University of Moratuwa
Faculty of Engineering
Department of Electronic and Telecommunication Engineering

15$^{\text{th}}$ of May, 2025

BM2102 - Modelling and Analysis of Physiological Systems

Assignement 1

By: Dulsara G.M.L.

220146A

Submitted in Partial Fulfillment of the Requirements for the Module **BM2102 - Modelling and Analysis of Physiological Systems**

1 Introduction

This report presents a comprehensive analysis of cardiac physiology under two specific conditions:

1. Normal cardiac rhythm
2. Cardiac rhythm affected by aortic valve stenosis

The human cardiac cycle is divided into three main phases: *atrial systole*, *ventricular systole*, and *complete cardiac diastole*. Variations in physiological parameters, such as changes in pressure and volume, can be effectively examined using a Wigger's diagram.

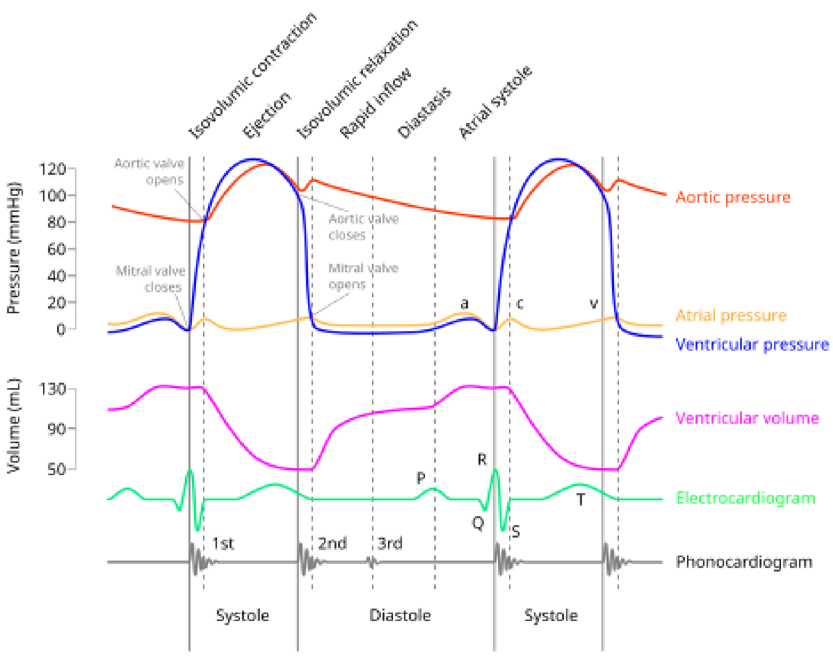


Figure 1: A Wigger's Diagram showcasing changes of parameters in one cardiac cycle. Source: `https://en.wikipedia.org/wiki/Wiggers_diagram`

According to the assignment the analysis is done using the Simulation software CircAdapt Simulator, software version v1.1.3.

