MECHANOCARDIOGRAMS

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I. THEORETICAL BACKGROUND

The two main activities of the heart are represented by the electrical and mechanical processes. The electrical activity of the heart is explored mainly using the electrocardiogram. The mechanical processes can be evaluated, among others, by special curves called mechanocardiograms.

1. The carotidogram (Carotid pulse - CP)

1.1. Definition: The carotidogram (or the carotid pulse) represents the graphic recording of volume variations of the carotid artery during the cardiac cycle. Using the carotidogram tracing, we can:
   - observe certain characteristic changes of the curve shape (can be wider or flatter);
   - identify different intervals that correspond to particular phases of the cardiac cycle;
   - calculate systolic time intervals, illustrating left ventricular systole. These intervals can be used as indicators for the cardiac performance.

1.2. The examination technique involves photoelectric plethysmography or placing mechanical transducers near the carotid artery, on the internal edge of the sternocleidomastoid muscle.

1.3. Morphological analysis of the carotidogram

The carotidogram consists of a positive waveform with two phases: systolic and diastolic (Figure 1).

   - the systolic phase begins at a point denoted by $E$, corresponding to the opening of the aortic valve. Starting from this point, the curve has a sharply upward trajectory (the anacrotic or the percussion wave) that ends in the $B$ point. The $B$ point is followed by a descending wave, interrupted by the dicrotic notch, marked on the curve by the $I$ point. The dicrotic notch is generated by the momentary reversal of blood flow from the compliant central arteries back toward the ventricle at the very end of ventricular ejection and corresponds with the moment of aortic valve closure. The descending portion of the trace is called the catacrotic wave.
   - the diastolic phase includes the dicrotic wave (of reascension), caused by the collision of the blood tending to flow back into the ventricle against the closed valves. This small ascension is followed by a slow descending wave, until the next contraction begins. Just before the next $E$ point, there will be a small ascending wave generated by the atrial systole.

The carotidogram offers us the possibility to calculate:

   - the Duchosal time (half-rise time): represents the interval of time needed for the carotid pulse to reach half of its maximum amplitude. This parameter can be used to evaluate the contractility of the left ventricle, being correlated with the transaortic pressure gradient created during left ventricular ejection. Normally, its value ranges between 0.04 sec and 0.06 sec.

   - systolic time intervals (See below - point 5.1).
1.4. The peripheral sphygmogram
The carotidogram is also known as *central sphygmogram*, since it is recorded on a large artery (the carotid artery), situated close to the heart. Using a similar examination technique, one can also obtain a *peripheral sphygmogram*, recorded on a muscular artery situated far away from the heart. As the pulse wave travels away from the aorta its shape changes because of vessel bifurcations, changes in blood vessels diameter and wall structure - the amplitude of the pulse wave increases and there is a progressive mitigation of the dicrotic notch.

2. The phonocardiogram (PC)
2.1. Definition: The phonocardiogram represents the graphic recording of the heart sounds. The recording is performed by placing on the body surface, in the classic auscultation points of the heart (*See below*), piezoelectric microphones that detect low-frequency sound waves.

During its mechanical activity, the heart generates vibrations of the cardiac walls, of the great vessels, and of the blood itself. These vibrations occur mainly due to the turbulent blood flow during the cardiac cycle (because of sudden acceleration or deceleration of the blood column) or due to the column of blood hitting various obstacles such as the heart walls or valves. These vibrations create sounds with different frequencies that can be recorded on the phonocardiogram trace. Depending on their physical characteristics, certain cardiac sounds can also be directly auscultated using a stethoscope.

2.2. The examination technique involves placing piezoelectric microphones with selective filters adapted for specific frequencies in the classic auscultation points of the heart (Figure 2):

- the **aortic area**: 2\(^\text{nd}\) right intercostal space, next to the sternum;
- the **pulmonic area**: 2\(^\text{nd}\) left intercostal space, next to the sternum;
- the **tricuspid area**: below the sternum;
- the **mitral area**: 5\(^\text{th}\) intercostal space, on the left midclavicular line.

![Figure 1. The carotidogram.](image)
Figure 2. Standard areas used for phonocardiogram recording and heart auscultation.

