

### FICK'S LAW

*Adolf Fick, 1858*

Fick's law of diffusion of a gas across a fluid membrane:

$$\text{Rate of diffusion} = KA(P_2 - P_1)/D$$

Wherein:

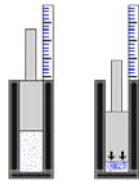
- K = a *temperature-dependent* diffusion constant.
- A = the surface area available for diffusion.
- $(P_2 - P_1)$  = The difference in concentration (partial pressure) of the gas across the membrane.
- D = the distance over which diffusion must take place.

### Properties of "Ideal" Gases

- Gases are composed of molecules whose size is negligible compared to the average distance between them.
  - Gas has a low density because its molecules are spread apart over a large volume.
- Molecules move in random lines in all directions and at various speeds.
  - The forces of attraction or repulsion between two molecules in a gas are very weak or negligible, except when they collide.
  - When molecules collide with one another, no kinetic energy is lost.
- The average kinetic energy of a molecule is proportional to the absolute temperature.
- Gases are easily expandable and compressible (unlike solids and liquids).
- A gas will completely fill whatever container it is in.
  - i.e., container volume = gas volume
- Gases have a measurement of pressure (force exerted per unit area of surface).
  - Units: 1 atmosphere [atm] ( $\approx$  1 bar) = 760 mmHg (= 760 torr) = 14.7 psi = 0.1 MPa

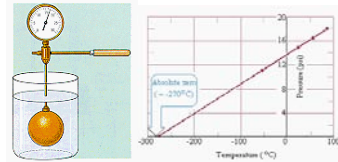
### Boyles Law

- Gas pressure (P) is **inversely** proportional to gas volume (V)
- $P \propto 1/V$
- $\therefore \uparrow V \rightarrow \downarrow P \quad \uparrow P \rightarrow \downarrow V \quad \downarrow V \rightarrow \uparrow P \quad \downarrow P \rightarrow \uparrow V$
- $P_1 V_1 = P_2 V_2$  (if no gas is added/lost and temperature is held constant)
- $\downarrow V \rightarrow$  also  $\uparrow$  density



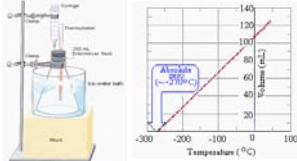
### Amontons Law

- Gas pressure (P) is **directly** proportional to **absolute** gas temperature (T in °K)
- $P \propto T$
- $\therefore \uparrow T \rightarrow \uparrow P \quad \uparrow P \rightarrow \uparrow T \quad \downarrow T \rightarrow \downarrow P \quad \downarrow P \rightarrow \downarrow T$
- $\therefore P_1/T_1 = P_2/T_2$  (if no gas is added/lost and volume is held constant)
- $0^\circ\text{C} = 273^\circ\text{K}$



### Charles Law

- Gas volume (V) is **directly** proportional to **absolute** gas temperature (T in °K)
- $V \propto T$
- $\therefore \uparrow T \rightarrow \uparrow V \quad \uparrow V \rightarrow \uparrow T \quad \downarrow T \rightarrow \downarrow V \quad \downarrow V \rightarrow \downarrow T$
- $\therefore V_1/T_1 = V_2/T_2$  (if no gas is added/lost and pressure is held constant)
- $0^\circ\text{C} = 273^\circ\text{K}$



### $\therefore$ Combined Gas Law

- Combining Boyles, Amontons & Charles Laws:
- $\therefore P_1 V_1 / T_1 = P_2 V_2 / T_2$  (if no gas is added/lost)
  - $P_1$  = initial pressure
  - $V_1$  = initial volume
  - $T_1$  = initial absolute temperature
  - $P_2$  = final pressure
  - $V_2$  = final volume
  - $T_2$  = final absolute temperature
- **Ideal Gas Law:**  $PV = nRT$ 
  - n = total number of gas molecules in the vessel
  - R = constant

# Diving Physiology

### Gas Exchange: notes

Carbon dioxide (0.03%)  
Argon (0.95%)  
Oxygen (20.95%) → Partial Pressure ( $P_{O_2}$ ) ~ 0.2 atmospheres

Nitrogen (78.09%) → Partial Pressure ( $P_{N_2}$ ) ~ 0.8 atmospheres  
**1.0 Atmosphere Total Pressure**

Air (gases) in our atmosphere are heavy and put pressure on us

2 Atmospheres of Pressure  
Push balloon 10 m underwater  
10 meters

Balloon shrinks to half its size at surface!  
Partial Pressure ( $P_{O_2}$ ) ~ 0.4 atmospheres  
Partial Pressure ( $P_{N_2}$ ) ~ 1.6 atmospheres  
**2.0 Atmospheres Total Pressure**

Water is heavy and increases pressure/compresses gasses.