2 Normal Sinus Rhythm

a) Aortic Valve Opening and Closing

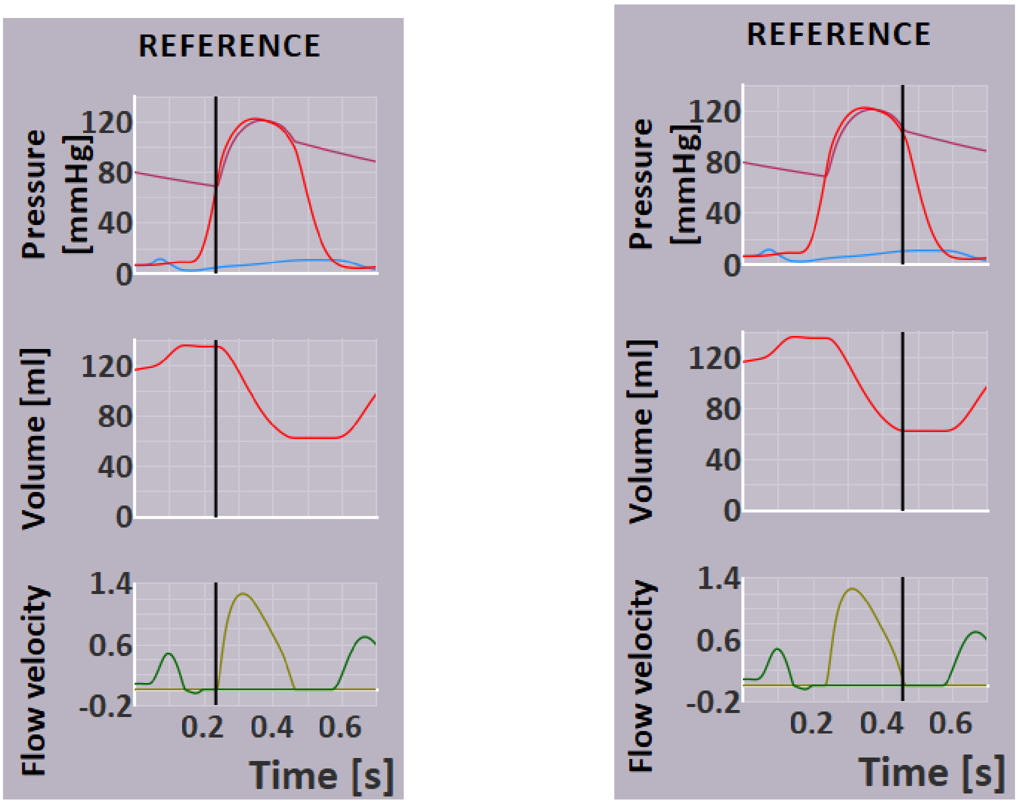


Figure 2: The timestamps marking the opening and closing of the aortic valve.

Parameter	Valve Opening	Valve Closing
Timestamp	0.24 S	0.46 S
Aortic Pressure	68.8 mmHg	105 mmHg
Left Ventricular Pressure	65.3 mmHg	100 mmHg

Table 1: State of Aortic Valve

By looking at the graphs, we can clearly see when the aortic valve opens and closes. During this time, the pressure in the left ventricle reaches its highest point, showing that the heart is pushing blood out with maximum force. At the same time, the volume in the left ventricle (shown in the second graph) decreases, meaning blood is being pumped into the aorta. This is also confirmed by the third graph, where the flow rate through the aortic valve (shown in lime green) suddenly spikes, indicating a fast and strong flow of blood into the aorta.

