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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.

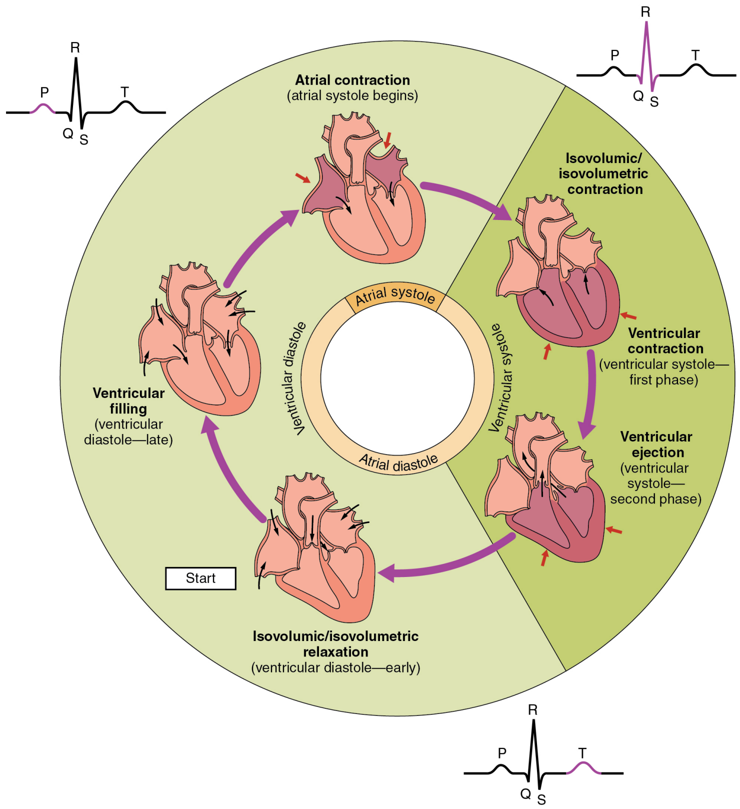


Figure 1: Cardiac Cycle

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, named after Dr. Carl Wiggers, is a visual representation used in cardiovascular physiology to illustrate key events during a cardiac cycle.

- A complex, composite figure showing the simultaneous events of the cardiac cycle.
- Includes: ECG, left atrial/ventricular/aortic pressures, heart sounds, and Volume changes.
- Providing a comprehensive view of the heart's electrical and mechanical activities.

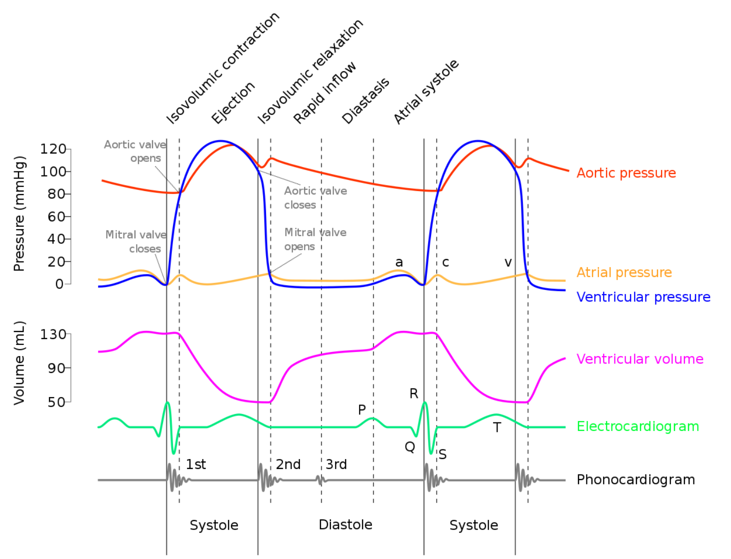


Figure 2: Wiggers Diagram of Cardiac Cycle

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.
- This event facilitates the ejection of blood from the left ventricle into the aorta.

