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Analysis of Cardiac Physiology

BM2102 Modelling and Analysis of Physiological Systems

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1 The Cardiac Cycle

The cardiac cycle is a rhythmic sequence of events that describes the pumping action of the heart.

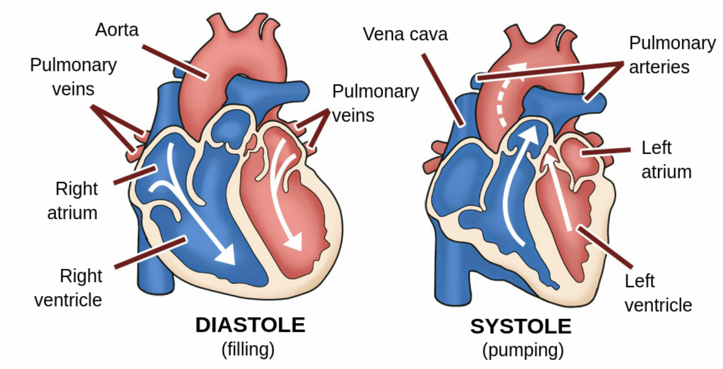

Figure 1: Cardiac Cycle

1.1 Parts of Cardiac Cycle

- **Diastole:** Ventricles fill with blood as the mitral and tricuspid valves open.
- **Atrial Contraction:** Atria contract, propelling more blood into ventricles.
- **Ventricular Contraction (Systole):** Ventricles contract, closing mitral/tricuspid valves, opening aortic/pulmonary valves.
- **Ventricular Relaxation:** Ventricles relax, aortic/pulmonary valves close, cycle repeats.

1.2 Physiological Parameters

- Left Ventricular Pressure
- Left Atrial Pressure
- Aortic Pressure
- Left Ventricular Volume
- Blood Flow Rate of Aortic Valve
- Blood Flow Rate of Mitral Valve

2 Normal Sinus Diagram

2.1 Wiggers Diagram

The Wiggers diagram, developed by Dr. Carl Wiggers, is a detailed chart that illustrates the major events occurring during a single cardiac cycle. It integrates various physiological parameters to show how the heart functions in a synchronized manner.

Key features of the Wiggers diagram include:

- **Electrocardiogram (ECG):** Displays the heart's electrical activity, indicating phases like atrial and ventricular depolarization and repolarization.
- **Pressure Curves:** Shows the pressure changes occurring in the left atrium, left ventricle, and aorta throughout the cardiac cycle.
- **Heart Sounds:** Marks the timing of valve closures (e.g., mitral and aortic valves) that generate the audible "lub-dub" sounds.
- **Volume Changes:** Tracks the variation in the volume of the left ventricle during the phases of filling and ejection.