b) Mitral Valve Opening and Closing

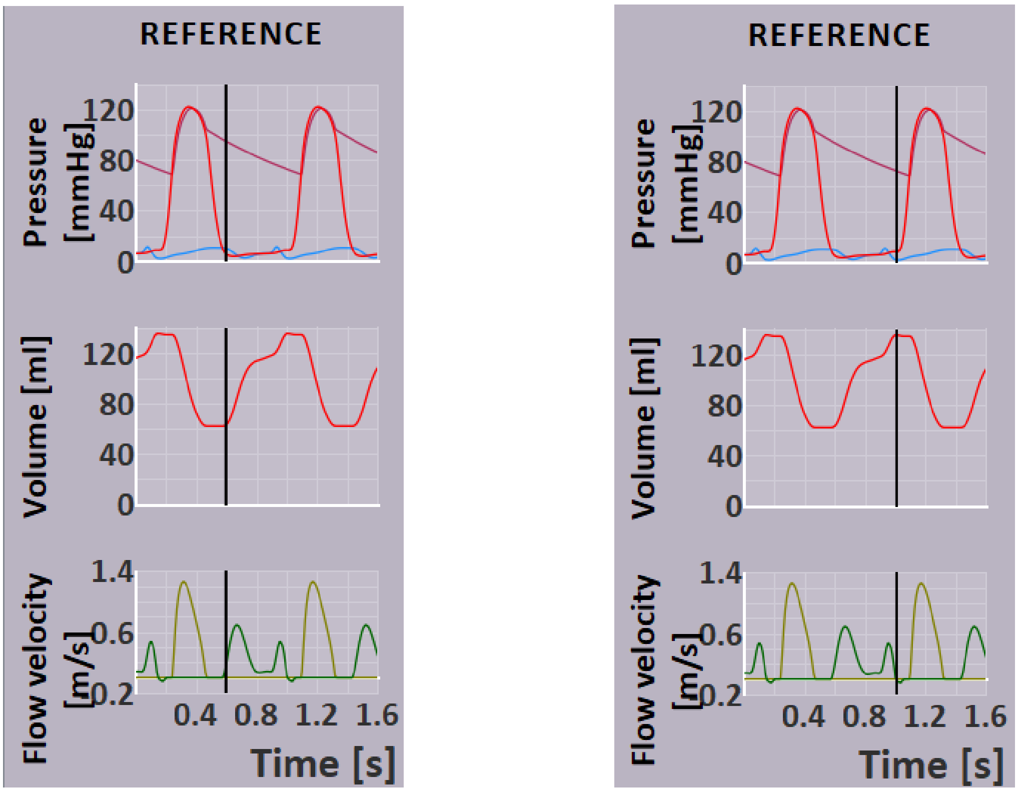


Figure 3: The timestamps marking the opening and closing of the mitral valve.

Parameter	Valve Opening	Valve Closing
Timestamp	0.60 S	1.01 S
Left Atrial Pressure	10.1 mmHg	2.05 mmHg
Left Ventricular Pressure	5.78 mmHg	8.59 mmHg

Table 2: State of Mitral Valve

The mitral valve opens when the pressure in the left atrium becomes slightly higher than the pressure in the left ventricle for a short time as shown in Table 2. This allows blood to flow into the left ventricle. In the volume graph, this is shown by the increase in ventricular volume. The flow through the mitral valve, shown by the dark green line in Graph 3, has two peaks, meaning the ventricle fills in two stages. This two-phase filling is clearly visible in the volume graph as well.

c) Identifying the points of Pressure - Volume graph

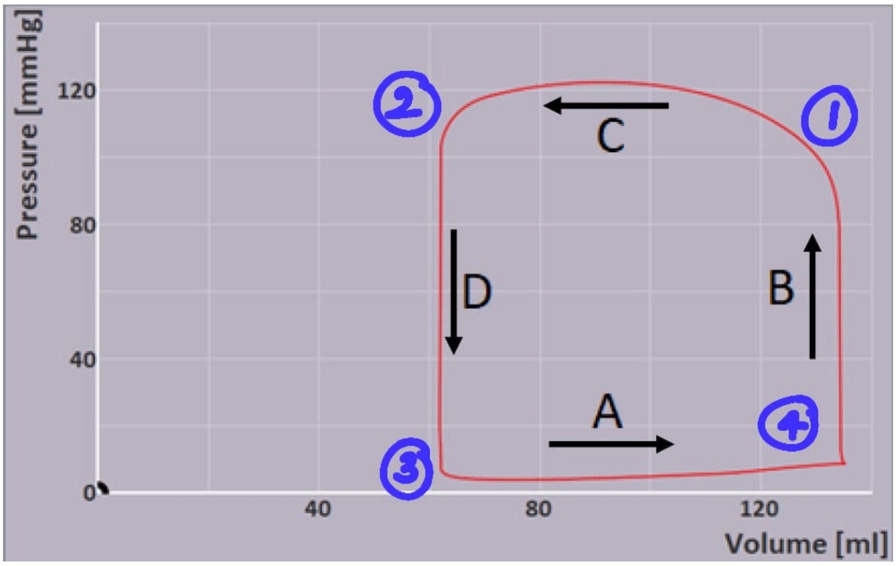


Figure 4: The pressure-volume graph of the left ventricle

The points marked in the graph are as follows.

1 - Aortic valve opening

2 - Aortic valve closing

3 - Mitral valve opening

4 - Mitral valve closing

The points at which the aortic and mitral valves open and close can be identified by observing the changes in left ventricular volume. When the aortic valve opens and closes, the ventricular volume decreases (from 1 to 2). In contrast, when the mitral valve opens and closes, the volume increases (from 3 to 4).

d) Phases of cardiac cycle

A - Filling

B - Isovolumic Contraction

C - Ejection

D - Isovolumic Relaxtion

e) Explaination

The aortic valve opens during ventricular systole, allowing blood to be pushed out into the aorta. This happens in a single strong flow, which appears as one hump in the flow graph. On the other hand, the mitral valve opens during diastole, and the filling of the left ventricle happens in two stages. First, blood flows quickly from the left atrium to the left ventricle due to a pressure difference—this is called Early Rapid Filling (E) and happens passively. Then, the atrium contracts to push the remaining blood into the ventricle—this is called Atrial Contraction (A). These two stages show up as two separate humps in the mitral valve flow graph.

