Biological and Medical Applications of Pressures and Fluids

Foundation Physics
Lecture 2.13
MH
Pressures in the human body

- All pressures quoted are gauge pressure
- Bladder Pressure
- Cerebrospinal Pressure
- Pressure in the Eye
- Pressure in the Gastrointestinal System
- Pressure in the Skeleton
## Typical Fluid Pressures (in mm Hg) in Humans

<table>
<thead>
<tr>
<th>Catagory</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Arterial blood pressures</strong></td>
<td></td>
</tr>
<tr>
<td>Maximum (systolic):</td>
<td></td>
</tr>
<tr>
<td>adult</td>
<td>100–140</td>
</tr>
<tr>
<td>infant</td>
<td>60–70</td>
</tr>
<tr>
<td>Minimum (diastolic):</td>
<td></td>
</tr>
<tr>
<td>adult</td>
<td>60–90</td>
</tr>
<tr>
<td>infant</td>
<td>30–40</td>
</tr>
<tr>
<td><strong>Venous blood pressures</strong></td>
<td></td>
</tr>
<tr>
<td>Venules</td>
<td>8–15</td>
</tr>
<tr>
<td>Veins</td>
<td>4–8</td>
</tr>
<tr>
<td>Major veins (CVP)</td>
<td>4</td>
</tr>
<tr>
<td><strong>Capillary blood pressure</strong></td>
<td></td>
</tr>
<tr>
<td>Arteriole end</td>
<td>35</td>
</tr>
<tr>
<td>Venule end</td>
<td>15</td>
</tr>
<tr>
<td><strong>Bladder</strong></td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>0–25</td>
</tr>
<tr>
<td>During micturition</td>
<td>110</td>
</tr>
<tr>
<td><strong>Brain, lying down (CSF)</strong></td>
<td></td>
</tr>
<tr>
<td>Eye, aqueous humor</td>
<td>5–12</td>
</tr>
<tr>
<td>Gastrointestinal</td>
<td>12–24</td>
</tr>
<tr>
<td><strong>Intrathoracic</strong></td>
<td></td>
</tr>
<tr>
<td>Intrathoracic</td>
<td>-4 to -8</td>
</tr>
<tr>
<td>Middle ear</td>
<td>&lt;1</td>
</tr>
</tbody>
</table>
The shape of the eye is maintained by fluid pressure. This pressure is called the intraocular pressure (its normal range is 12-24 mm Hg).

Aqueous humor is similar in character to cerebrospinal fluid and carries nutrients to the lens and cornea of the eye, neither of which has blood vessels.
Intraocular pressure can rise to as much as 85 mm Hg, the average arterial blood pressure. Above that pressure, aqueous humor penetrates arterial walls and is absorbed into the blood stream, so the pressure rises no higher. Excessive intraocular pressure is a symptom of glaucoma and can result in blindness due to deterioration of the retina.

Intraocular pressure is measured by a number of techniques, most of which involve exerting a force on the eye over a certain area (a pressure) and observing its resulting deformation and rebound. Measurements of intraocular pressure are complicated by the non-fluid character of the wall of the eye, which has a resilience of its own.
A number of biological processes, such as the movement of wastes and nutrients across cell membranes, can be explained in terms of the behavior of molecules.
The ideal gas law is a special form of an equation of state, i.e., an equation relating the variables that characterize a gas (pressure, volume, temperature, density, ….). The ideal gas law is applicable to low-density gases.

\[
\frac{pV}{T} = \text{constant} \quad (\text{fixed mass of gas})
\]

\[
pV = nRT
\]

\[
pV = Nk_B T
\]

\[
p = \rho RT
\]

One mole is \(N_A = 6.023 \times 10^{23}\) molecules (number of \(^{12}\text{C}\) atoms in 12 g of \(^{12}\text{C}\))

\(R = 8.31 \text{ N\cdot m/mol\cdot K}\)

1 mol of gas molecules at 0°C has a volume of 22.4 liters
Brownian molecular motion

- Small particles (e.g. dust) which are in a gas or liquid environment are never at rest. With a microscope you can observe that they constantly move irregularly in all directions.
- Robert Brown (1773-1858) discovered that molecular motion.
- The motion of the particles ‘Brownian motion’ is caused by collisions of the particles with the surrounding gas - or liquids molecules. The observation with the microscope visualizes directly the thermal motion.
Thermal motion

• A similar motion as the one of the dust particles in a gas or liquid environment is valid for the molecules themselves in the environment.