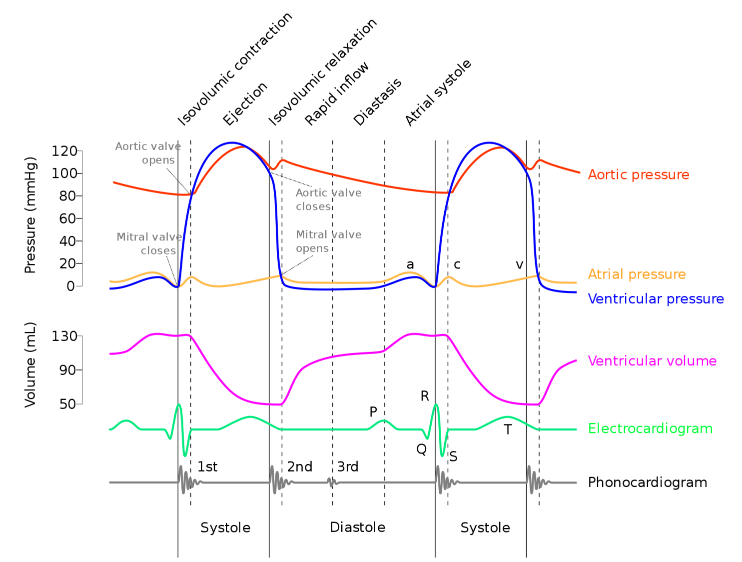

Figure 2: Wiggers Diagram of Cardiac Cycle

2.2 Aortic Valve Open/Close Phases

2.2.1 Aortic Valve Open

The aortic valve opens in response to the contraction of the left ventricle, facilitating the ejection of blood into the aorta. This event occurs when the left ventricular pressure rises to 69.8 mmHg, surpassing the aortic pressure of 68.8 mmHg. The resulting pressure gradient ensures the aortic valve opens, allowing for unidirectional blood flow from the ventricle to the aorta. As shown in Figure 3, this valve opening takes place when the left ventricular volume reaches 134 mL. This process is precisely synchronized with the peak of ventricular systole, thereby maximizing the efficiency of blood ejection. Ultimately, the timely opening of the aortic valve plays a critical role in maintaining physiological balance by ensuring adequate cardiac output and effective pressure regulation throughout the cardiovascular system.

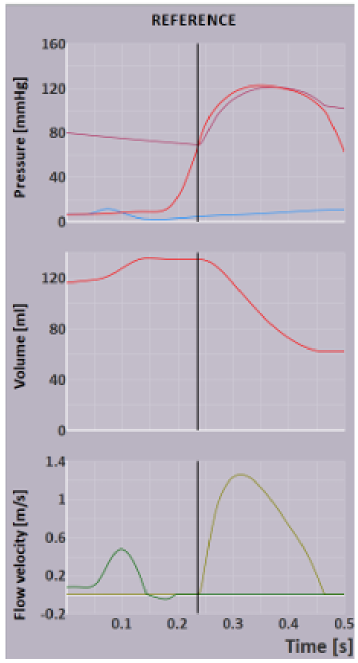

Figure 3: Aortic Valve Opening

2.2.2 Aortic Valve Close

The closure of the aortic valve marks the end of left ventricular contraction and initiates a reduction in left ventricular pressure. As illustrated in Figure 4, this closure leads to a phase known as isovolumetric relaxation, during which the left ventricular volume remains constant. At the moment of valve closure, the left ventricular pressure falls below the aortic pressure, specifically to 104 mmHg, prompting the valve to shut rapidly and preventing any backflow of blood into the left ventricle. The recorded left ventricular volume at the time of valve closure is 62.1 mL. Comparing this with the volume at the time of aortic valve opening (134 mL), it is evident that 71.9 mL of blood has been ejected during this cardiac cycle. This efficient ejection reflects the precision and effectiveness of the cardiovascular system's regulatory mechanisms in maintaining proper circulation and pressure balance.

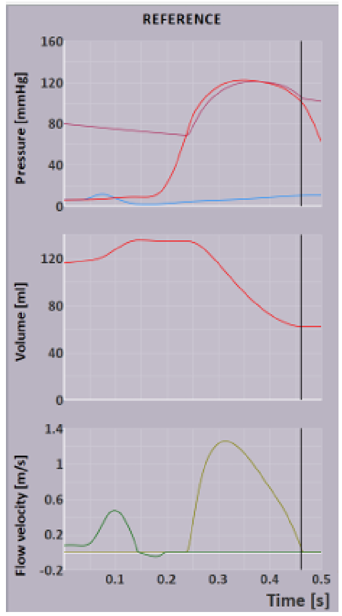

Figure 4: Aortic Valve Closing

2.3 Mitral Valve Open/Close Phases

2.3.1 Mitral Valve Open

The Mitral valve opens as the left ventricle enters its relaxation phase, allowing blood to flow from the left atrium into the ventricle. At this point, the left ventricular pressure is 8.89 mmHg, which is lower than the left atrial pressure of 10.4 mmHg. This pressure gradient ensures that the Mitral valve opens unidirectionally toward the left ventricle. The resulting flow facilitates the passive filling of the left ventricle during early diastole. At the moment of Mitral valve opening, the left ventricular volume is measured at 62 mL. This event marks an efficient and controlled filling process, demonstrating the precise coordination between pressure differentials and valve mechanics, and emphasizing the critical role of hemodynamic forces in cardiac function.