- The left ventricular pressure rises to 69.8 mmHg, exceeding the aortic pressure of 68.8 mmHg

  left ventricular pressure > aortic pressure

  .

- This pressure gradient causes the aortic valve to open, ensuring unidirectional (one-way) blood flow into the aorta.

- Figure 3 illustrates that the aortic valve opens when the left ventricular volume is 134 mL.

- This opening is a synchronized event, matching the peak of ventricular systole, maximizing efficiency in blood ejection.

- The process helps maintain physiological balance by ensuring proper cardiac output and pressure regulation.

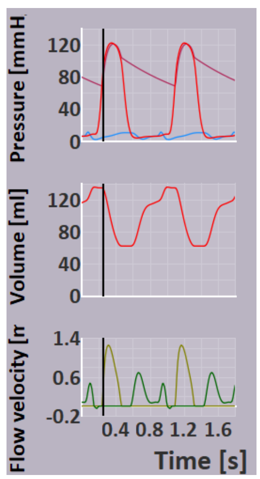


Figure 3: Aortic Valve Opening

2.2.2 Aortic Valve Close

- The closure of the aortic valve marks the conclusion of the left ventricular contraction, leading to a reduction in left ventricular pressure.

- As illustrated in Figure 4, this closure results in a phase where the left ventricular volume remains constant (isovolumetric relaxation).

- At the time of aortic valve closure, the left ventricular pressure drops below the aortic pressure (121mmHg)

  left ventricular pressure < aortic pressure

  .

- This pressure difference prompts the swift closure of the aortic valve, preventing any back-flow of blood into the left ventricle.
- According to the data, when the aortic valve closes, the left ventricular volume is measured at 62 mL.
- The difference between the volumes at aortic valve opening (134 mL) and closing (62 mL) indicates that 72 mL of blood has been ejected during this cardiac cycle.
- This efficient ejection highlights the precision and effectiveness of the cardiovascular system's regulation mechanisms.

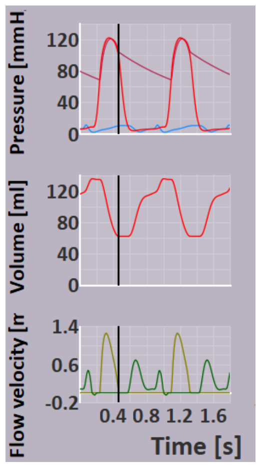


Figure 4: Aortic Valve Closing

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.
- During this phase, the left ventricular pressure is 7.98 mmHg, which is lower than the left atrial pressure of 10.4 mmHg

$$\textbf{left ventricular pressure} < \textbf{left atrial pressure}$$

.

- This pressure gradient ensures that the Mitral valve opens unidirectionally towards the left ventricle.
- The resulting flow facilitates the passive filling of the left ventricle with blood from the atrium.

- At the moment of Mitral valve opening, the left ventricular volume is measured at 62 mL.
- This ensures an efficient and controlled filling process during early diastole.
- The sequence demonstrates precise coordination between pressure differentials and valve mechanics, emphasizing the role of hemodynamic forces in cardiac function.

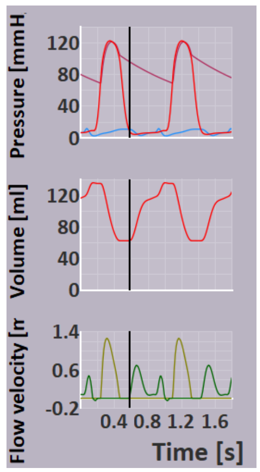


Figure 5: Mitral Valve Opening

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 rises to 8.69 mmHg, while the left atrial pressure remains lower at 2.24 mmHg

$$\textbf{left ventricular pressure} > \textbf{left atrial pressure}$$

.

- 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 134 mL.
- The difference between the volumes at Mitral valve opening (134 mL) and closing (62 mL) indicates that 72 mL of blood has been filled during this cardiac cycle.
- This indicates the completion of diastolic filling and the beginning of isovolumetric contraction.

