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

17th of May, 2025

BM2102: Modelling and Analysis of Physiological Systems

A3: Analysis of Cardiac Physiology

By: Fernando S.R.N.

220169V

Contents

1 Introduction 3

2 Normal Sinus Rhythm 4

2.1 Aortic valve opening 4

2.2 Mitral Valve Opening 5

2.3 Pressure-Volume graph of left ventricle 6

2.4 Phases of the cardiac cycle 6

2.5 Flow Velocity Pattern of Aortic and Mitral Valves 6

2.6 Change in Atrial Pressure 7

2.7) Identifying E, A waves of Mitral valve flow 8

2.8 Calculating E/A Ratio 8

2.9 Passive and Active Filling of Left Ventricle 9

2.10 Relation between blood flow velocity and flow rate 9

3 Aortic Valve Stenosis 10

3.1 Preload and Afterload 10

3.2 Simulating Aortic Valve Stenosis (AS) 10

3.3 4.3 Effects of Aortic Valve Stenosis 12

3.4 Pressure Drop Across the Aortic Valve 12

3.5 Duration of Ejection 13

3.6 Adaptation of Myocardial Tissue and Effect on Afterload 14

1 Introduction

The human cardiac cycle is a sequence of coordinated mechanical and electrical events that ensure efficient blood circulation throughout the body. It consists of three major phases: atrial systole, ventricular systole, and diastole. These phases involve changes in pressure and volume across the heart chambers and valves, which can be analyzed using the Wiggers diagram — a comprehensive tool for visualizing cardiac physiology in one cycle.

This report presents a detailed analysis of the cardiac physiology under two conditions:

- Normal sinus rhythm
- Cardiac rhythm during aortic valve stenosis

The simulations were carried out using CircAdapt Simulator, which allows real-time visualization of of cardiac physiology.

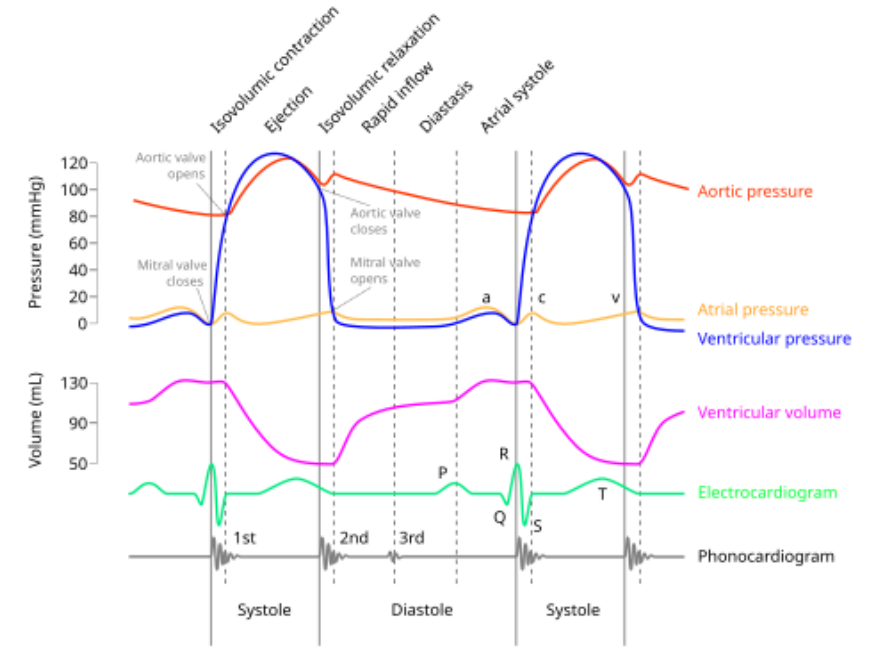

Figure 1: Representation of Model

From the above figure we can observe the main physiological parameters related to heart function as,

- Left Ventricular Pressure (LVP)
- Atrial Pressure (LAP)
- Aortic Pressure (AP)
- Ventricular Volume (LVV)
- Blood flow velocity through the Aortic Valve
- Blood flow velocity through the Mitral Valve

