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

Modelling and Analysis of Physiological Systems

Analysis of cardiac physiology

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Contents

1 Normal Sinus Rhythm

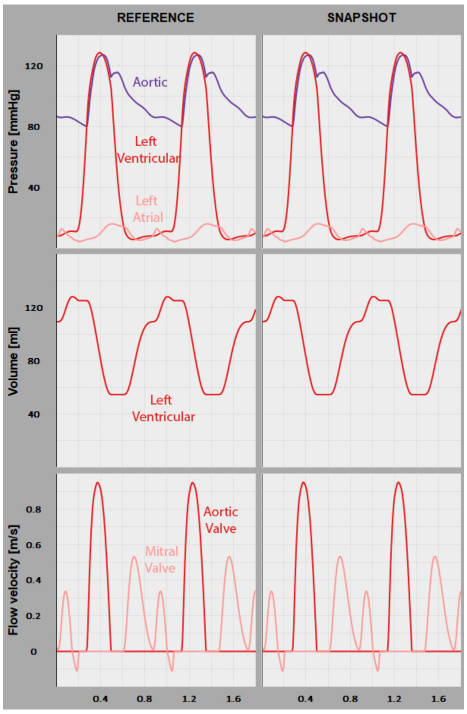

Figure 1: Legend

CircAdapt Simulator #1 used for 1st this section and switched to #2 as it does not allow to change AS.

a.

Aortic Valve Opening

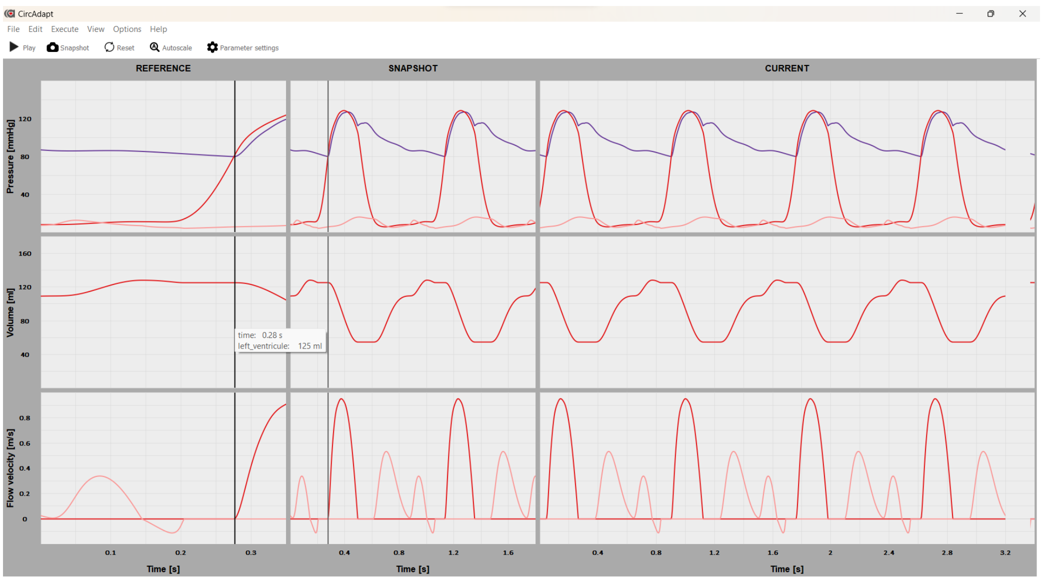

Figure 2: Aortic Valve Opening

Here during ventricular Systole, pressure increases in the ventricle as it contracts. when it's equal; to atrial pressure, the aortic valve opens. Ventricular pressure continues to increase even after it reaches its peak. In the period in which the ventricle pumps blood into the artery through the body. Hence, arterial pressure begins to increase as blood enters the aorta. After reaching the peak both pressures reduces as the blood flows out.

