Department of Electronic & Telecommunication Engineering,
University of Moratuwa, Sri Lanka.

Assignment 3
Analysis of Cardiac Physiology

Wickramasinghe S.D.
220700T

Submitted in partial fulfillment of the requirements for the module
BM 2102 Modelling and Analysis of Physiological Systems

5/15/2025

Contents

1 Introduction **2**

2 Normal Sinus Rhythm **3**

2.1 a) Opening and closing of the aortic valve 3
2.2 b) Opening and closing of the mitral valve 4
2.3 c) Pressure-volume relation corresponding to the closing and opening of the aortic and mitral valves 5
2.4 d) Names of the pressure-volume relation phases 5
2.5 e) Reasons for the different flow velocity patterns in the aortic and mitral valves . . 5
2.6 f) Relation of the atrial pressure and the ECG waveform 6
2.7 g) E and A waves of the mitral blood flow velocity signal 6
2.8 h) E/A-ratio 7
2.9 i) Relative amount of left ventricular filling 7
2.10 j) Properties needed to convert V_{valve} into Q_{valve} 7

3 Aortic Valve Stenosis **8**

3.1 a) Preload and Afterload 8
3.2 b) Simulating aortic valve stenosis 8
3.3 c) How aortic valve stenosis affects preload, afterload, and cardiac output 9
3.3.1 Preload 9
3.3.2 Afterload 9
3.3.3 Cardiac Volume 9
3.4 d) Aortic blood pressure and pressure drop across the stenotic aortic valve 10
3.5 e) Maximum pressure drop across the stenotic valve 10
3.6 f) Duration of ejection 10
3.7 g) Increase in external pump work 10
3.8 h) Effect on myocardial tissue of the left ventricle 10

1 Introduction

This report carries the output of the simulation results of the CircAdapt simulation software for the following 2 conditions.

- Normal cardiac rhythm
- Cardiac rhythm during aortic valve stenosis

The cardiac cycle can be divided into 3 stages.

1. Atrial systole: contraction of the atria.
2. Ventricular systole: contraction of the ventricles. This follows atrial systole after 0.1-0.2 seconds.
3. Diastole: relaxation of both the atria and ventricles.

Wigger's diagram demonstrates the varying pressures in the atrium, ventricle, and artery during one cardiac cycle.

Intracardiac pressures are different between the right and left sides of the heart. The left side has higher pressure, as it has to pump blood through the whole body, compared to the right side, which has to pump blood through the lungs only. However, the diagram of each side would demonstrate the same shape.