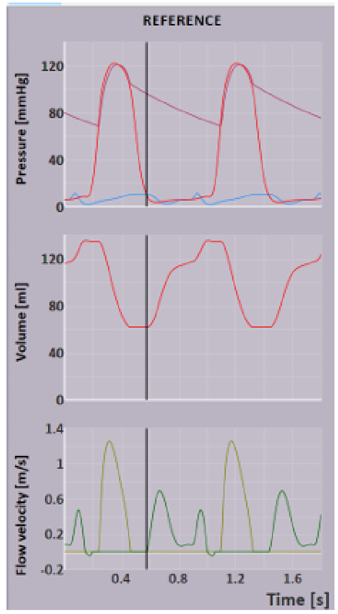

Figure 5: Mitral Valve Opening

2.3.2 Mitral Valve Close

The closure of the Mitral valve occurs when the left ventricle is fully filled with blood, marking the end of the ventricular filling phase. At this point, the left ventricular pressure is 8.61 mmHg, while the left atrial pressure remains lower at 2.13 mmHg. This pressure difference causes the Mitral valve to close, preventing any back-flow of blood into the left atrium. The left ventricular volume at the moment of Mitral valve closure is measured at 135 mL. The difference between the volumes at Mitral valve closing (135 mL) and opening (62 mL) indicates that 73 mL of blood has been filled during this cardiac cycle. This closure signifies the completion of diastolic filling and the beginning of isovolumetric contraction. The Mitral valve's closure is essential for maintaining unidirectional blood flow and preserving the efficiency of the cardiac cycle. This phase highlights the precise pressure-regulated valve control that ensures optimal functioning of the cardiovascular system.

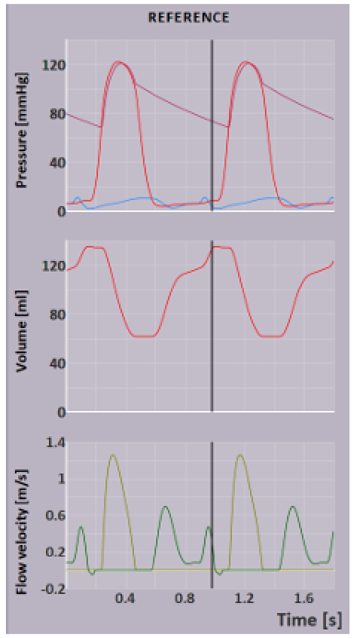

Figure 6: Mitral Valve Closing

2.4 Identify which points of the pressure-volume relation correspond to the closing and opening of the aortic and mitral valves

The left ventricular volume decreases during the opening of the aortic valve, while, conversely, the opening of the mitral valve leads to an increase in the left ventricular volume.

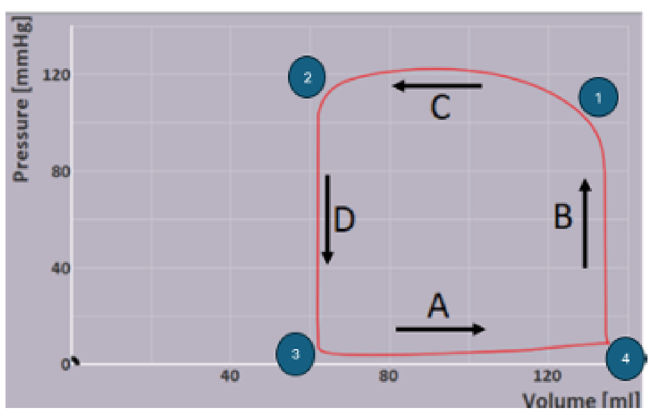

Figure 7: Cardiac Cycle: Valve Events

Path	Event
C	1(Aortic Opening)
D	2(Aortic Closing)
A	3(Mitral Opening)
B	4(Mitral Closing)

Table 1: Correspondence of Points to Cardiac Cycle Events

2.5 Identify with a Specific Stage of the Cardiac Cycle

- A: Filling
- B: Isovolumic Contraction
- C: Ejection
- D: Isovolumic Relaxation

2.6 Reason Behind the Singular Peak in the Flow Velocity Pattern of the Aortic Valve and the Dual Peaks in the Pattern of the Mitral Valve.