2.3. Morphological analysis of the phonocardiogram
Using the phonocardiogram we can usually distinguish *four heart sounds*. Their main characteristics are presented in Table 1.

Table 1. The main characteristics of the heart sounds.

<table>
<thead>
<tr>
<th>Heart sound</th>
<th>Duration</th>
<th>Loudness (frequency)</th>
<th>Etiology</th>
<th>ECG correlation (Figure 3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S₁</td>
<td>0.12-0.15 sec</td>
<td>greatly accentuated (30-40 Hz)</td>
<td>S₁a - mitral and tricuspid valves closure; tensioning of ventricular walls during isovolumic ventricular contraction; S₁b - sudden acceleration of the blood at the beginning of ventricular ejection; S₁c - vibrations of aortic walls when passing from the rapid to the slow ejection</td>
<td>0.02-0.04 sec after the Q wave</td>
</tr>
<tr>
<td>S₂</td>
<td>0.08-0.10 sec (duration is variable according to respiration)</td>
<td>lower than S₁ (50-70 Hz)</td>
<td>vibrations of the blood column during the closure of the aortic (S₂A) and pulmonary (S₂P) valves</td>
<td>corresponds to the descending phase of the T wave</td>
</tr>
<tr>
<td>S₃</td>
<td>0.02-0.04 sec</td>
<td>weak</td>
<td>ventricular walls vibrations during rapid filling</td>
<td>after the T wave</td>
</tr>
<tr>
<td>S₄</td>
<td>0.05-0.10 sec</td>
<td>very weak</td>
<td>additional acceleration of the blood column during atrial systole</td>
<td>0.02-0.04 sec after the P wave</td>
</tr>
</tbody>
</table>
When auscultating a patient's heart, only $S_1$ (heard as 'lub') and $S_2$ (heard as 'dub') can normally be distinguished. Because diastole takes about twice as long as systole, there is a longer pause between $S_2$ and $S_1$ than vice versa. Rapid heart rates (tachycardia) can shorten diastole to the point where it is difficult to discern which is $S_1$ and which is $S_2$. The situation in which $S_3$ and/or $S_4$ can also be auscultated, in addition to the normal $S_1$ and $S_2$ sounds, defines the gallop rhythm.

### 2.4. Pathological changes of the phonocardiogram (PC)

- **Heart murmurs**: represent abnormal, extra sounds with a relatively long duration (over 0.15 sec). These pathological heart sounds can be generated by turbulent flow, blood passage through valves with reduced diameters, or increased velocity of blood flow. Based on the moment in which they appear, heart murmurs can be classified as (Figure 4):
  - **systolic murmurs**, when they occur during systole (between $S_1$ and $S_2$);
  - **diastolic murmurs**, when they occur during diastole (between $S_2$ and $S_1$);
  - **continuous murmurs**, when they are present at all times.

- **Doubling of heart sounds**: is more common for $S_2$, when doubling appears as a longer interval of time between the aortic ($S_{2A}$) and the pulmonary ($S_{2P}$) components. This can happen physiologically during inhale, but is more common in pathological conditions such as pulmonary hypertension.

![Heart sounds diagram](image)

**Figure 3.** Synchronous recording of the phonocardiogram (PC) and electrocardiogram (ECG).

**Figure 4.** Heart murmurs.
3. The jugulogram (JP)

3.1. **Definition:** The jugulogram represents the graphic recording of the jugular pulse, which reflects the variations of pressure from the right atrium.

3.2. **The examination technique** involves placing special detectors over the right jugular vein, in the place where the venous pulsations are the most evident, just above the clavicle.

