Biophysics of blood circulation

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Why does blood flow?

- **Pressure gradient** created by the heart

\[
\text{Volumetric flow rate} = \frac{\text{pressure gradient}}{\text{tube resistance}} = \frac{\Delta p}{R} \quad \Rightarrow \quad I = \frac{U}{R}
\]

- **Blood pressure**: pressure exerted by the flowing blood on the vessel walls, and on the neighbouring amount of blood
  - It rhythmically fluctuates because of the intermittent functioning of the heart
  - The pressure wave running through the blood puts the vessel wall in motion: expansion and recoil palpable (**pulse**) and measurable

  - Highest value: **systolic** pressure
  - Lowest value: **diastolic** pressure

\[
\text{mean arterial pressure} = p_{\text{diast}} + \frac{1}{3} (p_{\text{syst}} - p_{\text{diast}})
\]
Blood pressure

In every 10 cm

\[
\Delta p = \Delta h \cdot \rho \cdot g = 0.1 \cdot 10.65 \frac{kg}{m^3} \cdot 9.81 \frac{m}{s^2} = 1.045 \rho \cdot g = 7.8 Hg mm
\]

Peripheral circulation

Function of peripheral circulation: maintain a steady, unidirectional and laminar (relatively slow) flow

Laws of hydrodynamics can be applied

1. Continuity equation

\[
I_1 = I_2 \quad A_1 \cdot v_1 = A_2 \cdot v_2
\]

\[
I = \sum_{i=1}^{n} I_i \quad A = \sum_{i=1}^{n} A_i
\]

\[
A \cdot v = \Sigma A \cdot \nu = \text{constant}
\]

It can be influenced by:
- Elasticity of the vessels
- Intermittent work of the heart
- Changes in blood volume (lymph formation)

Peripheral resistance

2. Law of Hagen-Poiseuille

\[
l = \frac{Q}{A} = \frac{\pi r^4 \cdot \Delta p}{8 \cdot \eta \cdot l}
\]

Pressure gradient \( \Delta p \cdot R \) resistance
Stroke volume

Resistance is different in the various kinds of vessels and depends on:
- Pressure fall
- Viscosity of blood
- Cross-section of the vessels

<table>
<thead>
<tr>
<th>Distributive vessels</th>
<th>high pressure</th>
<th>aorta, arteries</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistance vessels</td>
<td>high resistance</td>
<td>arterioles</td>
</tr>
<tr>
<td>Diffusive vessels</td>
<td>low velocity, filtration</td>
<td>capillaries</td>
</tr>
<tr>
<td>Capacitance vessels</td>
<td>low pressure</td>
<td>veins, lymph vessels</td>
</tr>
</tbody>
</table>
Pressure fall/gradient

Laws of Kirchoff:

- **Serial coupling**
  \[ R_{\text{tot}} = R_1 + R_2 + \cdots + R_n \]

- **Parallel coupling**
  \[ \frac{1}{R_{\text{tot}}} = \frac{1}{R_1} + \frac{1}{R_2} + \cdots + \frac{1}{R_n} \]

Many small parallel sub-circuits:
- Lower resultant resistance
- Local, independent regulation of the flow
- Better oxygen supply
- Capillaries in serial coupling only at specific places (e.g., 2 blood circuits!)

Aneurism

- Positive feedback
- Aneurysm (aneurism)
- Lowered pressure
- Increased flow
- Decreased pressure

Viscosity

Viscosity transforms kinetic energy into heat and lowers blood pressure

- Average viscosity of blood ~4.5 mPa·s
- It depends on:
  1. Haematocrit (e.g., leukemia)
  2. Concentration of plasma proteins (e.g., globulinemia)
  3. Deformability of the cellular components (RBC)

- Suspension of similar sized solid particles is hard as brick; viscosity of 95% RBC-suspension is only ~20 mPa·s
4. Aggregation property of rbc (raises viscosity)
5. Flow velocity
6. Vessels’ cross-section (Fåhræus-Lindqvist effect)

Cross-section of the vessels

\[ i = \frac{Q}{A_p} \]

\[ r_1 = 2r_2 \quad l_1 = 16f_2 \]

Most important way to regulate intensity of current and blood pressure:
Neural and hormonal (catecolamines)
In vessels with substantial smooth muscle content:
muscular arteries and arterioles

- Flow is normally under critical velocity, laminary
- At some spaces (valves, stenosis) can speed up causing turbulence
- It can be heard as various sounds (heart sounds and murmurs, Korotkov sound)

Heart cycle

- Ventricular systole 0,3s
  - Isovolumetric contraction
  - Ejection (rapid and reduced)
- Ventricular diastole 0,5s
  - Isovolumetric relaxation
  - Rapid filling
  - Diastasis
  - Atrial systole
- Atrial systole 0,1s
- Atrial diastole 0,7s

Generation of impulse

Cardiac Cycle

Cardiac cycle

- Generation of impulse
- Heart cycle
**Heart cycle**

- Cardiovascular Diagram
- Heart sounds

**Pump function**

- Cardiac output = stroke volume \times \text{heart rate}

- Heart rate = end-diastolic volume – end-systolic volume

- 120 ml – 50 ml = 70 ml

- Daily ~ 108,000 heartbeats (75x60x24) ~ 7.560 L blood ejected (5.25x60x24)

- Yearly ~ 40 million heartbeats ~ 2.76 million L (2.760 m^3) blood ejected

**Components of stroke volume**

- **Ejection fraction (EF)**
  - Ratio of stroke volume and end-diastolic volume
  
  \[ EF = \frac{70 \text{ ml}}{120 \text{ ml}} = 60\% \]

- **Preload**
  - End-diastolic pressure or volume in the ventricle
  - Load/stretch of the heart muscle cell before contraction
  - Effect of the blood returning to heart (filling pressure)
  - Increases sarcomere length
  - Determined by the venous pressure and venous return

- **Afterload**
  - Tension in the ventricle wall needed to eject blood
  - Pressure in the ventricle needed to open the semilunar valve
  - Determined by the systemic resistance/aortic pressure and pulmonary pressure
Components of stroke volume

- **Contractility**
  - Force exerted by the myocytes during contraction

**Frank-Starling law of the heart**
- Stroke volume is directly proportional to end-systolic ventricular volume
- Higher preload causes a greater stretch of the myocytes (increased sarcomere length) enhancing contractility

Heart muscle

Additional effect: stretch of the muscle fibre enhances troponin-C sensitivity for Ca that increases the number of actin-myosin cross-bridges

**Work of the heart**

**Volume-pressure loop**

A. Closure of mitral valves
B. Opening of aortic valve
C. Closure of aortic valve
D. Opening of mitral valves

\[
\text{power: } P = \frac{\text{work}}{\text{time}} = \frac{1.1\text{ J}}{0.86\text{ s}} = 1.28\text{ W}
\]
Summary

- Gross anatomy of the cardiovascular system
- Blood pressure
- Peripheral resistance
  - Pressure fall
  - Viscosity
  - Cross-section of the vessels
- Phases of the heart cycle
- Cardiac output
- Work of the heart

THANK YOU FOR YOUR ATTENTION!
ECG & Membrane Potential of Ventricular Cell

Fig. 11-2: Stages phase 0 means rapid depolarization.