- **Aortic Valve – Singular Peak:**
  - The aortic valve opens during ventricular systole when the left ventricle contracts strongly. This contraction forces blood out into the aorta in a swift, continuous flow, which creates one distinct sharp peak in the flow velocity. The blood flow speeds up to its highest point and then slows down as the pressure inside the ventricle falls, producing a single prominent systolic peak.
- **Mitral Valve – Dual Peaks:**
  - The mitral valve opens in diastole, enabling blood to pass from the left atrium into the left ventricle. The first peak, known as the E wave, corresponds to passive blood flow driven by the pressure difference between the atrium and ventricle. The second peak, called the A wave, is caused by the active contraction of the atrium, which pushes extra blood into the ventricle right before systole begins. This two-part filling process results in two clear peaks in the mitral valve's flow velocity pattern.
- These differences reflect the timing and mechanism of blood movement through each valve, with the aortic valve responding to a single strong contraction and the mitral valve influenced by both passive and active filling phases.

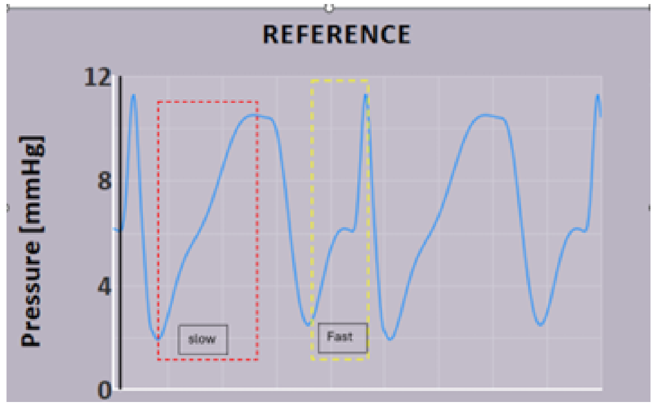

Figure 8: Flow Velocities of Aortic & Mitral Valves

2.7 Analysis of Atrial Pressure Changes in the Cardiac Cycle

- **Fast (Steep) Rise in Atrial Pressure:**
  - Occurs during **atrial systole**, when the atria contract.
  - Caused by **atrial depolarization**, leading to active contraction of atrial myocardium.
  - This contraction rapidly increases atrial pressure to push blood into the ventricle.
  - Corresponds with the **P-wave** on the ECG.
- **Slow Rise in Atrial Pressure:**
  - Occurs during **ventricular systole**, particularly the **isovolumetric contraction phase**.
  - During this time, the mitral valve is closed, and the atria begin to refill with blood.
  - Blood from the **pulmonary veins** flows passively into the left atrium.
  - This passive filling gradually increases atrial pressure.
  - This slow rise is not directly due to an ECG wave but follows the **QRS complex** (ventricular depolarization).
- **Significance:**
  - The steep and slow rises reflect the transition between active and passive atrial phases.
  - Careful observation of atrial pressure waveform helps correlate mechanical and electrical cardiac activity.

