UNIVERSITY OF MORATUWA, SRI LANKA
Faculty of Engineering
Department of Electronic and Telecommunication Engineering
Semester 4 (Intake 2020)

BM2102 Analysis of physiological systems
Assignment 2
Analysis of Cardiac Physiology

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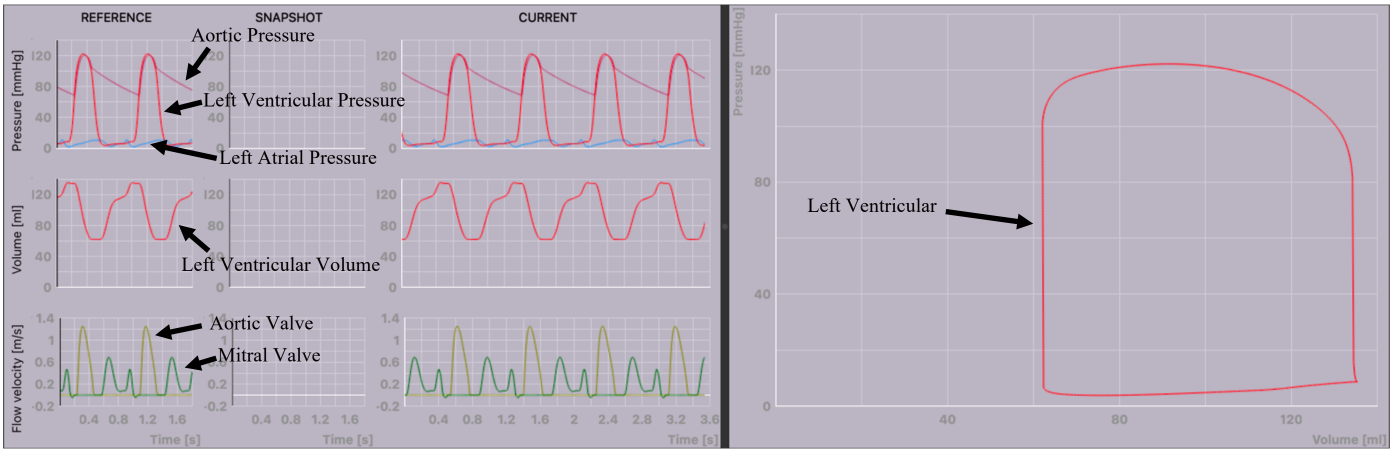
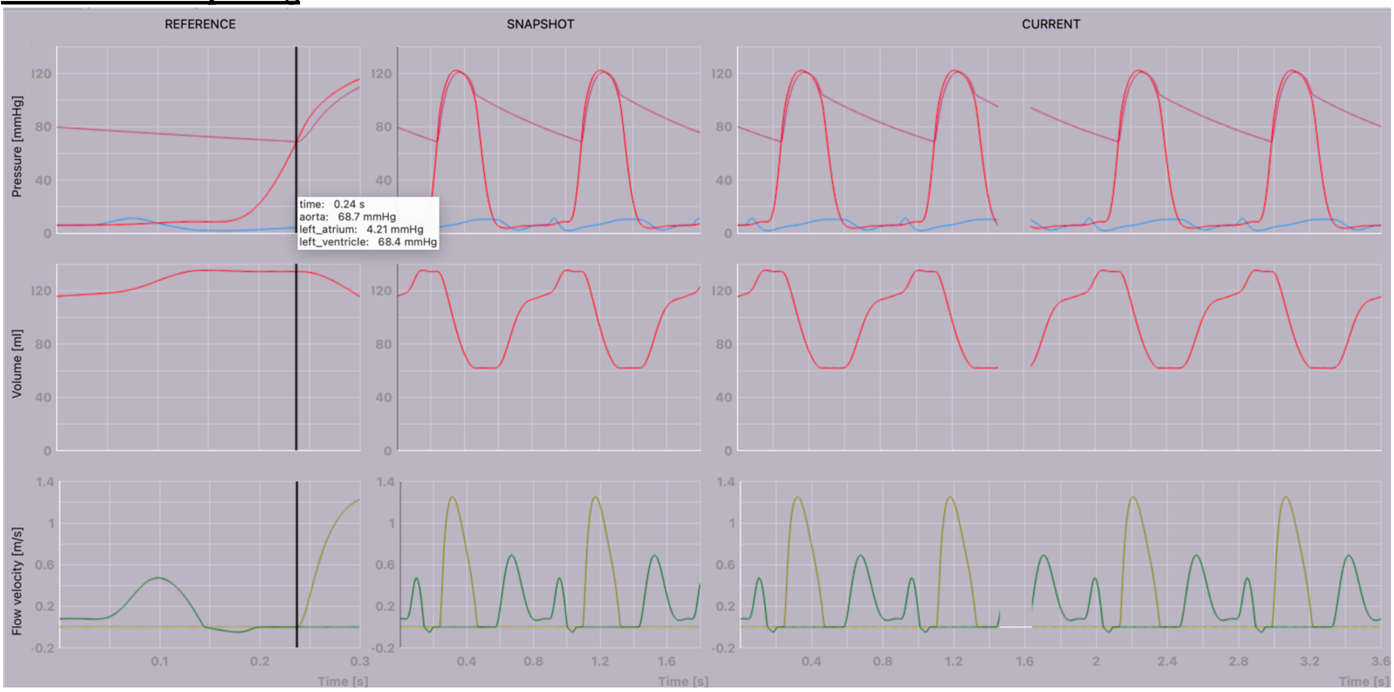
1. Normal Sinus Rhythm