Aortic Valve Closing

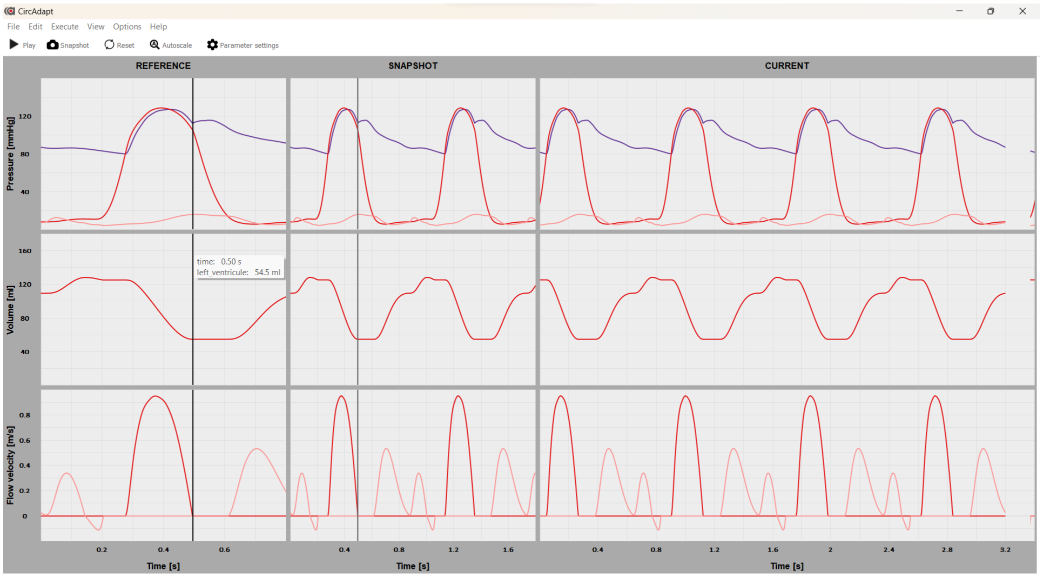

Figure 3: Aortic Valve Closing

As the ventricular pressure drops below the arterial, the aortic valve closes. Then the left ventricular pressure continues to decline without changing the volume since both valves are closed.

b.

Mitral Valve Opening

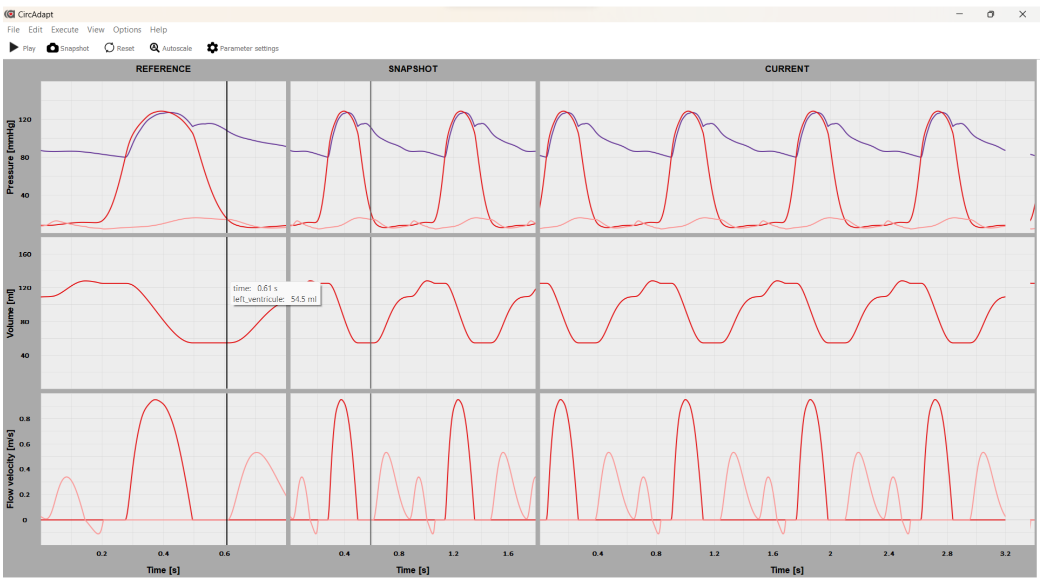

Figure 4: Mitral Valve Opening

Here during Ventricular diastole, the volume stays the same, and ventricular pressure declines as said earlier. when the pressure falls below the atrial pressure mitral valve opens. Blood fills into ventricles from atria and ventricular volume increases rapidly. As this continues ventricular pressure starts to build up reducing the volume filling rate. Then atrial contraction happens suddenly increasing the blood flow causing the mitral valve to close.