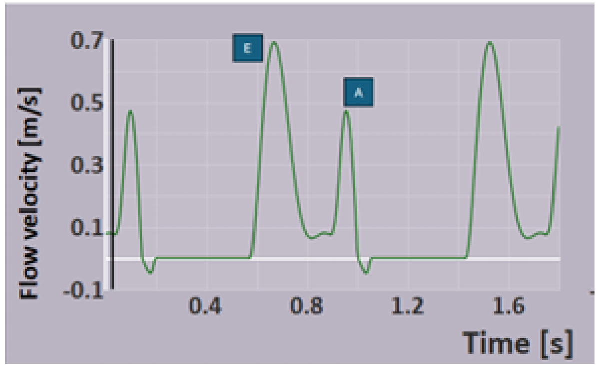

Figure 9: Mitral Valve Flow Velocity: E- and A-waves

2.8 E- and A-waves of Mitral Flow

E: Early/elastic filling; A: Atrial/active filling.

2.9 Calculate E/A-ratio

E = 0.683, A = 0.46

$$\frac{E}{A} \text{ Ratio} = \frac{0.683}{0.46} = 1.485$$

2.10 Amounts of Left Ventricular Filling

- Passive: 114 ml - 65 ml = 49 ml
- Active: 134 ml - 114 ml = 20 ml

2.11 Blood flow velocity in a valve is related to flow rate

- **Flow Rate Calculation:**
  - Blood flow rate through a valve (Q_{valve}) is calculated using the formula:

$$Q_{\text{valve}} = A \cdot V_{\text{valve}}$$

  - A = cross-sectional area of the valve.
  - V_{valve} = velocity of blood flow through the valve.
- **Importance of Valve Geometry:**
  - Accurate estimation of flow rate requires knowing the anatomical or geometrical property of the valve, especially its area.
  - The area can vary depending on physiological or pathological conditions (e.g., stenosis).

- **Units:**
  - Velocity (V_{valve}) is measured in **distance per unit time** (e.g., cm/s or m/s).
  - Flow rate (Q_{valve}) is measured in **volume per unit time** (e.g., mL/s or L/min).

3 Aortic Valve Stenosis

3.1 Preload and Afterload

Preload refers to the initial stretching of the cardiac myocytes prior to contraction. It is closely related to the end-diastolic volume (EDV), which determines the amount of ventricular filling. Afterload is the pressure the heart must work against to eject blood during systole. It is influenced by factors such as systemic vascular resistance and aortic pressure.

3.2 Simulating Aortic Valve Stenosis (AS)

Table 2: Change of peak pressure, peak velocity, peak volume with stenosis

Stenosis (%)	Peak Pressure (mmHg)	Peak velocity (m/s)	Peak Volume (ml)
0	121	1.25	135
5	122	1.30	135
10	122	1.38	135
15	123	1.46	135
20	124	1.53	135
25	125	1.63	135
30	126	1.73	135
35	127	1.84	136
40	128	1.97	136
45	130	2.11	136
50	132	2.28	136
55	135	2.47	136
60	139	2.69	136
65	143	2.95	137
70	149	3.28	138
75	158	3.68	139
80	171	4.2	141

According to Table 2, the peak flow velocity through the aortic valve increases progressively with the percentage of stenosis. This observation is expected based on the equation

$$Q_{\text{valve}} = A_{\text{valve}} \times V_{\text{valve}},$$

where the cross-sectional area of the valve (A_{valve}) decreases as stenosis worsens, while the flow rate (Q_{valve}) remains relatively constant. Consequently, the flow velocity (V_{valve}) must increase. Additionally, the peak left ventricular pressure shows a marked rise beyond 20% stenosis, whereas the increase in peak left ventricular volume is more gradual. This pressure-volume relationship is further illustrated in Figure 7. At 80% stenosis, the maximal left ventricular pressure reaches 171 mmHg.