• Between two collisions the molecules travel in a linear motion.

• The linear path covered in-between two collisions is defined as the ‘mean free path’ $\bar{l}$

• $\bar{l}$ is directly proportional to the density $n$ of particles per m$^3$. 
**Mean free path**

\[ \bar{l} = \frac{1}{\sqrt{2 \cdot n \cdot \sigma}} \]

\( \sigma \): geometrical collision cross-section \( \sigma = \pi (r_1 + r_2)^2 \)

\( r_1, r_2 \) radii of the two colliding particles

Example: gas at normal conditions (1 atm, 0° C)

\( r_1 = r_2 = 10^{-10} \text{m} \)

\( n = \frac{6.02 \cdot 10^{23} \text{ particles}}{0.0224 \text{ m}^3} \)

\[ \bar{l} = \frac{1}{\sqrt{2 \cdot 2.7 \cdot 10^{25} \cdot \pi (2 \cdot 10^{-10})^2}} = 2 \cdot 10^{-7} \text{ m} = 0.2 \mu\text{m} \]

In high vacuum \( \bar{l} = \frac{2 \cdot 10^{-7} \text{ m}}{10^{-9}} = 200 \text{ m} \)
Collision frequency

• From the mean free path $l$ and the mean translational speed $\sqrt{v^2}$ we can calculate the collision frequency $\bar{v}$ of the particles.

$$\bar{v} = \frac{\sqrt{v^2}}{l}$$

• $\sqrt{v^2}$ order of magnitude $10^3\text{m/s}$, $l$ at normal conditions $10^{-7}\text{m}$, $\bar{v} \sim 10^{10}\text{s}^{-1}$
Molecular motion

http://www.youtube.com/watch?v=6VdMp46ZIL8
http://www.youtube.com/watch?v=cDcprgWiQEY
Entropy and second law of thermodynamics

• The **first law in thermodynamics** states the conservation of energy. For a process which converts from condition 1 to condition 2

\[ \Delta U = \Delta Q - \Delta W \]

• where \( dU \) is a small increase in the internal energy of the system, \( \delta Q \) is a small amount of heat added to the system, and \( \delta W \) is a small amount of **work done by the system**

• Energy can not be generated nor can it be destroyed.

• Energy only can be converted from one form into an other.

• The first law does not state whether the process is able to spontaneously convert condition 2 into condition 1

Example: two bodies with the same temperature never exchange their heat, such that one body becomes hot and the other cools down.

• The **second law in thermodynamics** is providing insights in what direction thermo dynamical processes occur or in other words about the probability of a thermal state
Reversible or irreversible changes in state

- Changes in states (processes) are reversible in the directionality in which they occur if they can be reverted by changing small external parameters.
- The directionality in irreversible processes can not be changed by changing small external parameters.

Example: Free expansion of gas
• Definition of a change in Entropy:

\[ \Delta S = S_2 - S_1 \text{ in a reversible change in condition is given by } \Delta S = \int_{1}^{2} \frac{dQ}{T} \]

In isotherm, reversible processes we can write:

\[ \Delta S = \frac{\Delta Q}{T}; \quad [S] = 1 J / K \]
Second law of thermodynamics

- For the total change in entropy $\Delta S_{\text{tot}}$ (sum of the change in entropy of the system $\Delta S$ and the environment $\Delta S_{\text{env}}$):

  - $\Delta S_{\text{tot}} = \Delta S + \Delta S_{\text{env}} = 0$ (reversible processes)
  - $\Delta S_{\text{tot}} = \Delta S + \Delta S_{\text{env}} > 0$ (irreversible processes)

Since reversible processes are described under ideal conditions, which do not occur in reality, entropy is always increasing.
• If a drop of food coloring is placed carefully into a glass of still water, it very slowly spreads out until the entire glass of water is a uniform color.