3.3. **Morphological analysis of the jugulogram**

A normal jugulogram is a trace that consists of three positive waves (marked with a, c, and v) and two negative waves (noted x and y) (Figure 5):

- the **a wave** corresponds to atrial contraction. The wave is overlapped with the forth sound (S₄) from the phonocardiogram.
- the **c wave** corresponds to the beginning of right ventricular contraction (isovolumic contraction), when the atrioventricular floor is pushed upward, increasing right atrial pressure. It occurs after S₁ (the first sound from the phonocardiogram).
- the **x wave** corresponds to right ventricular ejection, when the atrioventricular floor is pulled downwards, causing the distension of the right atrium and a significant decrease in right intraatrial pressure.
- the **v wave** - the ascending part of the wave corresponds to the increase in right intraatrial pressure due to venous filling, the peak of the wave corresponds to the opening of the tricuspid valve, while the descending part of the wave corresponds to the beginning of right atrial emptying.
- the **y wave** corresponds to the filling phase of the right ventricle, when the pressure drops suddenly in the right atrium and is overlapped with the third sound from the phonocardiogram (S₃).

![Figure 5. Synchronous recording of the electrocardiogram (ECG) and jugulogram (JP).](image)

4. The apexcardiogram (AC)

4.1. **Definition:** The apexcardiogram represents the graphic recording of the vibrations generated by the apex of the heart during different phases of the cardiac cycle.

4.2. **Examination technique:** During ventricular systole, the apex is projected downward and forward and induces a pulsation in the fifth intercostal space, on the left midclavicular line. This vibration can be recorded using a piezoelectric microphone placed in this area.
4.3. **Morphological analysis of the apexcardiogram**

The apexcardiogram is a trace that consists of two waves (Figure 6):
- the *a wave* - has small amplitude and corresponds to atrial systole.
- the *main wave* - is a broad, fast, trapezoidal wave, caused by ventricular contraction.
  - The main wave includes:
    - the *V point*, corresponding to the onset of left ventricular contraction and the closure of the mitral valve;
    - the *VE slope*, corresponding to the isovolumic ventricular contraction;
    - the *E point* represents the systolic peak, corresponding to aortic valve opening and onset of left ventricular ejection;
    - the *EX interval*, corresponding to the ejection period, presents a plateau or slightly downward slope shape;
    - the *X point* represents the closure of the aortic valve and the beginning of isovolumic relaxation;
    - the *O point* represents the diastolic peak, corresponding to mitral valve opening at the beginning of the rapid ventricular filling phase; it is synchronous with the end of S₂ from the phonocardiogram;
    - the *F point* corresponds with the end of rapid ventricular filling and it is synchronous with S₃ from the phonocardiogram.

![Figure 6. Synchronous recording of the electrocardiogram (ECG) and apexcardiogram (AC).](image)

5. **Mechanocardiographic assessment of cardiac cycle phases**

5.1. **Systolic time intervals**

Using the simultaneous recording of the carotidogram, the ECG, and the phonocardiogram (Figure 7), we can measure the *systolic times*. These parameters characterize different phases of ventricular systole and provide information regarding cardiac performance.
Figure 7. Simultaneous recording of the electrocardiogram (ECG), phonocardiogram (PC), and carotidogram (CP). Systolic time intervals are indicated.

Systolic times are represented by:
- the pre-ejection period (PEP) - can be calculated indirectly, by subtracting the ejection time (ET) from the duration of the total electro-mechanical systole (Q-S₂), or it can be measured directly from the beginning of the Q wave from the ECG trace to the E point from the carotidogram.

\[
PEP = (Q - S_2) - LVEP
\]

- the left ventricular ejection period (LVEP) or the ejection time (ET) is measured from the E point to the dicrotic notch (I point) from the carotidogram trace.
- the total electro-mechanical systole (Q-S₂) is measured from the beginning of the Q wave from the ECG trace to the beginning of the second sound (S₂) from the phonocardiogram.

Certain systolic time intervals can also be measured using the apexcardiogram (Figure 8):
- the duration of isovolumic contraction (IVC) – between the V and E points on the apexcardiogram
- the duration of ventricular ejection (Ej) – between the E and X points on the apexcardiogram.

Figure 8. Systolic and diastolic time intervals on the apexcardiogram (AC).
5.2. **Diastolic time intervals**

Diastolic time intervals represent the durations of different phases of ventricular diastole. The value of these parameters consists in their correlation with the diastolic function of the heart. The only mechanocardiogram that allows us to assess the diastolic time intervals is the apexcardiogram (Figure 8).