CircAdapt Simulator Interface



Aortic Valve Opening



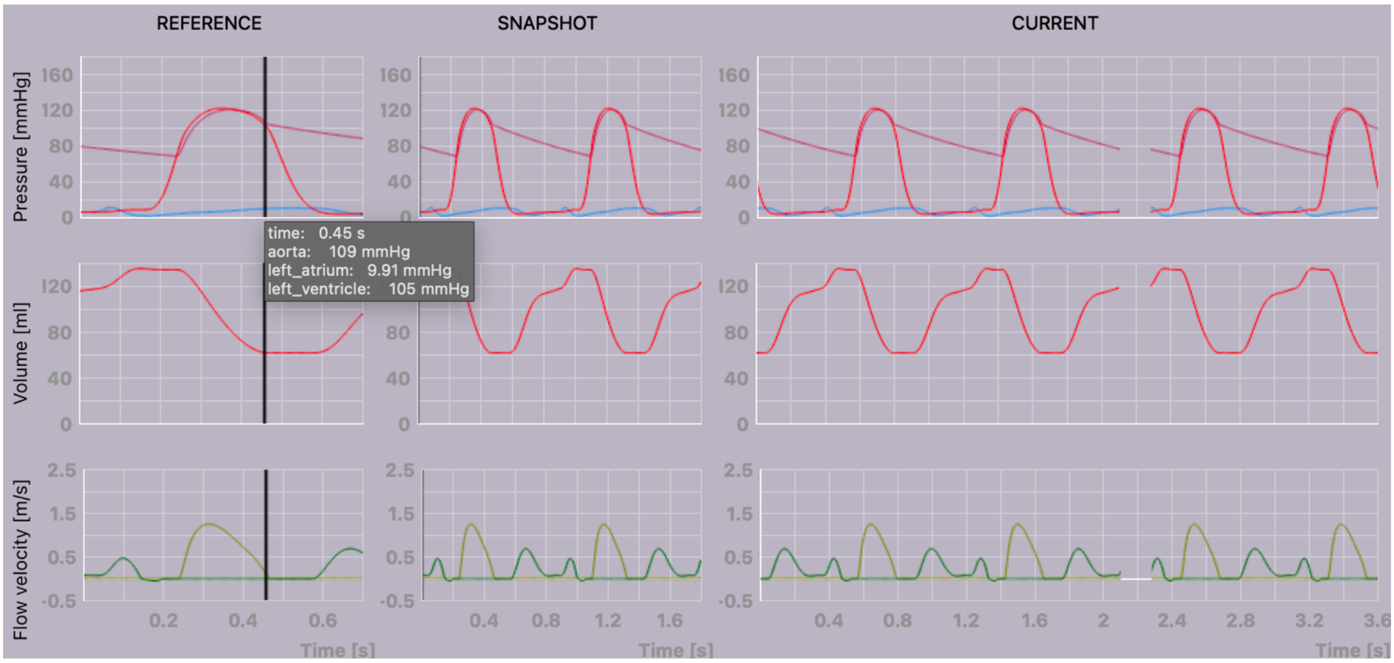
In Ventricular Systole, ventricular pressure increases as the ventricles contract. When the left ventricular pressure increases to a point where it becomes equal to the arterial pressure, the aortic valve opens. This instance is marked on the above plots.

