Department of Electronic and Telecommunications Engineering

BM2102 Modelling and Analysis of Physiological Systems

Assignment 2

Analysis of Cardiac Physiology

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Contents

1 Introduction

The following report carries out detailed analysis of the cardiac physiology under the following two conditions,

1. **Normal cardiac rhythm**
2. **Cardiac rhythm during aortic valve stenosis**

A cardiac cycle of the human heart consists of three major phases, namely, the atrial systole, ventricular systole and complete cardiac diastole. The physiological parameter changes such as changes of pressure and volume can be evaluated using a *Wigger's Diagram* [1].

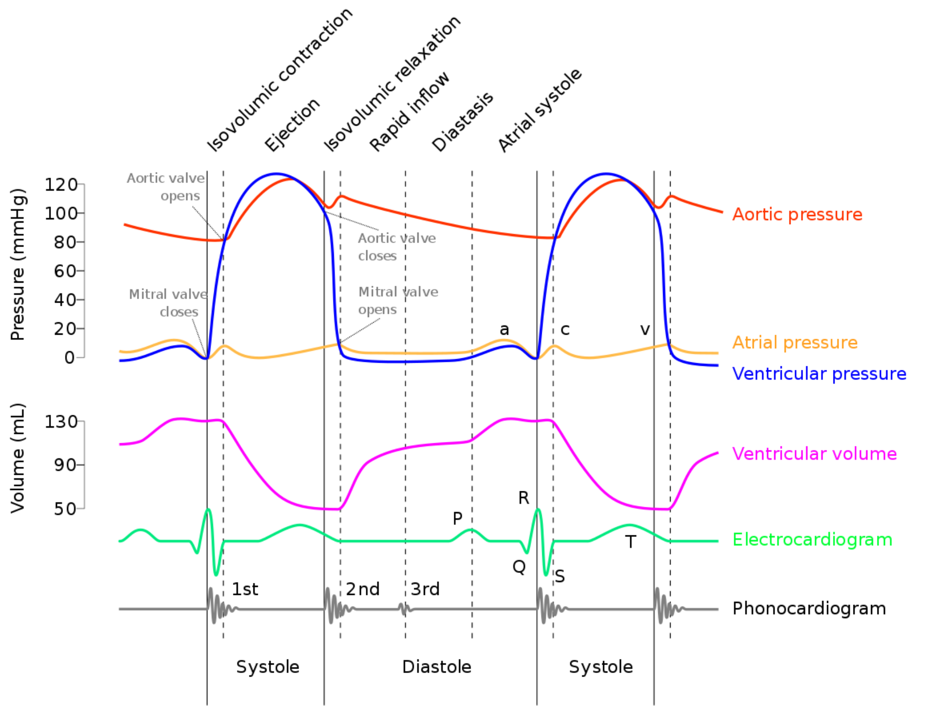

Figure 1: A Wigger's Diagram showcasing changes of parameters in one cardiac cycle.
Source: `https://en.wikipedia.org/wiki/Wiggers_diagram`

The following analysis will be carried out using the Simulation software **CircAdapt Simulator**. Software version v1.1.3 was used.

2 Important model parameters

As also seen in Figure 1, the most crucial physiological parameters in simulating the functionality of the heart are as follows,

1. **Left ventricular pressure**
2. **Left atrial pressure**
3. **Aortic pressure**

4. **Left ventricular volume**
5. **Flow rate of Aortic valve**
6. **Flow rate of Mitral valve**

