Department of Electronic & Telecommunication Engineering

University of Moratuwa

Sri Lanka

Analysis of cardiac physiology

210321X Kumarasinghe R D

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Contents

1 Introduction

In this report, I employ the CircAdapt simulation software to explore the dynamics of cardiac physiology, focusing on both normal sinus rhythm and the implications of aortic valve stenosis. Guided by the classical Wiggers diagram, our analysis encompasses key parameters such as left ventricular pressure, atrial pressure, aortic pressure, and left ventricular volume. Through meticulous examination of blood flow velocities in the aortic and mitral valves, as well as the pressure-volume relation of the left ventricle, we seek to correlate simulation findings with established physiological principles. The subsequent section delves into the nuanced alterations during aortic valve stenosis, considering factors like preload, afterload, and the external pump work generated by the left ventricle. Throughout the report, emphasis is placed on clarity and formality, supported by relevant screenshots and plots obtained from the simulation software.

2 Wiggers diagram

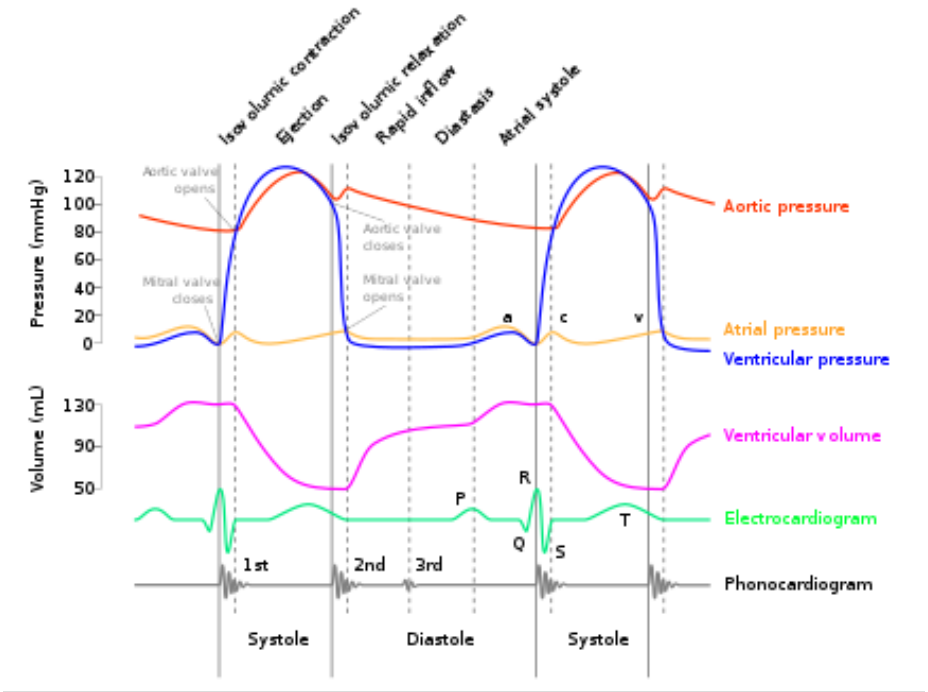


Figure 1: WiggersDiagram

Wigger's Diagram serves as a visual representation of pressure variations in the atrium, ventricle, and artery throughout a single cardiac cycle (Figure 2). Distinct pressure dynamics exist between the right and left sides of the heart, with the left side experiencing higher pressure to facilitate blood circulation throughout the entire body, while the right side handles pulmonary circulation. Despite the pressure differences, both sides of the heart exhibit similar diagrammatic shapes.

- **Atrial Systole:** In this phase (Figure 3):
  - Atrial pressure rises during atrial contraction.
  - Ventricular pressure experiences a slight increase, proportionate to atrial contraction, as blood moves from the atria to the ventricles.
  - Ventricular pressure surpasses atrial pressure, prompting the closure of the atrioventricular valve.

