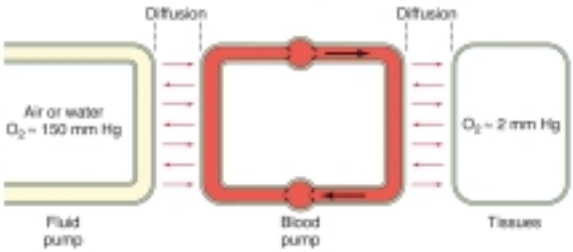
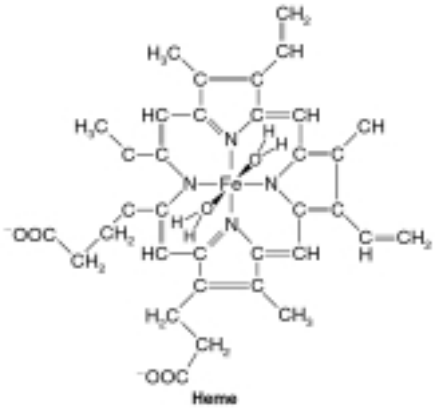
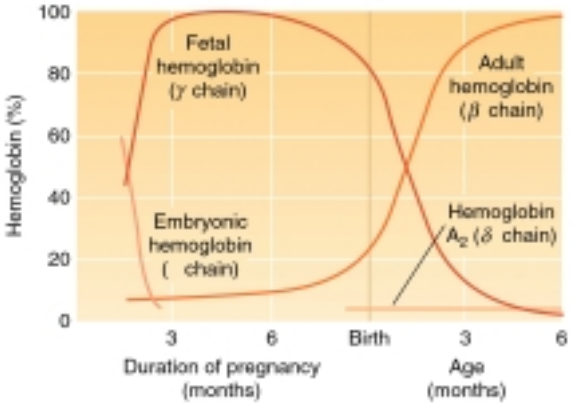
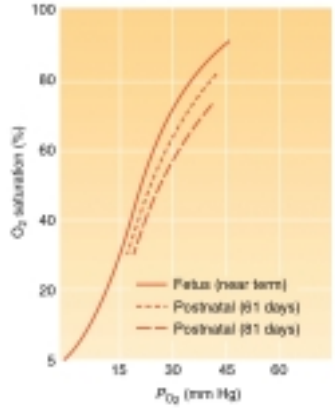
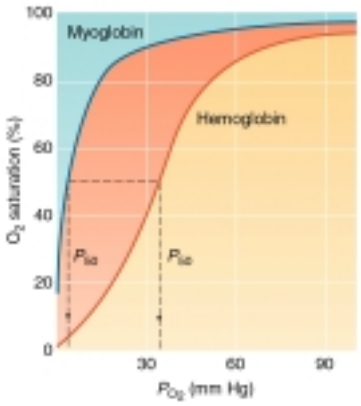
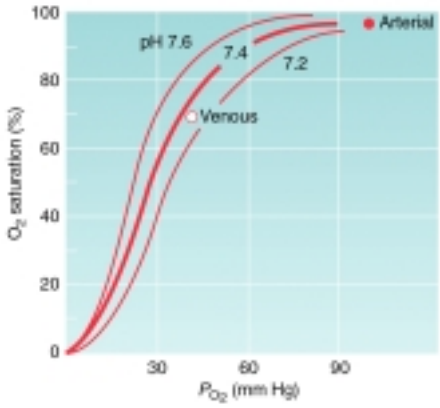

Diffusion
Diffusion
Air or water
$O_2$ = 150 mm Hg
$O_2$ = 2 mm Hg
Fluid pump
Blood pump
Tissues

