TRANSPORT PROCESSES IN LIVING ORGANISMS

- Diffusion, osmosis
- Fluid flow
- Biophysics of circulation, cardiac biophysics
- Transport across biological membranes, membrane potential

DIFFUSION AND OSMOSIS IN EVERY DAY LIFE

Hands are immersed in dishwater for a long time, skin looks bloated
Tee spreading in water

DIFFUSION AND OSMOSIS IN THE MEDICAL PRACTICE

TISSUES/Cells - CAPILLARIES

- NUTRIENTS AND OXYGEN FROM THE BLOOD FLOW INTO THE CELL
- WASTE SUBSTANCES AND CARBON DIOXIDE FROM THE CELLS INTO THE BLOOD FLOW

LUNGS - CAPILLARIES

- OXYGEN INTO THE BLOOD FLOW
- CARBON DIOXIDE OUT OF THE BLOOD FLOW

DIFFUSION AND OSMOSIS IN THE MEDICAL PRACTICE

ABSORPTION OF MEDICINES

KIDNEY DIALYSIS

Exclusion of wastes, reabsorption of vital nutrients

DIFFUSION AT THE MACROSCOPIC LEVEL

Experiment: add a droplet of ink to HOT and COLD water

Observation:
- the stain spreads in water: inhomogeneous \(\rightarrow\) homogeneous
- the spreading is faster in hot water than in cold water

WHY DO PARTICLES SPREAD IN WATER?
WHY IS IT FASTER AT HIGHER TEMPERATURES?
**DIFFUSION AT THE MICROSCOPIC – MOLECULAR LEVEL**

- most of the particles of biological systems are in constant motion
  - fluid phase – aqueous medium (50 – 60 % of the human body consists of water)
  - lipid phase – cell membrane

**Brownian motion**

- Robert Brown (Scottish botanist, 1827)
- microscopic investigation of pollen in water → random, zig-zag motion of pollen particles

**DIFFUSION**

- **CAUSE:** due to the non-uniform (inhomogeneous) distribution of particles
- **WHAT HAPPENS:** net transport* of the particles occurs from regions of higher concentration to regions of lower concentration by means of thermal motion
- **RESULT:** which continues until the distribution of the particles is uniform (homogeneous)

* Brownian motion

**QUANTIFYING DIFFUSION**

\[ \frac{\Delta m}{\Delta x \Delta t} = J \]

\[ J = -D \frac{\Delta c}{\Delta x} \]

- concentration difference/gradient \( \frac{\Delta c}{\Delta x} \) → rate of diffusion \( J \)
- properties of the media and particles \( D \): DIFFUSION COEFFICIENT

\( \Delta c \) is linearly proportional to the concentration gradient.

**WHAT DOES THE RATE OF DIFFUSION DEPEND ON?**

- Kinetic energy: \( \frac{1}{2} m v^2 = \frac{1}{2} kT \) – Temperature (thermal motion)
  - Particles are moving due to the continuous collision with water molecules.
  - Elevated temperature results in faster motion; which results in increased frequency of collision.

**DIFFUSION AS THERMAL MOTION OF PARTICLES**

MACROSCOPIC VIEW

MICROSCOPIC VIEW

\[ \text{Stokes' law} \]

\[ \text{LAW} \]
DIFFUSION COEFFICIENT - STOKES-EINSTEIN EQUATION

Do all particles diffuse at the same rate in all media?

For spherical particles (r: radius) in a viscous medium (η) at T temperature:

\[ D = \frac{k}{6\pi \eta r} \cdot \frac{T}{m} \]

- temperature (T)
- the higher the temperature, the faster the thermal motion
- geometry/shape of the particle (r)
- small/globular particle diffuse more easily than big/fibrillar particle
- molecular weight of the particle (M)
- heavier particles diffuse more slowly than the lighter ones
- viscosity of the medium (η)
- diffusion is faster in low viscosity media than in high viscosity media
- gases > liquids

k: Boltzmann constant k = 1.38 · 10⁻²³ joule/kevin

**Example:**

**DIFFUSION COEFFICIENT - STOKES-EINSTEIN EQUATION**

\[ \bar{R}(t) \sim \sqrt{2Dt} \]

- distance ~ \sqrt{time}
- relatively fast (< seconds) over short distances (100 µm)
- exceptionally slow (> days) over long distances (1 cm)

HOW FAR DOES A PARTICLE GET FROM ITS INITIAL POSITION?