f) Checking the atrial pressure

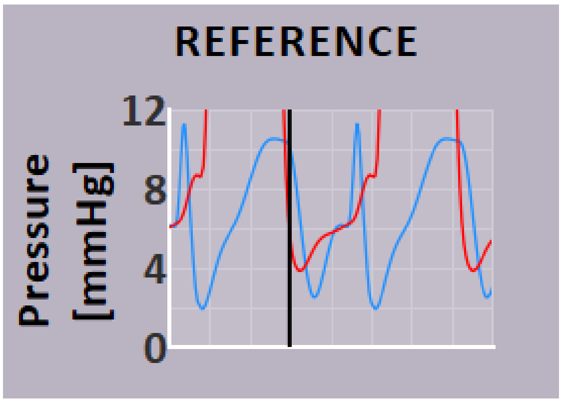


Figure 5: The slow and fast(steep) phases of atrial pressure increase

The sharp rise in atrial pressure happens during atrial systole, when the atria contract and push the remaining blood into the ventricles. The slower rise in atrial pressure occurs during diastole, when both the atria and ventricles are relaxed. During this time, blood flows into the left atrium from the pulmonary veins, causing a gentle increase in pressure. The part of the ECG that matches the sharp increase in atrial pressure is the QRS complex.

g) Identifying E, A waves of Mitral valve flow

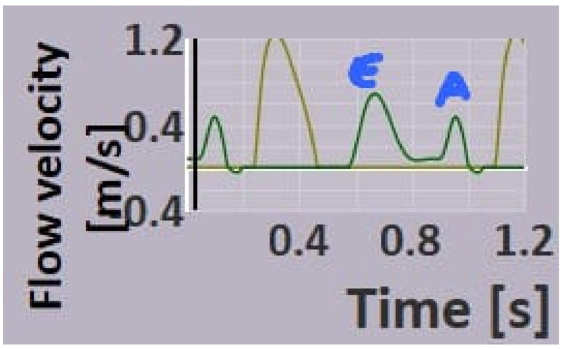


Figure 6: The Early Rapid Filling (E) and Atrial Contraction (A)

h) Calculation of E/A ratio

Peak	Time Stamp	Mitral valve flow velocity
E Peak	0.67 S	0.692 m/s
A Peak	0.96 S	0.473 m/s

Table 3: Mitral valve flow

E/A ratio = $\frac{0.692}{0.473}$ = 1.463

The calculated E/A ratio is above 1 therefore diastolic function is healthy.

i) Passive and Active filling of left ventricle

Instance	Time Stamp	Left Ventricular Volume
Mitral valve closed	0.61 S	64.5 ml
After early rapid filling (E peak)	0.68 S	87.2 ml
After atrial contraction (A peak)	0.96 S	127 ml

Table 4: Left ventricular volume

Passive and active filling can be calculated as follows.

Filling due to passive filling = 127 - 64.5 = 62.5 ml

Filling due to active filling = 127 - 87.2 = 39.8 ml

It can be seen that passive filling volume is greater than active filling volume.

j) Relation between blood flow velocity and flow rate

If the cross-sectional area of a heart valve is known, the blood flow rate (Qvalve) can be calculated using the velocity of blood flow through the valve (Vvalve).

3 Aortic Valve Stenosis

a) Preload and afterload

Preload, also called Ventricular End Diastolic Volume (VEDV), is the amount of blood in the ventricles just before they contract. It depends on how much blood returns to the heart (venous return), the total blood volume, and the strength of atrial contraction.
Afterload is the resistance the heart has to overcome to pump blood from the ventricles into the arteries. It is influenced by how stretchy and flexible the arteries and arterioles are.

b) Simulating Aortic Valve Stenosis (AS)

The procedure will be done by increasing the stenosis by 5% every step and observing the pressure and volume of the left ventricle.