- The closure of the Mitral valve is essential for maintaining the unidirectional flow of blood and preserving the efficiency of the cardiac cycle.
- This phase exemplifies the precise pressure-regulated valve control within the cardiovascular system.

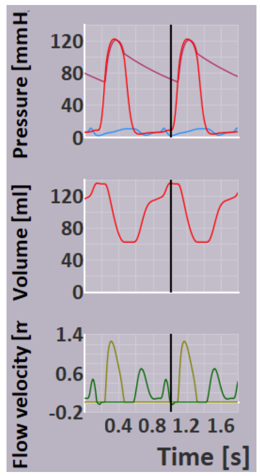


Figure 6: Mitral Valve Closing

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.

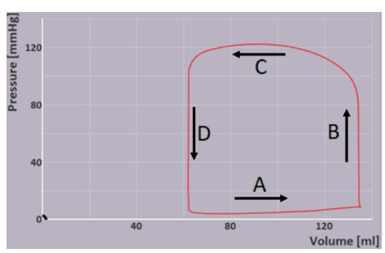


Figure 7: Cardiac Cycle: Valve Events

2.5 Identify with a Specific Stage of the Cardiac Cycle

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

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

Table 1: Correspondence of Points to Cardiac Cycle Events

(a) Mitral Opening (b) Mitral Closing

Figure 8: Opening and Closing of Mitral Valve

(a) Aortic Opening (b) Aortic Closing

Figure 9: Opening and Closing of Aortic Valve

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 systole, when the left ventricle contracts forcefully.
  - This contraction causes a rapid and continuous ejection of blood into the aorta, producing a single sharp peak in flow velocity.
  - The flow accelerates to a maximum and then decelerates as ventricular pressure decreases, resulting in one clear systolic peak.
- **Mitral Valve – Dual Peaks:**
  - The mitral valve opens during diastole, allowing blood to flow from the left atrium to the left ventricle.
  - The first peak (E wave) represents **passive filling** due to pressure differences between the atrium and ventricle.

- The second peak (A wave) results from **active atrial contraction**, which pushes additional blood into the ventricle before systole.
- This dual mechanism of ventricular filling leads to two distinct peaks in the flow velocity profile of the mitral valve.

- 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.

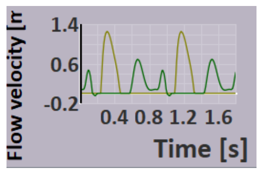


Figure 10: Flow Velocities of Aortic & Mitral Valves

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.

2.8 E- and A-waves of Mitral Flow

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

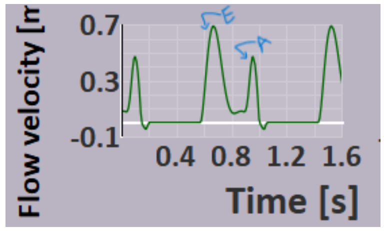
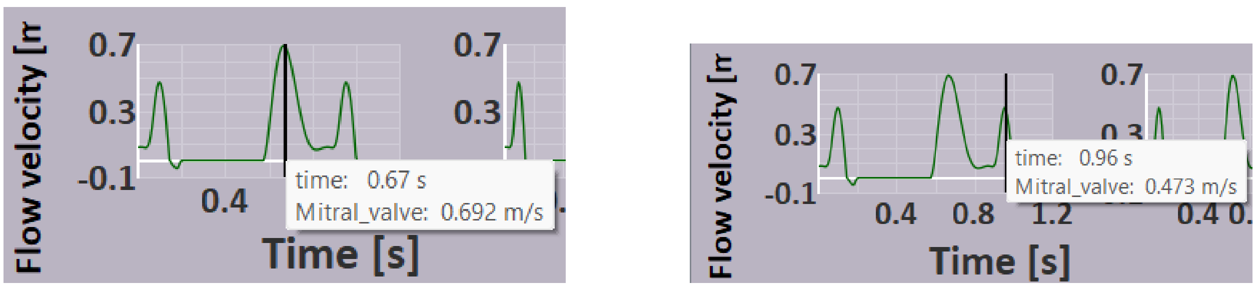