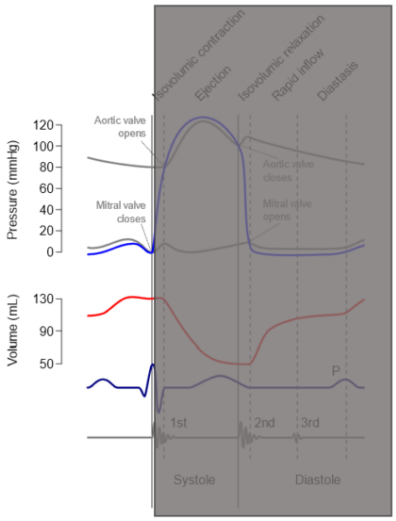


Figure 2: Atrial systole

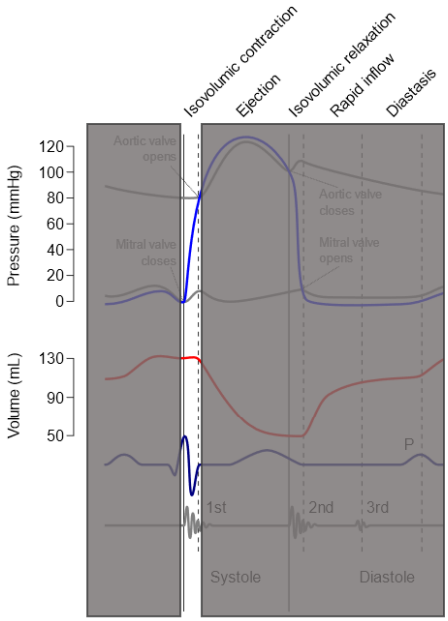


Figure 3: Isovolumetric contraction in ventricular systole

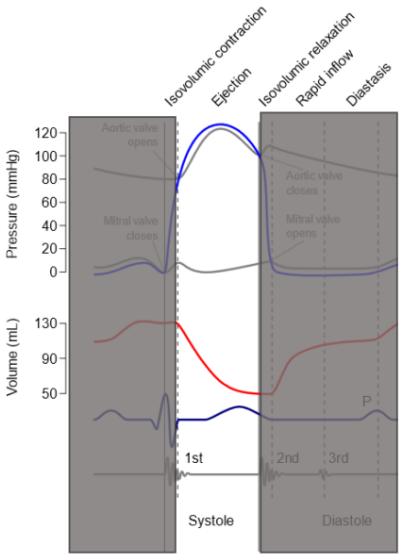


Figure 4: Ventricular systole

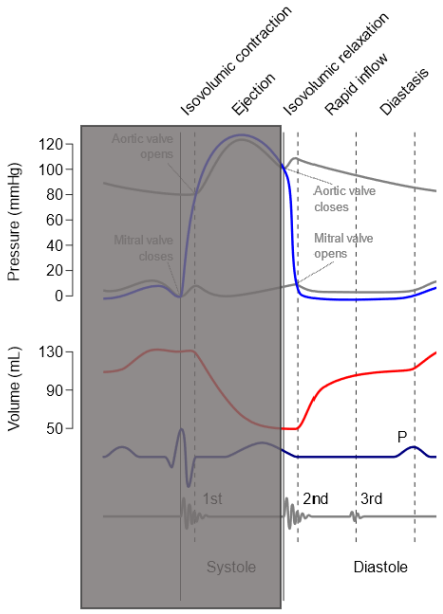


Figure 5: Diastolic phase

- **Ventricular Systole (Isovolumetric Contraction):** During isovolumetric contraction in ventricular systole (Figure 4):
  - Ventricular pressure rises as the ventricles contract.
  - Both the mitral and aortic valves remain closed, maintaining constant
  - ventricular volume during contraction (isovolumetric contraction).
  - Ventricular pressure equals arterial pressure, leading to the opening of the aortic valve.
- **Ventricular Systole (Ejection Phase):** In the ejection phase of ventricular systole (Figure 5):
  - Ventricular pressure continues to ascend until reaching its peak.
  - Blood is ejected from the heart during this phase.
  - Arterial pressure rises as blood enters the aorta, and both ventricular and arterial pressures decline after reaching their peaks.
  - Aortic valve closure follows when ventricular pressure falls below arterial pressure, resulting in the second heart sound (S2).
- **Diastole:** During diastole (Figure 6):
  - Both aortic and mitral valves are closed, maintaining constant ventricular volume during relaxation (isovolumetric relaxation).
  - When ventricular pressure drops below atrial pressure, the mitral valve opens.
  - Initial slight drops in atrial and ventricular pressure are followed by a rise due to diastolic filling as blood enters the atria.

2.1 Ventricular Volume and Pressure Curve

Descending ventricular volume curve at systole signifies blood ejection to systemic circulation.

- Phase 1 Systole involves isovolumic contraction with closed valves, initiating a rise in ventricular pressure.
- Phase 2 Systole features rapid ejection, causing ventricular pressure to surpass aortic pressure, prompting aortic valve opening.
- Phase 3 Systole sees reduced ejection as ventricular pressure falls below aortic pressure.

Diastole commences with the ventricular volume curve ascending, indicating atrial blood influx.

- Phase 1 Diastole involves isovolumic relaxation, both valves closed, and a ventricular pressure drop.
- Phase 2 Diastole experiences rapid filling as ventricular pressure falls below atrial pressure, allowing swift blood inflow.
- Phase 3 Diastole entails reduced filling, maintaining blood influx at a slower rate as ventricle nears full capacity.

2.2 Left Atrial Pressure Curve

Left atrial pressure rises during diastole and decreases during systole.

- "A" wave denotes atrial systole, contributing 10ml blood to ventricular volume during ventricular diastole.
- "C" wave post-QRS wave is caused by ventricular contraction and aortic blood ejection.
- "V" wave represents atrial filling with blood from pulmonary veins.

2.3 Aortic Pressure Curve:

- Aortic pressure curve unfolds as ventricular pressure surpasses aortic pressure, opening the aortic valve for blood ejection.
- In the rapid ejection phase, aortic pressure initially lags behind ventricular pressure but eventually surges above.
- Aortic valve closure, marking diastole onset, is influenced by declining ventricular pressure.
- Dicrotic notch or incisura results from a slight backflow of aortic blood, filling aortic valve cusps at ventricular systole's end.

3 Normal Sinus Rhythm

Normal Sinus Rhythm (NSR) is the optimal and regular electrical activity of the heart's natural pacemaker, the sinoatrial (SA) node. In NSR, the heart's rhythm follows a consistent pattern, with a regular rate between 60 to 100 beats per minute in adults. The SA node initiates each heartbeat, triggering the coordinated contraction of the atria and ventricles, ensuring efficient blood circulation. NSR is indicative of a well-functioning cardiac system, with deviations from this rhythm often signaling underlying heart conditions or disturbances in the heart's electrical conduction system.