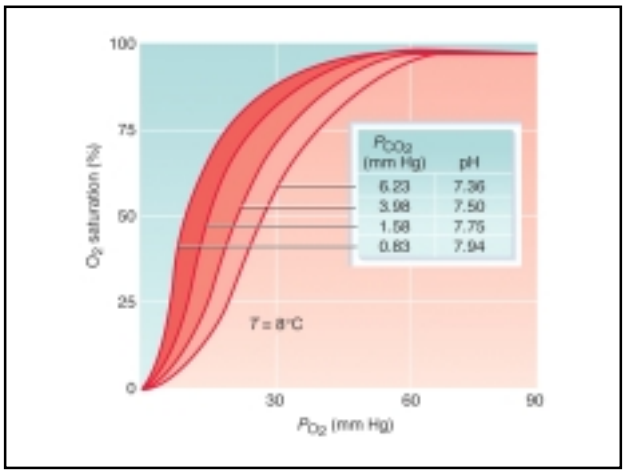

Heme

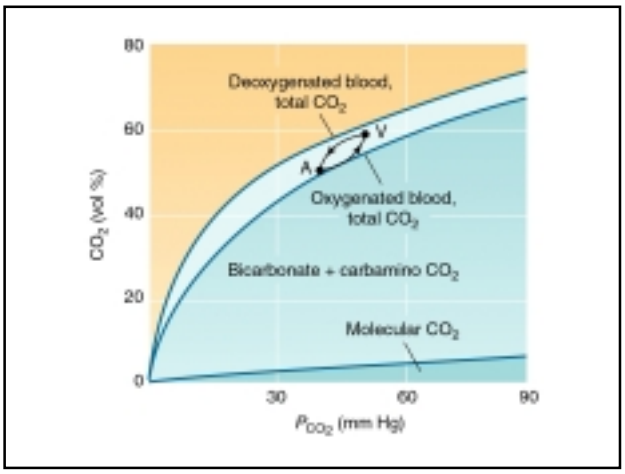

Hemoglobin (%)
Fetal hemoglobin (γ chain)
Adult hemoglobin (β chain)
Embryonic hemoglobin ( chain)
Hemoglobin $A_2$ (δ chain)
Duration of pregnancy (months)
Birth
Age (months)

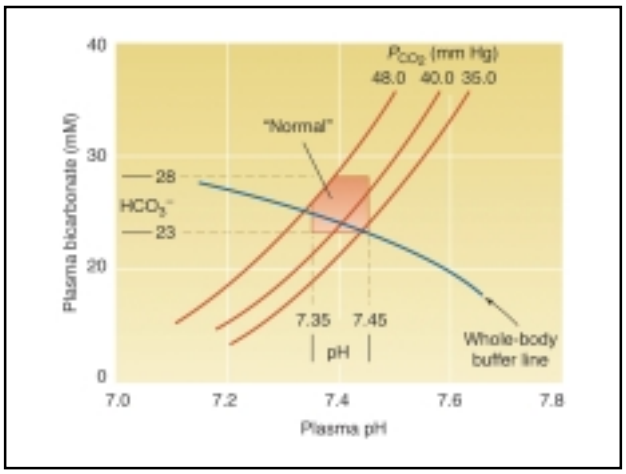

$O_2$ saturation (%)
Fetus (near term)
Postnatal (61 days)
Postnatal (81 days)
$P_{O_2}$ (mm Hg)

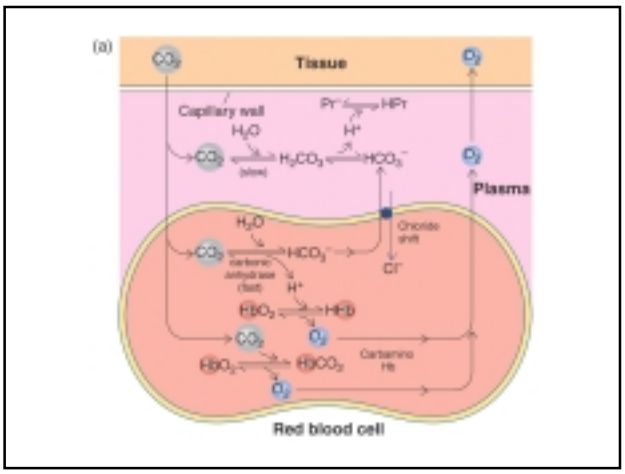

Myoglobin
Hemoglobin
$O_2$ saturation (%)
$P_{50}$
$P_{50}$
$P_{O_2}$ (mm Hg)