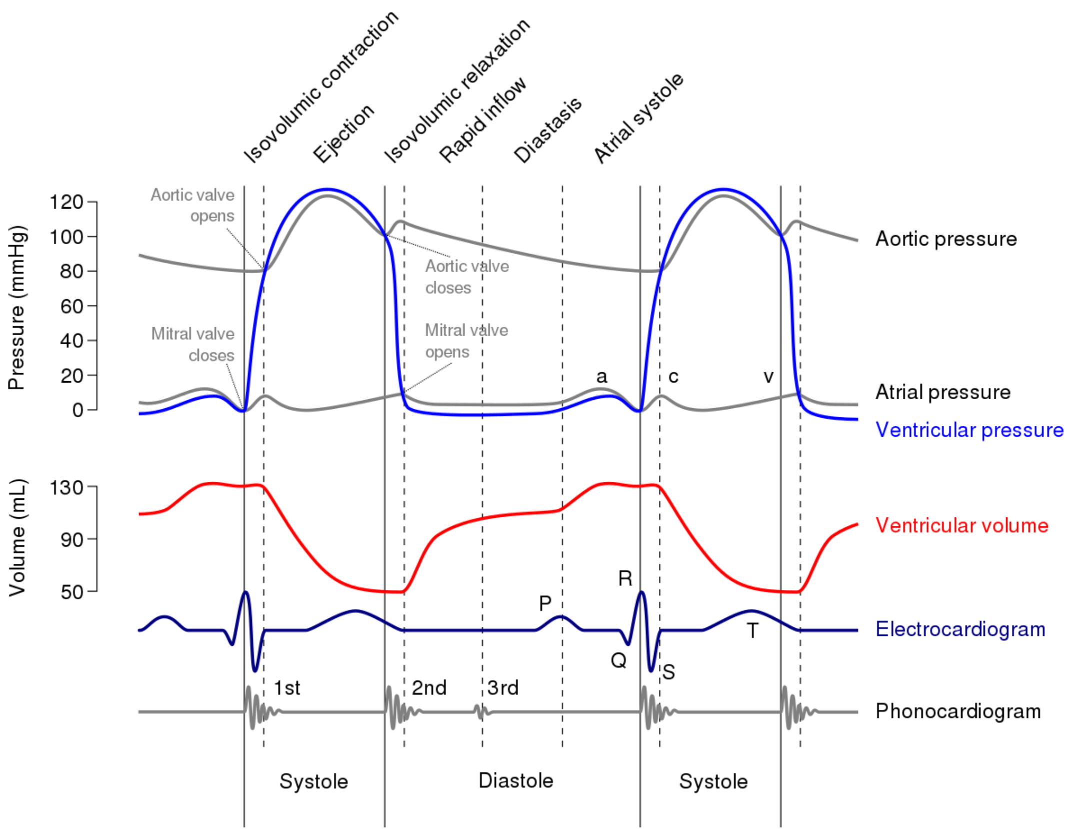

Figure 1: Wiggers Diagram of the Cardiac Cycle

2 Normal Sinus Rhythm

2.1 a) Opening and closing of the aortic valve

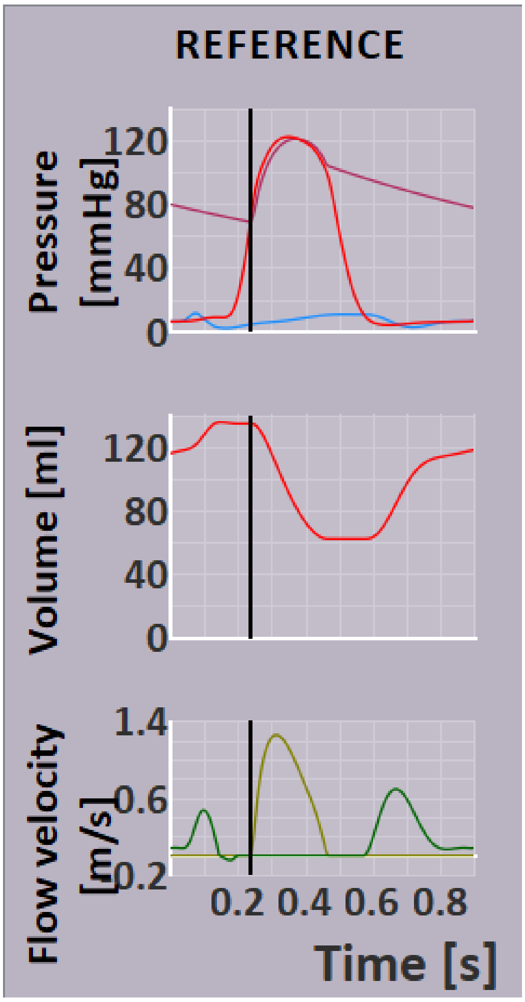

Figure 2: Aortic Valve Opening

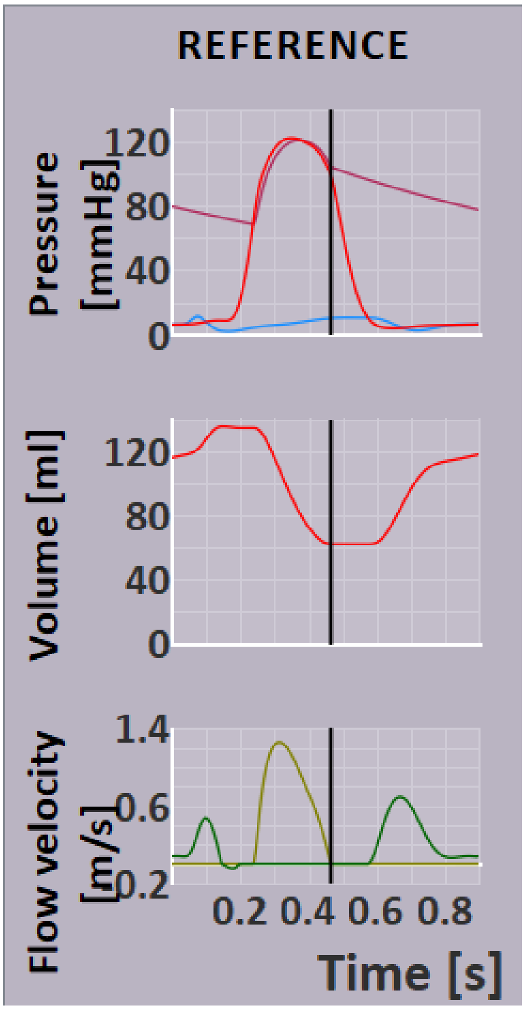

Figure 3: Aortic Valve Closing

Figure 4: Opening and closing points of the aortic valve

The aortic valve allows unidirectional blood flow from the left ventricle to the aorta. When the ventricle contracts in systole, intraventricular pressure increases and surpasses aortic pressure, causing the valve to open and blood to be ejected into systemic circulation. As the ventricle relaxes in diastole, the intraventricular pressure drops below aortic pressure, leading to the closure of the aortic valve, which prevents backflow and maintains effective forward circulation.