Figure 11: Mitral Valve Flow Velocity: E- and A-waves

2.9 Calculate E/A-ratio



(a) Velocity at E

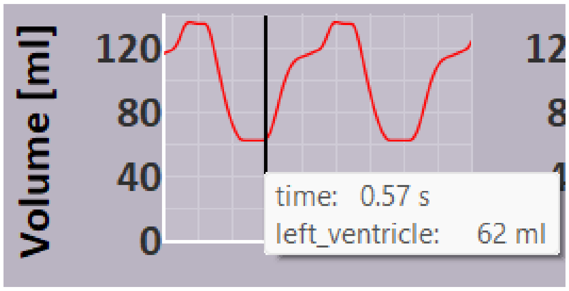
(b) Velocity at A

Figure 12: Velocities at E & A

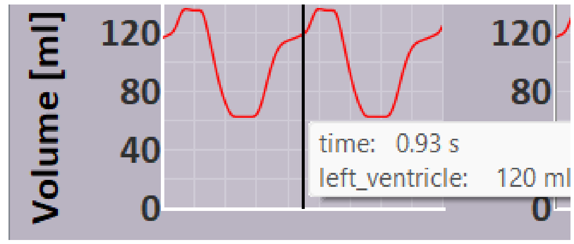
E = 0.692, A = 0.473

$$\frac{E}{A}\text{ Ratio} = \frac{0.692}{0.473} = 1.463$$

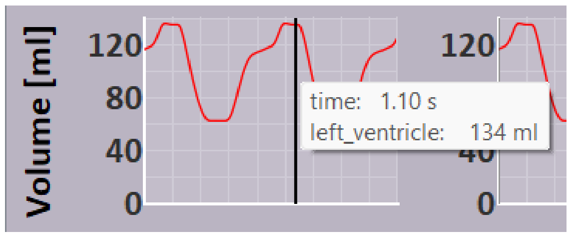
2.10 Amounts of Left Ventricular Filling



(a) End-Systolic Volume (ESV)



(b) After Passive filling



(c) After both filling phase

Figure 13: Left Ventricular Filling

- Passive: 120 ml - 62 ml = 58 ml
- Active: 134 ml - 120 ml = 14 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 Definition

- **Preload:**
  - Refers to the volume of blood present in the ventricles at the end of diastole (just before contraction).
  - It determines the initial stretching of cardiac myocytes prior to contraction.
  - Greater preload increases the force of systolic contraction, as described by the Frank-Starling mechanism.
- **Afterload:**
  - Defined as the pressure the heart must overcome to eject blood during systole.
  - Influenced by systemic vascular resistance and aortic pressure.
  - Conditions such as hypertension can increase afterload, placing additional strain on the heart.
  - Increased afterload can reduce stroke volume and cardiac output if not compensated.

Percentage of Stenosis (%)	Peak Flow Velocity (m/s)	Peak Pressure (mmHg)
Normal	1.25	122
5	1.31	123
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	2.20	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 2: Effect of Aortic Stenosis on Flow Velocity and Pressure

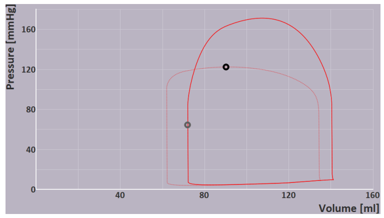


Figure 14: 80% Stenosis - Pressure Volume Diagram

- **Therefore, the maximum left ventricular pressure occurs at 80% stenosis equals to 171 mmHg.**