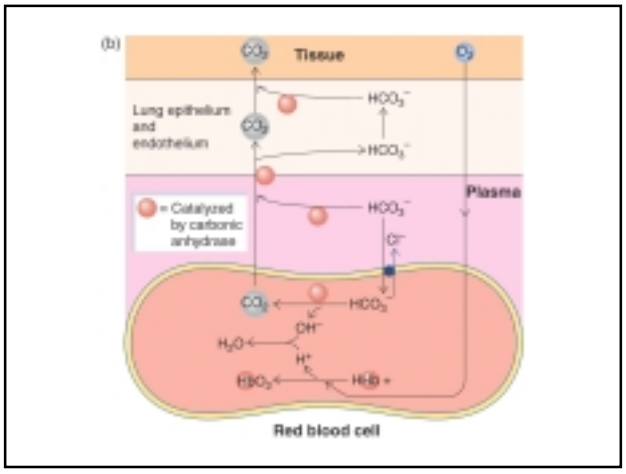

Arterial
pH 7.6
7.4
7.2
Venous
$O_2$ saturation (%)
$P_{O_2}$ (mm Hg)

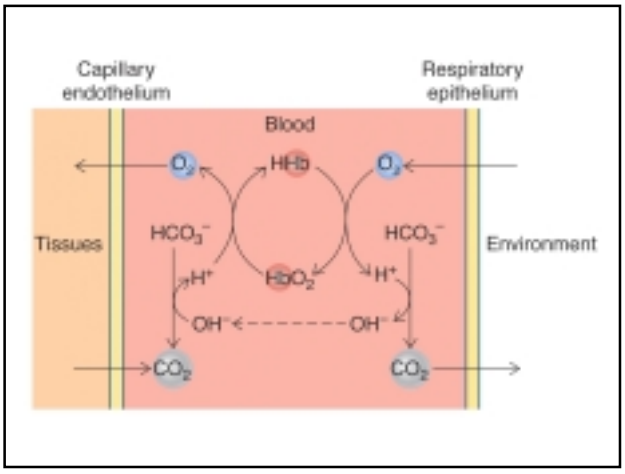

100
75
50
25
0
30
60
90
$O_2$ saturation (%)
$P_{O_2}$ (mm Hg)
$P_{CO_2}$ (mm Hg)
pH
6.23
7.36
3.98
7.50
1.58
7.75
0.83
7.94
T = 8°C

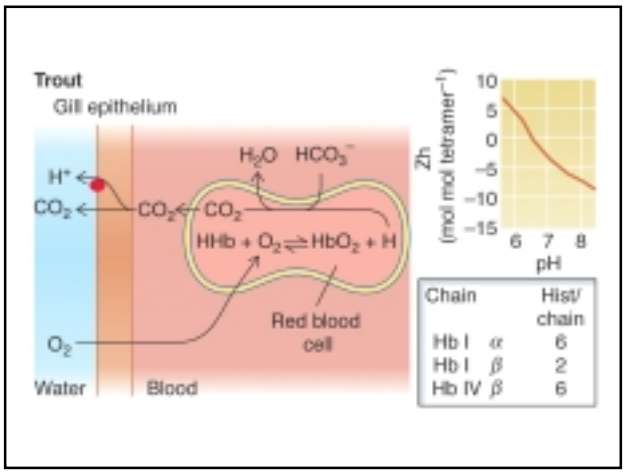

80
60
40
20
0
30
60
90
$CO_2$ (vol %)
$P_{CO_2}$ (mm Hg)
Deoxygenated blood, total $CO_2$
V
A
Oxygenated blood, total $CO_2$
Bicarbonate + carbamino $CO_2$
Molecular $CO_2$