After opening of aortic valve ventricular pressure continues to increase until it reaches a peak. During this period, blood is pumped from left ventricle into the aorta. Hence this phase is known as “Rapid Ejection Phase”. Arterial pressure increases as blood enters into the aorta and the blood is pumped throughout the body.

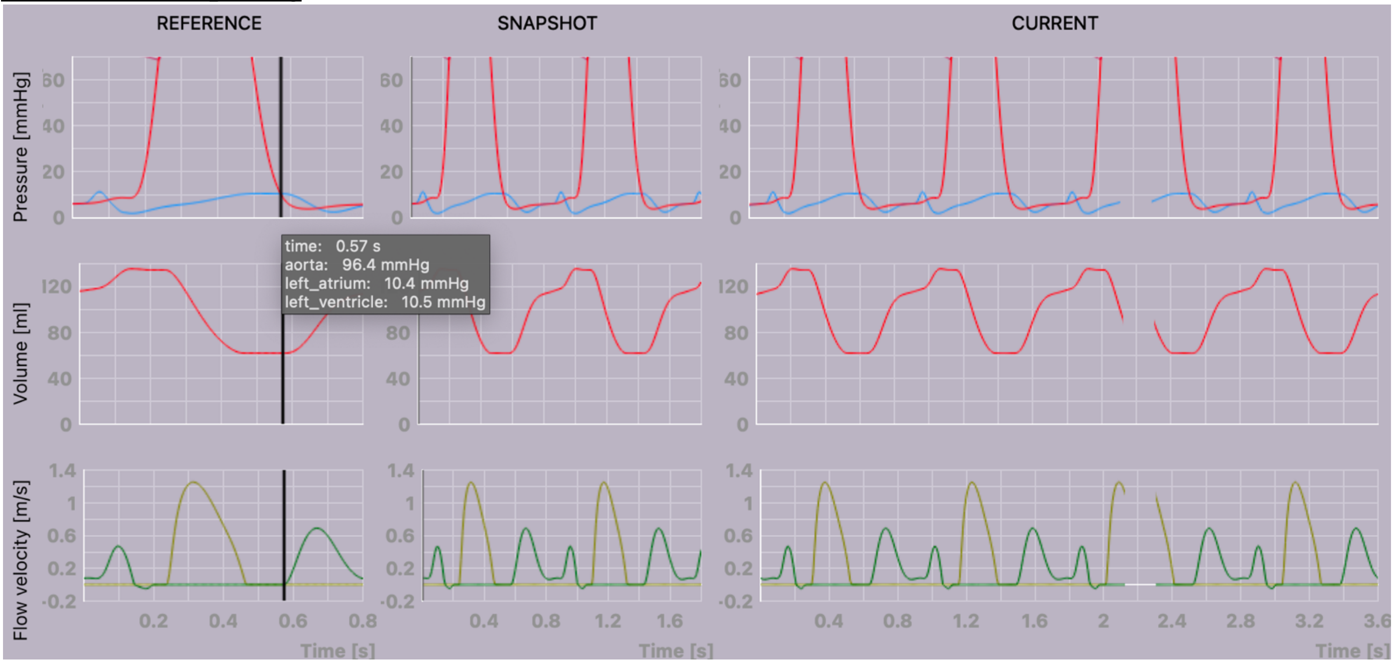
After reaching the peak, ventricular and arterial pressure declines as blood is leaving them.

Aortic Valve Closing

When the ventricular pressure falls below the arterial pressure, the aortic valve closes. This is known as the "Reduced Ejection Phase". After the closing of aortic valve, the left ventricular pressure declines further without changing the left ventricular volume as both Aortic and Mitral valves are closed.