3.2 How does stenosis impact preload, afterload, and cardiac output?

Hemodynamic Impact of Aortic Valve Stenosis

- **Preload:**
  - Initially **increases** due to incomplete emptying of the left ventricle.
  - The obstruction at the aortic valve causes blood to accumulate, increasing end-diastolic volume (EDV) and myocardial stretch.
- **Afterload:**
  - Significantly **increases** as the left ventricle must generate higher pressure to overcome the resistance posed by the narrowed aortic valve.
  - This pressure load increases the workload on the heart.
- **Cardiac Output:**

$$\textbf{Cardiac Output} = \textbf{Stroke Volume*Heart Rate}$$

  - **Decreases** due to reduced blood ejection through the stenotic valve.
  - Chronic pressure overload may lead to left ventricular hypertrophy, which further compromises diastolic filling and cardiac efficiency.

Parameter	**Effect**
Preload	Increased (due to residual volume)
Afterload	Significantly Increased (due to obstruction)
Cardiac Output	Decreased (due to limited forward flow)

Table 3: Summary of Aortic Valve Stenosis Effects

The maximum left ventricular pressure is 171 mmHg, corresponding to an aortic valve pressure of 105 mmHg. The pressure drop is determined by subtracting the aortic valve pressure from the left ventricular pressure:

Pressure drop = 171 mmHg -105 mmHg = 66 mmHg

This signifies a pressure difference of 68 mmHg across the aortic valve. Applying Bernoulli's equation allows us to estimate the maximum pressure drop:

Maximum Flow Velocity = 4.2 m/s

Simple Bernoulli Equation: $\Delta P = 4v^2 = 70.56$ mmHg

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

Comparing this with the previous calculation, the estimated pressure drop across the aortic valve is approximately 70.56 mmHg.

The calculation for the duration of ejection across the aortic valve is determined by subtracting the initial time of 1.12 seconds from the final time of 1.39 seconds:

Ejection Time: Duration = 1.39 s 1.12 s = 0.27 s

Thus, the duration of ejection across the aortic valve is 0.27 seconds.

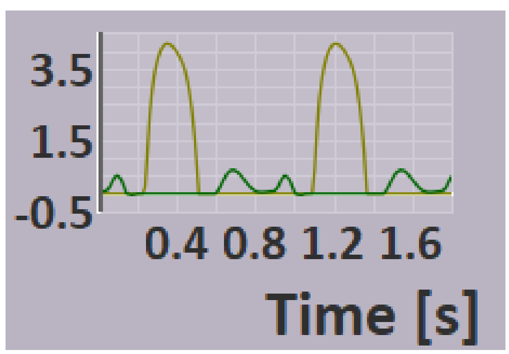


Figure 15: 80% Stenosis - Flow Velocity Diagram

3.3 Determine the external work done by the left ventricle's pump

To determine the external pump work produced by the left ventricle, one can calculate the surface area enclosed by the pressure-volume relation. Estimating the increase in external pump work due to 80% aortic valve stenosis involves counting the effective number of squares enclosed by the pressure-volume curve.

- External work done by the heart in a healthy individual: 20 squares
- External work done by the heart in a 80% Stenosis individual: 24 squares
- Increase =24 squares - 20 squares = 4 squares

3.4 Myocardial Adaptations and Effect on Afterload

- **Adaptation of Myocardial Tissue:**
  - The left ventricular myocardium undergoes **hypertrophy** in response to chronically increased pump work.
  - Individual cardiac muscle cells enlarge, leading to an increase in the overall **thickness of the ventricular wall**.
  - This structural adaptation enhances the contractile strength of the heart, enabling it to pump against elevated resistance.
- **Effect on Afterload:**
  - **Short-term benefit:** Hypertrophy allows the left ventricle to generate higher pressures during systole, helping it overcome elevated afterload (e.g., due to aortic stenosis).
  - **Long-term consequence:** Increased wall thickness may lead to myocardial **stiffness**, impairing diastolic filling.
  - This may paradoxically **increase afterload** further over time and contribute to cardiac dysfunction.

4 References

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