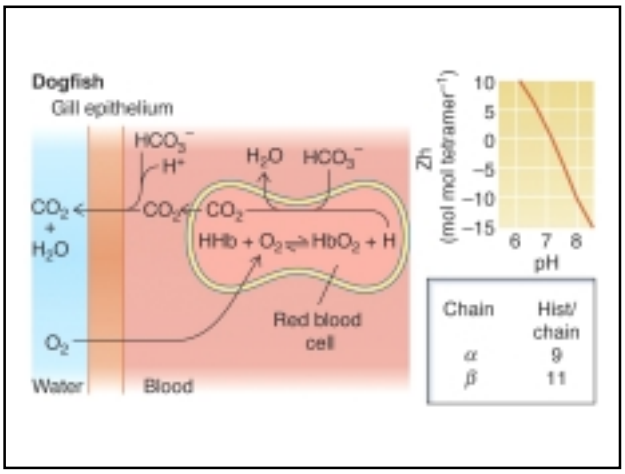

40
30
20
0
7.0
7.2
7.4
7.6
7.8
Plasma bicarbonate (mM)
Plasma pH
$P_{CO_2}$ (mm Hg)
48.0
40.0
35.0
"Normal"
28
$HCO_3^-$
23
7.35
7.45
pH
Whole-body buffer line

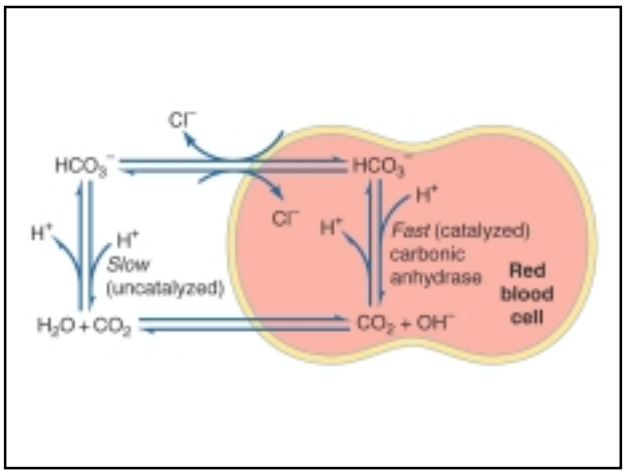

(a)
Tissue
Capillary wall
Plasma
Red blood cell

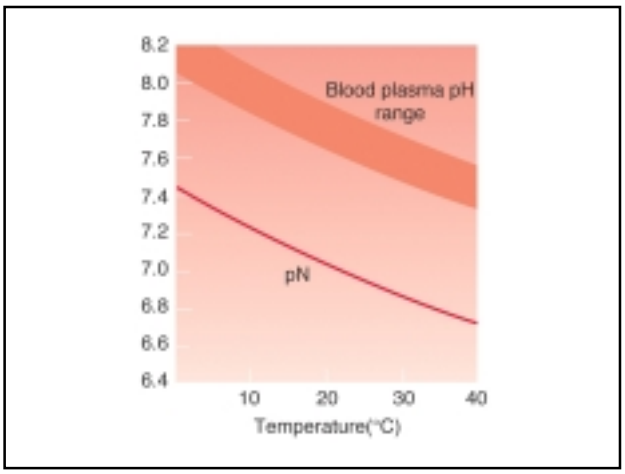

(b)
Tissue
Lung epithelium and endothelium
Plasma
= Catalyzed by carbonic anhydrase
Red blood cell