Example: GAS EXCHANGE BETWEEN BLOOD AND THE LUNGS

- time spent by the red blood cell \( t = 0.5 \text{ s} \)
- distance \( R = 1 \mu m \)

**Example: GAS EXCHANGE BETWEEN BLOOD AND THE LUNGS**

<table>
<thead>
<tr>
<th>molecule</th>
<th>diffusion distance [R]</th>
<th>diffusion coefficient [D], m²/s⁻¹</th>
<th>time needed [t], s</th>
</tr>
</thead>
<tbody>
<tr>
<td>O₂</td>
<td>1 µm = 10⁻⁶ m</td>
<td>2 · 10⁴ m/s⁻¹</td>
<td>0.5 · 10⁻² s = 500 µs &lt;&lt; 0.5 s</td>
</tr>
<tr>
<td>CO₂</td>
<td>1 µm = 10⁻⁶ m</td>
<td>1.2 · 10⁴ m/s⁻¹</td>
<td>0.8 · 10⁻⁴ s = 80 µs &lt;&lt; 0.5 s</td>
</tr>
<tr>
<td>O₃</td>
<td>1 cm = 10² µm</td>
<td>2 · 10⁻⁶ m/s⁻¹</td>
<td>0.5 · 10⁻⁰ s = 57.8 days</td>
</tr>
</tbody>
</table>

Effectivity of gas exchange:
short diffusional distance (µm), large diffusion speed (µs).

TRANSPORT PROCESSES ACROSS BIOLOGICAL MEMBRANES

I. TRANSPORT MECHANISM

<table>
<thead>
<tr>
<th>WITHOUT MEDIATOR</th>
<th>WITH MEDIATOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>PASSIVE DIFFUSION</td>
<td>FACILITATED DIFFUSION</td>
</tr>
<tr>
<td>ion channels</td>
<td>carrier proteins</td>
</tr>
<tr>
<td>Glucose</td>
<td>Glucose, ADP + Pi</td>
</tr>
</tbody>
</table>

II. ENERGETIC REQUIREMENTS

OSMOSIS AT THE MACROSCOPIC LEVEL

**Experiment:** place a dried leaf of salad into water

**Observation:** the leaf of salad becomes bigger (swells) and looks fresh again
CONNECTING OSMOSIS TO DIFFUSION
What is the difference between the „ink” experiment and the „salade” experiment?

OSMOSIS AT THE MICROSCOPIC – MOLECULAR LEVEL
SPECIAL WALL: SEMIPERMEABLE – „filter” allows smaller solvent molecules to pass through, but not the larger solute molecules.

OSMOSIS = restricted DIFFUSION
• unidirectional matter flow through a semipermeable membrane, which takes place by means of diffusion
• smaller molecules reach a uniform distribution, while larger molecules remain in the compartment.

QUANTIFYING OSMOSIS
OSMOTIC PRESSURE
• pressure that inhibits the net solvent flow
• pressure that has to be exerted on the solution connected to pure solvent by a semipermeable membrane to counteract osmosis to reach dynamic equilibrium

\[ P_{\text{o}smotic} = \rho gh \]

VAN’T HOFF’s LAW
for dilute solutions and perfect semipermeable membranes

\[ V: \text{volume} \]
\[ n: \text{mole fraction} \]
\[ T: \text{temperature} \]
\[ P_{\text{o}smotic} \sim c \]
\[ R: \text{universal gas constant} \]