3.1 Opening the aortic valve

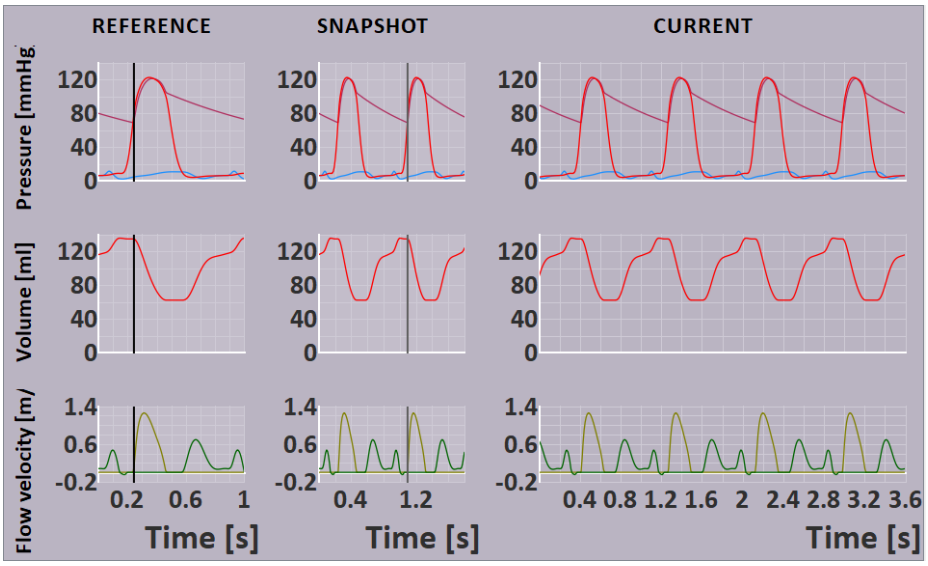


Figure 6: Aortic valve opening

- In pressure-time curve
  - Purple: Aorta
  - Red -Left: Ventricle
  - Light blue: Left Artrium
- In volume-time curve
  - Red: Left ventricle
- In flow rate curve
  - Light Green:Aortic valve
  - Dark Green: Mitral valve

- Left ventricular pressure surpasses aortic pressure, causing the aortic valve to open.
- Forceful ejection of blood into the aorta contributes to increased aortic pressure.
- Left ventricular pressure decreases as blood is expelled, leading to a decline in left ventricular volume.
- The pressure-volume relationship graph in the left ventricle displays an upward trend during aortic valve opening.

3.2 Closing the aortic valve

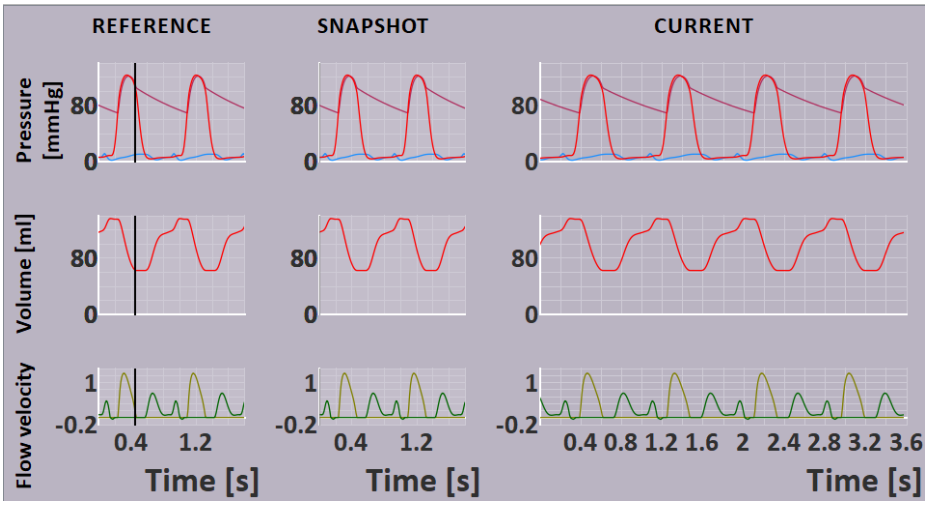


Figure 7: Aortic valve closing

- In pressure-time curve
  - Purple: Aorta
  - Red -Left: Ventricle
  - Light blue: Left Artrium
- In volume-time curve
  - Red: Left ventricle
- In flow rate curve
  - Light Green:Aortic valve
  - Dark Green: Mitral valve

- Marks the conclusion of the ejection phase in the cardiac cycle.
- Occurs after the aortic valve allows blood to pass from the left ventricle into the aorta.
- Blood flow velocity through the aortic valve decreases as the valve begins to close.
- Aortic pressure starts to decline as the valve closes, preventing backflow into the left ventricle during diastole.
- Left ventricular volume begins to rise as the ventricle fills with blood from the left atrium.
- The pressure-volume graph shows a downturn, reflecting the isovolumetric relaxation phase.
- Synchronization between aortic valve events and corresponding changes in flow rates, pressures, and volumes ensures an efficient cardiac cycle, crucial for maintaining circulation.

3.3 Opening the mitral valve

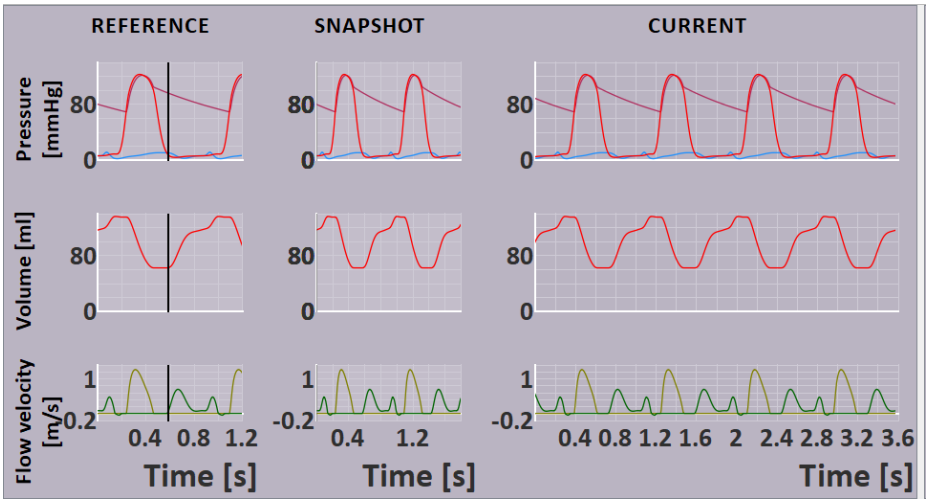


Figure 8: Mitral valve opening

- In pressure-time curve
  - Purple: Aorta
  - Red -Left: Ventricle
  - Light blue: Left Artrium
- In volume-time curve
  - Red: Left ventricle
- In flow rate curve
  - Light Green:Aortic valve
  - Dark Green: Mitral valve
- Marks the commencement of the ventricular filling phase in the cardiac cycle.
- Occurs during diastole as the left ventricle relaxes.
- Blood flows from the left atrium into the left ventricle through the open mitral valve.
- Results in an increase in left ventricular volume and a subsequent rise in left atrial pressure.
- The mitral valve opens when left atrial pressure exceeds left ventricular pressure.
- Blood flow velocities through the mitral valve are elevated during this phase.
- The pressure-volume graph in the left ventricle shows an initial rise during mitral valve opening.