2 Normal Sinus Rhythm

2.1 Aortic valve opening

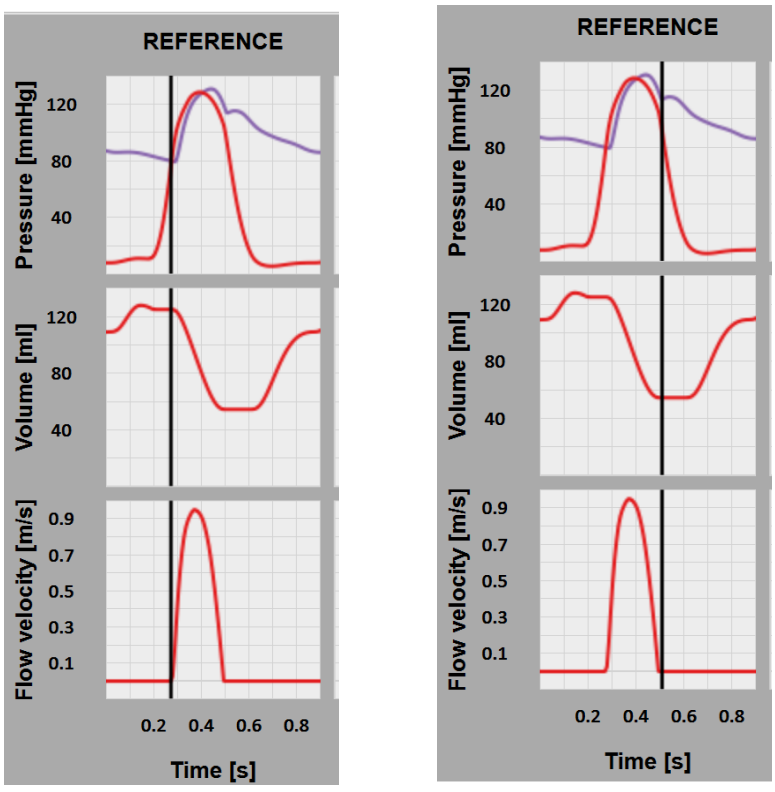

Figure 2: Opening and closing point of arotic valve

By looking at the graph we can observe that during a cycle:

- A sharp rise and fall in aortic flow velocity is observed.
- LV volume decreases as blood is ejected into the aorta.
- The pressure-volume loop shows a leftward movement, indicating outflow.