3 Normal Sinus Rhythm

3.1 a) Aortic valve opening

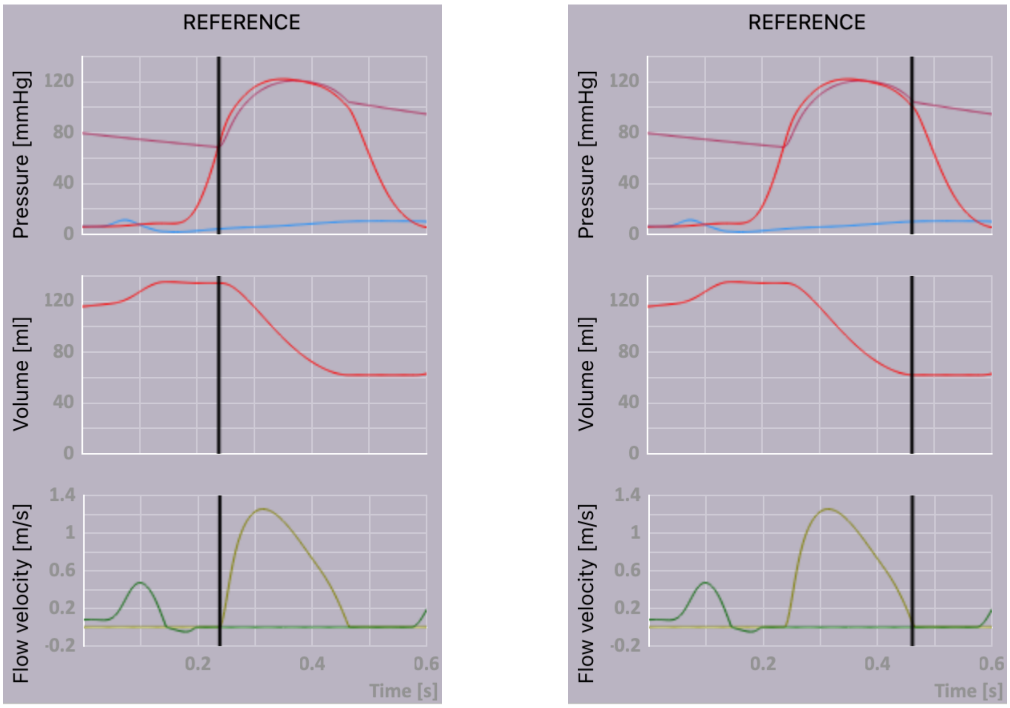

Figure 2: The timestamps marking the opening and closing of the aortic valve.

Parameter	Valve opening	Valve closing
Timestamp	0.24s	0.46s
Aortic pressure	68.8 mmHg	104 mmHg
Left ventricular pressure	65.3 mmHg	99.7 mmHg

Table 1: Important physiological parameters which help to determine the state of the Aortic valve.

By observing the above graphs it can be clearly identified when the aortic valve is opening and closing. The pressure of the left ventricle peaks during the mid of this time period, meaning maximum force is exerted necessary for systemic circulation. Also the volume of the left ventricle (shown in the second graph) drops. This means that blood volume is pushed into the aorta. We can confirm our observation using the 3rd graph where the flow rate of the aortic valve is denoted in lime green. The sudden spike means a large, swift outflow of blood into the aorta.

