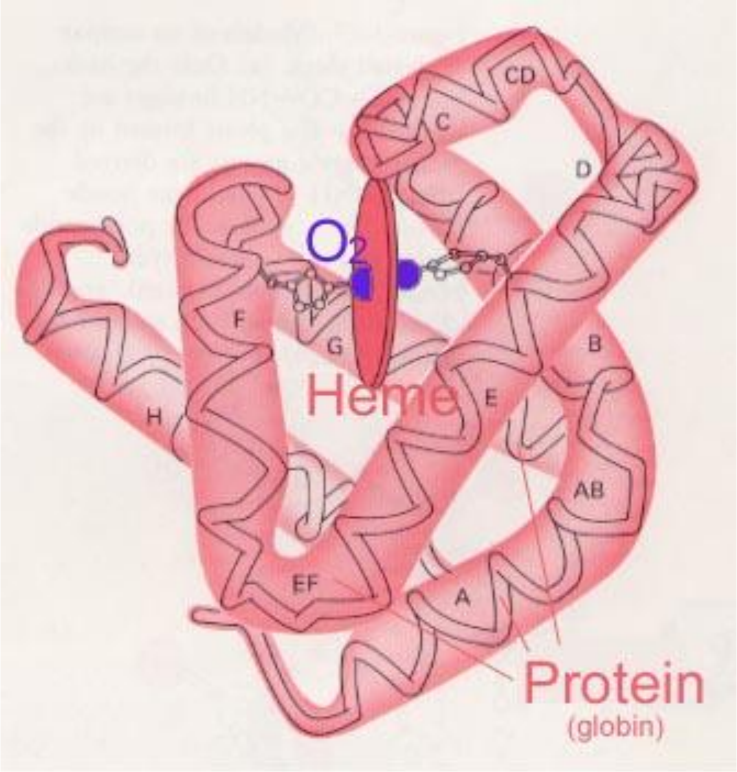
The total amount of oxygen in arterial blood is closer to 20 vol%.

Thus the bulk of the oxygen (98.5%) is carried by hemoglobin.

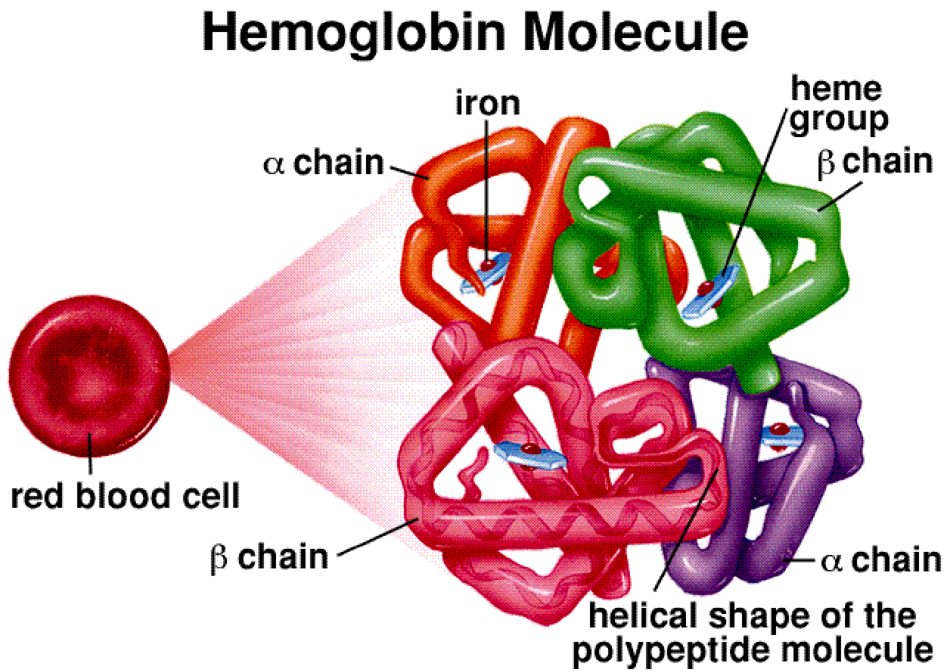
Hemoglobin



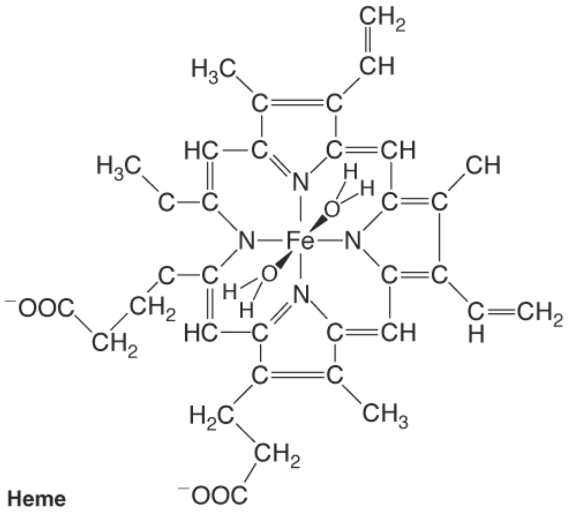
Tissue cell
Tissue
PCO_2 = 45 mm Hg
Cellular CO_2
CO_2 combined with hemoglobin to form carbaminohemoglobin
Blood flow from systemic arteriole
Blood flow to systemic venule
Plasma
Red blood cells
Capillary wall