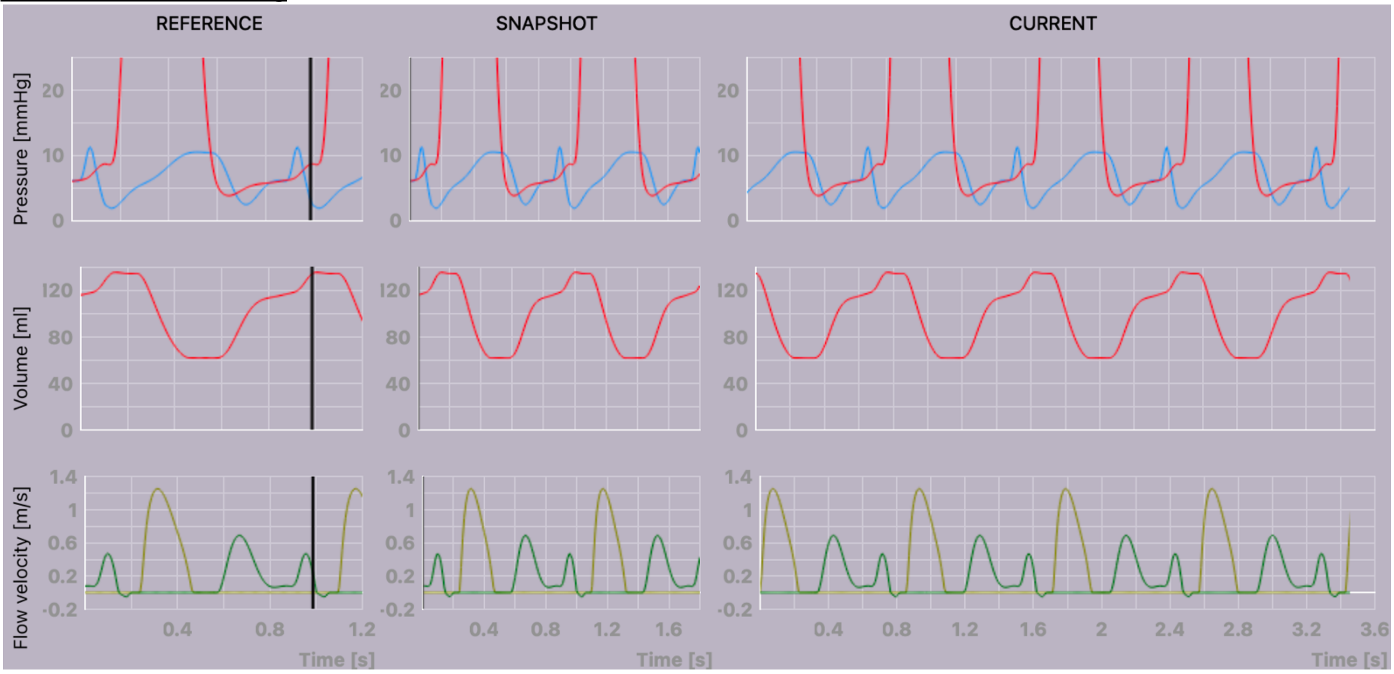


Mitral Valve Opening



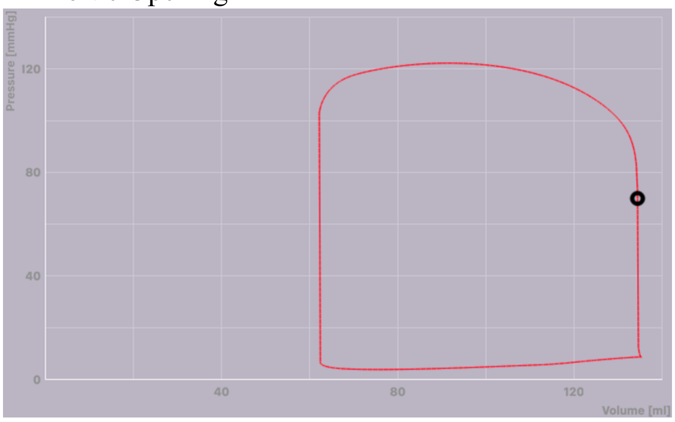
In Ventricular Diastole, when the ventricular volume remains constant and ventricular pressure declines as mentioned above, the mitral valve will open when the ventricular pressure falls below the atrial pressure. Then blood fills into the ventricles from the atria and the ventricular volume increases rapidly and hence the name "Rapid Filling Phase". This can be observed in the plot of Ventricular volume vs. Time (after the marker placement). When the ventricular volume increases, the ventricular pressure starts to build up and due to that, the rate of filling declines. Then due to the atrial contraction, a pulsive increase of atrial pressure occurs and additional blood will be filled into the ventricles increasing the ventricular pressure and causing the Mitral valve to close.