Stenosis	**Peak velocity**	**Peak pressure**	**Peak volume**
0%	1.21 m/s	120 mmHg	133 ml
5%	1.25 m/s	121 mmHg	133 ml
10%	1.35 m/s	121 mmHg	133 ml
15%	1.43 m/s	122 mmHg	133 ml
20%	1.45 m/s	122 mmHg	133 ml
25%	1.62 m/s	123 mmHg	133 ml
30%	1.71 m/s	125 mmHg	133 ml
35%	1.80 m/s	125 mmHg	133 ml
40%	1.64 m/s	127 mmHg	133 ml
45%	2.04 m/s	128 mmHg	134 ml
50%	2.25 m/s	131 mmHg	134 ml
55%	2.45 m/s	133 mmHg	134 ml
60%	2.67 m/s	138 mmHg	134 ml
65%	2.93 m/s	142 mmHg	135 ml
70%	3.25 m/s	146 mmHg	135 ml
75%	3.64 m/s	154 mmHg	138 ml
80%	4.15 m/s	170 mmHg	139 ml

Table 5: Change of peak flow velocity

According to Table 5, the peak flow velocity across the aortic valve gradually increases with percentage of stenosis. This is trivial according to,

$$Qvalve = Avalve \times Vvalve$$

as cross sectional area of the valve (Avalve) decreases with % of stenosis and Qvalve remains constant, Vvalve must increase. The peak pressure of the left ventricle also starts to increase rapidly after 20% stenosis. The increase of peak left ventricular volume is slow-paced. The pressure-volume relation can be further observed using the following graph (Figure 7). Maximal left ventricular pressure is 170 mmHg at 80%

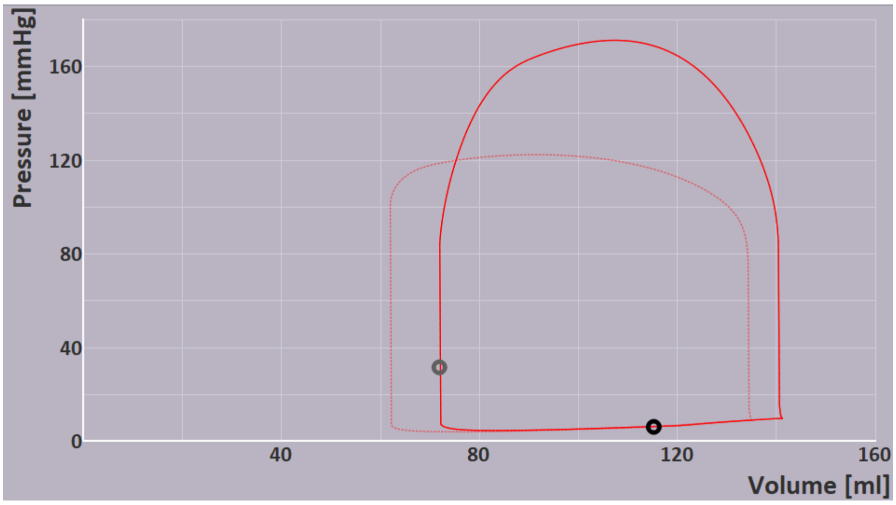


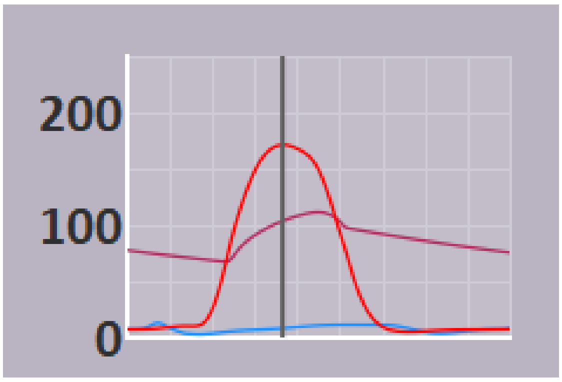
Figure 7: The change of pressure-volume graph of the left ventricle at 80%

c) Effect of Aortic Stenosis on Preload, Afterload and Cardiac Output

Variable	Effect of Stenosis
Preload	Aortic valve becomes narrower. Ventricles are unable to push the entire ventricular blood volume outwards; therefore, some amount of blood remains in the ventricles. This accumulated volume contributes to increased preload.
Afterload	Afterload directly increases because resistance to outflow is higher due to the smaller cross-sectional area.
Cardiac Output (CO)	Since cardiac output is given by Stroke Volume $\times$ Heart Rate, the increase in preload raises stroke volume, thereby increasing cardiac output.

