Analysis of Cardiac Physiology

Department of Electronic and Telecommunication

University of Moratuwa

BM-2101 – Modelling and Analysis of Physiological Systems

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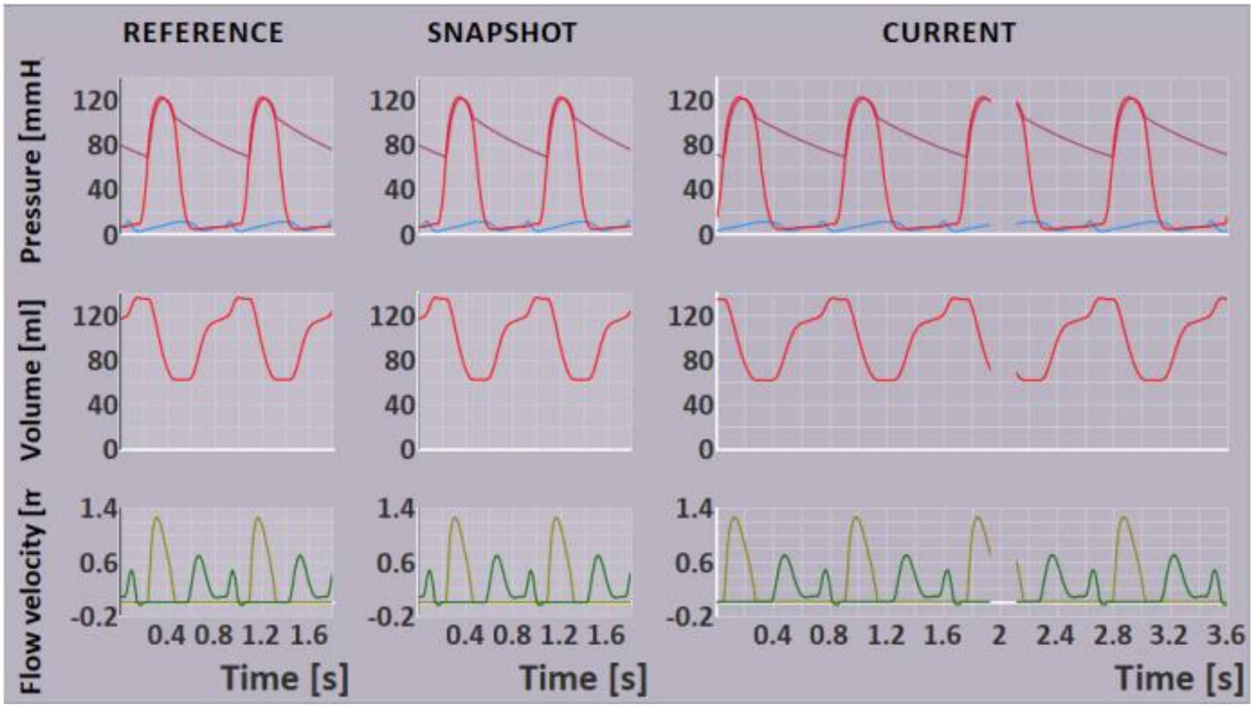
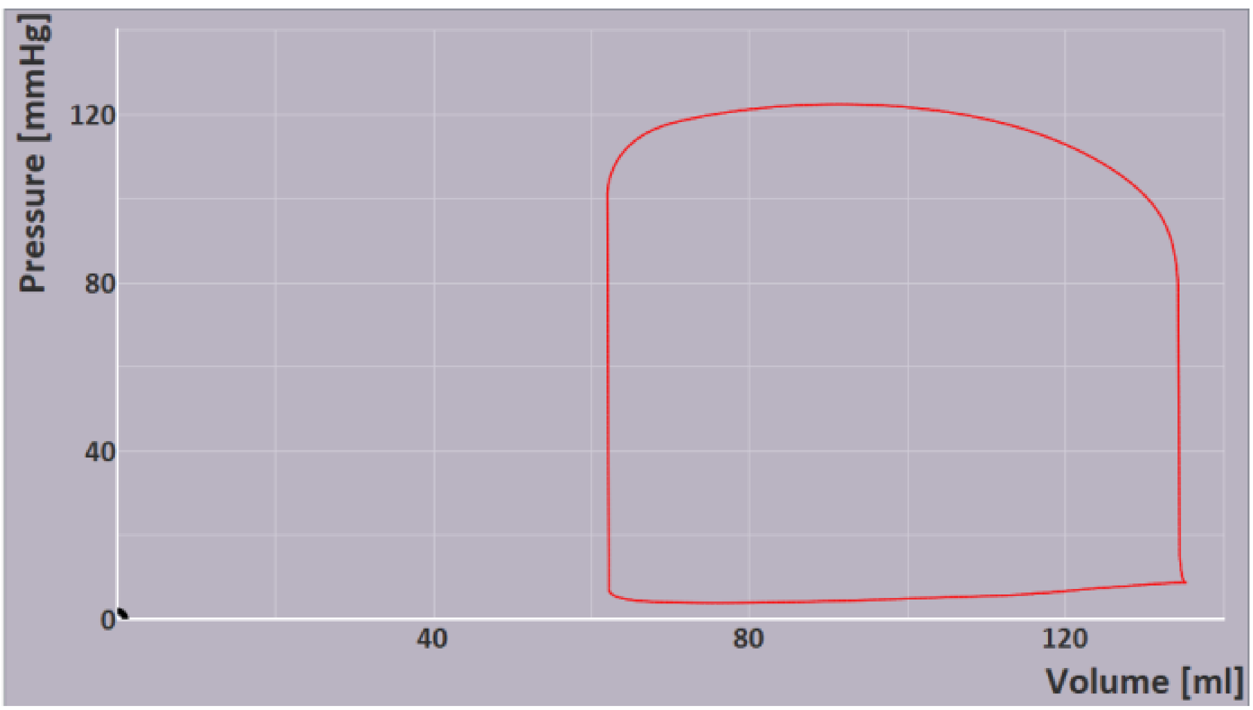
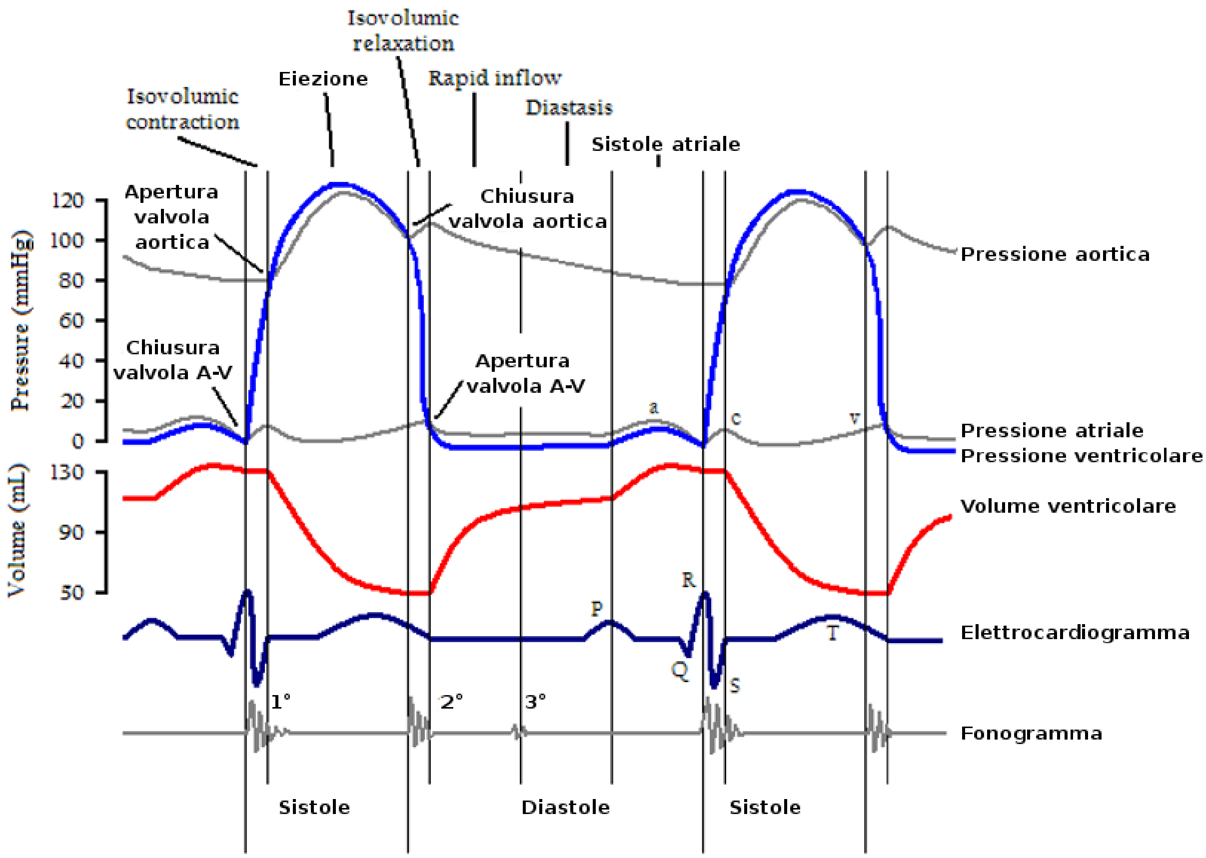
1. Normal sinus rhythm