Mitral Valve Closing

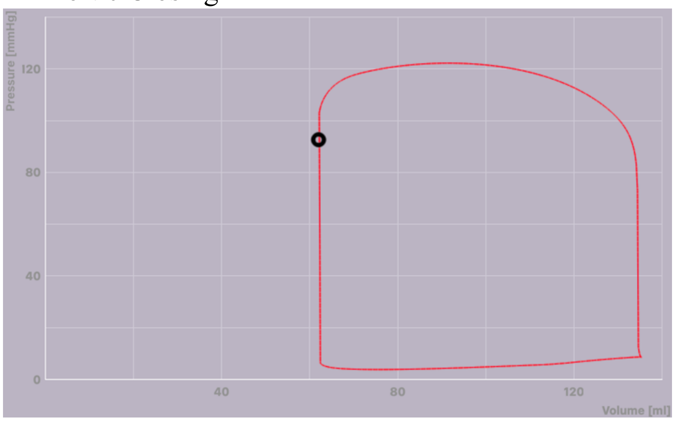


Pressure-Volume Relation of Left Ventricle

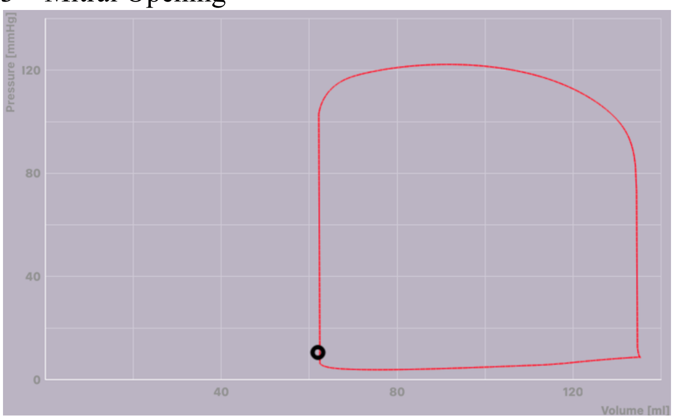
1 – Aortic Opening



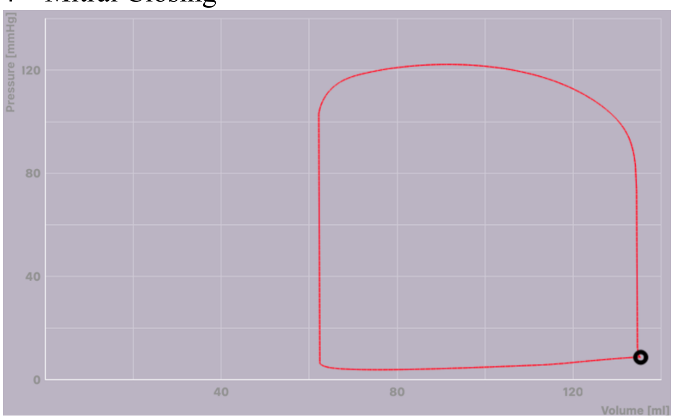
2 – Aortic Closing

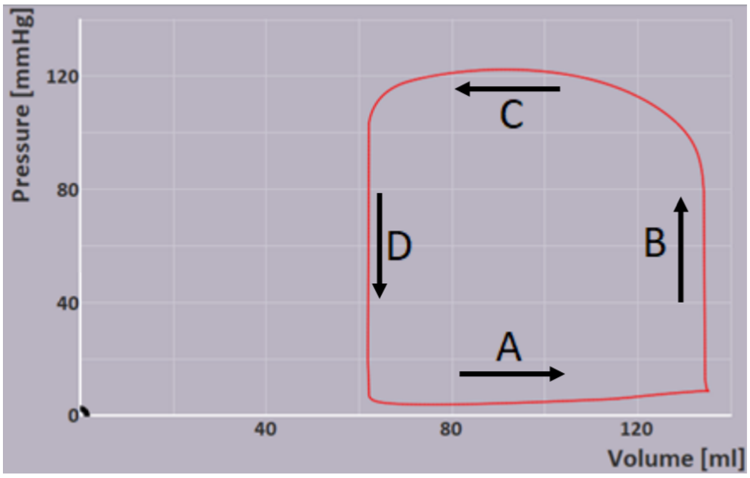


3 – Mitral Opening



4 – Mitral Closing





A – Filling Phase
B – Isovolumic Contraction
C – Ejection
D – Isovolumic Relaxation