2.2 Mitral Valve Opening

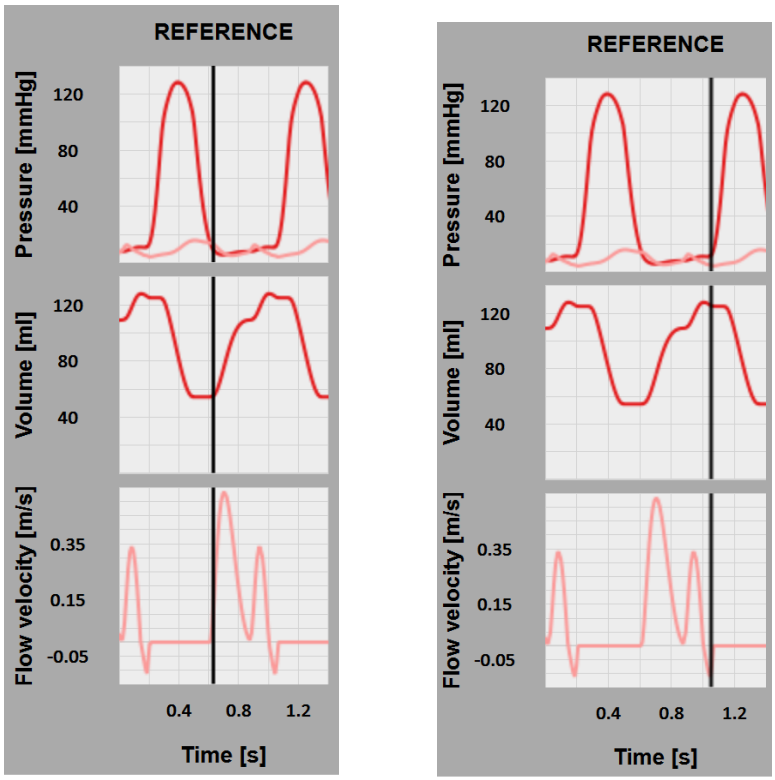

Figure 3: Opening and closing point of mitral valve

By observing the above graphs we can see that the mitral valve opens when the left atrial pressure briefly exceeds the left ventricular pressure. This allows the left ventricle to refill, as seen in the volume graph. The status of the mitral valve can also be verified using the pressure graph the mitral valve flow rate exhibits two distinct spikes, indicating that left ventricular refilling occurs in two phases, a pattern which can be seen in the graphs.

2.3 Pressure-Volume graph of left ventricle

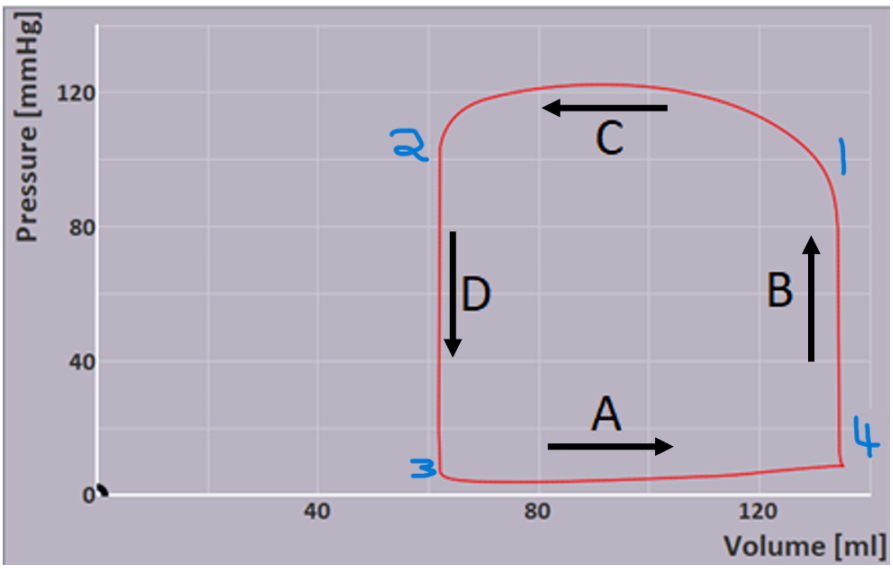

Figure 4: Pressure-Volume graph of left ventricle

(1-aortic opening, 2-aortic closing, 3-mitral opening, 4-mitral closing)

These changes were determined by observing the change of volume in the left ventricle.

2.4 Phases of the cardiac cycle

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

2.5 Flow Velocity Pattern of Aortic and Mitral Valves

The flow velocity pattern in the aortic valve shows a single hump because it opens only during ventricular systole, when the left ventricular pressure exceeds the aortic pressure, causing a single, rapid ejection of blood into the aorta. In contrast, the mitral valve flow pattern shows two humps: the first (E-wave) occurs during early diastole when blood

flows passively from the left atrium into the ventricle due to a pressure difference, and the second (A-wave) results from atrial contraction, which actively pushes additional blood into the ventricle at the end of diastole.