3.2 b) Mitral valve opening

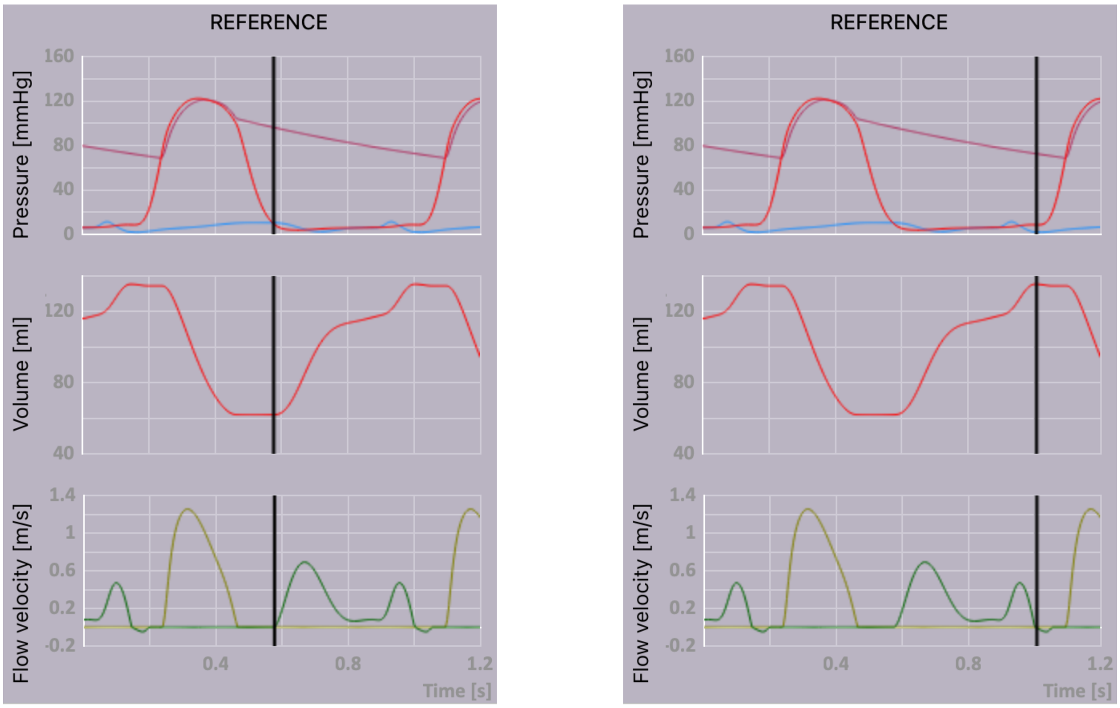

Figure 3: The timestamps marking the opening and closing of the mitral valve.

Parameter	Valve opening	Valve closing
Timestamp	0.51s	1.01s
Left atrial pressure	10.3 mmHg	1.98 mmHg
Left ventricular pressure	7.21 mmHg	8.58 mmHg

Table 2: Important physiological parameters which help to determine the state of the mitral valve.

The opening of the mitral valve is signified by the left atrial pressure becoming larger than left ventricular pressure for a short period of time. (Refer Table 2). The refilling of the left ventricle can be observed in the volume graph (Graph 2 of Figure 3). The state of the mitral valve can be further confirmed using the dark green curve of graph 3. The flow rate of the mitral valve has two spikes, meaning the refilling of the left ventricle occurs in two phases. This is perfectly seen in the volume graph.

3.3 c) Pressure-Volume graph of left ventricle

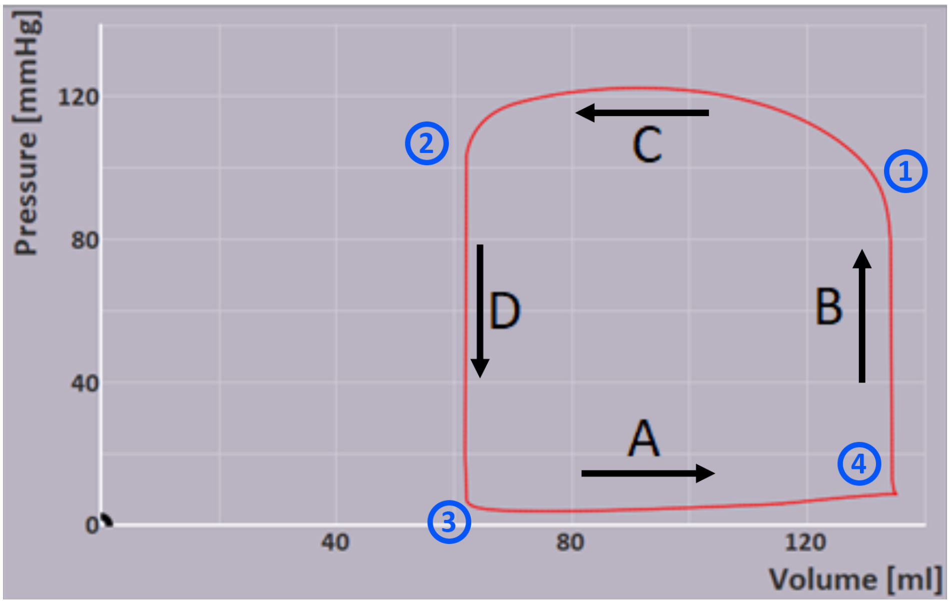

Figure 4: The pressure-volume graph of the left ventricle

Where,
1 - Aortic valve opening
2 - Aortic valve closing
3 - Mitral valve opening
4 - Mitral valve closing

The positions for opening and closing of the aortic and mitral valves can be determined using the volume change of the left ventricle. The opening and closing of the aortic valve reduces the volume (from ① → ②). The opening and closing of the mitral valve increases the volume (from ③ → ④).

3.4 d) Rectangular approximation and phases of cardiac cycle

A - Filling
B - Isovolumic Contraction
C - Ejection
D - Isovolumic Relaxtion

d) Rectangular approximation and phases of cardiac cycle

The aortic valve opens during ventricular systole. This process pushes the blood outwards through the aorta, hence it usually occurs in one hump. The mitral valve however opens during diastole. This occurs in two steps. First blood flows from left atrium to left ventricle rapidly. This is called Early Rapid Filling (E) and occurs passively due to pressure difference. Then the remaining flow is active and is due to atrial contraction (A) during atrial systole. These two phases are recorded as two humps in the mitral valve flow diagram.