Mitral Valve Closing

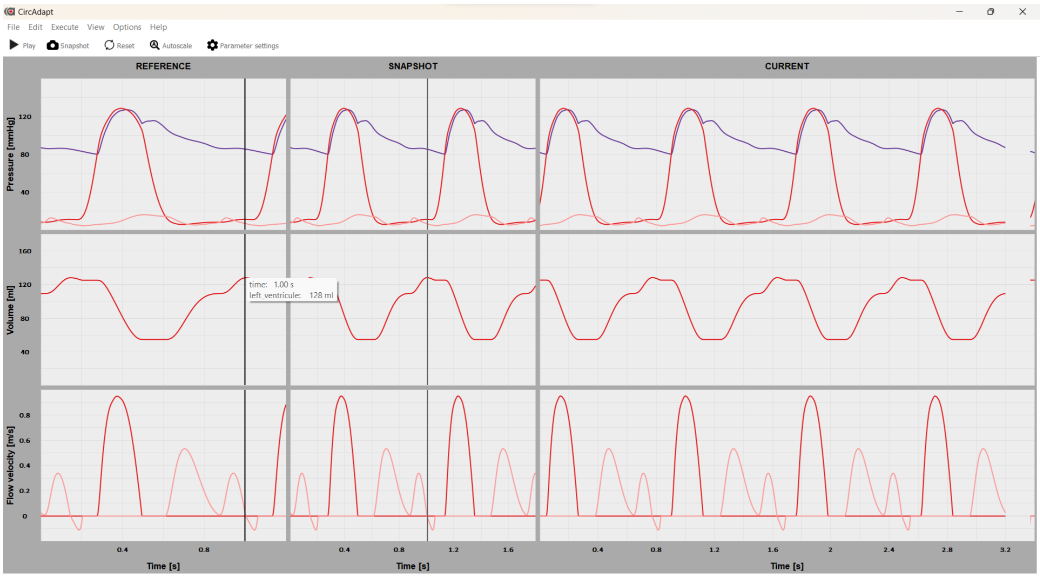

Figure 5: Mitral Valve Closing

As the ventricular pressure drops below the arterial, the aortic valve closes. Then the left ventricular pressure continues to decline without changing the volume since both valves are closed.

c.