3.4 Closing the mitral valve

- In pressure-time curve
  - Purple: Aorta
  - Red -Left: Ventricle
  - Light blue: Left Artrium
- In volume-time curve
  - Red: Left ventricle
- In flow rate curve
  - Light Green:Aortic valve
  - Dark Green: Mitral valve
- Indicates the end of the ventricular filling phase in the cardiac cycle.
- Occurs as the left ventricle begins to contract during systole.

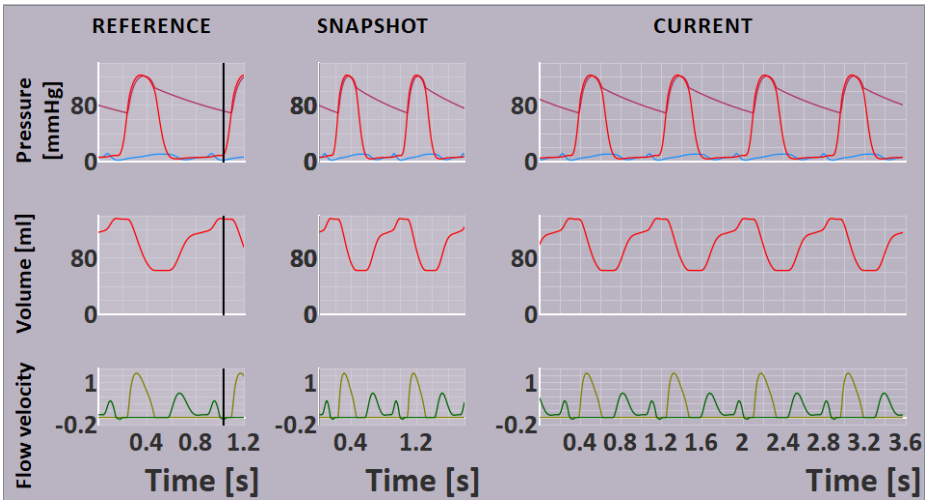


Figure 9: Mitral valve closing

- Mitral valve closes to prevent backflow of blood from the left ventricle to the left atrium.
- Blood flow velocities through the mitral valve decrease as the valve closes.
- Left ventricular pressure surpasses left atrial pressure, causing the mitral valve to shut.
- The closure of the mitral valve contributes to an increase in left ventricular pressure.
- Left ventricular volume starts to decrease as blood is ejected into the aorta.

3.5 Pressure-volume relation of left ventricle

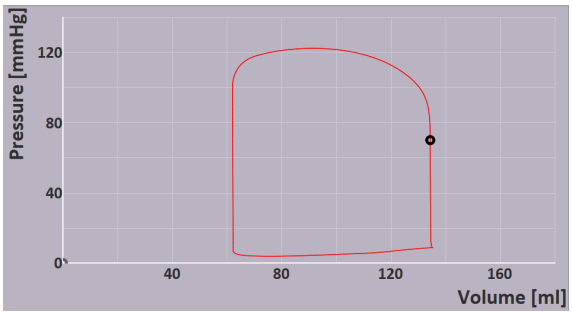


Figure 10: 1-aortic opening

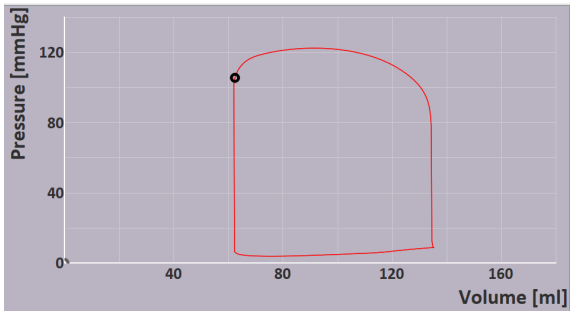


Figure 11: 2-aortic closing

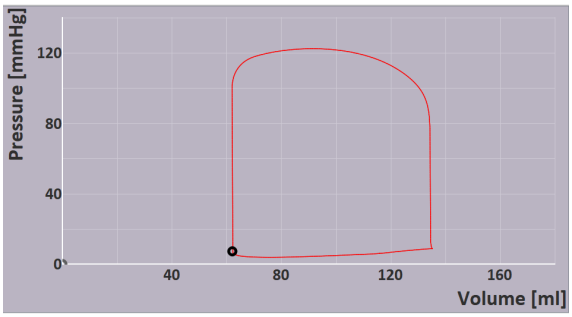


Figure 12: 3-mitral opening

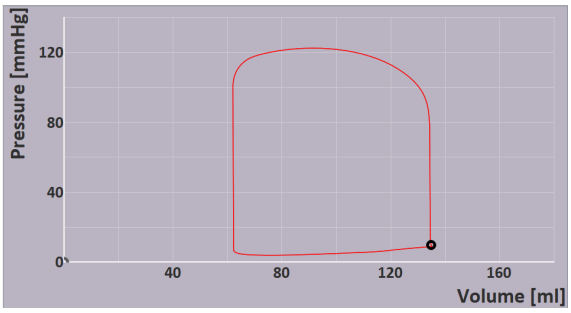


Figure 13: 4-mitral closing

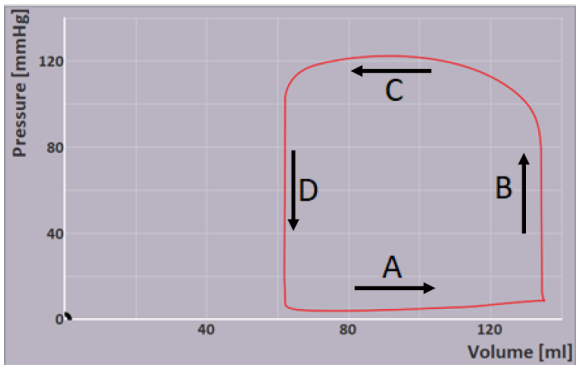


Figure 14: Fihure for part d

- A: Filling
- B: Isovolumic contraction
- C: Ejection
- D: Isovolumic relaxation