3.5 f) Checking atrial pressure

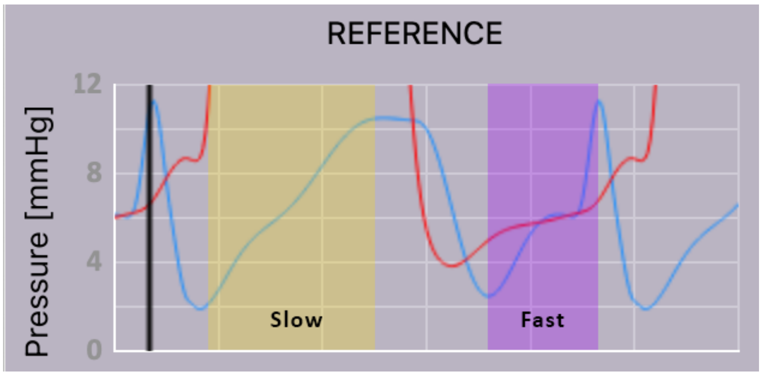

Figure 5: The slow and fast(steep) phases of atrial pressure increase in the left atrium. Yellow region shows slow increase and purple region shows fast increase.

The steep increase of atrial pressure is due to atrial systole. Here the atria contracts and pushes the blood remaining in the atria to the ventricles.

The slow increase of atrial pressure is due to diastole. This is when both atria and ventricles are relaxed and the left atrium is being filled with blood coming from the pulmonary veins. This passive filling gently increases blood pressure in the left atrium.

The portion of the ECG corresponding to the sharp rise in atrial pressure is the **QRS complex**.

3.6 g) Identifying E, A waves of Mitral valve flow

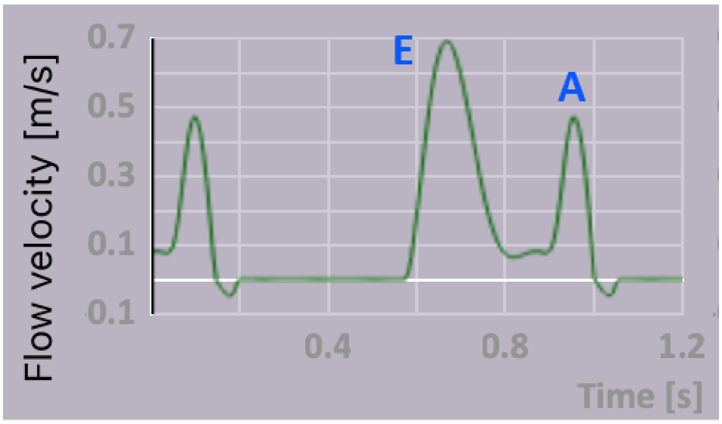

Figure 6: The Early Rapid Filling (E) and Atrial Contraction (A) represented as two humps in the mitral valve blood flow graph.

3.7 h) Calculation of E/A ratio

Peak	**Timestamp**	**Mitral valve flow velocity**
E peak	0.67s	0.69 ms^{-1}
A peak	0.96s	0.451 ms^{-1}

Table 3: Mitral valve flow

$$E/A\,ratio = \frac{0.69}{0.451} = 1.53$$

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

3.8 i) Passive and Active filling of left ventricle

Instance	**Timestamp**	**Left ventricular volume**
Mitral valve closed	0.58s	62 ml
After early rapid filling (E peak)	0.80s	113 ml
After atrial contraction (A peak)	1.02s	135 ml

Table 4: Left ventricular volume

Filling due to passive filling $= 113 - 62 = 51\,ml$
Filling due to active filling $= 135 - 113 = 22\,ml$

It can be seen that passive filling volume is almost as twice as active filling volume.

3.9 j) Relation between blood flow velocity and flow rate

The blood flow velocity through a cardiac valve (V_{valve}) can be used to calculate the blood flow rate (Q_{valve}) if the **cross sectional area of the valve** is given.

4 Aortic Valve Stenosis

4.1 a) Preload and afterload

Preload or otherwise known as **Ventricular end diastolic volume (VEDV)** is the volume of blood in the ventricles immediately before they contract. This depends on venous return, total blood volume and atrial contraction.

Afterload is the resistance to blood being pumped from the ventricles into the arteries. It is affected by the distensibility and elasticity of arteries and arterioles.