Gases can *diffuse* (spread out to less-concentrated places) and dissolve in water.

High Concentration/  
Partial Pressure

Low Concentration/  
Partial Pressure

Also note: When carbon dioxide ( $CO_2$ ) dissolves in water, it creates an *acid* (carbonic acid → lower pH).

## Gas Exchange *diving*

- ✦ Diving: potential hazards
- ✦ Why seals can dive so long (and avoid the hazards)

### Regulation of the drive to breathe

Inadequate breathing → Increased blood  $CO_2$  concentration ( $P_{CO_2}$ )

Decreased blood pH → Peripheral chemoreceptors (aortic and carotid bodies)

Decreased cerebrospinal fluid pH → Central chemoreceptors

Regulation of Breathing by Chemo-receptors

Brain stem respiratory center → Increased breathing

Maxilla oblongata

✦ **Increasing  $P_{CO_2}$  decreases pH, stimulating you to breathe**

c.f., Fig. 42.28

### Free diving & shallow-water blackout

- ✦ Free diving = breath-hold diving
- ✦ Hyperventilate → ↓  $P_{CO_2}$  in blood → you don't feel the need to breathe → dive long & deep.
- ✦ Diving → ↑ depth → ↑  $P_{O_2}$ , so you extract more  $O_2$  from air.
- ✦ With low  $P_{CO_2}$  in blood, you still don't feel the need to breathe.
- ✦ Ascent → ↓ depth → ↓ ↓  $P_{O_2}$ .
- ✦ ↓  $P_{O_2}$  in blood to brain → loss of consciousness

### SCUBA: self-contained underwater breathing apparatus


#### Decompression Sickness (Bends)

- ✦ SCUBA: breathing air at ambient pressure
- ✦ At 30 meters depth, your whole body feels a pressure of 4 atm (1+3) -- including the air in your lungs.
- ✦ Diving → ↑ depth → ↑  $P_{N_2}$ .  $N_2$  dissolves in tissues.
- ✦ Ascent → ↓ depth → ↓  $P_{N_2}$  (decompress).  $N_2$  tissues comes out of solution → microbubbles.
- ✦ If enough microbubbles form, may collect in tissues & small vessels causing bends.

### SCUBA: self-contained underwater breathing apparatus


#### Air Embolism

- ✦ SCUBA: breathing air at ambient pressure
- ✦ At depth, lungs filled with air at high pressure
- ✦ Ascent → ↓ depth → ↓ total pressure.
  - ✦ ↓  $P$  → ↑  $V$
  - ✦ If holding your breath, lung volume overexpands
- ✦ Alveoli rupture → air bubbles into bloodstream
- ✦ Bubbles may lodge in tissues & small vessels causing stroke, heart attack, etc..



**SCUBA: self-contained underwater breathing apparatus**  
**The 3 Rules!**

- ❖ Don't panic!
  - ❖ You brought air with you — no need to rush
  - ❖ Stop! — Breathe! — Think!
- ❖ Never hold your breath!
  - ❖ if breathing compressed air
- ❖ Ascend slowly!
  - ❖ Allow your body to adapt gradually





**Marine Mammal Diving Physiology**

**Why can they dive so much better than us?**


*California sea lion*

**Elephant Seals**




**Elephant seal dives:**

- ❖ Telemetry tagged study

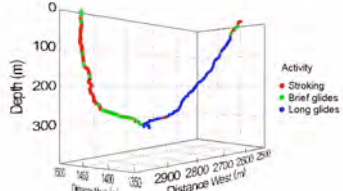


This male elephant seal was tracked with a geographic location time-depth recorder. Location of the area was substituted using measurements of light intensity and water temperature when the seal came to the sea surface to breathe.




**Elephant seal dives:**

- ❖ Swim 90 km/day
- ❖ Underwater 90% of time
- ❖ Ave. dive = 24 min — max 2 hr — with 2.5 min surface intervals
- ❖ Dives ave. 400+ meters — max 1500 meters



Activity

- Stroking
- Brief glides
- Long glides



**It's not in the lungs**

- ❖ Lung volume  $\approx$  4.6% of body volume for all mammals -- including marine mammals.
- ❖ Marine mammals don't rely on the air in their lungs while underwater.



**Marine mammals have 2 kinds of tricks:**

- ❖ Use oxygen slowly.
- ❖ Store a lot of oxygen.