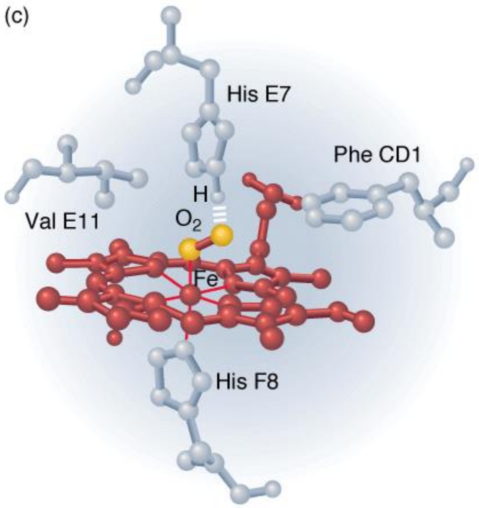
O2
Heme
Protein
(globin)
CD
C
D
F
G
B
E
H
AB
EF
A



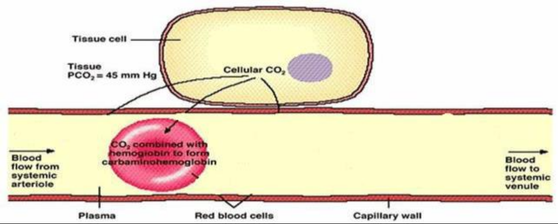
Hemoglobin Molecule
iron
heme group
α chain
β chain
red blood cell
β chain
α chain
helical shape of the polypeptide molecule