Simulation results of circadapt software

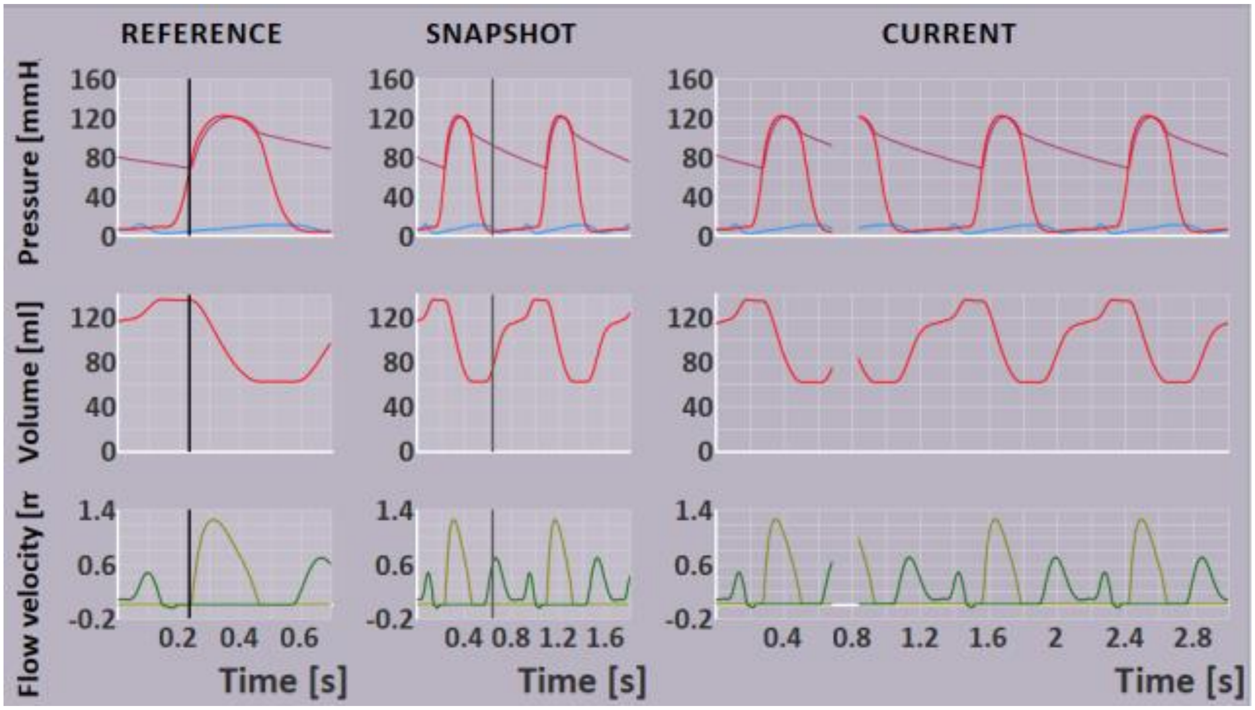




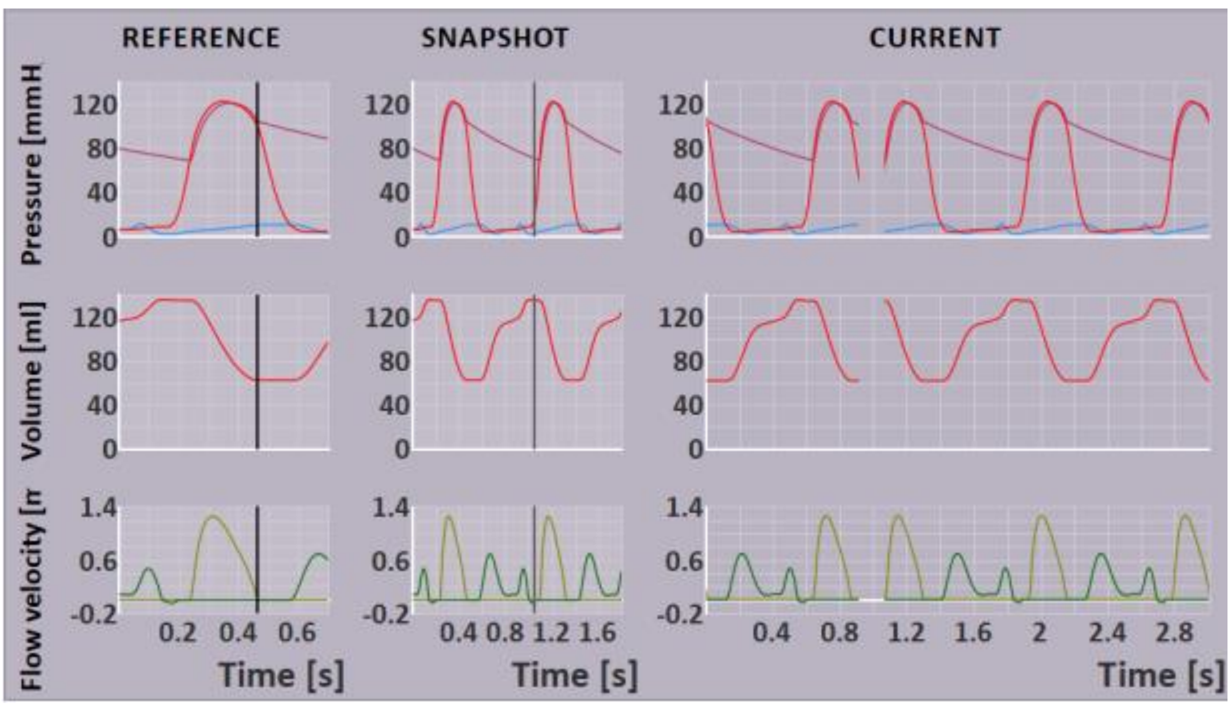
Wiggers diagram



a. Check left ventricular and aortic blood pressure signals in the REFERENCE column and determine when the aortic valve is open and when the aortic valve is closed. Also check whether this corresponds with the change of left ventricular volume. Click on the appropriate point of time on the REFERENCE column to place a vertical line at that point to mark the opening and closing points of the aortic valve.