***Use oxygen slowly:***  
**The Diving Reflex:**

- ❖ Heart rate slows
- ❖ Blood pressure decreases
- ❖ Peripheral circulation decreases
- ❖ Spleen shrinks: more blood into circulation



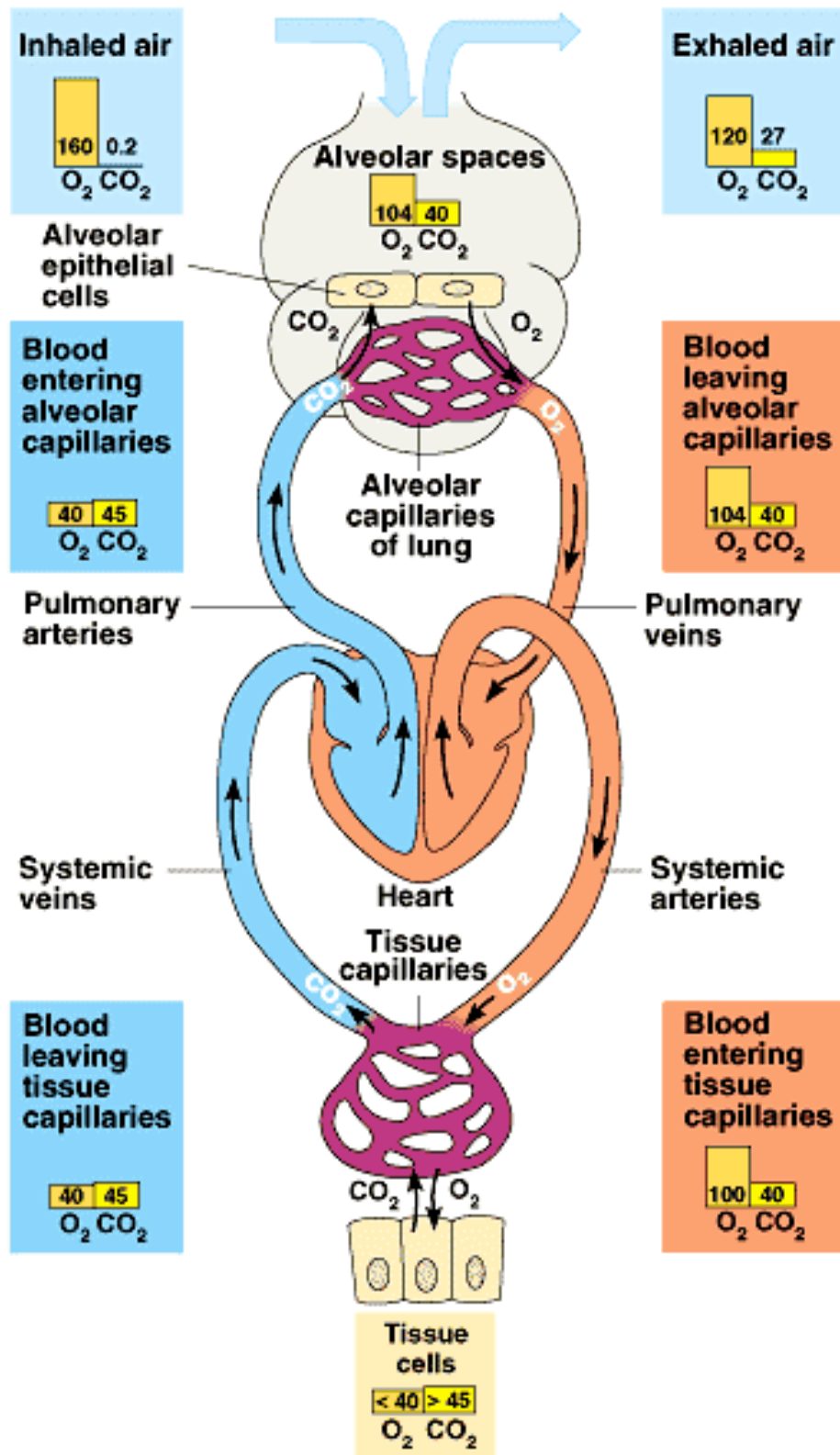
**Store a lot of oxygen:**

- ❖ Large blood volume
- ❖ High concentration of red cells
- ❖ High concentration of hemoglobin in red cells
- ❖ High concentration of myoglobin in muscle



**Why can they dive so much better than us?**

***Why don't they get air embolisms?***  
***Why don't they get the bends?***  
***Why don't they get shallow water blackout?***



c.f., Fig. 42.29

$O_2$  &  $CO_2$  diffuse from high concentration to low concentration.