I. THEORETICAL BACKGROUND

Cardiac catheterization is an invasive method used for assessing the mechanical and electrical activity of the heart, as well as the blood vessels. During this procedure a catheter (thin plastic tube) is inserted into an artery or a vein of the upper limb (usually the brachial or the radial artery, or the subclavian or internal jugular vein, respectively) or of the lower limb (usually the common femoral artery or the femoral vein, respectively). From there, depending on the purpose of the procedure and the access site, the catheter can be advanced into the aorta, the chambers of the heart or into the coronary arteries. If the catheter is inserted through a vein, the right chambers of the heart (right atrium and right ventricle) and the pulmonary artery can be investigated, whereas if the catheter is inserted through an artery, the aorta, the coronary arteries, and the left ventricle can be explored. The method is used in order to:
- measure blood pressure within the heart and major blood vessels
- measure blood oxygenation (how much oxygen is in the blood)
- measure the pumping ability of the heart muscle
- inject dye into the heart chambers (angiocardiology) or coronary arteries (coronary angiography or coronary arteriography)
- perform various therapeutic procedures (e.g., dilate narrowed arteries - angioplasty)
- record intracavitary electrograms.

When performed on humans, the catheter is usually introduced through a large artery/vein after using a percutaneous puncture needle, whereas during animal experiments the catheter may be introduced after dissection of the region and visualization of the vessel. The catheter then is guided into position using radioscopy.

1. Measurement of blood pressure

1.1. Examination procedure

The measurement of blood pressure is possible using external electromanometers, which are in contact with saline solution inside the catheter, or using micromanometers placed at the tip of the catheter, in direct contact with the blood stream. This last method is more accurate, it is not influenced by the liquid column inertial forces or by mechanical resonances that may occur inside the catheter. The great advantage of this method is the real-time accurate values provided for the systolic and diastolic pressures and the possibility to detect very small changes in blood pressure.

The right chambers of the heart and the pulmonary artery are easily accessible through right heart catheterization. Meanwhile, left heart catheterization only allows assessing the pressure in the left ventricle, but not in the left atrium. As the catheter cannot be pushed from the left ventricle into the left atrium through the mitral valve, the left atrium is inaccessible for direct catheterization. Instead, left atrial pressure is estimated using the pulmonary wedge pressure (Figure 1). This method relies on the principle that the pressure in the left atrium is transmitted retrogradely into the pulmonary vessels and can be
estimated by wedging a catheter with an inflated balloon into a small pulmonary arterial branch. Therefore, left atrial pressure is also estimated using right, and not left heart catheterization.

**Figure 1.** Recording of the pulmonary wedge pressure. Pa – pulmonary artery; Pv – pulmonary vein; LA – left atrium.

The recorded curves are always used in parallel with the ECG trace. After recording the pressure curves, the maximum (systolic), minimum (diastolic), and mean blood pressure values are read or calculated for each cardiovascular compartment (Figure 2). The normal values of pressure in different compartments of the heart are presented in Figure 9.

**Figure 2.** Pressure curve recording from the pulmonary artery (Pa), then from the right ventricle (RV) and right atrium (RA), in parallel with the electrocardiogram (ECG).

1.2. **Clinical relevance**

Pressures in heart chambers are modified by cardiac malformations, valvular heart diseases, pulmonary diseases, pericardial diseases, or diseases affecting myocardial contractility and can be used to diagnose such conditions.

2. **Angiocardiography**

2.1. **Examination procedure**

*Angiocardiography* is done by injecting a radiopaque dye into different compartments of the heart and recording the images with an X-Ray machine called *angiograph* (Figure 3).

**Figure 3.** Angiocardiography images of the human heart during systole (A) and diastole (B).
2.2. Clinical relevance
This method enables the study of the radiological anatomy of the heart, the diagnosis of cardiac malformations or valvulopathies (diseases of the cardiac valves). The method also enables the calculation of ventricular volumes, by considering the left ventricle as an ellipsoid (see the ‘Echocardiography’ chapter). Using the calculated end-systolic and end-diastolic volumes we can calculate the ejection fraction, the most widely used indicator of ventricular contractility. Normal values obtained with this technique are listed in Table 1.