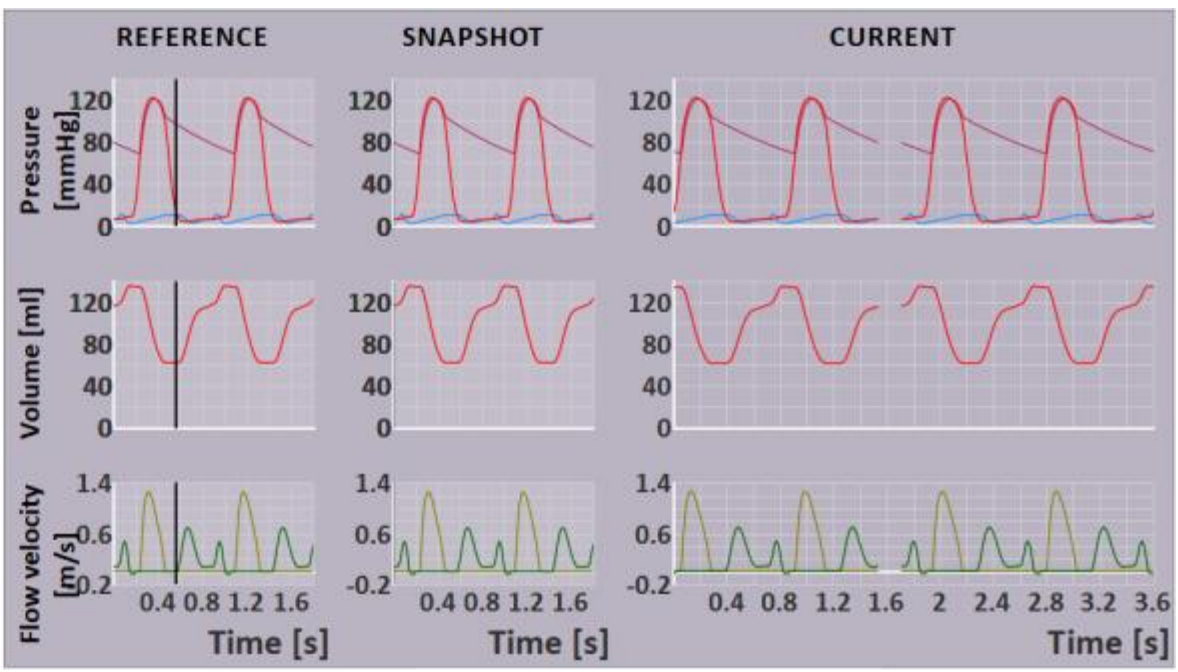
Opening of aortic valve



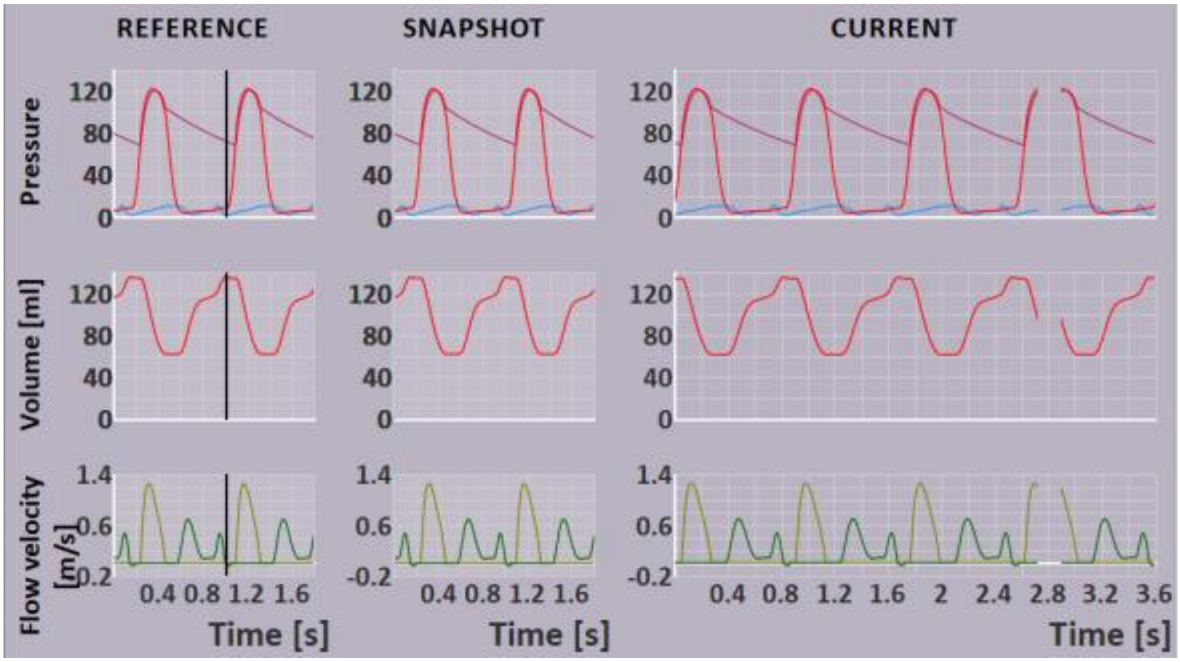
Closing of aortic valve

At the start of systole, the ventricles undergo contraction, resulting in a rapid increase in pressure within them. This phase, called isovolumetric contraction, is characterized by the closure of both the mitral and aortic valves, preventing any blood from entering or leaving the ventricles. As the ventricular pressure exceeds the aortic pressure, the aortic valve opens, initiating the rapid ejection of blood from the ventricles and causing a quick decrease in ventricular volume. Following this, the ventricular pressure gradually decreases. Once the ventricular pressure becomes lower than the aortic pressure, the aortic valve closes, marking the beginning of the isovolumic relaxation phase. During this phase, the ventricular pressure continues to decrease, but the volume of the ventricles remains constant as both the mitral and aortic valves remain closed.

b. Check left ventricular and left atrial blood pressure signals in the REFERENCE state and determine when the mitral valve is open and when the mitral valve is closed. Also check whether this corresponds with the change of left ventricular volume. Click on the appropriate point of time on the REFERENCE column to place a vertical line at that point to mark the opening and closing points of the mitral valve.