2.2 b) Opening and closing of the mitral valve

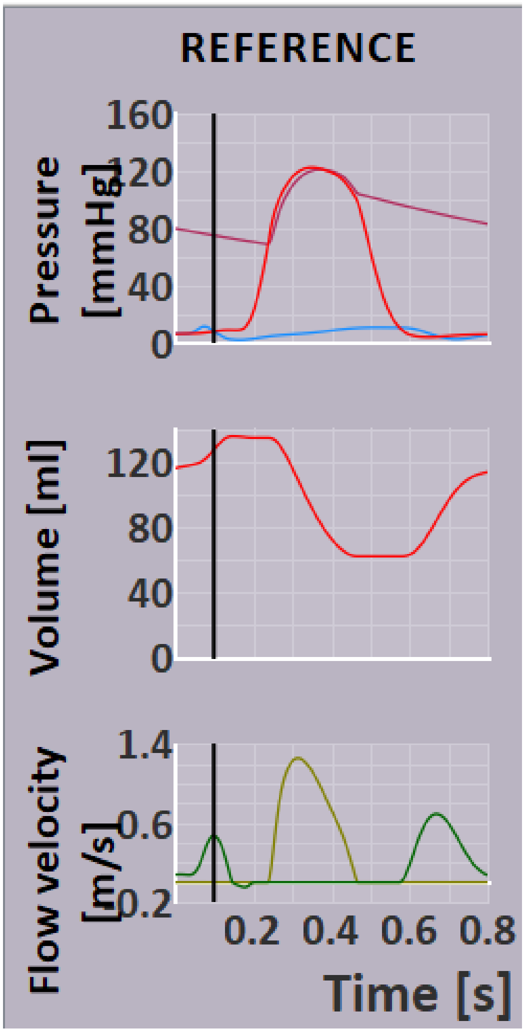

Figure 5: Mitral Valve Opening

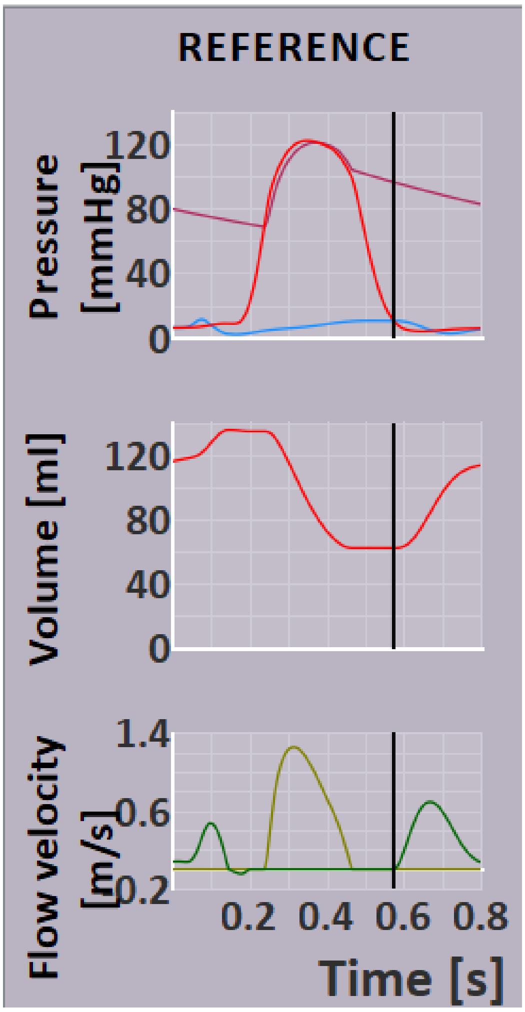

Figure 6: Mitral Valve Closing

Figure 7: Opening and closing points of the mitral valve

The mitral valve regulates blood flow between the left atrium and left ventricle. During diastole, the valve opens as the pressure in the ventricle drops below that of the atrium, allowing oxygenated blood to fill the ventricle passively and actively during atrial contraction. As the ventricle contracts in systole and pressure rises, the mitral valve closes to prevent backflow into the atrium, ensuring efficient filling of the ventricle.

2.3 c) Pressure-volume relation corresponding to the closing and opening of the aortic and mitral valves

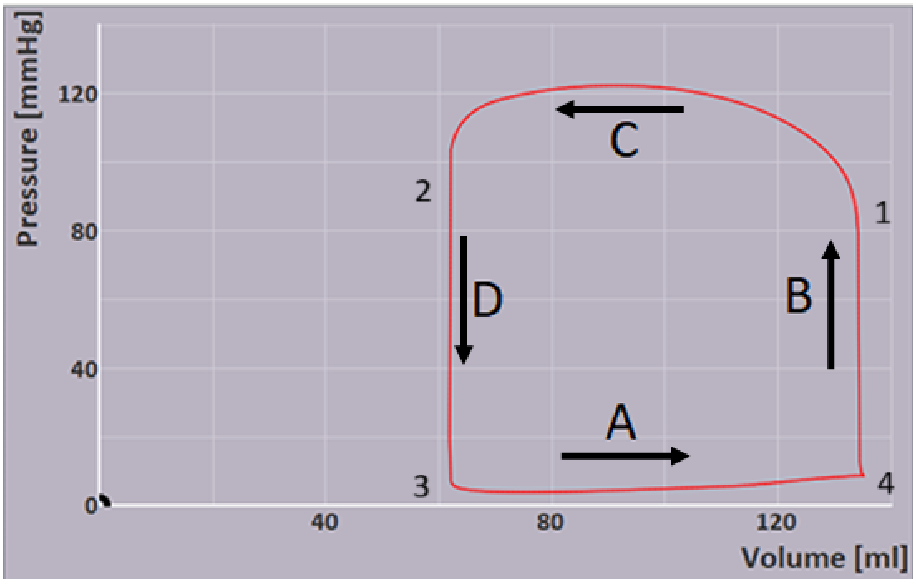

Figure 8: Points of the Pressure-volume Relation Corresponding to the Closing and Opening of the Aortic and Mitral Valves

The points are as follows:

- 1: Aortic opening
- 2: Aortic opening
- 3: Mitral opening
- 4: Mitral opening

2.4 d) Names of the pressure-volume relation phases

The pressure-volume relation can be regarded as a rectangle with each of its four sides corresponding to a phase of the cardiac cycle.

The names of the phases in the above graph are as follows:

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

2.5 e) Reasons for the different flow velocity patterns in the aortic and mitral valves

The flow velocity pattern in the aortic valve displays a single hump because it corresponds to the active ejection phase of the cardiac cycle. When the left ventricular pressure exceeds the aortic pressure, the aortic valve opens, and blood is forcefully ejected into the aorta during systole. This rapid, unidirectional flow produces a single, sharp peak in velocity before declining as the ventricular contraction ends and the valve closes.