3.6 Flow rates of Mitral valve and Aortic valve

flow rate curve

- Light Green:Aortic valve
- Dark Green: Mitral valve

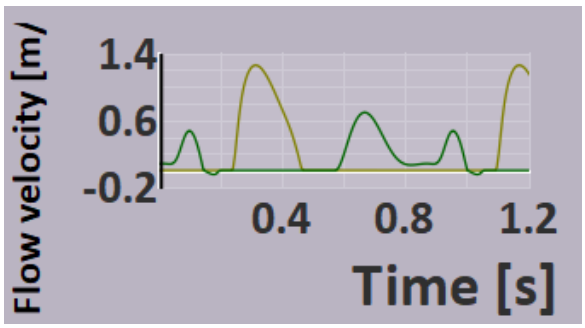


Figure 15: Flow rates

3.6.1 Aortic Valve

Single Hump: The aortic valve opens when the left ventricular pressure exceeds that in the aorta. This triggers a relatively smooth and continuous flow of blood from the left ventricle into the aorta. The single hump in the flow velocity pattern is a consequence of the streamlined flow through the narrowed valve opening in conditions such as aortic stenosis. As the valve orifice narrows, blood accelerates through the restricted opening, resulting in a single prominent hump in the velocity pattern.

3.6.2 Mitral Valve

Two Humps: The mitral valve opens when the pressure in the left atrium surpasses that in the left ventricle. The unique anatomical structure of the mitral valve, with its two leaflets, contributes to a less smooth flow pattern. During the initial opening of the mitral valve, the first hump corresponds to the passive flow from the large left atrium into the left ventricle (passive filling). The second hump occurs during systole when reverse flow into the left atrium happens due to closure of the valve leaflets (active contraction). The fluttering or vibrating of the mitral valve leaflets causes this two-hump pattern in the flow velocity. In summary, the differences in the number of humps in the flow velocity patterns of the aortic and mitral valves are attributed to variations in their anatomical structures, mechanisms of opening, and the specific phases of the cardiac cycle they are associated with.

3.7 Analysis of atrial pressure

During the cardiac cycle, atrial pressure exhibits two distinct rises:

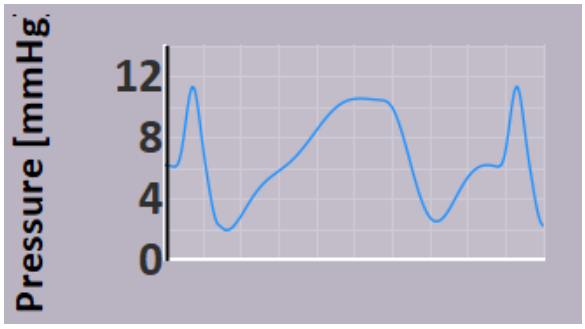


Figure 16: Artrial pressure

- **Fast (Steep) Increase in Atrial Pressure:**

  Cause: Atrial contraction during atrial systole pushes additional blood into the ventricles, resulting in an abrupt rise in atrial pressure. This leads to an increase in ventricular pressure, prompting the closure of atrioventricular valves (mitral/tricuspid).

  ECG Waveform Correspondence: The P-wave on the ECG, representing atrial depolarization, aligns precisely with this rapid increase in atrial pressure.

- **Slow Increase in Atrial Pressure:**

  Cause: During ventricular filling in diastole, blood gradually flows from the vena cava and pulmonary veins into the relaxed atria, contributing to a slow increase in atrial pressure. Additionally, a slight atrial contraction at the end of diastole adds a small amount of extra blood to the ventricles.

  ECG Waveform Correspondence: The end of the T-wave on the ECG corresponds to atrial

contraction (atrial repolarization) and aligns with the gradual rise in atrial pressure during this phase.

3.8 Analysis of Mitral flow rate

In the context of normal cardiac function, the diastolic filling of the left ventricle involves two distinct phases:

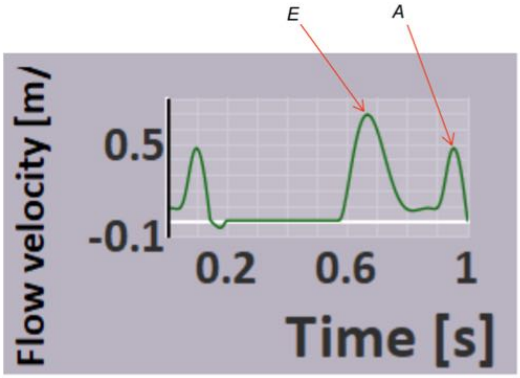


Figure 17: E- and A-waves of the mitral blood flow velocity

- **E-wave (Early Passive Filling):**

  The E-wave represents the early passive filling phase, where blood flows from the atria to the ventricles purely due to the pressure gradient and elasticity of the ventricles. This occurs before atrial contraction.

- **A-wave (Late Active Filling):**

  The A-wave signifies the late active filling phase, occurring as a result of atrial contraction. During atrial systole, the atrial muscles contract, actively pushing an additional volume of blood into the ventricles.