Table 6: Effects of Aortic Stenosis on Key Cardiac Parameters

d) Pressure calculation



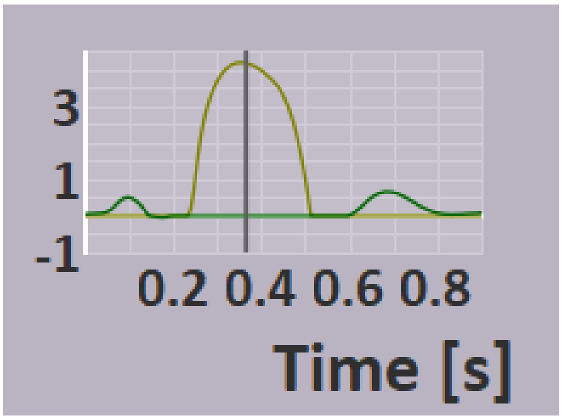
Aortic pressure during maximum left ventricular pressure is **106 mmHg**

$$Pressure\ drop = 170 - 103 = 64\ mmHg$$

e) Pressure calculation using formula

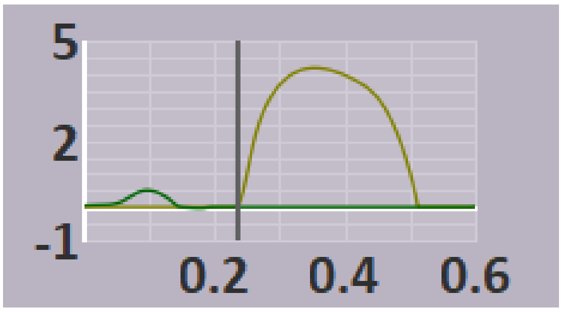
Maximum flow velocity of the aortic valve is v = 4.14m/s

$$Pressure\ drop = 4v^2 = 68.56\ mmHg$$



This calculated value is close to the measured value.

f) Duration of ejection



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

$$Duration\ of\ ejection = 0.52s - 0.24s = 0.28s$$

g) External pump work by left ventricle

Analasys is done using the Figure 7: The change of pressure-volume graph of the left ventricle at 80% in page 10.

External pump work in Normal person = Approximately 20 squares

External pump work at 80% stenosis = Approximately 24 squares

Increase in pump work = Approximately 3 squares

h) Change in the myocardial tissue of left ventricle

To cope with the chronically increased pump work (e.g., due to aortic stenosis), the myocardial tissue of the left ventricle undergoes concentric hypertrophy, where the walls of the ventricle thicken. This allows the heart to generate higher pressures to overcome the increased resistance.
However, this adaptation further increases afterload, as the stiffer, thicker walls reduce ventricular compliance, making it harder for the heart to fill and increasing the pressure needed to eject blood.

4 References

1. J. R. Mitchell and J.-J. Wang, "Expanding application of the Wiggers diagram to teach cardiovascular physiology," *Advances in Physiology Education*, vol. 38, no. 2, pp. 170–175, Jun. 2014. `https://doi.org/10.1152/advan.00123.2013`

2. A. Waugh and A. Grant, *Ross & Wilson Anatomy and Physiology in Health and Illness*, 14th ed. Edinburgh: Elsevier, 2023.

3. A. B. Bornstein, S. S. Rao, and K. Marwaha, "Left Ventricular Hypertrophy," *PubMed*, 2021. `https://www.ncbi.nlm.nih.gov/books/NBK557534/`

4. "Cardiac Cycle — Atrial Pressure — Part 3 — Jugular Venous Pulse — JVP — Cardiac Physiology," *YouTube*, `https://www.youtube.com/watch?v=9otb9X8hEeo`, accessed Mar. 11, 2024.

5. "The Bernoulli Equation - Medical Applications (Fluid Mechanics - Lesson 8)" *YouTube*, `https://www.youtube.com/watch?v=cO6B9Q3At1Y`