4.2 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%	1.25 ms^{-1}	122 $mmHg$	135 ml
5%	1.30 ms^{-1}	123 $mmHg$	135 ml
10%	1.37 ms^{-1}	123 $mmHg$	135 ml
15%	1.46 ms^{-1}	123 $mmHg$	135 ml
20%	1.49 ms^{-1}	124 $mmHg$	135 ml
25%	1.63 ms^{-1}	125 $mmHg$	135 ml
30%	1.73 ms^{-1}	126 $mmHg$	135 ml
35%	1.83 ms^{-1}	127 $mmHg$	135 ml
40%	1.96 ms^{-1}	129 $mmHg$	135 ml
45%	2.08 ms^{-1}	130 $mmHg$	136 ml
50%	2.28 ms^{-1}	132 $mmHg$	136 ml
55%	2.47 ms^{-1}	135 $mmHg$	136 ml
60%	2.69 ms^{-1}	139 $mmHg$	136 ml
65%	2.95 ms^{-1}	143 $mmHg$	137 ml
70%	3.28 ms^{-1}	149 $mmHg$	137 ml
75%	3.67 ms^{-1}	156 $mmHg$	139 ml
80%	4.18 ms^{-1}	171 $mmHg$	141 ml

Table 5: Change of peak flow velocity through aortic valve, peak pressure and peak volume in the left ventricle with percentage stenosis

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

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

as cross sectional area of the valve (A_{valve}) decreases with % of stenosis and Q_{valve} remains constant, V_{valve} 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 **171** $mmHg$ at 80%

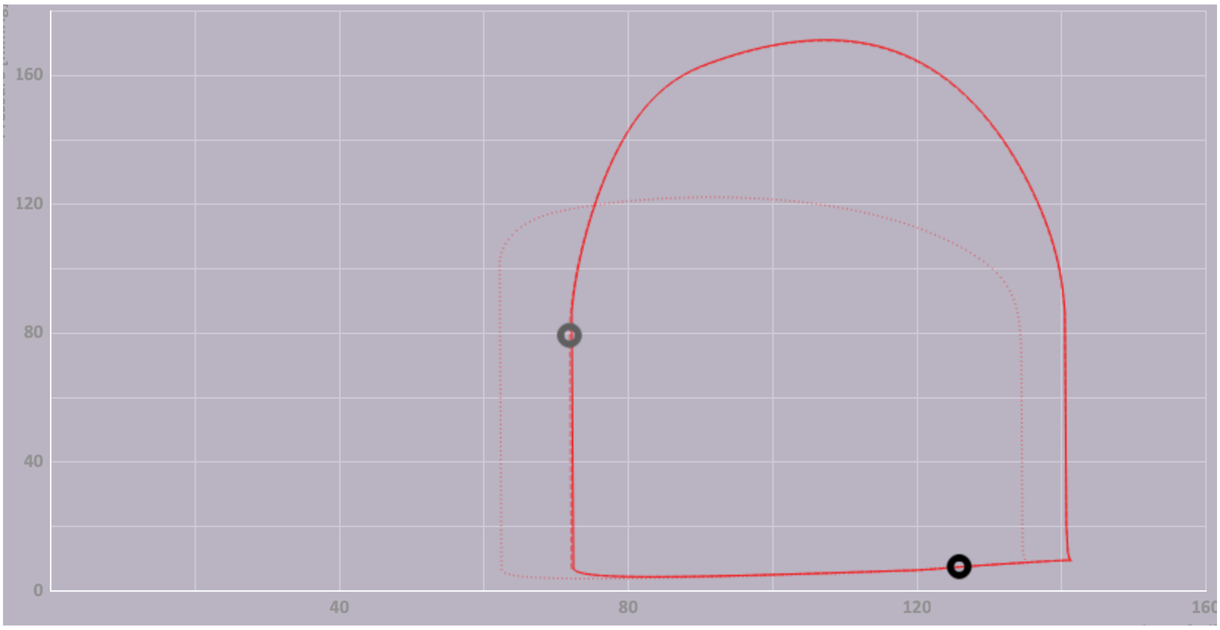

Figure 7: The change of pressure-volume graph of the left ventricle. The dashed line is represents the normal condition while the red solid line denotes 80% stenosis.