Diastolic times are represented by:
- the *isovolumic relaxation (IVR)* – measured from the *X* point to the *O* point on the apexcardiogram trace
- the *rapid ventricular filling (RF)* – measured from the *O* point to the *F* point on the apexcardiogram trace.

II. **EXPERIMENTAL OBJECTIVES AND PROCEDURES**

1. **Synchronous recording of the electrocardiogram and peripheral sphygmogram, using the BIOPAC SYSTEM**

1.1. **Experimental objectives**
- to perform the simultaneous recording of the ECG and peripheral sphygmogram
- to analyze the correlation between different ECG and peripheral sphygmogram elements, as a marker of the correlation between electrical and mechanical phenomena of the heart
- to measure the Duchosal time (on the peripheral sphygmogram) and the systolic time intervals

1.2. **Materials**
- BIOPAC recording system (BIOPAC data acquisition unit connected to a computer)
- transducers for ECG (SS2L) and peripheral sphygmogram (SS4L) recording
- disposable electrodes, conductive gel

![Figure 9. Connection of electrodes for ECG recording (lead II).](image-url)
1.3. Experimental methods

General observations

For the synchronous recording of the ECG and peripheral sphygmogram the subject is resting, in supine position. Place the three ECG electrodes required for the recording of lead II on the right hand, the left and right feet, and connect them to Channel 1. Connect the ECG cables, as follows (Figure 9):

- right arm – white cable (negative electrode)
- left foot – red cable (positive electrode)
- right foot – black cable (ground electrode).

Place the sensor of the pulse transducer on the tip of the right index finger snugly, but not too tight (Figure 10) and connect it to Channel 2.

In order to ensure an adequate recording, please respect the following:

- remove any metal object from your hand and forearm (watch, bracelet)
- check the position and the connection of the cables (see Figures 9 and 10)
- avoid body movements during the recording.

After connecting the transducers, follow the lead of the lab assistant who will guide you through the necessary steps of the recording.

Measurement of the Duchosal time

On the peripheral sphygmogram trace, select the interval between the beginning (E point) and the top (B point) of the anacrotic wave. The total amplitude of the wave is automatically calculated (P-P). Calculate the value of half of this maximum amplitude (P-P/2). Then, select the interval between the beginning of the anacrotic wave and the point that corresponds to half of its maximum amplitude and read the time needed for the pulse wave to reach half of its maximum amplitude (Delta T) (Figure 11). This will represent the Duchosal time (half-rise time).
**Measurement of systolic time intervals**

Using the synchronous recording of the ECG and the peripheral sphygmogram you can measure:

- the *left ventricular ejection period (LVEP)* or the *ejection time (ET)*. Select the interval between the beginning of the anacrotic wave (∈ point) and the dicrotic notch (∇ point) on the peripheral sphygmogram (Figure 12). The LVEP is automatically measured (Delta T).

![Figure 12.](image)

- the *total electro-mechanical systole (Q-S₂)*. Since S₂ coincides with the dicrotic notch from the pulse wave, the position of the dicrotic notch can be used instead of that of S₂. Select the interval between the beginning of the Q wave from the ECG trace and the dicrotic notch from the peripheral sphygmogram (Figure 13). The total electro-mechanical systole is automatically calculated (Delta T).

![Figure 13.](image)
- the pre-ejection period (PEP). Select the interval between the beginning of the Q wave from the ECG trace and the E point from the peripheral sphygmogram. The pre-ejection period is automatically calculated (Delta T). Then, calculate the duration of the pre-ejection period using the equation described previously.

**Interpretation of results**

All measured parameters will have to be interpreted by comparison with the ideal values. For calculating ideal systolic time intervals, measure the heart rate for the selected trace (the recordings where you previously measured the systolic time intervals). Then, calculate the ideal values (according to Weissler equations – Table 2). Report your results to the ideal calculated values. Express the result in percentage. The results are considered pathological if the difference between the measured and the ideal values exceeds 15%.