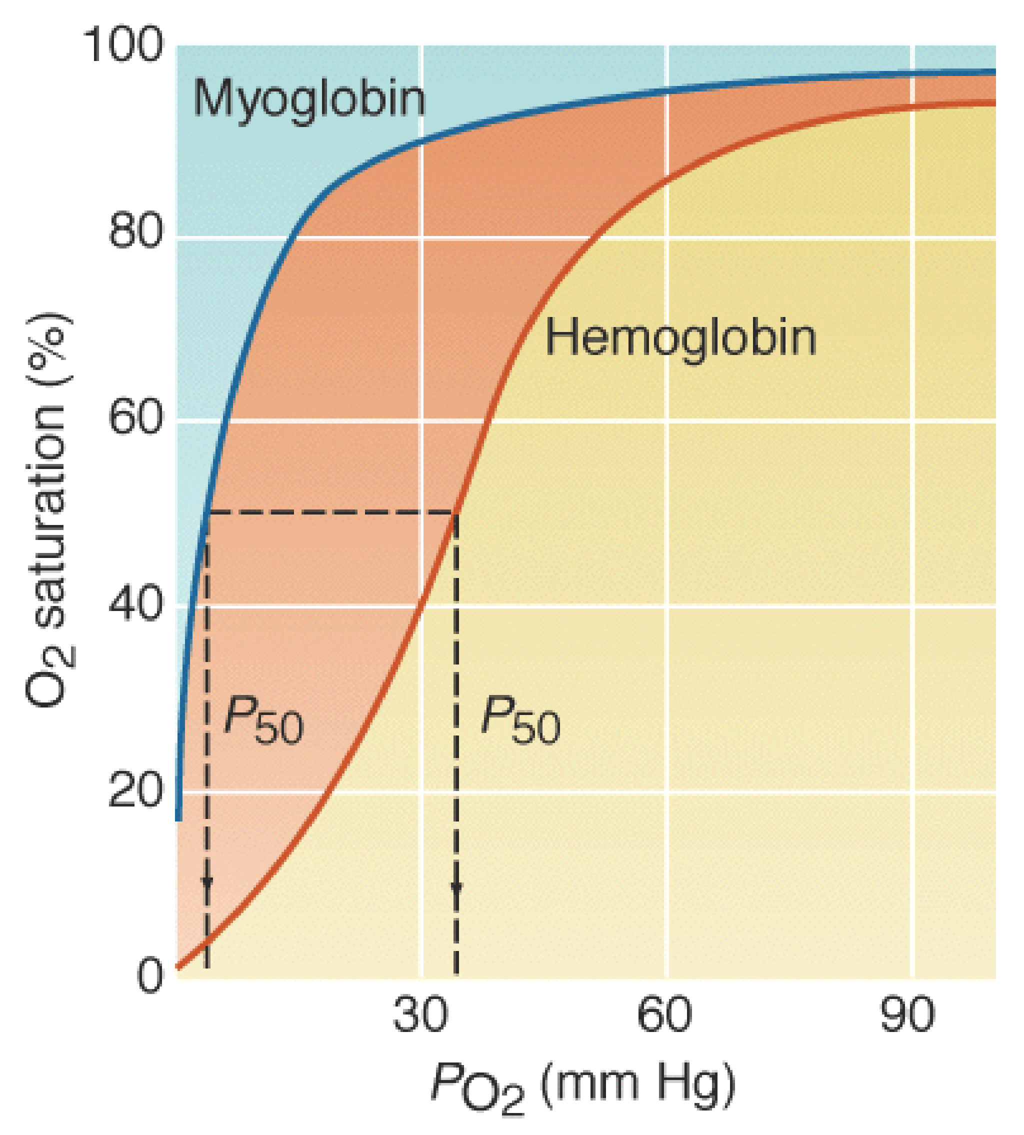


Heme



(c)
His E7
Phe CD1
Val E11
H
O_2
Fe
His F8



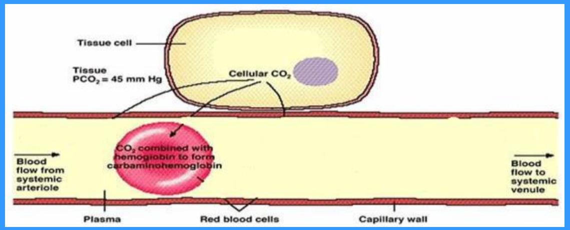


The hemoglobin loading curve

The hemoglobin loading curve is sigmoidal due to the “cooperativity effect” of the hemoglobin monomers.

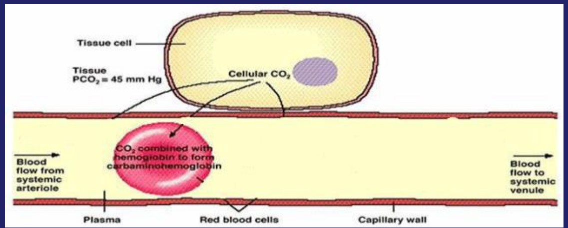
The P50 for hemoglobin is a measure of the affinity of the hemoglobin for oxygen (like the Km for enzyme reactions)

- The P50 for myoglobin is less than that for hemoglobin allowing it to “steal” oxygen from hemoglobin.
- The P50 of hemoglobin for carbon monoxide is about 1/200 of that for oxygen. (and the binding is irreversible)

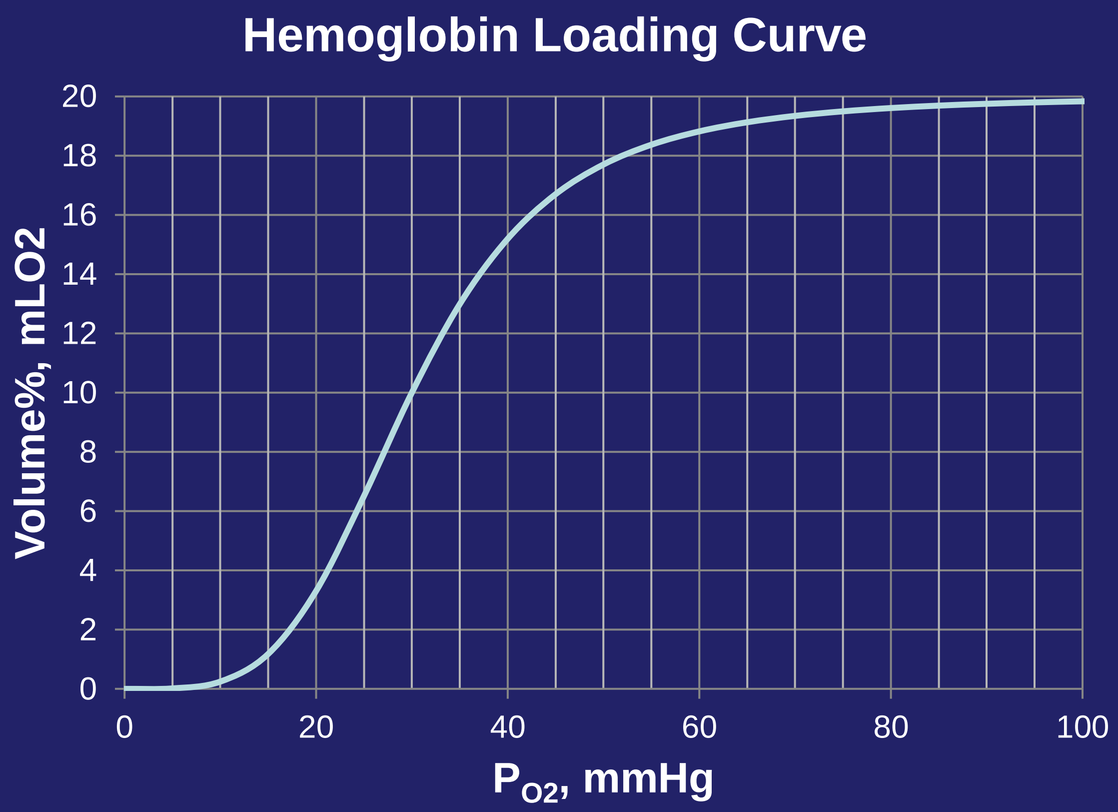


Characteristics of some vertebrate hemoglobins

Animal	P_{50} mmO_2	O_2 Capacity ml O_2 /100 ml blood
Human adult	30	20
Human fetus	20	8.4
Alpaca	18.4	18
Seal (Cystophora)	24	36
Penguin	34	22
Crocodile	38	8-10
Frog (Rana catesbiana)	13.2	9.8
Mackerel	16	15.7
Shark (Squalus)	17	4.4