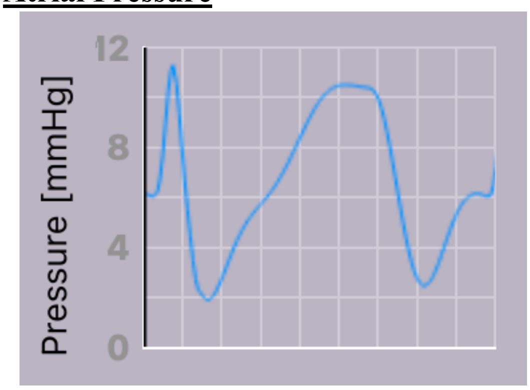
Flow Velocity Pattern in the Aortic valve

During the ejection phase (C), when the left ventricle contracts, the pressure in the left ventricle exceeds the pressure in the aorta, causing the aortic valve to open and blood is pumped out into the aorta. As blood is ejected into the aorta, the flow velocity increases rapidly, resulting in a sharp rise in flow velocity, represented by one hump on the flow velocity diagram during the ejection phase (C). The high flow velocity quickly reaches its peak, and as the left ventricle relaxes and begins the isovolumetric relaxation phase (D), the aortic valve closes to prevent backflow of blood into the ventricle.

Flow Velocity Pattern in the Mitral valve

During the isovolumetric contraction phase (B), the left ventricle contracts and builds up pressure while all valves (aortic and mitral) are closed. As the pressure in the left ventricle surpasses the pressure in the left atrium, the mitral valve opens, allowing blood to flow from the atrium into the ventricle.
Initially, blood initially flows passively from the atrium to the ventricle due to the pressure gradient, causing the first hump on the flow velocity diagram. However, the flow velocity decreases briefly as the ventricular pressure builds up upon filling the ventricle.
Subsequently, the atria contract, actively pushing more blood into the ventricle. This additional blood flow increases the flow velocity again, producing the second hump on the flow velocity diagram.

Atrial Pressure

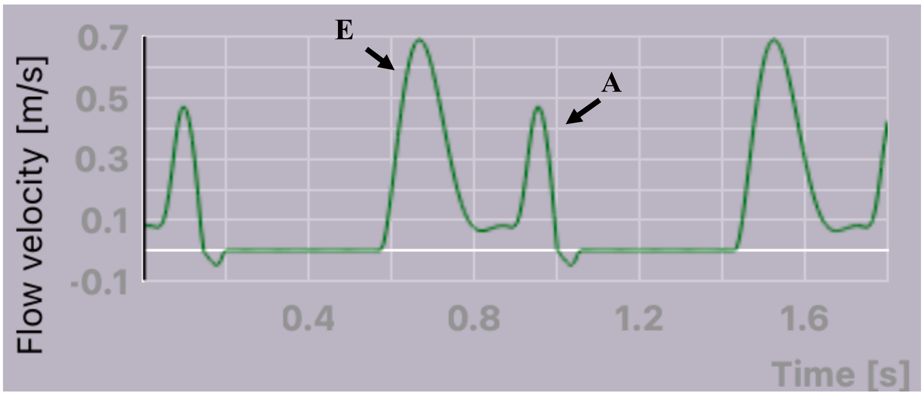


The two atrial pressure rises in a single cardiac cycle are related to the events that occur during atrial contraction (atrial systole) and atrial relaxation (atrial diastole).

Fast (Steep) Atrial Pressure Rise: The first atrial pressure rise occurs during atrial systole. During this phase, the atria contract forcefully, pushing blood into the ventricles to complete their filling. This rapid filling generates a sharp increase in atrial pressure, represented as the first pressure rise on the curve.
ECG Waveform: The P-wave of the ECG waveform which represents the electrical depolarization (contraction) of the atria, corresponds to this fast atrial pressure rise.