Table 1. Normal values of parameters measured using angiocardiography.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Normal value</th>
</tr>
</thead>
<tbody>
<tr>
<td>End-diastolic volume (EDV)</td>
<td>70 ± 20 ml/m²</td>
</tr>
<tr>
<td>End-systolic volume (ESV)</td>
<td>24 ± 10 ml/m²</td>
</tr>
<tr>
<td>Stroke volume (SV)</td>
<td>45 ± 13 ml/m²</td>
</tr>
<tr>
<td>Ejection fraction (EF)</td>
<td>67 ± 8%</td>
</tr>
<tr>
<td>Cardiac output (CO)</td>
<td>5.2 L/min</td>
</tr>
</tbody>
</table>

EDV - the volume of blood in a ventricle at the end of filling (diastole); ESV - the volume of blood in the left ventricle at the end of contraction (systole); SV - the volume of blood pumped from one ventricle of the heart with each beat; EF - the fraction of blood pumped out of a ventricle with each heart beat; CO - the volume of blood pumped by the heart during one minute.

3. Angiography

3.1. Definition: Angiography is a variant of angiocardiography applied for the blood vessels. The method is used to assess the radiological anatomy of the aorta (aortography; Figure 4), the peripheral arteries (arteriography; Figure 5), including the coronary arteries (coronary angiography; Figure 6), or of the veins (venography).

Figure 4. Aortography of the ascending aorta (A). The two coronary arteries can be observed (arrows). Notice the three Valsalva sinuses, located at the aortic root. Aortography of the descending aorta (B). The aortic bifurcation into the two common iliac arteries can be seen.
3.2. Coronary angiography

Coronary angiography is a variant of peripheral angiography, when the radiopaque dye is injected directly into one of the coronary arteries. Thus, the anatomy and the status of the coronary arteries can be appreciated (Figures 6). The visualization of a stenosis (abnormal narrowing of the blood vessel) or an occlusion (complete blockage of a blood vessel) has both diagnostic and therapeutic consequences.

In a large number of cases, a critical stenosis (refers to a narrowing that causes a significant reduction in maximal flow capacity in the distal vascular bed) can be dilated using a catheter with a balloon at its tip. To maintain the artery open, a small metallic prosthesis called stent can be placed inside the artery (Figure 7).
4. Measurement of blood oxygenation

4.1. Examination procedure

Blood samples are collected from different areas of the cardiovascular system in order to determine \( O_2 \) saturation and hemoglobin concentration. Results are expressed either in ml \( O_2 \) in 100 ml of blood or as a percentage of the maximal \( O_2 \) saturation of the hemoglobin. Between the two there is a constant relationship (1 g of hemoglobin can maximally bind 1.34 ml of \( O_2 \)). Normal values of \( O_2 \) saturation in different compartments of the heart are presented in Figure 9.

4.2. Clinical relevance

Oxygen saturation will be modified in all cardiac congenital malformations in which there is a communication between the left and the right side of the heart (e.g. ventricular or atrial septal defect). Based on the magnitude of the modification of \( O_2 \) saturation, the output through the defect can be calculated. **Fick's method** allows us to calculate the cardiac output based on blood oxygenation (Figure 8).

\[
\text{\( V_O_2 \)} = \text{CO} \times (\text{\( C_O_2 \)}_{\text{Pv}} - \text{\( C_O_2 \)}_{\text{Pa}})
\]

**Figure 7.** (A) Stent used for the angioplasty of a severe stenosis of the left anterior descending artery (B, arrow) and the post-angioplasty result (C).

**Figure 8.** Schematic representation of Fick's method to calculate the cardiac output (CO). \( \text{\( C_O_2 \)}_{\text{Pv}} \) = oxygen concentration in the pulmonary vein, \( \text{\( C_O_2 \)}_{\text{Pa}} \) = oxygen concentration in the pulmonary artery, \( \text{\( V_O_2 \)} \) = oxygen consumption.
5. Dilution curves

5.1. Examination procedure
For this procedure a special catheter is used with a small thermistor (temperature probe) about 3 cm proximal to the tip. Cold fluid is injected (under 10°C or room temperature) using an opening of the catheter in the right atrium (typically 10 ml of saline - i.e. 0.9% NaCl, or isotonic glucose 5%). As the cooler fluid passes the tip thermistor, a very brief drop in the blood temperature is recorded (in the pulmonary artery). By measuring the area of the temperature drop curve the thermodilution curve can be plotted.

The same information can be obtained by injecting a small amount of indicator that will be distributed only in the intravascular fluid compartment (such as a dye, e.g. Evans blue), into the right atrium and assessing the changes in the concentration of that dye as it passes through one of the peripheral arteries. However, these methods are not used any more in humans.

5.2. Clinical relevance
The dilution of the cold fluid is inversely proportional with the flow of blood in that territory, thus the cardiac output can be calculated.

6. Intracavitary electrograms

6.1. Examination procedure
Intracavitary electrograms are recorded using the same method as for the surface ECG, the genesis of the waves being exactly the same (see the 'Electrocardiography' practical and Figure 9).