2.6 Change in Atrial Pressure

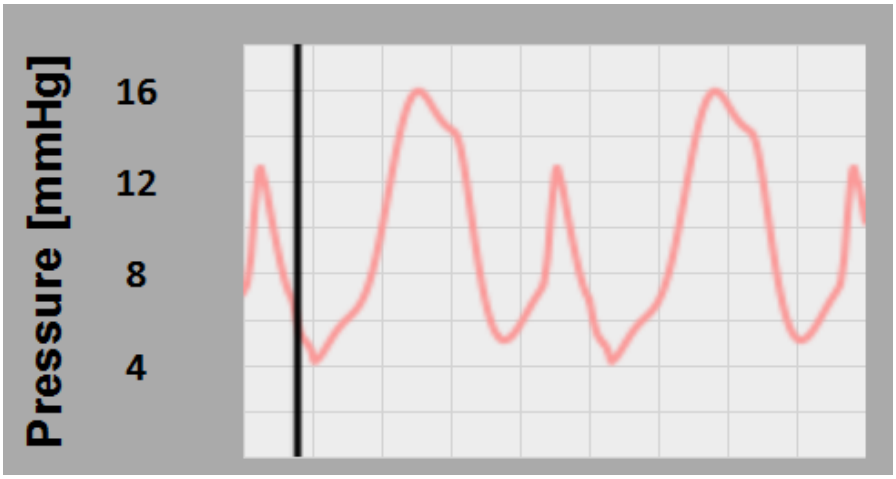

Figure 5: Change in atrial pressure

By closely examining the atrial pressure curve, two distinct increases can be observed during a single cardiac cycle. The slow rise in pressure occurs during ventricular systole, as blood returning from the lungs gradually fills the relaxed left atrium. The steep, fast rise corresponds to atrial contraction (atrial systole), where the atrial muscles actively push blood into the left ventricle. This sharp increase in pressure is synchronized with the **P-wave** on the ECG, which represents atrial depolarization and the initiation of contraction.

2.7) Identifying E, A waves of Mitral valve flow

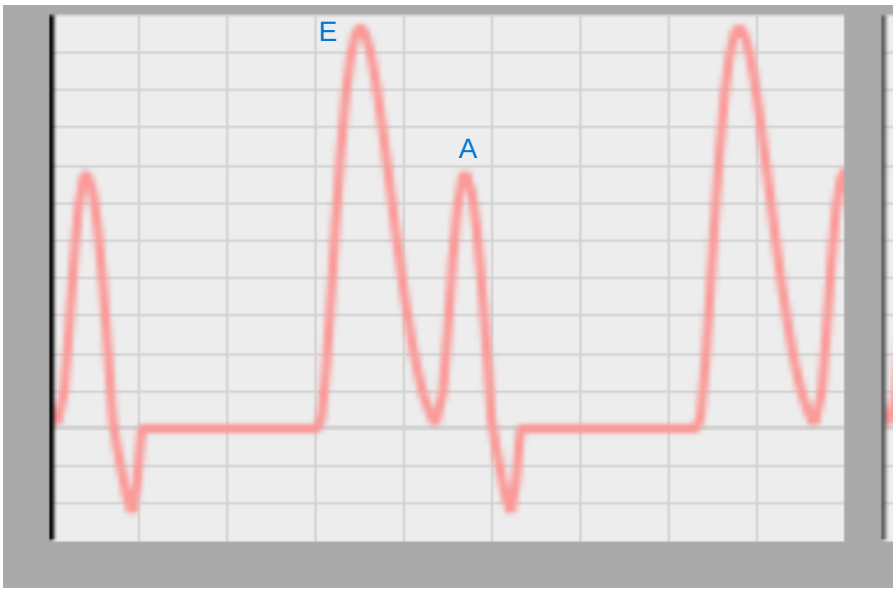

Figure 6: Mitral blood flow velocity

2.8 Calculating E/A Ratio

The E/A ratio is calculated using the peak velocities of the E-wave and A-wave from the mitral valve flow velocity curve.

$$\text{E/A Ratio} = \frac{\text{Peak velocity of E-wave}}{\text{Peak velocity of A-wave}} = \frac{0.535}{0.337}$$

$$\text{E/A Ratio} \approx 1.59$$

Since the E/A ratio is greater than 1, it indicates normal diastolic function of the left ventricle.

2.9 Passive and Active Filling of Left Ventricle

Instance	Time	Left ventricular volume
Mitral valve closed	0.57s	$60\,ml$
After early rapid filling (E peak)	0.79s	$110\,ml$
After atrial contraction (A peak)	1.01s	$132\,ml$

Table 1: Left ventricular volume

Filling due to passive filling $= 110 - 60 = 50\,ml$
Filling due to active filling $= 132 - 110 = 22\,ml$

It can be observed that passive filling volume is much more greater than the active filling volume.