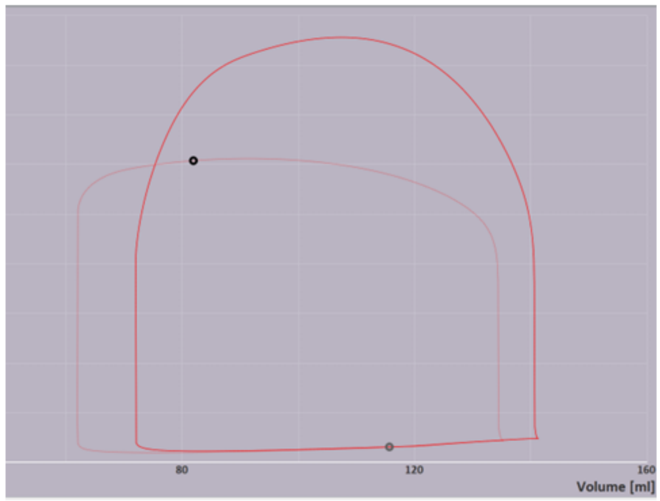

Figure 10: P-V diagram at 80% stenosis (dashed line normal condition)

3.3 Effect of Aortic Stenosis on Preload, Afterload and Cardiac Output

Aortic stenosis (AS) significantly impacts cardiac function by altering preload, afterload, and cardiac output.

- **Preload:** The narrowing of the aortic valve limits the amount of blood the ventricles can eject. Consequently, some blood remains in the ventricles, leading to accumulation and increased preload.
- **Afterload:** Afterload increases directly due to the higher resistance against blood flow caused by the reduced cross-sectional area of the stenotic valve.
- **Cardiac Output (CO):** Since cardiac output is the product of stroke volume and heart rate, the increased preload can elevate stroke volume, potentially increasing cardiac output despite the stenosis.

3.4 Pressure drop across the stenotic aortic valve

Aortic pressure during maximum left ventricular pressure is 103 mmHg.

$$\text{Pressure drop} = 171 - 103 = 68 \text{ mmHg}$$

3.5 Maximal pressure drop using formula

Maximum flow velocity of the aortic valve is $v = 4.2$ m/s. Pressure drop (ΔP) is calculated using the formula:

$$\Delta P = 4v^2 = 4 \times (4.2)^2 = 4 \times 17.64 = 70.56 \text{ mmHg}$$

This calculated value is close to the measured value.

3.6 Calculation of duration of ejection

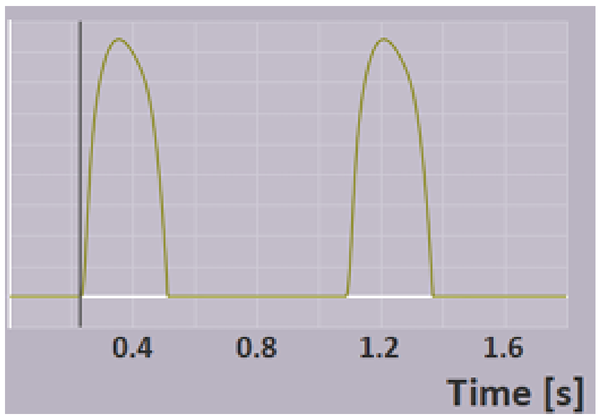

Figure 11: Flow velocity diagram with 80% stenosis

Time taken to eject ventricular blood through the narrowed aortic valve is calculated as follows:

$$\text{Duration of ejection} = 0.53 \text{ s} - 0.23 \text{ s} = 0.30 \text{ s}$$

3.7 External pump work by left ventricle

Using Figure 10:

- External pump work in a normal person $\approx$ 20 squares
- External pump work at 80% stenosis $\approx$ 23 squares
- Increase in pump work $\approx$ 3 squares

3.8 Change in the myocardial tissue of left ventricle

To cope with the chronically increased pump work caused by aortic stenosis, the myocardial tissue of the left ventricle undergoes hypertrophy, resulting in thickening and enlargement of the ventricular muscle. This adaptation increases the contractile strength, allowing the ventricle to generate the higher pressures required to overcome the elevated afterload.

However, ventricular hypertrophy leads to a stiffer ventricular wall, which may impair relaxation and filling. Additionally, the increased muscle mass raises myocardial oxygen demand and can further increase the afterload, thereby imposing an even greater workload on the heart.

4 References

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