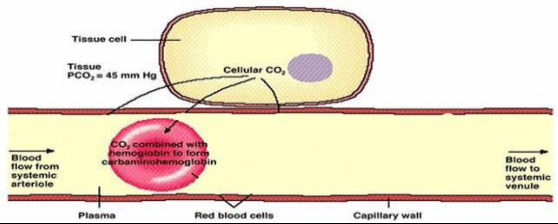


O_2 Delivery

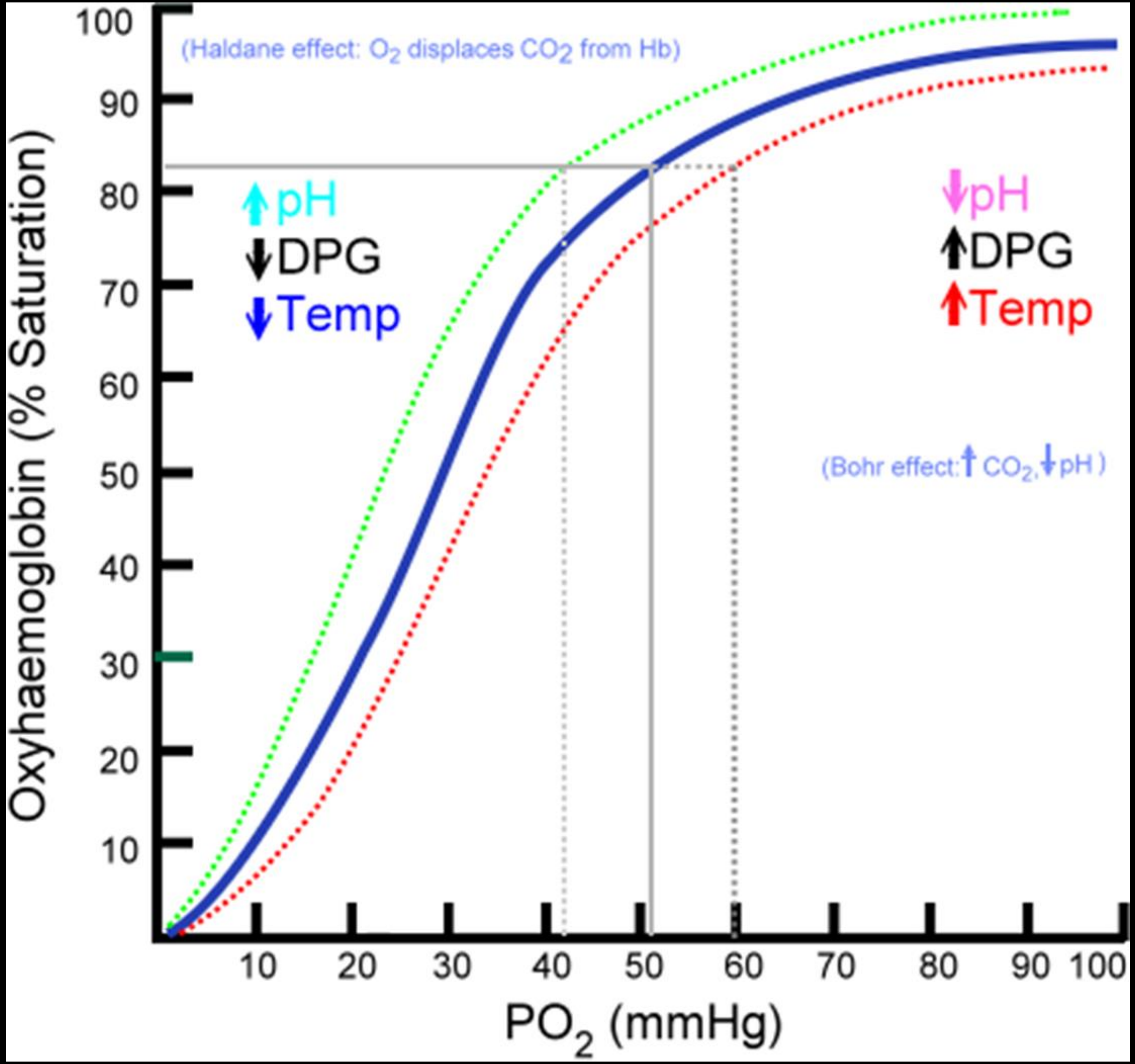


ΔP_{O2} mmHg	ΔV_{O2} Vol%
100 to 40	4.8
100 to 30	10
100 to 20	16.7

PO2 mmHg	% Saturation
100	99.2
80	98.06



Modulation of the Binding Curve



A drop in pH causes a shift to the right (decreased affinity). Why is this beneficial?