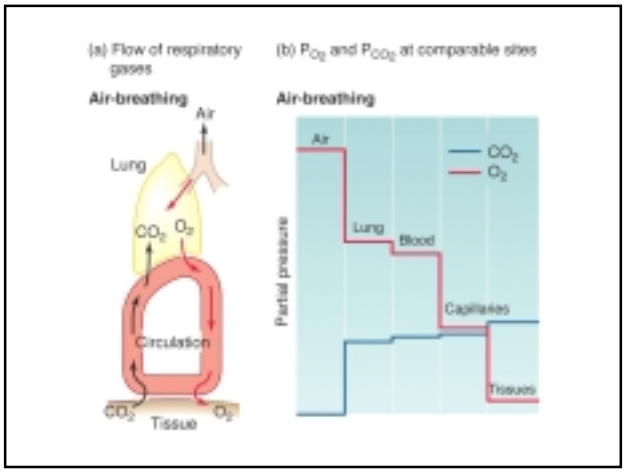

Capillary endothelium
Respiratory epithelium
Blood
Tissues
Environment

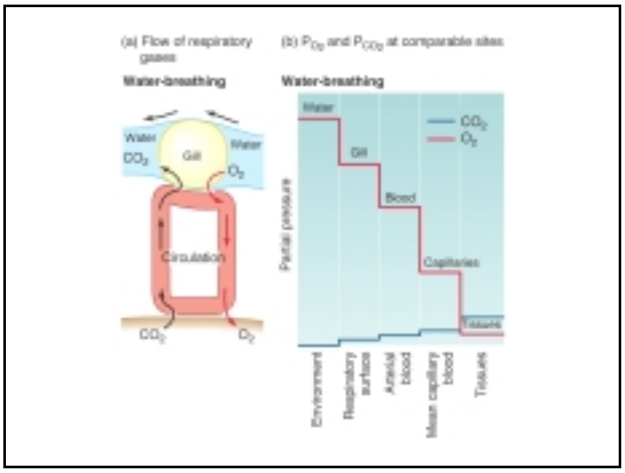

Trout
Gill epithelium
$H^+$
$CO_2$
$CO_2$
$CO_2$
$H_2O$ $HCO_3^-$
$HHb + O_2 \rightleftharpoons HbO_2 + H$
Red blood cell
$O_2$
Water
Blood
Zh (mol mol tetramer$^{-1}$)
10
5
0
−5
−10
−15
6 7 8
pH
Chain | Hist/chain
Hb I α 6
Hb I β 2
Hb IV β 6

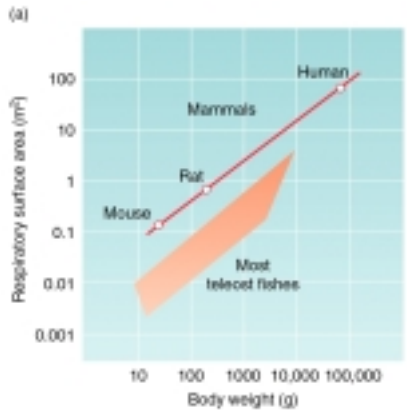

Dogfish
Gill epithelium
$HCO_3^-$
$H^+$
$CO_2 + H_2O$
$CO_2$
$CO_2$
$H_2O$ $HCO_3^-$
$HHb + O_2 \rightleftharpoons HbO_2 + H$
Red blood cell
$O_2$
Water
Blood
Zh (mol mol tetramer$^{-1}$)
10
5
0
−5
−10
−15
6 7 8
pH
Chain | Hist/chain
α 9
β 11

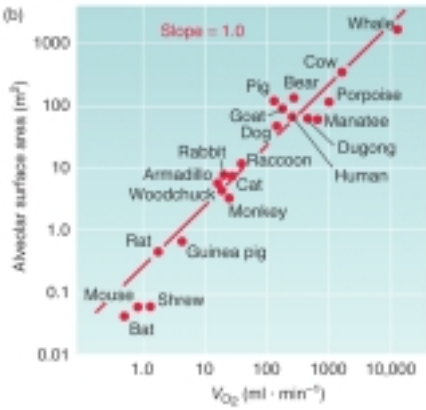

$Cl^-$
$HCO_3^-$
$HCO_3^-$
$Cl^-$
$H^+$
$H^+$
$H^+$
$H^+$
Slow (uncatalyzed)
Fast (catalyzed) carbonic anhydrase
Red blood cell
$H_2O + CO_2$
$CO_2 + OH^-$