2.10 Relation between blood flow velocity and flow rate

The blood flow velocity (V_{valve}) through a cardiac valve is related to the flow rate (Q_{valve}) by the following equation:

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

where A_{valve} is the **cross-sectional area** of the valve.

To convert velocity to flow rate, one must know the **geometrical/anatomical property** of the valve, which is the **effective valve area** (A_{valve}).

- V_{valve} has units of m/s
- A_{valve} has units of m^2
- Q_{valve} then has units of m^3/s

Thus, knowing the valve's cross-sectional area allows accurate conversion of velocity into flow rate.

3 Aortic Valve Stenosis

3.1 Preload and Afterload

Preload refers to the initial stretching of the cardiac muscle fibers (myocardium) prior to contraction. It is largely determined by the **end-diastolic volume (EDV)** — the volume of blood in the ventricle at the end of diastole. Preload depends on factors such as venous return, total blood volume, and atrial contraction.

Afterload is the pressure or resistance the ventricles must overcome to eject blood during systole. In the case of the left ventricle, afterload is primarily influenced by the pressure in the aorta and the systemic vascular resistance. Aortic valve stenosis increases afterload due to the narrowed valve opening, which requires the ventricle to generate higher pressure for blood ejection.

3.2 Simulating Aortic Valve Stenosis (AS)

The procedure was carried out by increasing the stenosis percentage in 5% increments and recording the changes in peak flow velocity, peak pressure, and peak volume of the left ventricle.

According to the table below, the peak flow velocity across the aortic valve increases with the degree of stenosis. This can be explained using the equation:

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

As the cross-sectional area of the aortic valve (A_{valve}) decreases with increasing stenosis, and assuming the flow rate Q_{valve} remains constant, the velocity V_{valve} must increase to compensate.

Additionally, the peak pressure in the left ventricle begins to rise more noticeably after around 20% stenosis. The increase in end diastolic volume is more gradual.

Stenosis	Peak velocity	Peak pressure	Peak volume
0%	1.22 ms^{-1}	120 $mmHg$	135 ml
5%	1.28 ms^{-1}	121 $mmHg$	135 ml
10%	1.34 ms^{-1}	122 $mmHg$	135 ml
15%	1.42 ms^{-1}	123 $mmHg$	135 ml
20%	1.47 ms^{-1}	124 $mmHg$	135 ml
25%	1.60 ms^{-1}	126 $mmHg$	135 ml
30%	1.70 ms^{-1}	127 $mmHg$	135 ml
35%	1.81 ms^{-1}	128 $mmHg$	136 ml
40%	1.95 ms^{-1}	130 $mmHg$	136 ml
45%	2.10 ms^{-1}	132 $mmHg$	136 ml
50%	2.32 ms^{-1}	134 $mmHg$	137 ml
55%	2.52 ms^{-1}	137 $mmHg$	137 ml
60%	2.75 ms^{-1}	141 $mmHg$	138 ml
65%	3.05 ms^{-1}	145 $mmHg$	139 ml
70%	3.35 ms^{-1}	150 $mmHg$	139 ml
75%	3.75 ms^{-1}	157 $mmHg$	140 ml
80%	4.20 ms^{-1}	172 $mmHg$	142 ml