In contrast, the mitral valve shows a double-hump velocity pattern due to its two distinct filling phases. The first hump occurs during early diastole, when the mitral valve opens passively as the left atrial pressure exceeds the left ventricular pressure, allowing blood to flow rapidly into the ventricle (early passive filling). The second hump results from atrial contraction (late diastole), which actively pushes additional blood into the ventricle, creating a second, smaller velocity peak before the valve closes in preparation for systole.

2.6 f) Relation of the atrial pressure and the ECG waveform

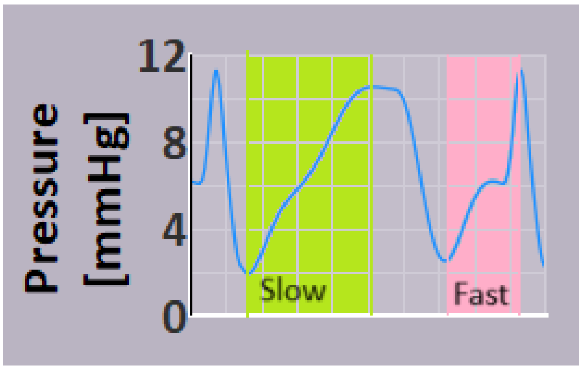

Figure 9: Atrial Pressure during a Single Cardiac Cycle

- Fast (Steep) Rise occurs due to atrial contraction, which actively forces blood into the ventricle. It corresponds to the P-wave on the ECG, indicating atrial depolarization.
- Slow Rise happens during ventricular systole when the atrioventricular valves are closed. The atria fill passively from the venous return, leading to a gradual buildup of pressure until the AV valves open again.

2.7 g) E and A waves of the mitral blood flow velocity signal

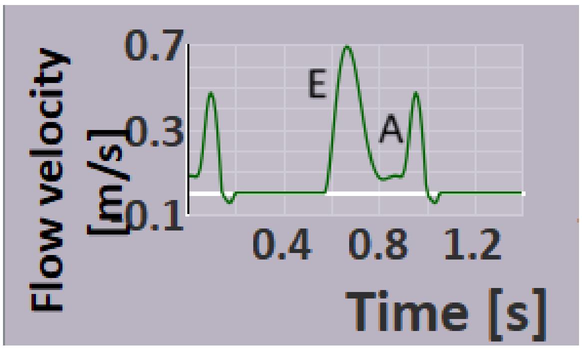

Figure 10: The Early Rapid Filling (E) and Atrial Contraction (A) Marked in the Mitral Valve Blood Flow Graph

2.8 h) E/A-ratio

The peak velocities of E and A waves are as follows:

Peak	Mitral Valve Flow Velocity (m/s)
E	0.692
A	0.468

Table 1: Peak Flow Velocities of E and A Waves

$$\text{E/A-ratio} = \frac{0.692}{0.468} = 1.4786 \tag{1}$$

2.9 i) Relative amount of left ventricular filling

The volume of the left ventricle at certain instances is as follows:

Instance	Left Ventricular Volume (ml)
Mitral Valve Closed	62
At E Peak	81
At A Peak	127

Table 2: Volume of the Left Ventricle

$$\text{Relative amount of left ventricular filling due to passive filling} = 81 - 62 = 19\,\text{ml}$$
$$\text{Relative amount of left ventricular filling due to active filling} = 127 - 62 = 65\,\text{ml}$$

2.10 j) Properties needed to convert V_{valve} into Q_{valve}

To convert the blood flow velocity through a valve (V_{valve}) into the volumetric flow rate (Q_{valve}), the following equation is used:

$$Q_{\text{valve}} = V_{\text{valve}} \times A \tag{2}$$

Where:

- Q_{valve} is the flow rate (e.g., in mL/s or L/min),
- V_{valve} is the velocity of blood flow through the valve (e.g., in cm/s),
- A is the cross-sectional area of the valve orifice (e.g., in cm^2).

Therefore, the valve orifice area is the anatomical parameter required to convert velocity into flow.

3 Aortic Valve Stenosis

Aortic valve stenosis is when the aortic valve becomes narrowed or obstructed, making it harder for blood to flow from the heart into the rest of the body.

3.1 a) Preload and Afterload

Preload is the initial stretching of the cardiac muscle fibers (particularly in the ventricles) at the end of diastole, just before contraction.