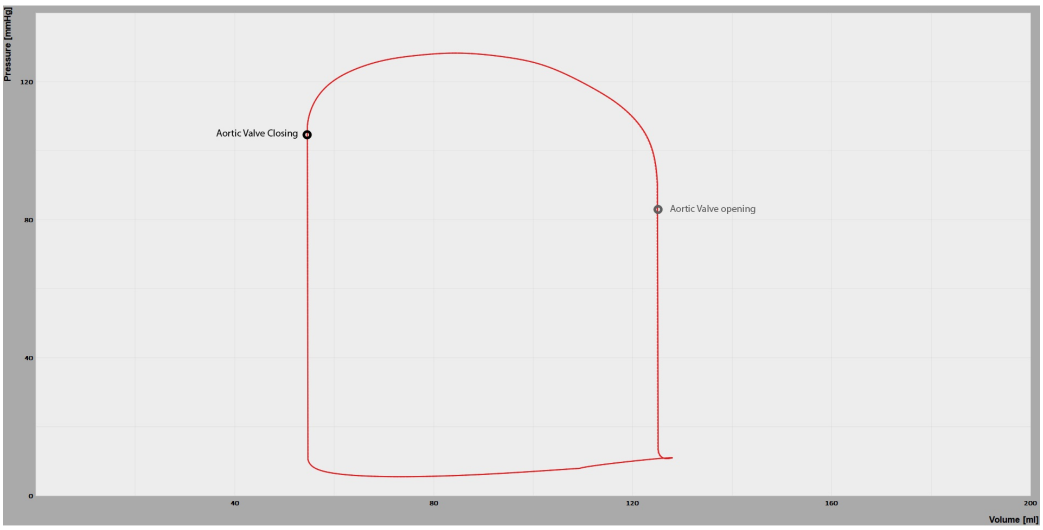

Figure 6: Pressure-Volume Relation of Left ventricle - 1

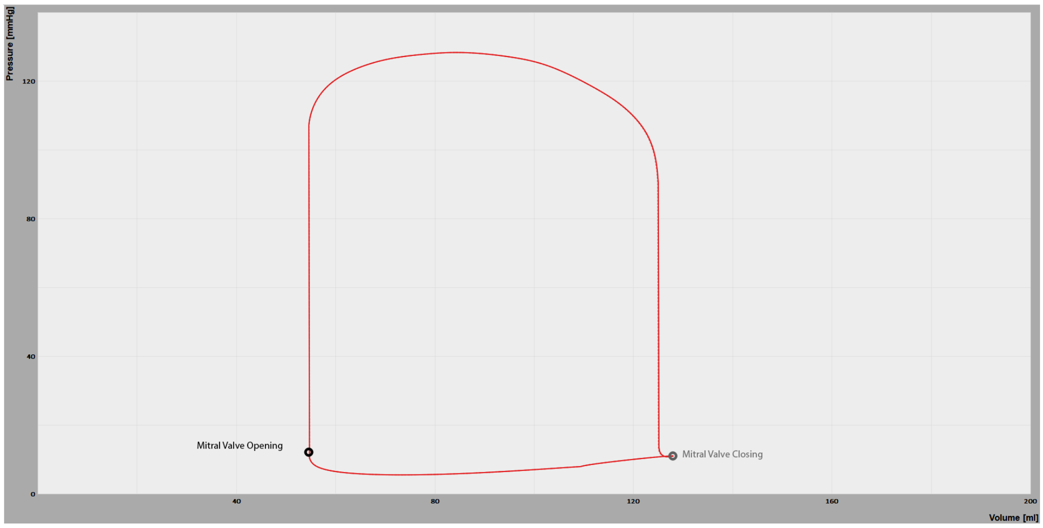

Figure 7: Pressure-Volume Relation of Left ventricle - 2

d.

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

e.

When the left atrial pressure becomes greater than the left ventricular pressure, the mitral valve passively opens, allowing blood to flow from the atrium into the ventricle. The initial flow of blood from the atrium into the ventricle results in the first hump in the flow velocity pattern.
However, after the initial rapid filling, there is a brief deceleration phase when the blood flow slows down before reaching the ventricular maximum. This deceleration is due to the interaction of the inflowing blood with the walls of the ventricle, as well as the elasticity of the ventricular tissue. The slowing of flow during this deceleration phase produces the second hump in the flow velocity pattern in the mitral valve.
Hence the flow velocity pattern in the mitral valve has two humps due to the passive filling process from the atrium to the ventricle and the deceleration phase, While the aortic valve flow velocity pattern has one hump because of the rapid ejection of blood from the ventricle into the aorta.

f.