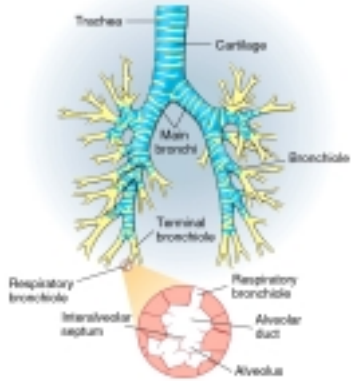

8.2
8.0
7.8
7.6
7.4
7.2
7.0
6.8
6.6
6.4
Blood plasma pH range
pN
10 20 30 40
Temperature(°C)

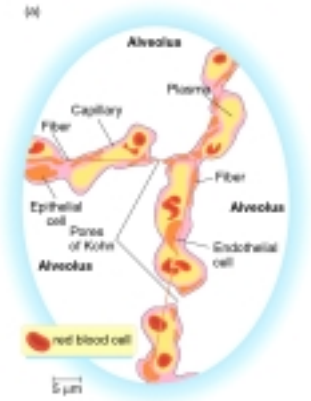

(a) Flow of respiratory gases
(b) $P_{O_2}$ and $P_{CO_2}$ at comparable sites
Air-breathing
Air-breathing
Air
Lung
$CO_2$ $O_2$
Circulation
$CO_2$ Tissue $O_2$
$CO_2$
$O_2$
Air
Lung
Blood
Capillaries
Tissues
Partial pressure

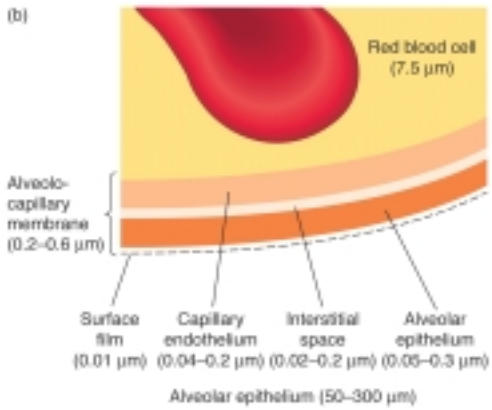

(a) Flow of respiratory gases
(b) $P_{O_2}$ and $P_{CO_2}$ at comparable sites
Water-breathing
Water-breathing
Water
$CO_2$
Gill
Water
$O_2$
Circulation
$CO_2$
$O_2$
Water
Gill
Blood
Capillaries
Tissues
Partial pressure
Environment
Respiratory surface
Arterial blood
Mixed capillary blood
Tissues

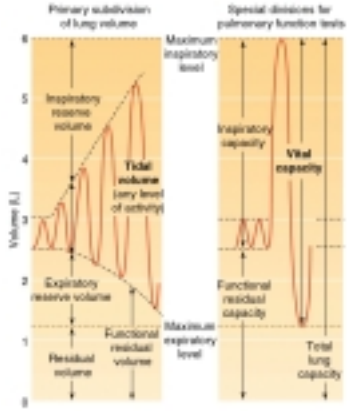

(a)
Respiratory surface area (m²)
100
10
1
0.1
0.01
0.001
Human
Mammals
Rat
Mouse
Most
teleost fishes
10
100
1000
10,000
100,000
Body weight (g)

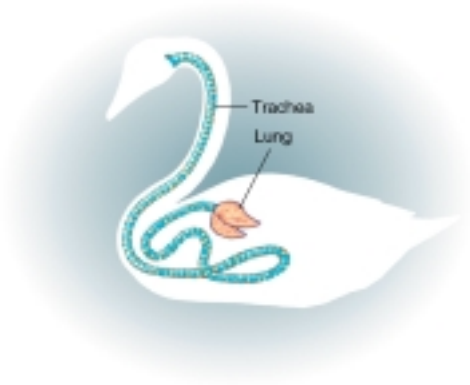

(b)
Slope = 1.0
Alveolar surface area (m²)
1000
100
10
1.0
0.1
0.01
Whale
Cow
Pig
Bear
Porpoise
Goat
Manatee
Dog
Dugong
Rabbit
Raccoon
Armadillo
Human
Cat
Woodchuck
Monkey
Rat
Guinea pig
Mouse
Shrew
Bat
1.0
10
100
1000
10,000
V̇O₂ (ml · min⁻¹)