The osmotic pressure is linearly proportional to the concentration:

concentration ↑  →  osmotic pressure ↑

QUANTIFYING OSMOSIS
Upon OSMOSIS the net particle transport occurs from the low-concentration regions (of the solute!!!!) (low osmotic pressure) to the high-concentration regions (high osmotic pressure)
• always the more dense solution becomes diluted

\[ P_1 < P_2 \]
\[ P_1^{\text{osmotic}} < P_2^{\text{osmotic}} \]
**CLASSIFYING SOLUTIONS ON THE BASIS OF OSMOTIC PRESSURE**

<table>
<thead>
<tr>
<th>HYPERTONIC</th>
<th>ISOTONIC</th>
<th>HYPOTONIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>higher concentration</td>
<td>same concentration</td>
<td>lower concentration</td>
</tr>
<tr>
<td>c &gt; c_x</td>
<td>c = c_x</td>
<td>c &lt; c_x</td>
</tr>
<tr>
<td>higher osmotic pressure</td>
<td>same osmotic pressure</td>
<td>lower osmotic pressure</td>
</tr>
<tr>
<td>p &gt; p_x</td>
<td>p = p_x</td>
<td>p &lt; p_x</td>
</tr>
</tbody>
</table>

for the cells of the human body, blood:
- 0.87% (0.15 M) NaCl
- physiologic saline solution
- 5.5% (0.3 M) glucose

x: reference, e.g. intracellular environment

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**INJECTION, INFUSION**

- drugs are dissolved in physiological saline solution
  - isotonic environment, compared to the body fluid

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**OSMOSIS IN THE MEDICAL PRACTICE**

**TREATMENT OF OEDEMAS, INFLAMED AREAS**

- abnormal accumulation of fluid beneath the skin or in one or more cavities of the body that produces swelling (fluid accumulation)
- hypertonic environment is created (compared to the swollen areas)
- induces water outflow from the swollen areas
- reduced swelling

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**OSMOSIS IN THE MEDICAL PRACTICE**

**TREATMENT OF CONSTIPATION - LAXATIVE SALTS**

- laxative salts are not absorbed by the large intestine
  - hypertonic environment is created in the large intestine
  - results in water influx into the large intestine
  - dilution of colonic content, facilitated excretion

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**HAEMODIALYSIS**

- treatment of patient with severe kidney disease
- remove soluble chemicals toxic for the body

[Diagram of haemodialysis]
Quick question 1

The image shows atoms of helium gas in a box. The box is divided into two sections of equal volume by a membrane which is permeable to helium.

Which of the following scenarios is most likely to occur?
A. There will be a net movement of helium atoms from left to right.
B. There will be a net movement of the helium atoms from the top of the box to bottom of the box.
C. There will be a net movement of helium atoms from right to left.
D. There will be no net movement of helium atoms.

Quick question 2

The figure below shows a beaker filled with water and a solute. The beaker has membrane down the center, which is permeable only to water.

Which of the following best describes the way the water will flow through the semipermeable membrane?
A. Nothing, the water levels are already equal.
B. Water will flow into side B.
C. Water will flow into side A.

Quick question 3

Tahira placed a collection of red blood cells into a container filled with an unknown solution. Once in the container, Tahira noticed that the red blood cells swelled and some of them burst.

What type of solution were the red blood cells placed in?
A. An isotonic solution
B. A hypotonic solution
C. A hypertonic solution
SUMMARY – EXAM TOPICS

MOLECULAR INTERPRETATION OF DIFFUSION
FICK’S 1ST LAW
DIFFUSION CONSTANT, STOKES-EINSTEIN EQUATION
EXAMPLES: DIFFUSION THROUGH THE CELL MEMBRANE, GAS EXCHANGE BETWEEN LUNGS AND BLOOD

MOLECULAR INTERPRETATION OF OSMOSIS
OSMOTIC PRESSURE, VAN’T HOFF’S LAW
CLASSIFYING SOLUTION ON THE BASIS OF OSMOTIC PRESSURE
EXAMPLES: HAEMODYALYSIS, APPLICATION OF MEDICINES