**Table 2.** Ideal values for the systolic time intervals, according to the heart rate (HR).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Male</th>
<th>Female</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q-S&lt;sub&gt;2&lt;/sub&gt;</td>
<td>564 - 2.1 x HR</td>
<td>549 - 2.0 x HR</td>
</tr>
<tr>
<td>LVEP (ET)</td>
<td>413 - 1.7 x HR</td>
<td>418 - 1.6 x HR</td>
</tr>
<tr>
<td>PEP</td>
<td>131 - 0.4 x HR</td>
<td>133 - 0.4 x HR</td>
</tr>
</tbody>
</table>

Using these systolic time intervals we can calculate different other parameters that can be used as indicators of cardiac contractility:

- the **ejection ratio** = 1.125 x (PEP / LVEP) x 1.25
- the **normal hemodynamic index** (Blumberger index) = LEVP / PEP

Normal values for the Blumberger index: 2.5-5.

2. Synchronous recording of the electrocardiogram and phonocardiogram, using the BIOPAC SYSTEM

2.1. **Experimental objectives**

- to perform the simultaneous recording of the ECG and phonocardiogram
- to analyze the correlation between the ECG and the phonocardiogram, as a marker of the correlation between electrical and mechanical phenomena of the heart
- to analyze the heart sounds on the phonocardiogram in terms of duration, amplitude, frequency, position on the trace, and correlation with certain ECG elements
- to measure certain systolic time intervals (the total electro-mechanical systole)

2.2. **Materials**

- BIOPAC recording system (BIOPAC data acquisition unit connected to a computer)
- transducers for ECG recording (SS2L)
- sound amplification system (DA100C) with adapted transducer for physiological sounds recording (TSD108)
- STM100C stimulation system for audio signal, connected to audio headset OUT100
- disposable electrodes, conductive gel
2.3. Experimental methods

General observations

For the synchronous recording of the ECG and phonocardiogram the subject is resting, in supine position. Place the ECG electrodes as described in the previous section (Figure 9) and connect them to Channel 1. Place the microphone for the phonocardiogram in the Botkin-Erb point (the 3rd left intercostal space, next to the sternum) and connect it to Channel 2.

In order to ensure an adequate recording, please respect the following:
- remove any metal object from your hand and forearm (watch, bracelet)
- check the position and the connection of the cables and of the microphone
- avoid body movements during the recording
- avoid any additional noise during the procedure.

After connecting the transducers and the microphone, follow the lead of the lab assistant who will guide you through the necessary steps of the recording.

Analysis of the heart sounds

Identify $S_1$ and $S_2$ heart sounds on the phonocardiogram (Figure 14). Select successively the two heart sounds and measure their amplitude ($P-P$), duration ($\Delta T$), and frequency (BPM). Assess the position of the two heart sounds in relationship with the corresponding ECG elements.

![Figure 14. Synchronous recording of the ECG (lower panel) and phonocardiogram (upper panel).](image)

Measurement of the total electro-mechanical systole

Using the synchronous recording of the ECG and phonocardiogram, select the interval between the beginning of the Q wave from the ECG trace and the beginning of $S_2$ on the phonocardiogram. The total electro-mechanical systole is automatically calculated ($\Delta T$). Compare the value with that obtained using the synchronous recording of the ECG and peripheral sphygmogram.
TEST YOUR KNOWLEDGE

1. The second heart sound is caused by:
   a. mitral and tricuspid valves closure
   b. aortic and pulmonary valves opening
   c. mitral and tricuspid valves opening
   d. aortic and pulmonary valves closure
   e. atrial systole

2. Which parameter calculated using mechanocardiogram recordings is better correlated with left ventricular contraction?
   a. the electro-mechanical systole
   b. the EX interval
   c. the ejection period
   d. the Duchosal time
   e. the rapid ventricular filling time

3. The aortic area used for auscultation of normal heart sounds is located on:
   a. the 5th intercostal space on the left midclavicular line
   b. the second right intercostal space next to the sternum
   c. the second left intercostal space next to the sternum
   d. the second left intercostal space on the midclavicular line
   e. the 5th right intercostal space next to the sternum

4. The first heart sound:
   a. has a duration of 0.12-0.15 sec
   b. has a duration of 0.05-0.10 sec
   c. appears 0.02-0.04 sec after the T wave
   d. is partly caused by the vibration of ventricular walls during isovolumic relaxation
   e. can be heard in case of gallop rhythm