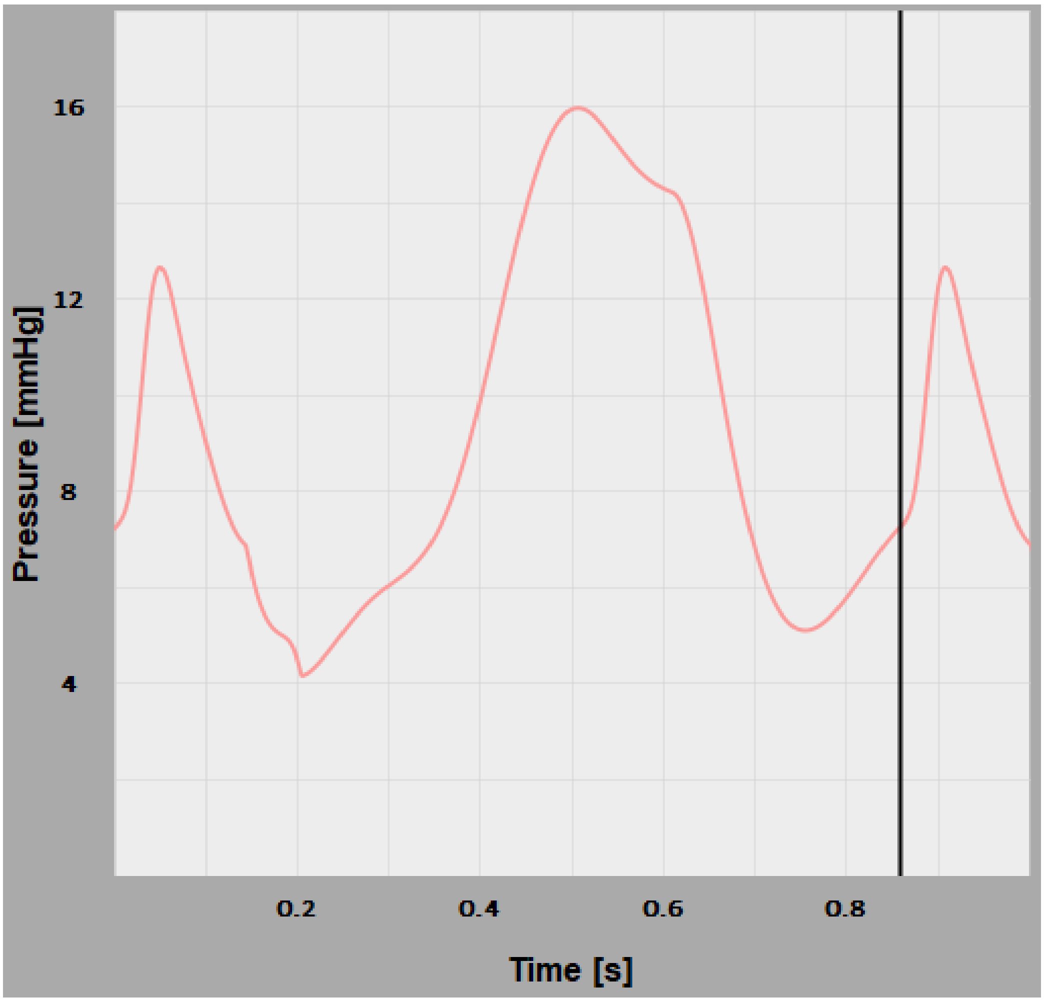

Figure 8: Atrial pressure variation

The first atrial pressure rise(Steep) occurs during the initial phase of ventricular filling, known as the atrial contraction or atrial systole. During this phase, the atria contract to push the remaining blood into the ventricles before ventricular contraction begins. The contraction of the atria causes a rapid increase in atrial pressure, representing the first atrial pressure rise. The corresponding ECG waveform for the first atrial pressure rise is the P-wave.
The second atrial pressure rise(Slow) occurs during the late phase of ventricular filling, known as the atrial kick or atrial systole. This occurs just before the ventricles contract (ventricular systole). During the atrial kick, the atria contract again to provide an additional force that further fills the ventricles with blood. T-wave of the ECG waveform correspond to this part.

g.