3.8.1 E/A-ratio

The E/A-ratio is calculated by dividing the amplitude of the E-wave by that of the A-wave in the mitral blood flow velocity signal. A higher E/A ratio is indicative of good ventricular diastolic function. In the simulation, analyzing the mitral blood flow velocity signal and computing the E/A ratio provides valuable insights into the efficiency of ventricular diastolic function.

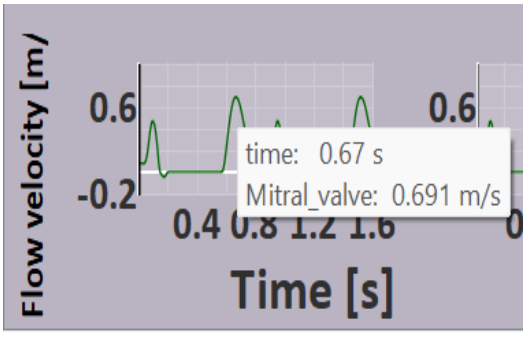


Figure 18: Value of E

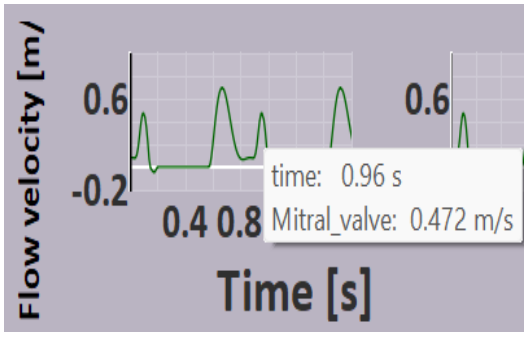
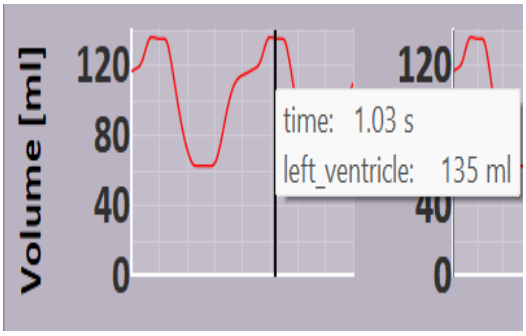
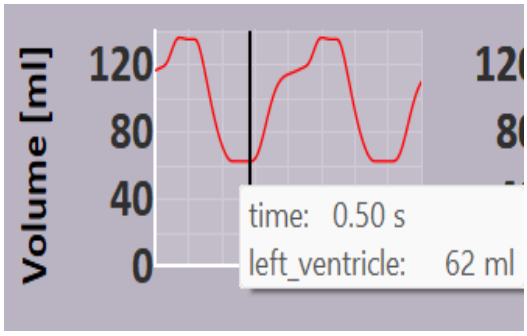


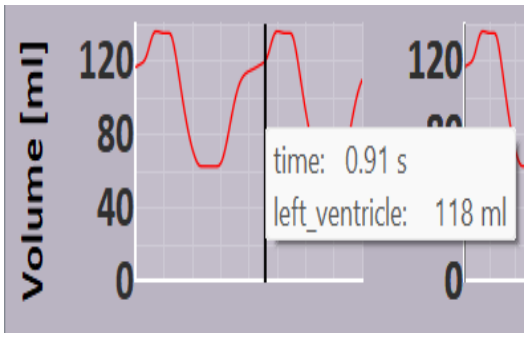
Figure 19: Value of A

$$E/Aratio = \frac{E}{A} = \frac{0.691}{0.472} = 1.464 \tag{1}$$

3.9 Relative amount of left ventricular filling







3.9.1 Passive filling

Both rapid filling and diastasis collectively make up the passive filling phase during diastole.

- **Rapid Filling (Early Diastole):** The immediate drop in ventricular pressure after the closure of the aortic and pulmonary valves creates a pressure gradient, leading to a rapid flow of blood from the atria to the ventricles. This phase accounts for a substantial portion of ventricular filling.
- **Diastasis (Mid-Diastole):** Following rapid filling, there is a slower but continuous inflow of blood, maintaining a gradual filling of the ventricles. Although this phase is slower than rapid filling, it still contributes to a significant volume of blood entering the ventricles.

Relative amount of left ventricular filling that is due to passive filling $= 118ml - 62ml = 56ml$

3.9.2 Active filling

Active filling refers to the phase of ventricular filling during diastole that involves an active contraction of the atria, specifically the atrial systole. The active filling phase occurs towards the end of diastole and contributes an additional force to propel blood from the atria into the ventricles.

Relative amount of left ventricular filling that is due to active filling $= 135ml - 118ml = 17ml$

3.10 Continuity Equation and Geometrical Considerations in Blood Flow

The relationship between blood flow velocity (V_{valve}) and flow rate (Q_{valve}) through a valve is given by the continuity equation:

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

To convert V_{valve} into Q_{valve}, it is necessary to know the cross-sectional area (A_{valve}) of the valve. The units for each quantity are:

- Q_{valve} (flow rate): Typically expressed in milliliters per second (ml/s) or liters per minute (L/min). - A_{valve} (cross-sectional area): Typically expressed in square millimeters (mm^2) or square centimeters (cm^2). - V_{valve} (blood flow velocity): Typically expressed in centimeters per second (cm/s) or meters per second (m/s).

The conversion from blood flow velocity to flow rate involves multiplying the cross-sectional area by the blood flow velocity:

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

The geometrical property required to convert blood flow velocity (V_{valve}) into flow rate (Q_{valve}) using the continuity equation is the cross-sectional area (A_{valve}) of the valve. **The opening cross-sectional area** represents the area perpendicular to the blood flow direction and is a crucial parameter in calculating the volume of blood passing through the valve per unit time.