Table 2: Change Peak Velocity, Pressure and Volume

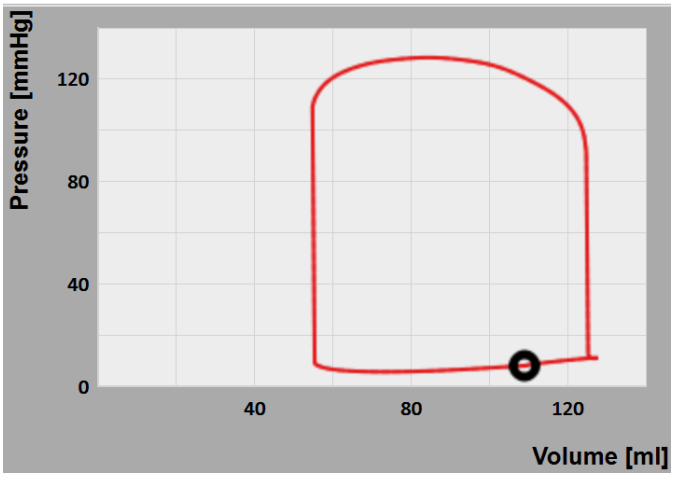

Figure 7: Change in P-V graph

3.3 4.3 Effects of Aortic Valve Stenosis

Preload: Aortic valve stenosis increases the resistance against which the left ventricle must pump. Due to the narrowed valve opening, the ventricle is unable to fully eject its contents during systole. As a result, some blood remains in the ventricle and adds to the incoming blood during the next filling phase. This accumulation increases the **end-diastolic volume (EDV)**, thereby increasing the **preload**.

Afterload: The narrowed aortic valve increases the pressure the left ventricle must generate to open the valve and eject blood. This leads to a significant increase in **afterload**, defined as the resistance the ventricle must overcome to eject blood into the aorta.

Cardiac Output (CO): Cardiac output is defined as the product of stroke volume and heart rate:

$$CO = SV \times HR$$

In early stages of stenosis, increased preload can partially compensate by increasing stroke volume, thereby maintaining cardiac output. However, as stenosis becomes more severe, the high afterload reduces the efficiency of ejection and may ultimately lead to a decrease in stroke volume and thus a reduction in cardiac output. Over time, this can lead to heart failure if compensation is no longer sufficient.

3.4 Pressure Drop Across the Aortic Valve

At the moment of maximal left ventricular pressure (171 mmHg), the corresponding aortic pressure was measured as 103 mmHg. Therefore, the pressure drop across the stenotic aortic valve is calculated as:

$$\Delta P = P_{\text{LV}} - P_{\text{Aorta}} = 171\,\text{mmHg} - 103\,\text{mmHg} = 68\,\text{mmHg}$$

4.5 Pressure Drop Using Simplified Bernoulli's Equation

To estimate the pressure drop using Bernoulli's equation, we apply the clinical approximation:

$$\Delta P \approx 4v^2$$

Given that the peak flow velocity through the stenotic aortic valve at 80% stenosis is:

$$v = 4.18\,\text{m/s}$$

$$\Delta P \approx 4 \times (4.18)^2 = 4 \times 17.47 = 69.88\,\text{mmHg}$$

This estimated value is very close to the directly measured value (68 mmHg), validating the simplified Bernoulli approach for noninvasive assessment.

3.5 Duration of Ejection

From the simulation, the aortic valve opens at approximately 0.24 s and closes at 0.52 s. Therefore, the duration of ejection is:

$$\text{Ejection Duration} = 0.52\,\text{s} - 0.24\,\text{s} = 0.28\,\text{s}$$

4.7 External Pump Work Estimation

The surface area enclosed by the pressure-volume (PV) loop is proportional to the external pump work done by the left ventricle.

- Normal heart: Approximate area = 20 squares
- At 80% stenosis: Approximate area = 23 squares
- Increase in pump work = 23 - 20 = 3 squares

Hence, the left ventricle performs more work to maintain blood flow under stenotic conditions, reflecting an increased mechanical demand.

3.6 Adaptation of Myocardial Tissue and Effect on Afterload

To cope with the chronically increased afterload caused by aortic valve stenosis, the myocardial tissue of the left ventricle undergoes concentric hypertrophy. This structural adaptation increases the thickness of the ventricular wall, allowing it to generate higher pressure without dilating. This condition is commonly referred to as Left Ventricular Hypertrophy (LVH).

While LVH helps the ventricle cope with elevated pressures, it does not reduce the actual afterload, since afterload is primarily determined by the resistance across the stenotic valve. Over time, LVH can impair ventricular relaxation and lead to diastolic dysfunction if not managed.