6.2. Clinical relevance
Intracavitary electrograms are used in diagnosing a wide range of arrhythmias and conduction disorders. The procedure can be used for therapeutic purposes as well (cardiac stimulation or ablation techniques).
Figure 9. Maximal, minimal and mean pressures measured during different phases of the heart cycle. The saturation of oxygen (Sat O₂) of the blood in different compartments is also presented.
II. EXPERIMENTAL OBJECTIVES AND PROCEDURES

1. Experimental objectives:
   - to recapitulate and extend the knowledge regarding the anatomy of the arterial and venous systems
   - to understand the principle and methods of cardiac catheterization
   - to understand the principles of cardiac output calculation
   - to record invasively the systolic and diastolic blood pressures in the aorta
   - to record and explain the in vivo effects of noradrenalin and acetylcholine on the electrical and mechanical activity of the heart.

2. Materials
   - for understanding the utility of cardiac catheterization: educational video (arterial and venous catheterization of a dog)
   - for invasive measurement of blood pressure:
     - BIOPAC recording system (BIOPAC data acquisition unit connected to a computer)
     - SS13L for recording the blood pressure.

3. Experimental methods

   3.1. Video demonstration of principal uses of cardiac catheterization
   All students and the teacher are watching together the educational video. Stop the video as many times as necessary to ask questions. Students should assume nothing and ask about anything that does not seem straightforward. Discuss in detail the observed electrical and mechanical activity of the heart.

   3.2. Invasive measurement of blood pressure
   During this recording the BIOPAC system will be used to record directly the blood pressure of a rat as well as to demonstrate the effect of sympathetic and parasympathetic mediators on the heart. The recording system will be set up by lab assistants.
   For the procedure the animal will be anesthetized with a mixture of Ketamine and Xylazine administered intramuscularly. Then, the animal is placed in dorsal decubitus and the ventral face of the neck is shaved. This is followed by a median incision, longitudinally, on the ventral face of the neck. The different anatomical planes under the skin are dissected until the right sternocleidomastoid muscle is exposed. In order to expose the carotid artery the muscle will be tractioned laterally. The right common carotid artery is isolated from the rest of the vascular components, then two threads are passed below the artery: one in the proximal end of the isolated artery and one in the distal end (i.e. cephalic). The thread in the distal end will be tied and a clamp will be placed on the proximal end. Then, the artery is partially sectioned with scissors (cross-section) between the clamp and the distal ligature. A catheter, connected to the pressure transducer and filled with heparinized saline will be gently inserted into the carotid artery towards the clamp. Once the clamp is reached it is gently removed and the catheter is slid forward until the pressure wave is recorded. Once the catheter is in position it will be fixed by tightening the proximal thread.

   Animals used for demonstration and experimental purpose are healthy. Nevertheless always avoid direct contact with their blood, faeces or secretion. Do not touch animals except when specifically told by the demonstrator and always wear gloves. Do not pet the animals and do not feed them.
First record a baseline trace; the recording should look like Figure 10. Complete the tasks in the corresponding section of the Worksheet.

![Figure 10. Pressure curve recording in basal conditions.](image)

Record continuously. Administer adrenaline through the jugular vein (Figure 11). Complete the tasks in the corresponding section of the Worksheet.

![Figure 11. The effect of adrenaline on the in vivo rat heart.](image)

Record continuously. Administer acetylcholine through the jugular vein (Figure 12). Complete the tasks in the corresponding section of the Worksheet.
Figure 12. Effect of acetylcholine on the *in vivo* rat heart.
TEST YOUR KNOWLEDGE

1. Calculate how much oxygen (ml \(O_2\) / ml blood) is in a patient's blood if the patient's hemoglobin is 17g% and the \(O_2\) saturation is 65%.

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2. Using Fick's equation calculate the cardiac output of a patient whose body weight is 70 kg, the \(O_2\) consumption is 3.5 ml \(O_2\)/kgbw/min, the \(O_2\) content of the arterial blood is 18 ml \(O_2\)/100 ml blood and the venous content is 14 ml \(O_2\)/100 ml blood.

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3. Noradrenalin:
   a. increases the heart rate
   b. decreases the heart rate
   c. has positive inotropic effect
   d. has negative inotropic effect
   e. decreases myocardial contractility

4. Atrial pressure is greater than ventricular pressure during which phase of the cardiac cycle?
   a. ventricular ejection
   b. isovolumetric contraction
   c. atrial contraction
   d. isovolumetric relaxation
   e. ventricular filling