4.3 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 volume remains in the ventricles. This small volume gets accumulated and contributes to increase preload.
Afterload	Afterload directly increases because resistance to outflow has been increased due to smaller cross sectional area.
Cardiac Output (CO)	Since Cardiac Output is given by $Stroke\,Volume \times Heart\,Rate$ the increase in preload increases stroke volume. Thereby it increases CO.

4.4 d) Pressure calculation

Aortic pressure during maximum left ventricular pressure is **103** $mmHg$.

$$Pressure\ drop = 171 - 103 = 68\, mmHg$$

4.5 e) Pressure calculation using formula

Maximum flow velocity of the aortic valve is $v = 4.18ms^{-1}$.

$$Pressure\ drop\ (\Delta P) = 4v^2 = 4(4.18)^2 = 69.88\, mmHg$$

This calculated value is indeed close to the measured value.

4.6 f) Duration of ejection

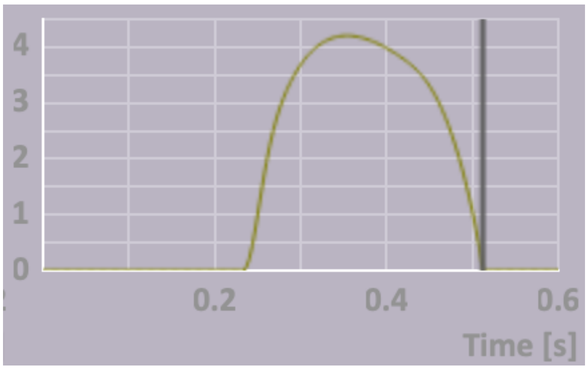

Figure 8: Duration of aortic valve opening

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

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

4.7 g) External pump work by left ventricle

Using Figure 7 (Page 9),

External pump work in Normal person = 20 squares
External pump work at 80% stenosis = 23 squares
Increase in pump work = 3 squares

4.8 h) Change in the myocardial tissue of left ventricle

Initially, the myocardium of the left ventricle adapts to stenosis by hypertrophy. Concentric hypertrophy of the left ventricle or more commonly known as **Left Ventricular Hypertrophy (LVH)** is the abnormal increase of myocardial mass caused by chronic increased workload on the heart [3]. This adaptation does not have an effect on the afterload since afterload is merely the resistance through the aortic valve. But the ventricle is now better prepared to handle the increased afterload due to AS.

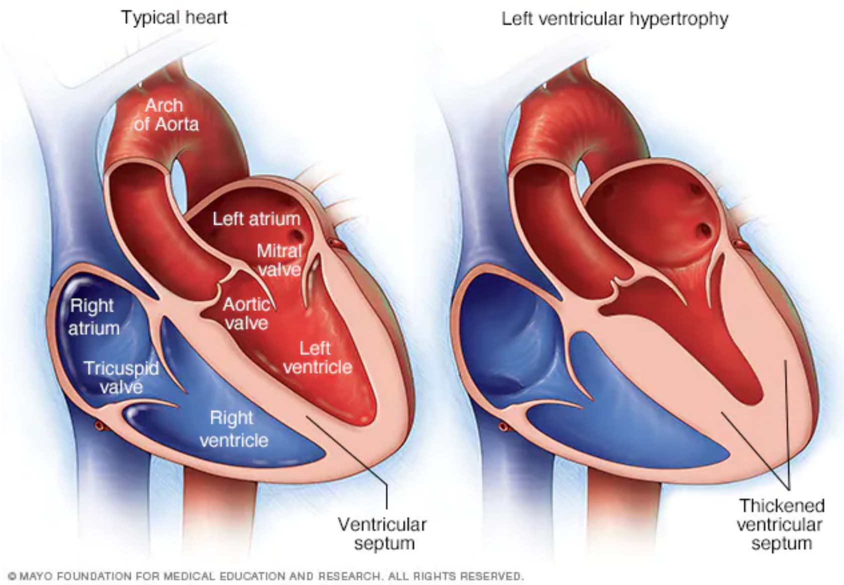

Figure 9: Left Ventricular Hypertrophy occurred due to chronic aortic stenosis. Source: `https://www.mayoclinic.org/diseases-conditions/left-ventricular-hypertrophy/symptoms-causes/syc-20374314`

5 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, doi: `https://doi.org/10.1152/advan.00123.2013`.

[3] 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," www.youtube.com. `https://www.youtube.com/watch?v=9otb9X8hEeo` (accessed Mar. 11, 2024).