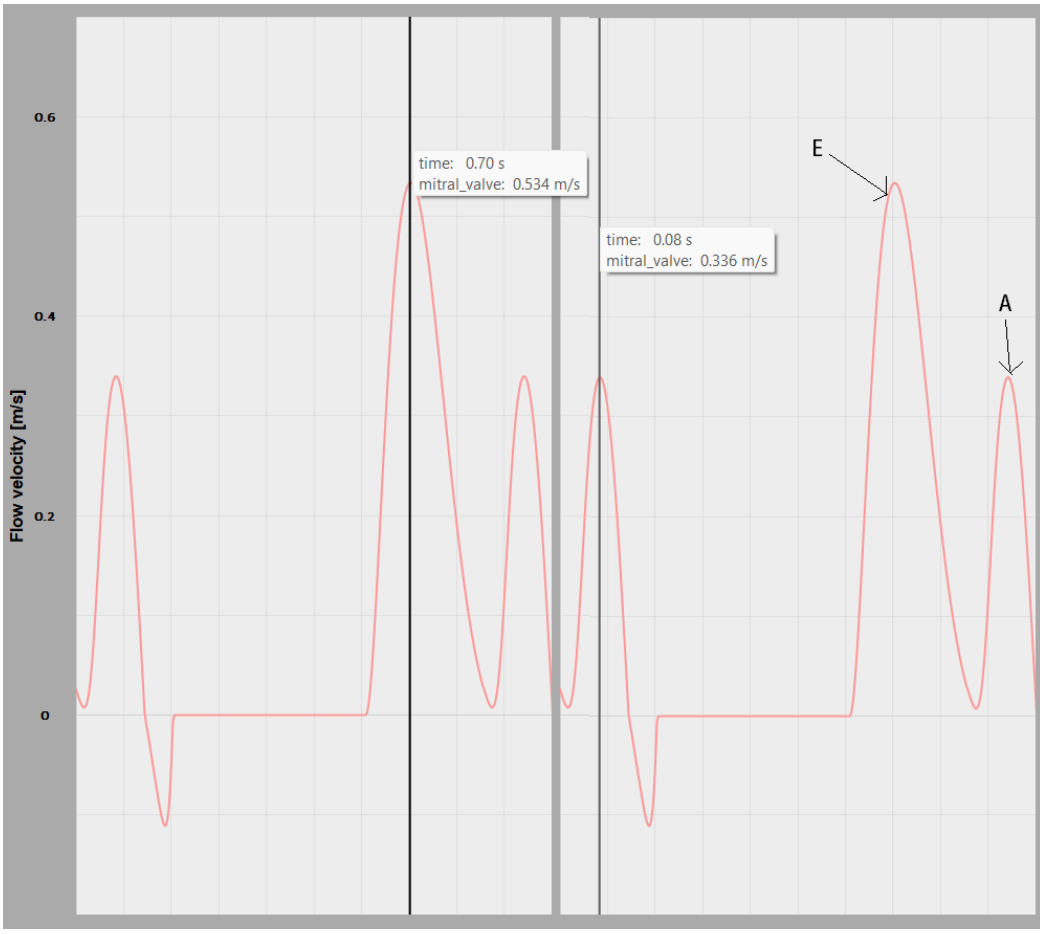

Figure 9: Atrial flow

E: Early Passive filling
A: Late Active filling

h.

$$\frac{E}{A} = \frac{0.534}{0.336} = 1.589$$

i.

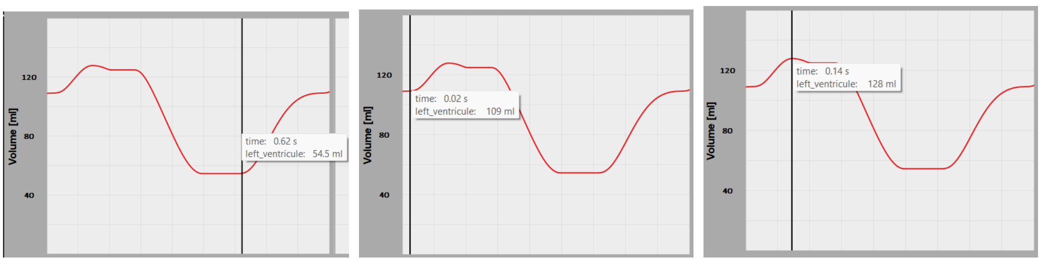

Figure 10: Volume

Left Ventricular volume before Passive filling	= 54.5 ml
Left Ventricular volume after Passive filling	= 109 ml
Left Ventricular volume after Active filling	= 128 ml
Left Ventricular filling due to Passive filling	= 109 – 54.5 ml
	= 54.5 ml
Left Ventricular filling due to Active filling	= 128 – 109 ml
	= 19 ml

j.

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

2 Aortic Valve Stenosis

a.

Preload is the initial volume of ventricle before contraction.
Afterload is the resistance that heart has to overcome when ejecting blood into arteries.

b.