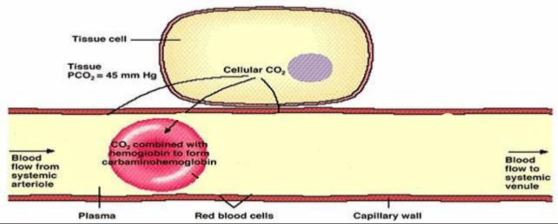
Other factors:

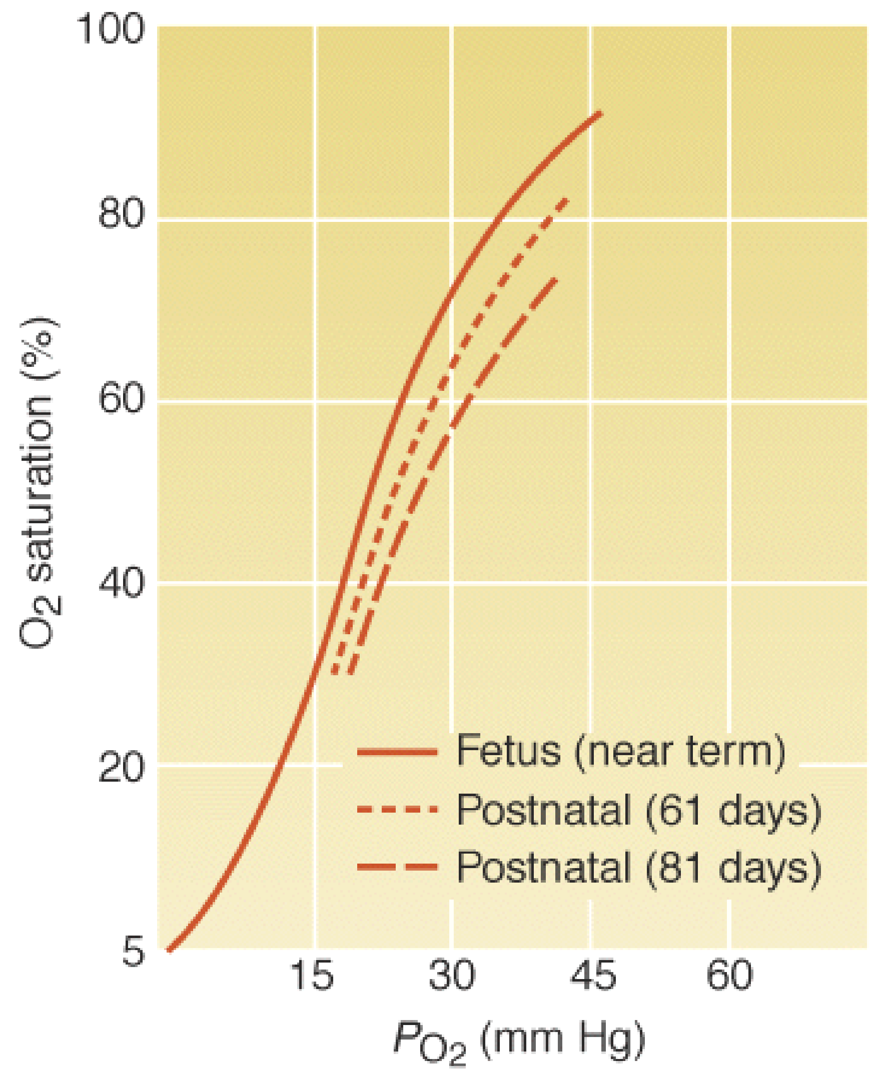
•Elevated temp: right shift

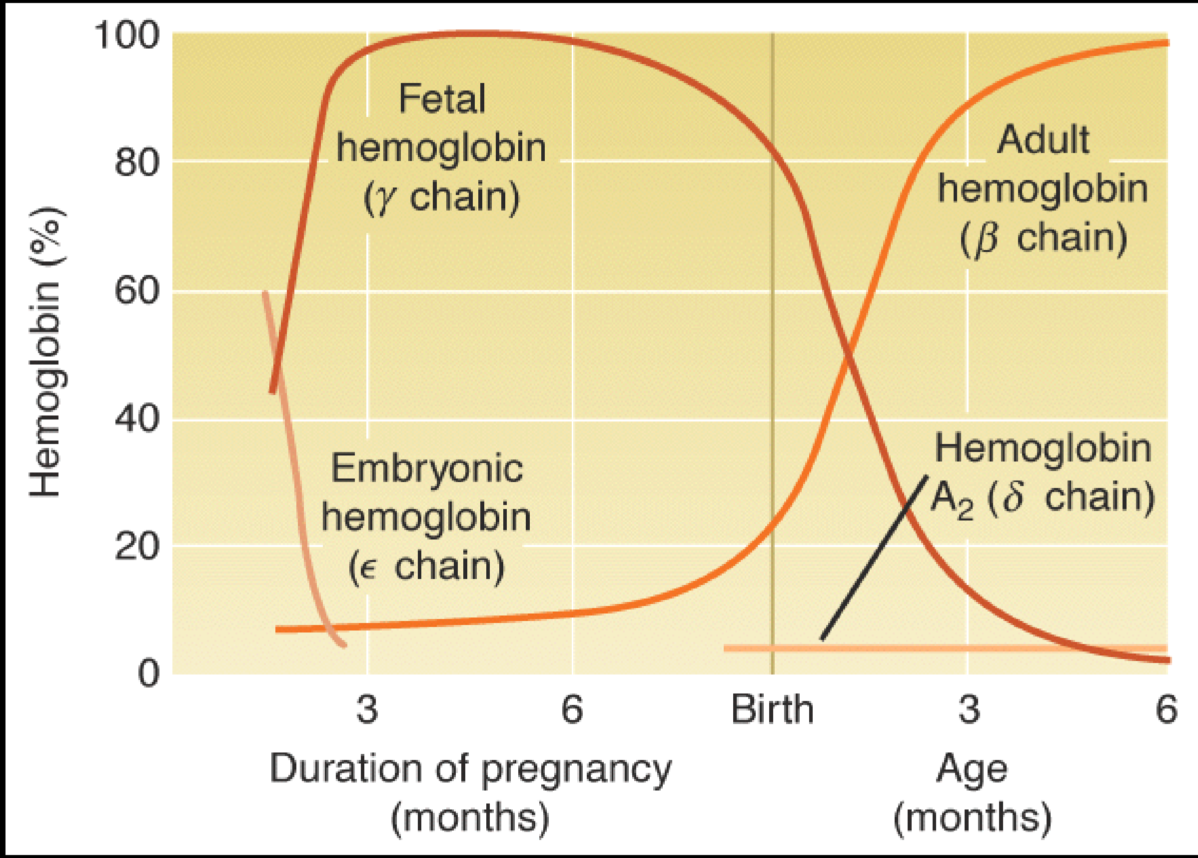
•Binding of organic phosphates (BPG in humans): right shift