4 Aortic Valve Stenosis

Aortic Valve Stenosis (AS) is a cardiovascular condition characterized by the narrowing of the aortic valve, restricting the flow of blood from the left ventricle into the aorta. This practical investigation explores the physiological implications of AS, emphasizing its impact on preload and afterload, simulating stenotic conditions, and analyzing changes in left ventricular pressure-volume relations. Through simulations and calculations, the study aims to estimate pressure drops, assess the duration of ejection, and quantify the external pump work generated by the left ventricle. Understanding these dynamics provides insights into the multifaceted challenges posed by aortic valve stenosis on cardiovascular function.

4.1 Preload and Afterload

- **Preload:** Preload refers to the initial stretching or load on the cardiac muscle fibers just before the contraction (systole) phase. It is influenced by the volume of blood returning to the heart and represents the degree of stretch on the ventricular muscle.
- **Afterload:** Afterload is the resistance the heart must overcome to eject blood into the systemic circulation. It is primarily determined by the pressure in the aorta and the resistance in the systemic arteries.

4.2 Hemodynamic Changes with increasing Aortic Stenosis

As the severity of aortic stenosis (AS) progresses, the left ventricle encounters escalating challenges in efficiently pumping blood through the narrowed aortic valve. Several key observations highlight the impact of increasing AS severity:

- **Elevated Left Ventricular Pressure during Systole:**

  The aggravation of AS demands heightened efforts from the left ventricle to overcome the obstruction. This leads to a discernible increase in left ventricular pressure during systole. The constrained opening of the aortic valve, attributable to stenosis, contributes to elevated resistance during ejection.

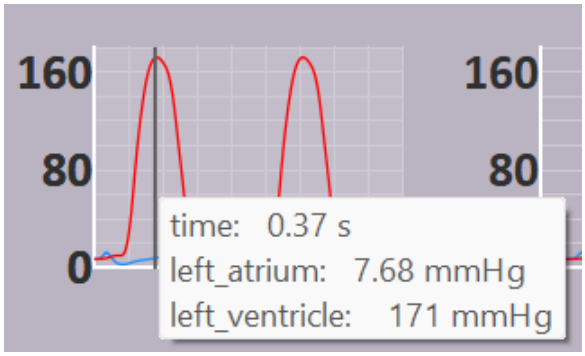


Figure 20: Pressure graph

- **Accelerated Blood Flow across the Aortic Valve:**

  To sustain an adequate cardiac output, blood flow through the constricted valve accelerates. The left ventricle compensates by exerting greater force to propel blood through the narrowed opening. The accelerated flow velocity across the aortic valve assists in overcoming the obstruction.

- **Pressure-Volume Loop Changes:**

  With the progression of AS severity, the pressure-volume loop undergoes a distinct rightward and upward shift. The augmented area under the curve, representing one complete cardiac cycle, signifies increased left ventricular work. This shift in the pressure-volume loop reflects a greater expenditure of myocardial energy as the heart works harder to effectively eject blood in the presence of stenosis.

Percentage of Stenosis	**Peak Flow Velocity (ms^{-1})**	**Peak Pressure at Left Ventricle (mmHg)**
0%	1.24	121
5%	1.30	121
10%	1.38	123
15%	1.46	124
20%	1.53	124
25%	1.62	125
30%	1.73	126
35%	1.84	127
40%	1.97	129
45%	2.11	130
50%	2.28	132
55%	2.47	135
60%	2.69	139
65%	2.96	143
70%	3.28	149
75%	3.67	158
80%	4.20	171

Table 1: Percentage of Stenosis, Peak Flow Velocity (ms^{-1}), and Peak Pressure at Left Ventricle (mmHg)

In summary, the exacerbation of aortic stenosis places additional demands on the left ventricle, leading to elevated pressure during systole, accelerated blood flow, and notable changes in the pressure-volume loop indicative of heightened myocardial work. These observations underscore the physiological adaptations required to cope with the challenges posed by increasing AS severity.

4.2.1 Effect on preload. afterload, cardiac output

- **Effect on Preload:**

  Aortic valve stenosis restricts the efficient ejection of blood from the left ventricle into the aorta during systole. The impaired flow through the narrowed valve may lead to inadequate filling of the left ventricle during diastole. Consequently, the preload, representing the volume of blood entering the left ventricle, may be compromised due to the impediment in blood flow, potentially resulting in increased left ventricular end-diastolic pressure.

- **Effect on Afterload:**

  Aortic valve stenosis elevates afterload, which is the resistance the left ventricle must overcome to eject blood into the aorta. The narrowed aortic valve increases resistance during systole, requiring the left ventricle to work harder to pump blood through the restricted opening. The heightened afterload poses an additional challenge to the left ventricle, demanding increased force to overcome the obstruction.

- **Effect on Cardiac Output:**

  Due to the increased afterload and compromised preload, cardiac output may be adversely affected. The left ventricle faces difficulties in efficiently ejecting blood into the aorta, resulting in a potential reduction in stroke volume. With compromised preload and heightened afterload, the overall impact on cardiac output is a decrease, reflecting the challenges posed by aortic valve stenosis on the heart's ability to pump blood effectively.