Afterload is the resistance the left ventricle must overcome to eject blood into the aorta during systole.

3.2 b) Simulating aortic valve stenosis

The hemodynamic changes of the left ventricle per step increase (5%) of Arotic Valve Stenosis (AS) are as follows:

Percentage of Stenosis	**Peak Pressure (mmHg)**	**Peak Volume (ml)**	**Peak Flow Velocity (m/s)**
0%	122	135	1.26
5%	122	135	1.31
10%	123	135	1.38
15%	124	135	1.46
20%	124	135	1.53
25%	124	135	1.63
30%	126	135	1.72
35%	127	135	1.84
40%	128	135	1.97
45%	130	135	2.11
50%	132	136	2.28
55%	135	136	2.47
60%	139	136	2.68
65%	143	137	2.96
70%	149	138	3.28
75%	158	139	3.68
80%	171	140	4.18

Table 3: Hemodynamic Changes of the Left Ventricle per Step Increase of AS

Maximal left ventricular pressure is 171 mmHg, which is at 80% stenosis.

The left ventricular pressure-volume relation curve is here.

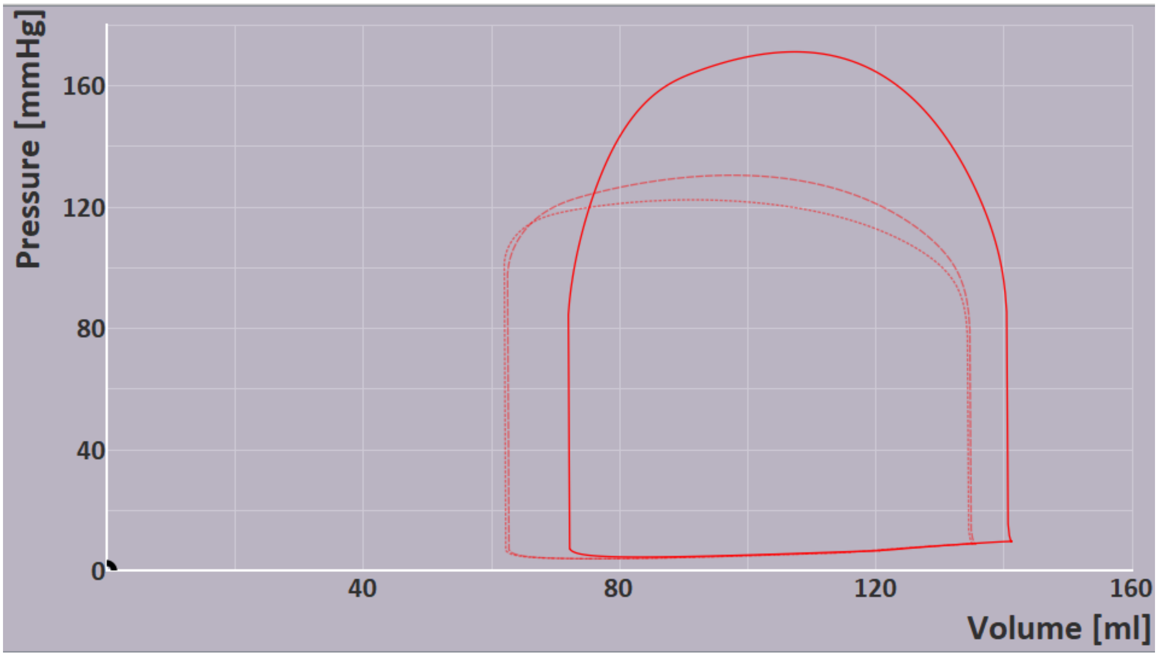

Figure 11: Left Ventricular Pressure-Volume Relation: The dashed line is represents the normal condition while the red solid line denotes 80% stenosis.

3.3 c) How aortic valve stenosis affects preload, afterload, and cardiac output

3.3.1 Preload

Aortic stenosis increases the resistance the heart faces, impacting hemodynamics. Initially, preload—the blood volume in the ventricle at the end of diastole can rise because the left ventricle struggles to fully eject blood during systole, leading to increased end-diastolic volume. Though this may temporarily maintain stroke volume via the Frank-Starling mechanism, prolonged high preload can result in ventricular dilation and heart failure.