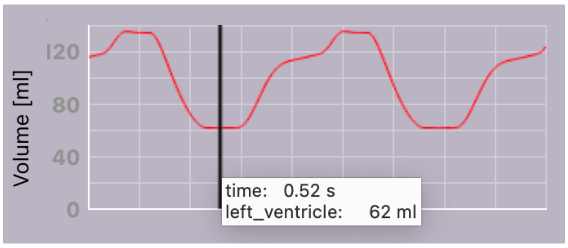
Slow Atrial Pressure Rise: The second atrial pressure rise occurs during atrial diastole. After the atrial contraction (atrial systole), the atria relax and enter the diastole phase. During this period, the atria passively receive blood from the veins. This passive filling causes a gradual and slower increase in atrial pressure, which is represented as the second pressure rise on the pressure-volume curve.
ECG Waveform: The T-wave of the ECG waveform which represents the repolarization (relaxation) of the ventricles, corresponds to this slow atrial pressure rise.

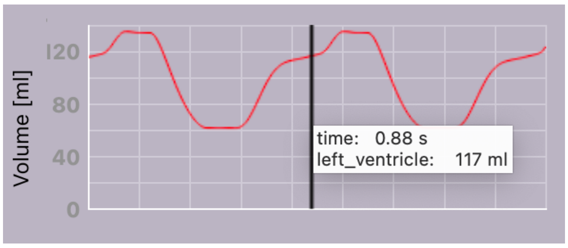
Diastolic Filling of the Left Ventricle

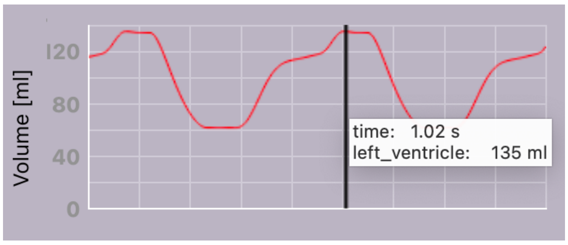


E – Early Passive Filling
A – Late Active Filling

$$\frac{E}{A} = \frac{0.691}{0.471} = 1.467$$







Left Ventricular volume before Passive filling = 62 ml

Left Ventricular volume after Passive filling = 117 ml

Left Ventricular volume after Active filling = 135 ml

∴ Left Ventricular filling due to Passive filling = 117 – 62 ml
= 55 ml

∴ Left Ventricular filling due to Active filling = 135 – 117 ml
= 18 ml

To convert V_{valve} into Q_{valve} we need to know the **Opening Cross Sectional Area** of the valve.

2. Aortic Valve Stenosis

Preload refers to the initial stretching of the heart's ventricular muscle fibers just before contraction and is determined by the volume of blood present in the ventricles at the end of diastole (the filling phase of the cardiac cycle).

Afterload is the resistance that the heart has to overcome during ventricular contraction to eject blood into the arteries and is determined by the pressure in the arteries that the heart must push against to pump blood during systole.

Simulation of Aortic Stenosis

As the aortic valve becomes more stenotic, the left ventricle has to work harder to overcome the obstruction and eject blood into the aorta during systole. This results in an increased afterload, causing a rise in left ventricular pressure during contraction. The left ventricular pressure-volume relationship becomes steeper, indicating that the left ventricle must generate higher pressures to maintain cardiac output.

Maximal Left Ventricular Pressure – 171 mmHg

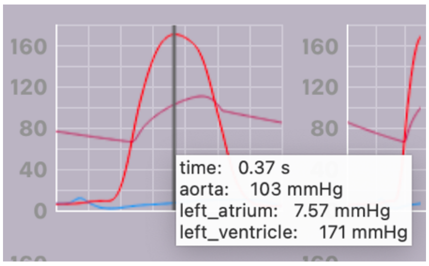
Effects of Aortic Valve Stenosis on Preload, Afterload of the left ventricle and Cardiac Output

Preload of the left ventricle: The stenotic aortic valve impedes the flow of blood from the left ventricle into the aorta during systole (contraction phase). As a result, some blood is retained in the left ventricle during diastole (filling phase) as it cannot be effectively ejected. This leads to an increase in end-diastolic volume, which is the volume of blood in the ventricle just before it contracts. Hence, the preload increases due to the stenotic valve.

Afterload of the left ventricle: Aortic valve stenosis increases the afterload on the left ventricle. Since the aortic valve is narrowed, the left ventricle has to work harder to pump blood through the narrowed valve and into the aorta. This elevated resistance in the aorta increases the pressure that the left ventricle needs to generate during systole to overcome the obstruction and eject blood into the aorta.