4.2.2 Pressure drop across the stenotic aortic valve

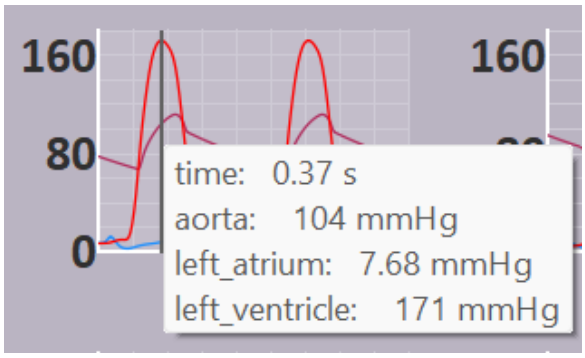


Figure 21: Pressure values

$$\text{Maximum Left Ventricular Pressure} = 171\,\text{mmHg}$$

$$\text{Aorta Pressure when Maximum Ventricular Pressure Occurs} = 104\,\text{mmHg}$$

$$\text{Pressure Drop Across Stenotic Aortic Valve} = 171\,\text{mmHg} - 104\,\text{mmHg} = 67\,\text{mmHg}$$

4.2.3 Estimation for Pressure drop across the stenotic aortic valve

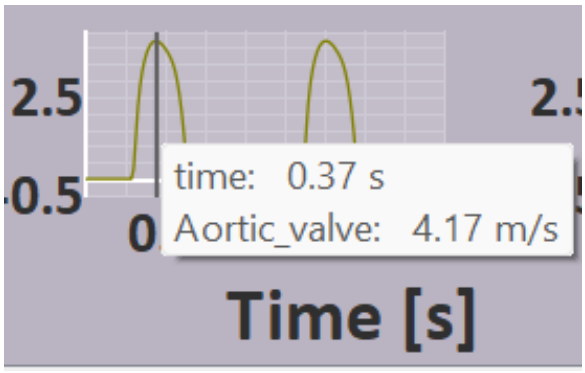
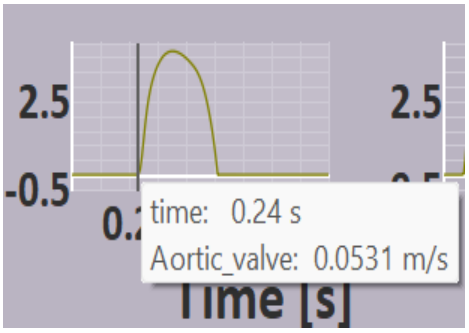


Figure 22: Flow rate

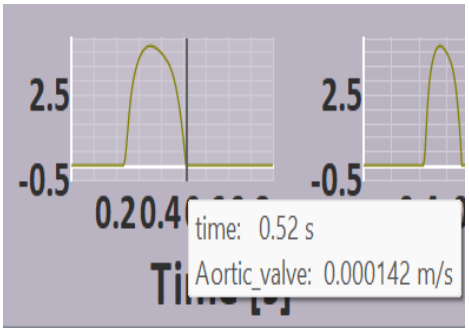
$$\Delta P \approx 4v^2$$
$$\Delta P \approx 4 \times 4.17^2$$
$$\Delta P \approx 69.56\,\text{mmHg}$$

Pressure drop is approximately equal

4.2.4 Duration of ejection



(a) Starting point



(b) Ending point

Figure 23: Comparison between starting and ending points

$$\text{Duration of ejection} = 0.52\,\text{ms} - 0.24\,\text{ms} = 28\,\text{ms}$$

4.2.5 Increase in external pump work generated

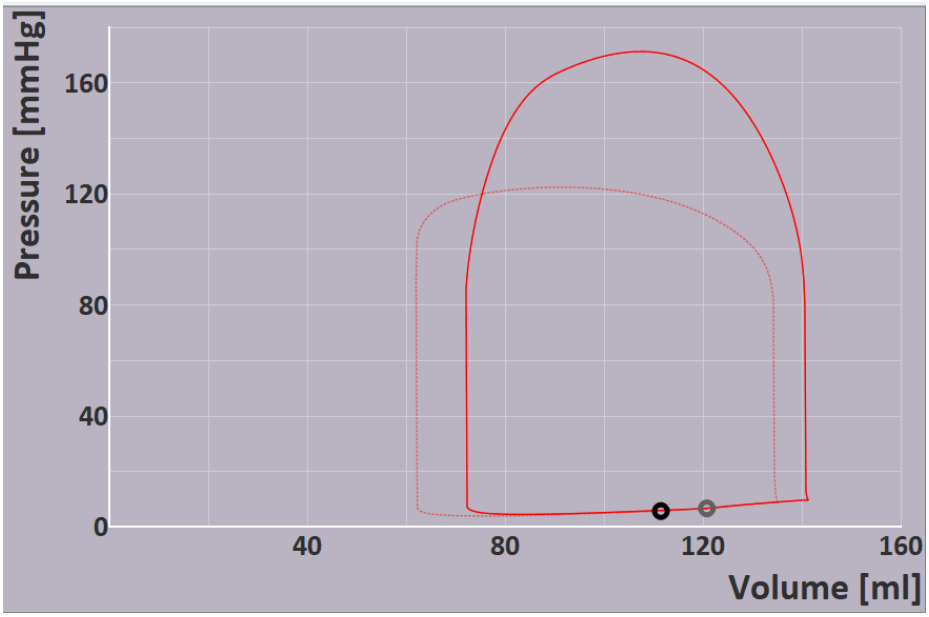


Figure 24: Pressure-Volume curve

$$\text{Number of squares before 80\% AS} \approx 20$$

$$\text{Number of squares after 80\% AS} \approx 24$$

$$\text{Increase} \approx 4\,\text{squares}$$

$$\approx 4 \times 20 \times 20$$

$$\approx 1600\,\text{ml mmHg}$$

4.3 Myocardial Adaptations to Increased Pump Work

- **Hypertrophy:**

  Heart muscle cells undergo enlargement and thickening. Enhances the heart's ability to generate more force. Enables the heart to overcome increased afterload, the resistance during ejection.

- **Increased Contractility:**

  Heart muscle cells exhibit heightened contractility. Facilitates the ejection of a larger volume of blood with each contraction. Contributes to the maintenance of optimal cardiac output despite elevated workload.

- **Increased Compliance:**

  Heart muscle becomes more compliant. Improves elasticity, allowing for easier stretching. Facilitates the maintenance of a normal preload during diastole.

- **Impact on Left Ventricular Wall Tension:**

  Combined effects of increased muscle mass and contractility lead to heightened left ventricular wall tension. While beneficial for overcoming afterload, necessitates careful management to prevent potential long-term consequences, including fibrosis and diastolic dysfunction.