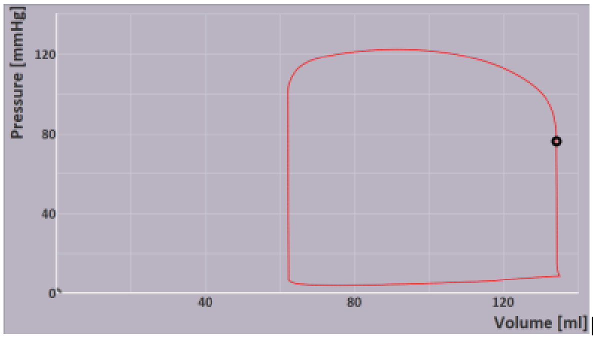
Opening of mitral valve



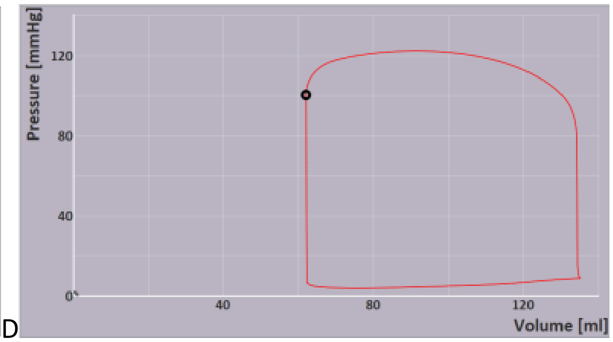
Closing of mitral valve

At the beginning of diastole, the ventricular pressure declines, but the volume of the ventricles remains unchanged due to the closure of both the mitral and aortic valves, resulting in isovolumetric relaxation. However, when the ventricular pressure falls below the pressure in the atria during diastole, the mitral valve opens. This allows the ventricles to fill, causing a rapid increase in ventricular volume during the Rapid Onflow phase. As the ventricular volume rises, the ventricular pressure gradually increases, causing the filling rate to slow down, almost reaching a stop (Reduced Filling / Diastasis). Following this, during atrial contraction, the pressure in the atria rises, resulting in more blood being pumped into the ventricles during the atrial systole phase. This causes an increase in ventricular pressure that exceeds the atrial pressure, leading to the closure of the mitral valve once again. Throughout this period, the ventricular volume remains constant as both valves remain closed.