• This is an example of diffusion, the movement of substance due to random thermal motion. Even in the absence of large scale flow, molecules move about, bounce off one another, and mix continuously.

• Other examples:
  Diffusion of atoms in a solid
  Mixing of two layered fluids

http://www.youtube.com/watch?v=o6nqYcrLtiQ
• The average speed of the molecules depends on their mass and temperature, being higher for lighter molecules and for higher temperatures.

• These numerous collisions slow down diffusion since molecules cannot travel very far before having a collision that may scatter them in any direction, including back in the direction from which they came.
Diffusion (III)

• The direction and rate of diffusion are described by Fick’s first law, named after Adolf Fick (1829-1901), a German physiologist:

  • The direction of diffusion is always from a region of higher concentration to one of lower concentration.
  • The rate of diffusion is directly proportional to the difference in concentration between the two regions. \[\frac{dc}{dx}\] and is depending on the temperature.
A box with more molecules on the right of an imaginary dashed line than on the left. Pure chance dictates that more molecules will move from right to left than vice versa. A higher temperature results in a higher diffusion due to a higher mean speed of the particles.

\[ \text{v}_{\text{rms}} = \sqrt{\text{v}^2} = \sqrt{\frac{3 \cdot R \cdot T}{M}} \]
• Quantitative for the diffusion in one direction:

\[
\frac{dm}{dt} = \dot{m} = -D \cdot A \cdot \frac{dc}{dx}
\]

\( \dot{m} \): massflow

D: Diffusion constant (depending on substance and temperature)

A: Cross-sectional area

\( \frac{dc}{dx} \): concentration gradient
## Diffusion constants

<table>
<thead>
<tr>
<th>Substance</th>
<th>In</th>
<th>D in m²/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>Air (0°C)</td>
<td>6.3x10⁻⁵</td>
</tr>
<tr>
<td>Water vapor</td>
<td>Air (0°C)</td>
<td>2.4x10⁻⁵</td>
</tr>
<tr>
<td>CO₂</td>
<td>Air (0°C)</td>
<td>1.4x10⁻⁵</td>
</tr>
<tr>
<td>CS₂</td>
<td>Air (0°C)</td>
<td>1.0x10⁻⁵</td>
</tr>
<tr>
<td>NaCl</td>
<td>Water (15°C)</td>
<td>1.1x10⁻⁹</td>
</tr>
<tr>
<td>Sugar</td>
<td>Water (12°C)</td>
<td>3.0x10⁻¹⁰</td>
</tr>
</tbody>
</table>

Example: Fresh water and salt water are connected by a tube of 1m length and a cross-section of 1cm². The salt concentration c=9g/l. How much salt diffuses in one hour through the tube?
Diffusion through membranes

Permeability. Most diffusion in biological organisms takes place through membranes. All cells and some structures within cells, such as the nucleus, are surrounded by membranes. These membranes are very thin, from $65 \times 10^{-10}$ to $100 \times 10^{-10}$ m across (less than 100 atoms thick). Most membranes are selectively permeable; that is, they allow only certain substances to cross them.
Diffusion through membranes
Active transport

• All these processes for transporting substances on the cellular level are passive in nature. The driving energy for passive transport comes from molecular kinetic energy or pressure. There is another class of transport phenomena, called active transport, in which the living membrane itself supplies energy to cause the transport of substances.

• Biological organisms sometimes need to transport substances from regions of low concentration to high concentration - the direction opposite to that in osmosis or dialysis.
The concentration of potassium in red blood cells is about 20 times larger than that of sodium, whereas the blood plasma surrounding them has about 20 times as much sodium as potassium. Active transport maintains this against the tendency of dialysis to transport sodium into the cell and potassium out of the cell.