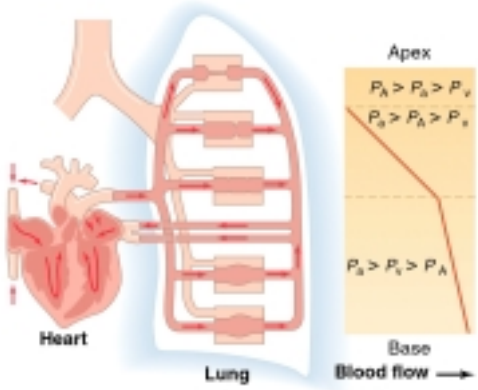

Trachea
Cartilage
Main bronchi
Bronchiole
Terminal bronchiole
Respiratory bronchiole
Respiratory bronchiole
Interalveolar septum
Alveolar duct
Alveolus

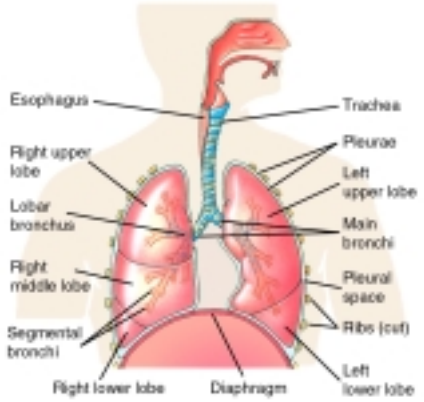

(A)
Alveolus
Plasma
Capillary
Fiber
Fiber
Epithelial cell
Alveolus
Pores of Kohn
Endothelial cell
Alveolus
red blood cell
5 µm


(b)
Red blood cell
(7.5 µm)
Alveolo-capillary membrane
(0.2–0.6 µm)
Surface film
(0.01 µm)
Capillary endothelium
(0.04–0.2 µm)
Interstitial space
(0.02–0.2 µm)
Alveolar epithelium
(0.05–0.3 µm)
Alveolar epithelium (50–300 µm)

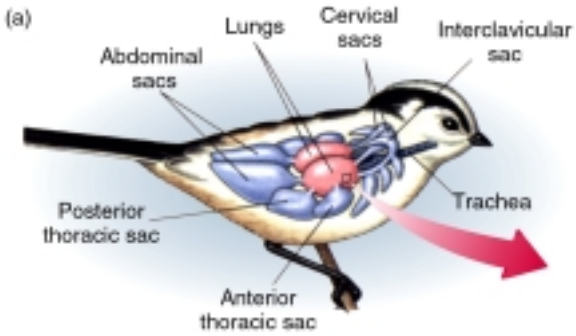

Primary subdivision of lung volume
Special divisions for pulmonary function tests
Maximum inspiratory level
Inspiratory reserve volume
Tidal volume
Inspiratory capacity
Vital capacity
Volume (L)
Expiratory reserve volume
Functional residual capacity
Residual volume
Functional residual volume
Maximum expiratory level
Total lung capacity