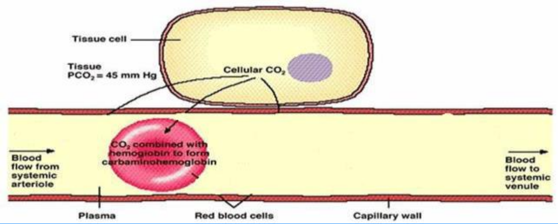
Other organic phosphates: ATP, GTP, IP_3.

Fetal Hemoglobin in Mammals



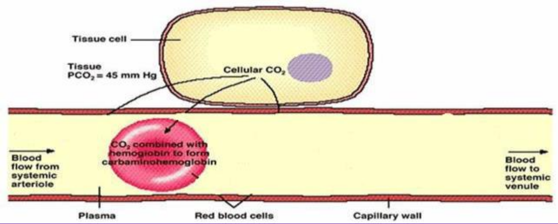






Other Oxygen Transporters

	Hemoglobin	Erythro-cruorin	Chloro-cruorin	Hem-erythrin	Hemo-cyanin
Units	4	12	12	8	12
mW (kD)	64	3500	3000	105	1500
P_{50}	25	26	58	8	103
n	4	1.5	1.5	1	3
Basis	Fe	Fe	Fe	Fe	Cu
Color (ox/deox)	Red/Blue	Red/Blue	Red/Green	Red/Blue	Blue/Clear
In Cells?	Yes	No	No	No	No
Organisms	Mammals, etc.	Marine annelids	Marine annelids	Marine annelids	Molluscs, Some arthropods (Limulus, Homarus)



CO_2 Transport in Blood

The governing equation: $CO_2 + H_2O \leftrightarrow H_2CO_3 \leftrightarrow H^+ + HCO_3^-$

For the carbonic acid – bicarbonate reaction, pK=6.1 at 37^0C.

pH is maintained at about 7.4 by buffering (protiens, phosphate buffer, etc.)

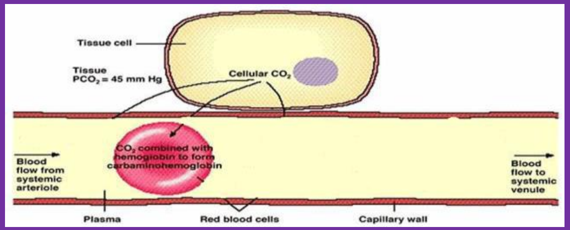
$$K=\frac{[H^+][HCO_3^+]}{[H_2CO_3]}$$

$$[H^+]=K\frac{[H_2CO_3]}{[HCO_3^-]}$$

$$pH=pK-\log\frac{[H_2CO_3]}{[HCO_3^-]}$$

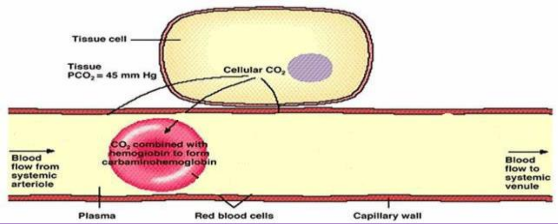
$$-\log\frac{[H_2CO_3]}{[HCO_3^-]}=pH-pK=7.4-6.1=1.3$$

$$\frac{[H_2CO_3]}{[HCO_3^-]}=\frac{1}{20}$$



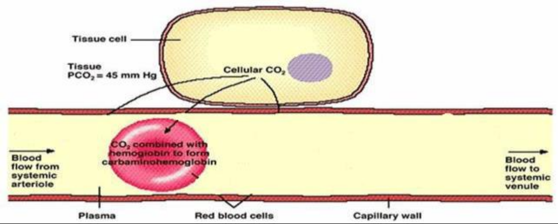
Effect of pH on bicarbonate transport

pH	$[H_2CO_3]/[HCO_3]$	% Bicarb
7.0	1/7.9	12.5
7.2	1/12.5	8
7.4	1/20	5
7.6	1/32	3
7.8	1/50	2
8.0	1/79	1.2