3.3.2 Afterload

In aortic stenosis, afterload increases because the narrowed valve opening raises the pressure the heart must overcome to eject blood. The left ventricle thickens its walls (concentric hypertrophy) to generate the necessary pressure. However, this thickening reduces compliance, impairing diastolic filling and leading to diastolic dysfunction with time.

3.3.3 Cardiac Volume

Cardiac output is the volume of blood the heart pumps per minute and may decline as disease progresses. A stenotic valve creates an obstruction that limits stroke volume, especially during exertion, leading to a decreased cardiac output. Despite increased preload and effort, the heart struggles to increase output due to this limitation. As a result, patients with severe aortic stenosis may experience fatigue, shortness of breath, and syncope, risking compromised systemic perfusion and heart failure in advanced stages.

3.4 d) Aortic blood pressure and pressure drop across the stenotic aortic valve

Aortic blood pressure at the moment of maximal left ventricular pressure is 104 mmHg.

Pressure drop across the stenotic aortic valve at that moment = 171 - 104 = 67 mmHg.

3.5 e) Maximum pressure drop across the stenotic valve

Maximum blood flow velocity across the aortic valve is 4.18 m/s.

Maximum pressure drop across the aortic valve can be calculated as follows:

$$\Delta p = 4v^2 = 4 \times (4.18)^2 = 69.89 \text{ mmHg} \tag{3}$$

The calculated value is close to the actual maximum value of 67 mmHg.

3.6 f) Duration of ejection

Ejection period of the aortic valve at the 80% stenosis stage is as follows:

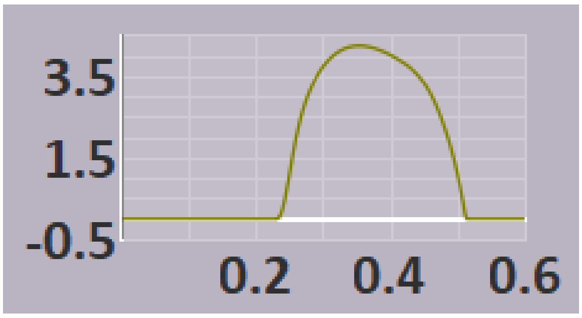

Figure 12: Ejection Period of the Aortic Valve

Duration of Ejection = 0.50 s - 0.23 s = 0.27 s

3.7 g) Increase in external pump work

Using the pressure volume relation curve in figure 11,

External pump work in normal conditions = 20 squares
External pump work at 80Increase in pump work = 3 squares

3.8 h) Effect on myocardial tissue of the left ventricle

In response to chronically increased pump work, such as that caused by conditions like aortic valve stenosis or hypertension, the myocardial tissue of the left ventricle adapts by undergoing concentric hypertrophy. This means the muscle fibers of the ventricular wall thicken, increasing the wall thickness without significantly enlarging the chamber size. This adaptation allows the heart to generate higher pressures to overcome the elevated resistance and maintain adequate cardiac output. This is called as Left Ventricular Hypertrophy.

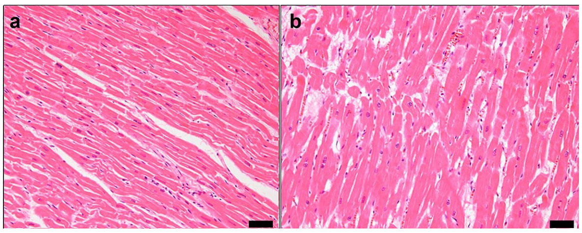

Figure 13: Comparison of normal myocardium (left) to hypertrophied myocardium (right)

However, this hypertrophic response also increases the afterload over time. As the ventricular wall thickens, ventricular compliance decreases, making the heart stiffer and less efficient during diastolic filling. It can eventually lead to diastolic dysfunction, increased oxygen demand, and potentially heart failure.

References

[1] "Wiggers Diagram," Wikipedia, Available: https://en.wikipedia.org/wiki/Wiggers_diagram.

[2] "The Cardiac Cycle," Geeky Medics, Available: https://geekymedics.com/the-cardiac-cycle/.