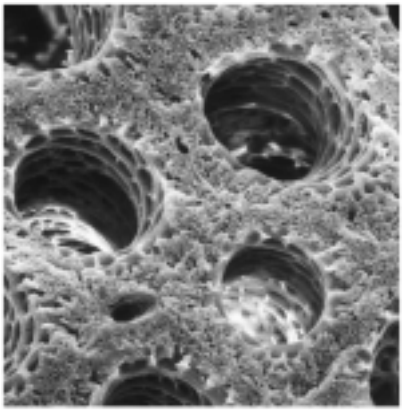

Trachea
Lung

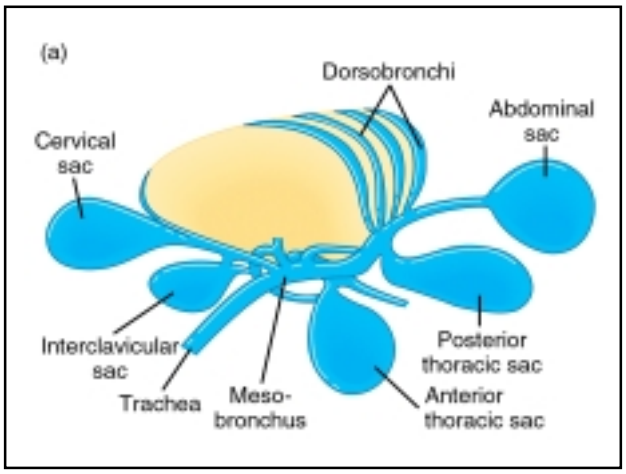

Apex
$P_A > P_a > P_v$
$P_a > P_A > P_v$
$P_a > P_v > P_A$
Base
Heart
Lung
Blood flow

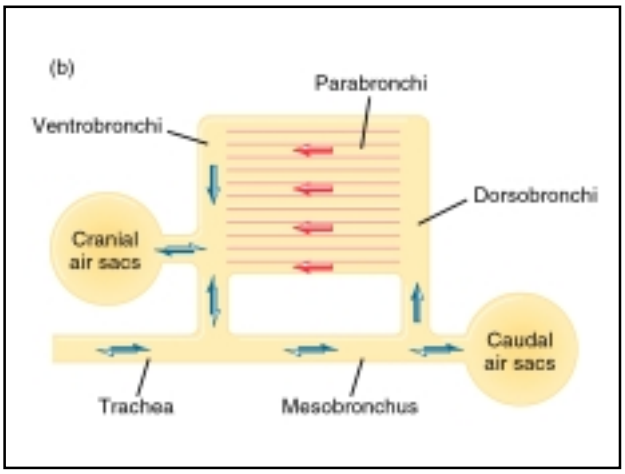

Esophagus
Trachea
Right upper lobe
Pleurae
Left upper lobe
Lobar bronchus
Main bronchi
Right middle lobe
Pleural space
Ribs (cut)
Segmental bronchi
Right lower lobe
Diaphragm
Left lower lobe

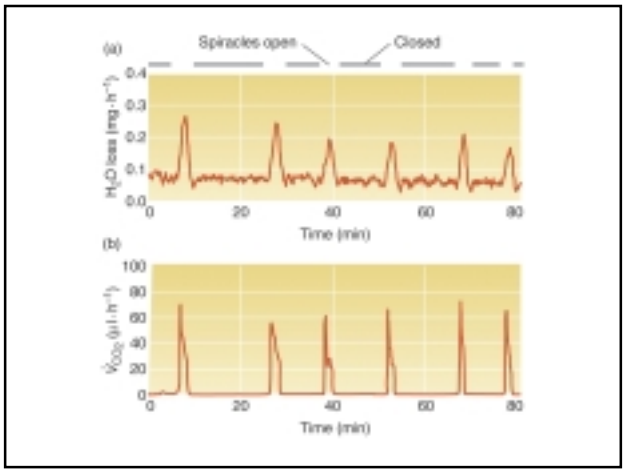
(a) Inhalation
Vertebral column
Rib
Rib movement
Diaphragm
Internal intercostal
External intercostal
(b) Exhalation
Rib
Diaphragm
Internal intercostal
External intercostal
Rib movement


(a)
Lungs
Cervical sacs
Interclavicular sac
Abdominal sacs
Trachea
Posterior thoracic sac
Anterior thoracic sac




(a)
Dorsobronchi
Abdominal sac
Cervical sac
Interclavicular sac
Trachea
Meso-bronchus
Posterior thoracic sac
Anterior thoracic sac


(b)
Parabronchi
Ventrobronchi
Dorsobronchi
Cranial air sacs
Caudal air sacs
Trachea
Mesobronchus


(a)
Spiracles open
Closed
Time (min)
(b)
Time (min)