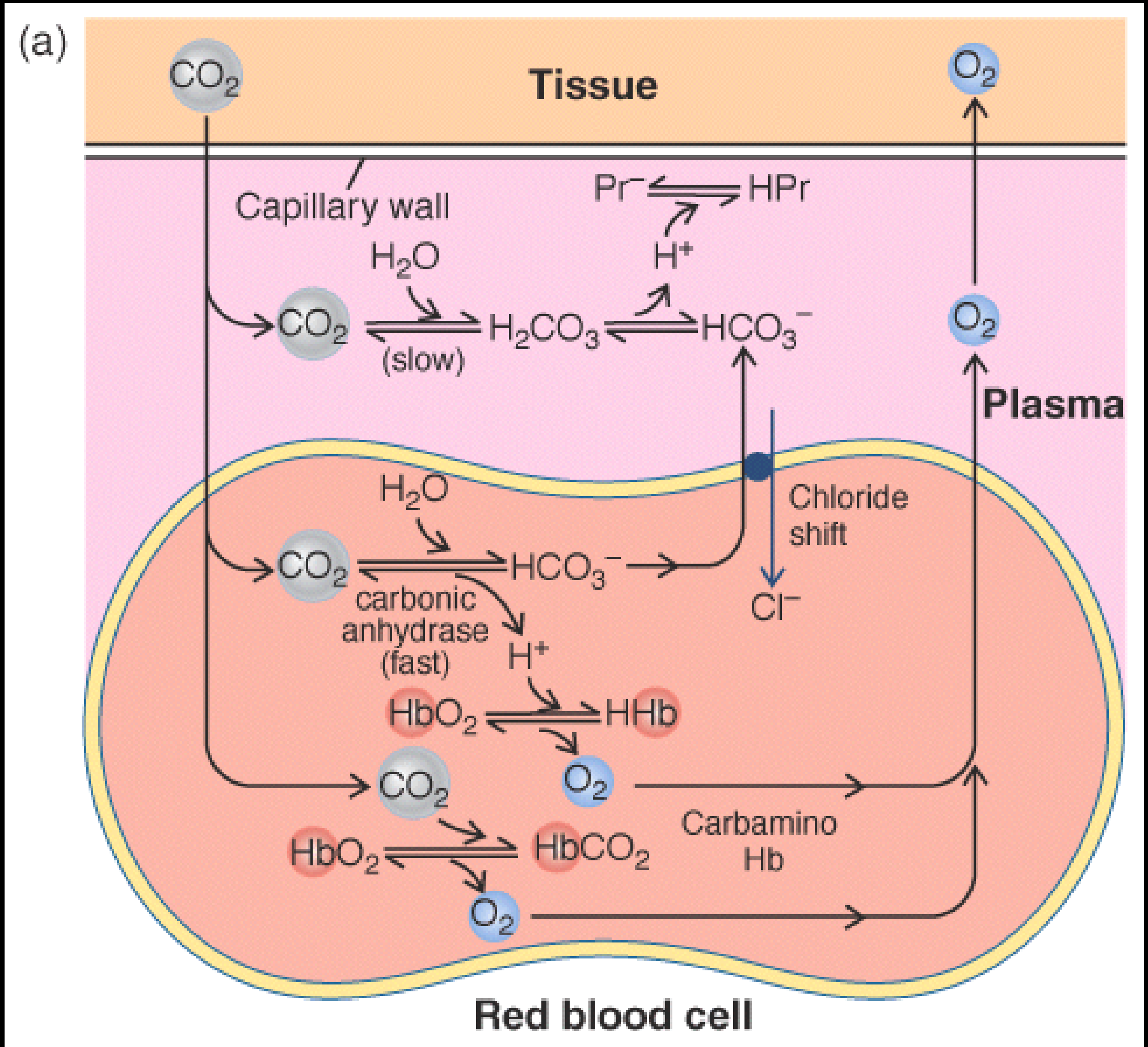


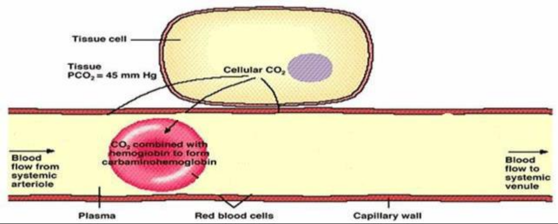
Carbon Dioxide Transport

- There are three pools of CO_2 in the blood:
  - Dissolved CO_2 : 5%
  - Carbamino CO_2 : 5%
    - Protein-NH_2 + $CO_2 \leftrightarrow H^+$ + protein-$NHCOO^-$
  - Bicarbonate : 90%