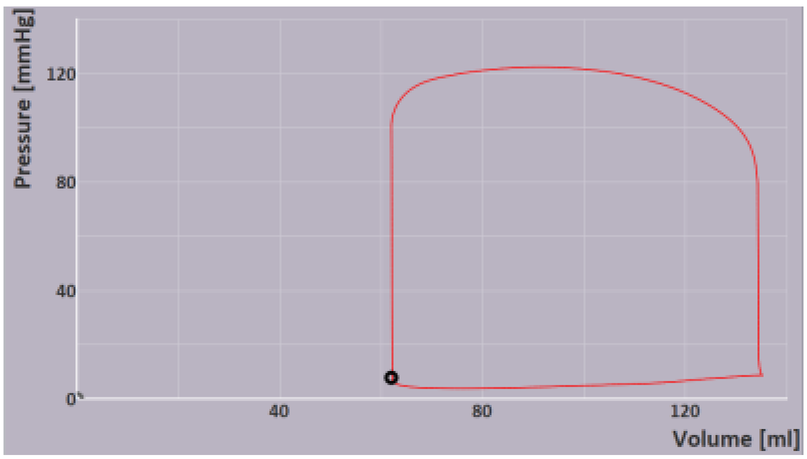
c. Identify which points of the pressure-volume relation correspond to the closing and opening of the aortic and mitral valves and place the numbers 1, 2, 3 and 4 in the right place on the figure below. (1- aortic opening, 2-aortic closing, 3-mitral opening, 4-mitral closing)



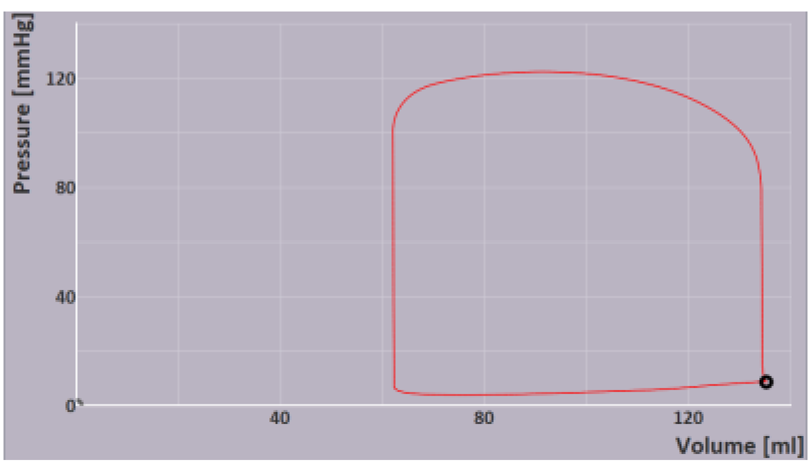
D



Opening of aortic valve *closing of Aortic valve*



Opening of mitral valve



Closing of mitral valve

d. A - Filling

B - Isovolumic contraction

C- Ejection

D- Isovolumic relaxation

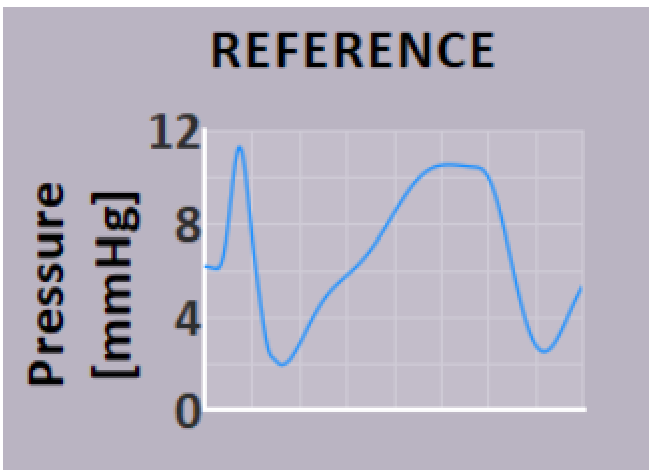
e. Explain why the flow velocity pattern in the aortic valve one hump and the pattern in the mitral valve has two.

The flow velocity patterns in the aortic and mitral valves show distinct shapes because their opening mechanisms and the pressure gradients involved are different.

Aortic Valve Flow Velocity Pattern: The aortic valve opens only towards the aorta when the left ventricular pressure exceeds the aortic pressure, allowing rapid ejection of blood from the ventricles during systole. Conversely, during diastole, when ventricular pressure falls below aortic pressure, the aortic valve closes, preventing the backflow of blood from the aorta into the ventricles. This opening and closing of the aortic valve create a flow velocity pattern with a single hump in the flow curve. In essence, the aortic valve's behavior during systole and diastole leads to distinct flow patterns in the blood flow.