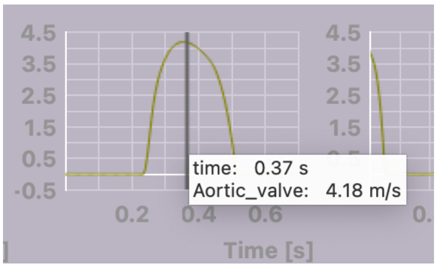
Cardiac output: Cardiac output is the amount of blood pumped by the heart per minute and is calculated by multiplying the heart rate by the stroke volume (the volume of blood ejected by the left ventricle with each heartbeat).
in the early stages of aortic valve stenosis, the slight increase in preload may help maintain stroke volume and cardiac output. However, as the condition progresses and the ventricular walls thicken, the left ventricle may become less compliant, leading to reduced diastolic filling, decreased preload, and ultimately a decline in cardiac output.

Determining Aortic Blood Pressure at the moment of maximal left ventricular pressure



Left Ventricular Pressure – 171 mmHg
Aortic Pressure – 103 mmHg

Pressure drop across stenotic aortic valve = 171 – 103 mmHg
= 68 mmHg

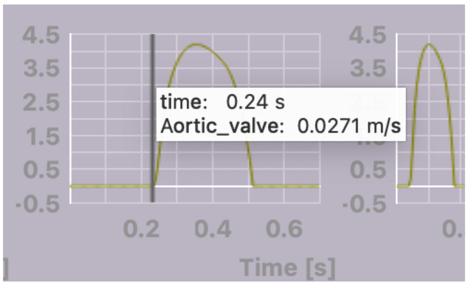


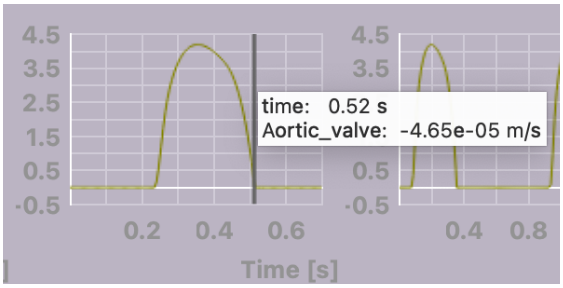
Flow velocity through Aortic valve at maximal pressure drop,

$$v = 4.18\, ms^{-1}$$
$$\Delta P = 4v^2$$
$$\Delta P = 4(4.18)^2$$
$$\Delta P = 69.89\, mmHg$$

This is closer to the pressure drop calculated directly by obtaining the two pressures.

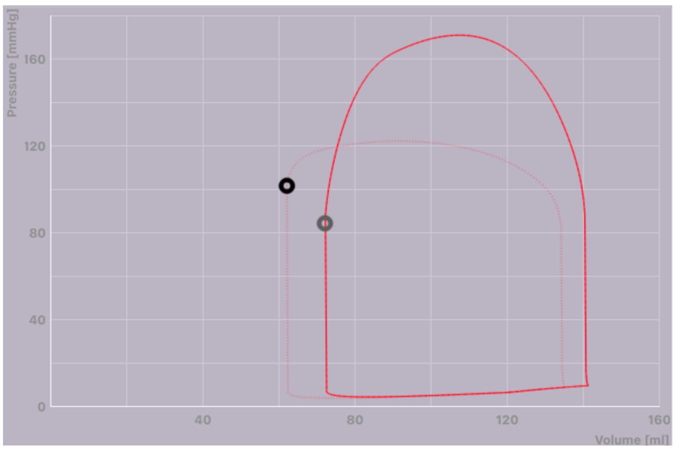
Duration of Ejection through Aortic Valve





Duration = 0.52 – 0.24 s
= 0.28 s

Increase in External Pump Work generated by the Left Ventricle due to 80% AS



Area enclosed by Pressure-Volume curve,

Before 80% AS ≈ 20.75 squares

After 80% AS ≈ 24.5 squares

Increase ≈ 3.75 squares
≈ 1500 mmHgml

In response to chronic increased pump work caused by 80% aortic stenosis, the left ventricle adapts by thickening its muscle fibers (left ventricular hypertrophy). This helps generate higher pressure (leading to increases afterload) to overcome the narrowed aortic valve and maintain sufficient blood flow. However, prolonged hypertrophy can lead to weakening of cardiac muscles over time leading to a risk of heart failure.