As the severity of aortic stenosis (AS) worsens, the left ventricle faces greater challenges in propelling blood through the constricted aortic valve. This leads to elevated left ventricular pressure during systole. Moreover, to compensate for the obstruction and maintain sufficient cardiac output, blood flow accelerates through the narrowed valve, resulting in increased flow velocity. The pressure-volume loop, which represents the left ventricular pressure and volume over one cardiac cycle, shifts to the right and upwards with increasing AS severity. This indicates a larger area under the curve, signifying heightened left ventricular work and greater myocardial energy expenditure needed to overcome the stenosis and efficiently eject blood.
Maximum Left Ventricular pressure = 171mmHg.

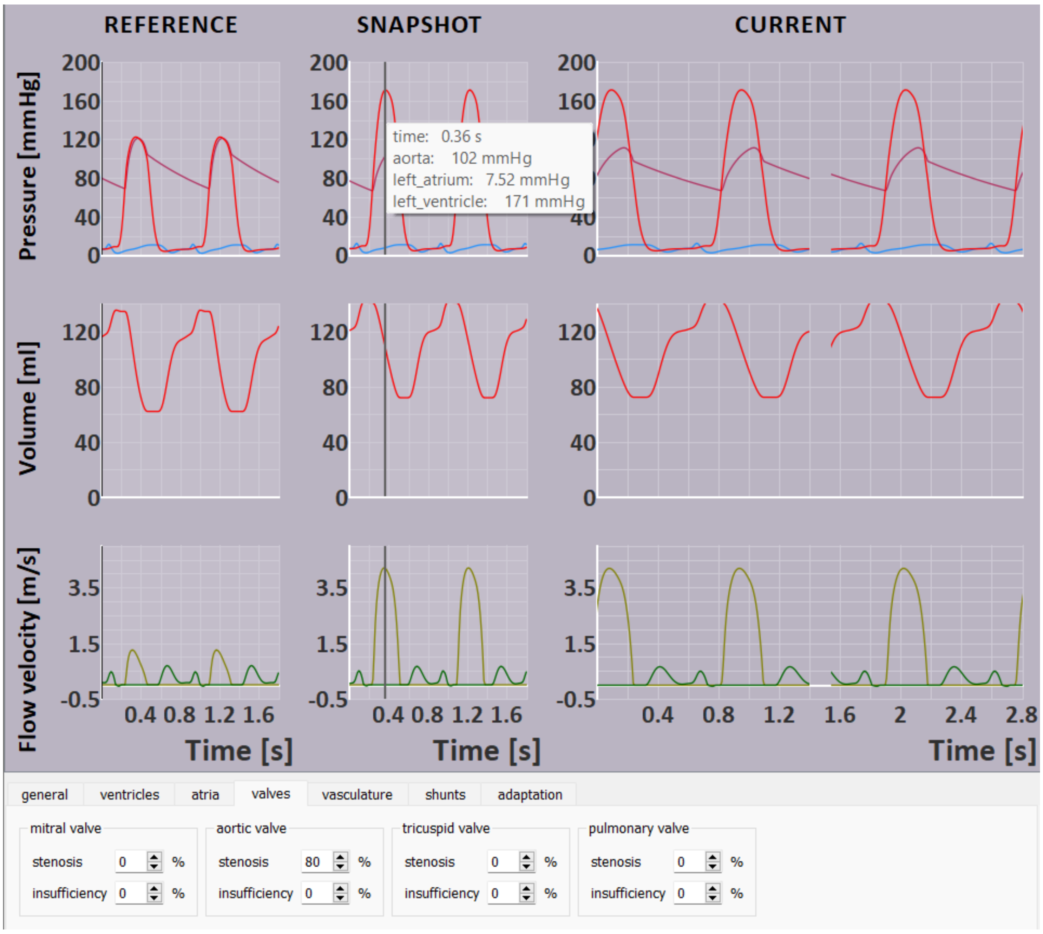

Figure 11: Aortic Valve Stenosis

c.