Mitral Valve Flow Velocity Pattern: The mitral valve opens passively when the left atrial pressure exceeds the left ventricular pressure during diastole. This causes a rapid flow of blood from the left atrium into the left ventricle, resulting in the first hump in the flow velocity pattern. However, the flow velocity decreases afterward as the ventricles fill with blood and their pressure increases, leading to a reduced filling rate or "diastasis." The second hump in the flow velocity pattern occurs during atrial systole when the atrial wall contracts, increasing atrial pressure and pumping more blood into the ventricles through the mitral valve.

f.

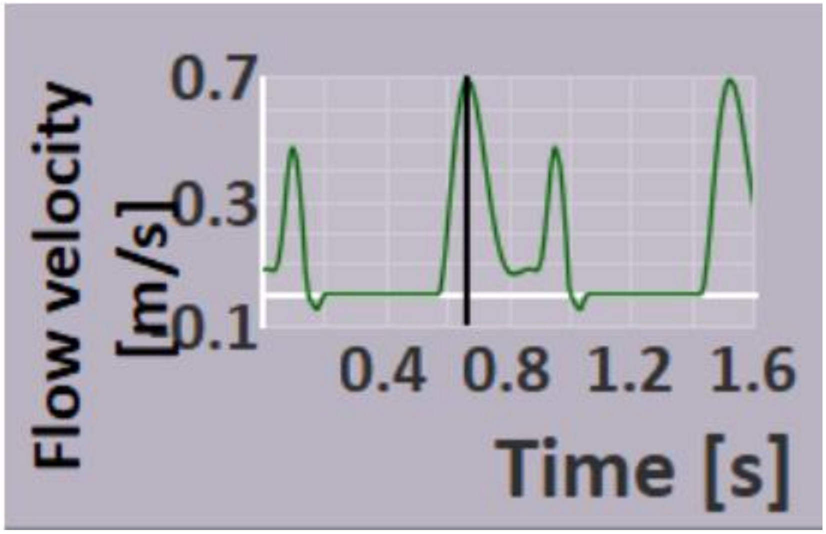


Fast (Steep) Increase in Atrial Pressure: The mitral valve opens passively when the left atrial pressure exceeds the left ventricular pressure during diastole. This causes a rapid flow of blood from the left atrium into the left ventricle, resulting in the first hump in the flow velocity pattern. However, the flow velocity decreases afterward as the ventricles fill with blood and their pressure increases, leading to a reduced filling rate or "diastasis." The second hump in the flow velocity pattern occurs during atrial systole when the atrial wall contracts, increasing atrial pressure and pumping more blood into the ventricles through the mitral valve.

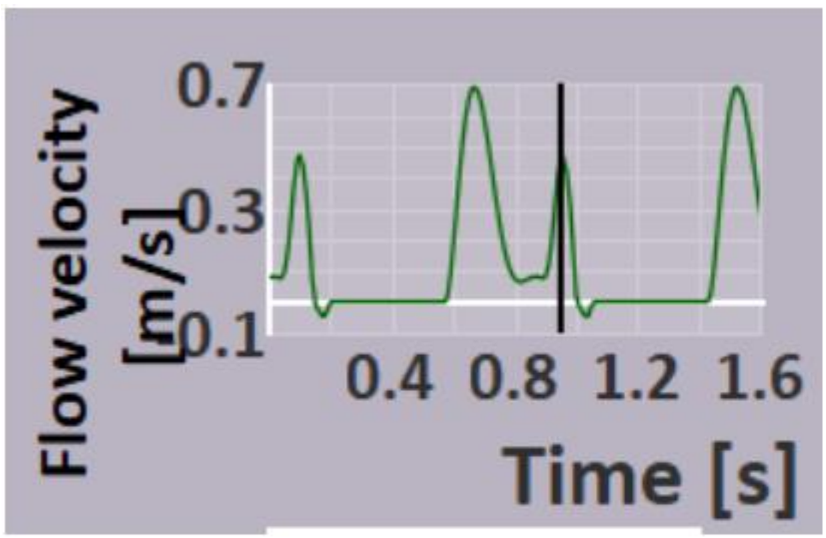
Slow Increase in Atrial Pressure: The second, slower increase in atrial pressure occurs during ventricular systole, specifically in the isovolumic contraction phase. As the ventricles contract to open the aortic valve and pump blood into the aorta, the left ventricular pressure rises. This increase in ventricular pressure causes the mitral valve to close, preventing blood from flowing back into the atrium. As a result, there is a gradual increase in atrial pressure during isovolumic contraction, as the atria become isolated from the ventricles. This slow rise in atrial pressure is evident on the atrial pressure waveform during the isovolumic contraction phase.