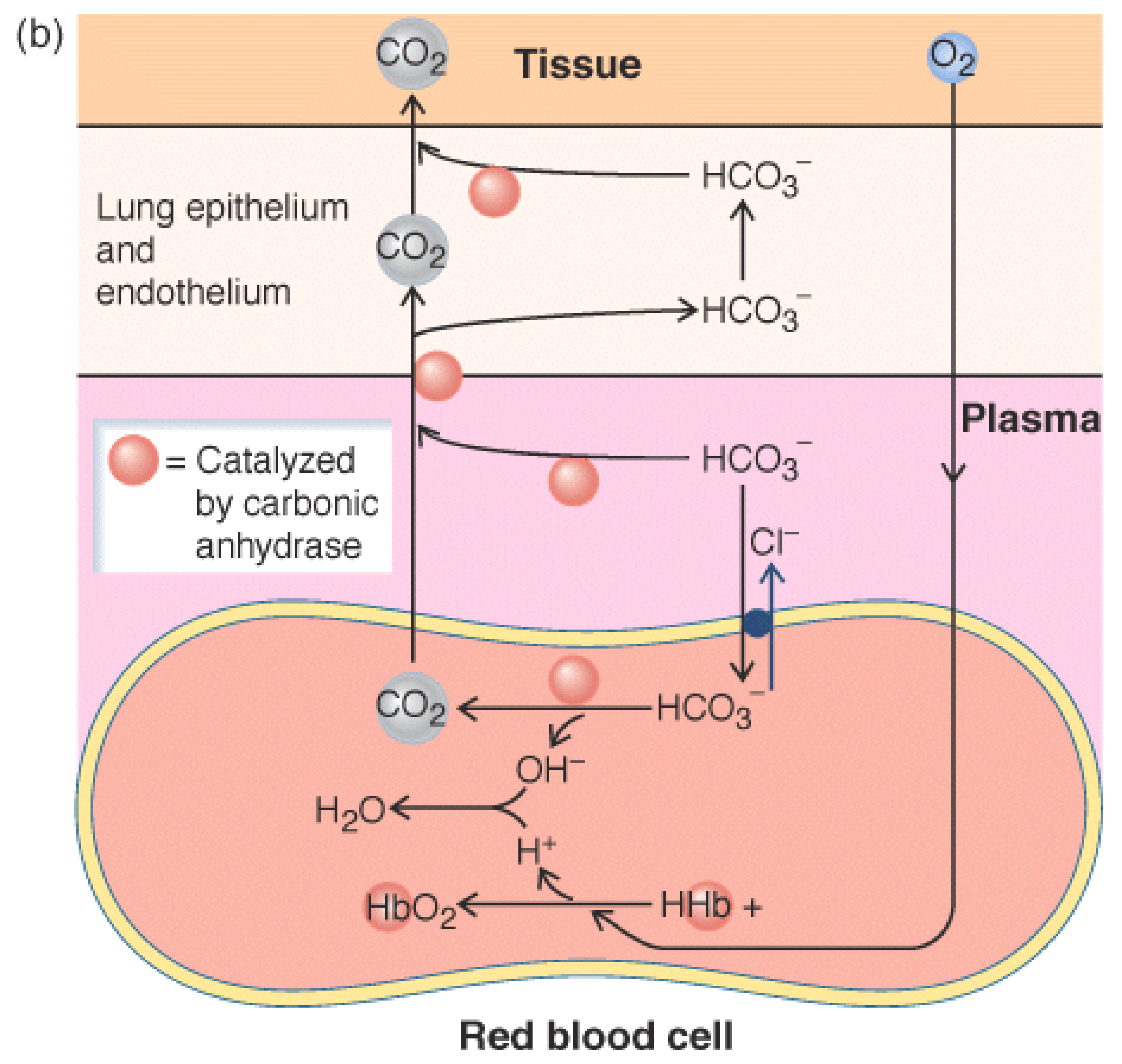


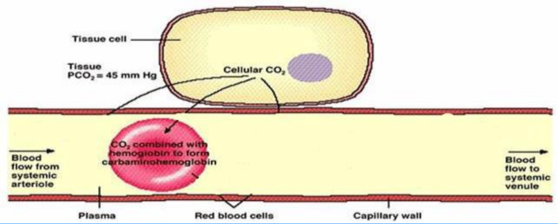
Summary:Gas Exchange in the tissues





Gas Exchange in the Lung





Altitude adaptations

- Increased hematocrit (increased RBC mass)
- higher concentration of capillaries in skeletal muscle tissue
- increased myoglobin
- increased mitochondria
- increased aerobic enzyme concentration
- increase in 2,3-BPG (lower affinity).
- The length of full hematological adaptation can be approximated by multiplying the altitude in kilometers by 11.4 days. For example, to adapt to 4,000 metres (13,000 ft) of altitude would require around 46 days.

Problem: hypoxic pulmonary vasoconstriction, leads to pulmonary edema due to elevated pulmonary blood pressure (exacerbated by right ventricular hypertrophy).