Aortic Valve Stenosis (AS) leads to a small increase in the volume of blood in the left ventricle before contraction (approximately 7ml for 80% stenosis). This occurs because the narrowed valve hinders efficient blood ejection from the left ventricle into the aorta, causing a backlog of blood in the left ventricle during diastole.

The AS narrows the opening area of the aorta, which directly increases resistance to blood flow from the ventricles to the aorta. This elevated afterload makes it more challenging for the left ventricle to pump blood out of the heart during systole.

Although the slight increase in preload doesn't significantly affect stroke volume, the cardiac output remains relatively unchanged in mild AS. This is due to compensatory mechanisms that help the heart contract more forcefully to maintain adequate blood flow.

However, over time, the increased afterload can lead to ventricular hypertrophy, thickening the ventricular walls. This can reduce ventricular compliance, hindering the heart's ability to fill with blood during diastole and potentially impacting cardiac function.

d.

Aortic blood pressure at the moment of maximal left ventricular pressure	= 102 mmHg
Maximal left ventricular pressure	= 171 mmHg
Pressure drop across stenotic valve	= 171-102
	= 69 mmHg

e.

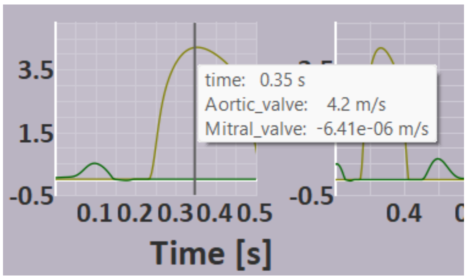

Figure 12: Aortic Valve Stenosis

$$
\begin{aligned}
\Delta p &\approx 4v^2 \\
\Delta p &\approx 4 * 4.2^2 \\
&\approx 70.56 mmHg
\end{aligned}
$$

Very similar to earlier obtained value.

f.

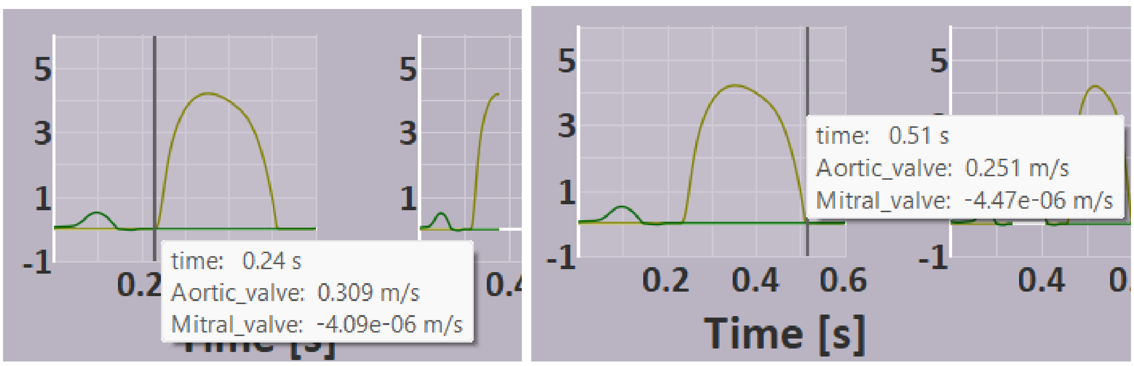

Figure 13: Ejection period

$$
\begin{aligned}
\text{Ejection period} &= 0.51\text{s} - 0.24\text{s} \\
&= 0.27\text{s}
\end{aligned}
$$

g.

work generated by the left ventricle	= 4*20*20
	= 1600 mmHgml

h.

Due to the chronic strain caused by 80% aortic stenosis, the left ventricle undergoes adaptive changes by thickening its muscle fibers, resulting in left ventricular hypertrophy. This hypertrophy enables the heart to generate higher pressure, effectively countering the resistance caused by the narrowed aortic valve and ensuring adequate blood flow. However, prolonged hypertrophy can weaken the cardiac muscles over time, increasing the risk of heart failure.

References

1. Youtube: The Bernoulli Equation - Medical Applications (Fluid Mechanics - Lesson 8)
2. Manual : CircAdapt Simulator #2