ECG Waveform Corresponding to the Sharp Rise in Pressure: The sharp rise in atrial pressure, linked to atrial contraction (atrial systole), corresponds to the P-wave on the electrocardiogram (ECG). The P-wave represents atrial depolarization, which happens before atrial contraction. Hence, the rapid increase in atrial pressure occurs simultaneously with the P-wave on the ECG.

g.



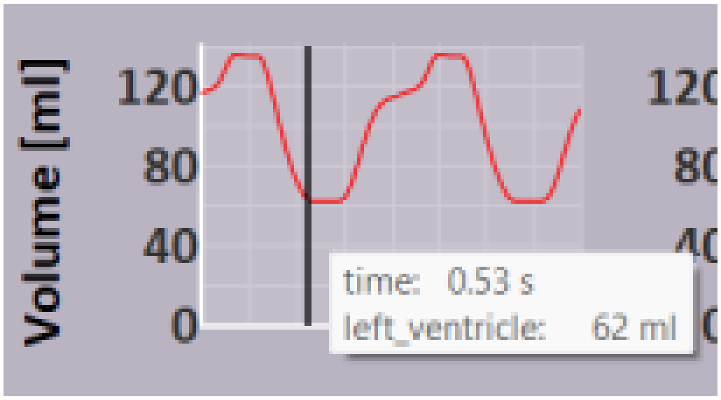
E – 0.691

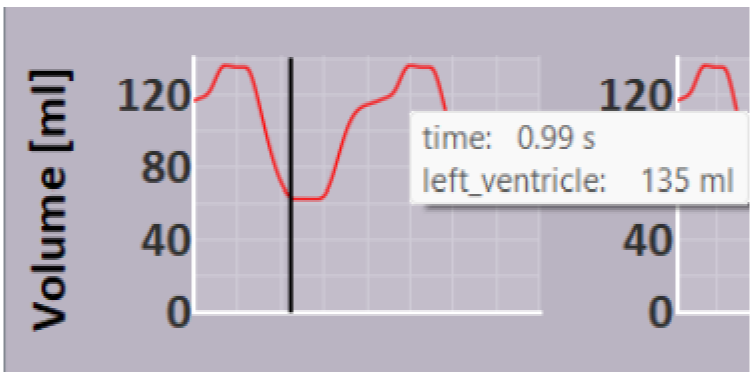


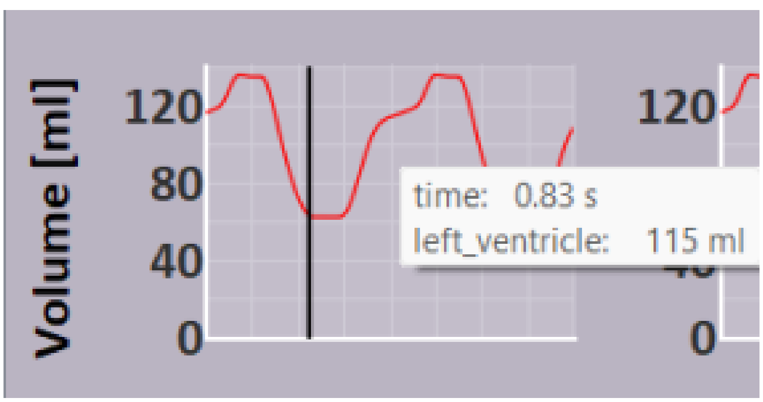
A – 0.485

h. $\frac{E}{A} = \frac{0.691}{0.485} = 1.4247$

i.







$$left\ ventricular\ filling\ due\ to\ passive\ filling = 115 - 62 = 53ml$$
$$left\ ventricular\ filling\ due\ to\ active\ filling = 135 - 115 = 20ml$$

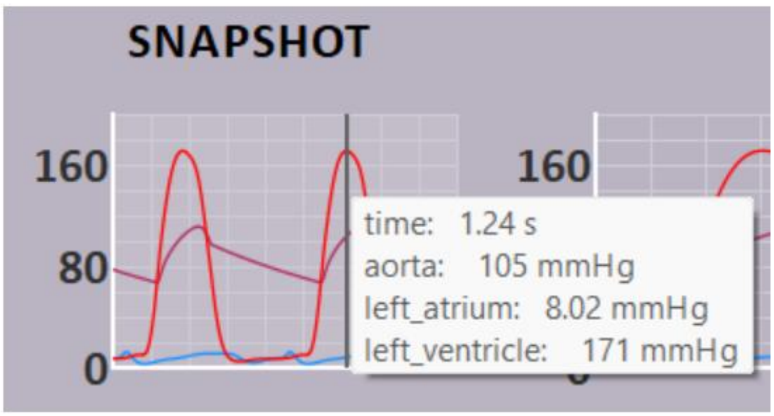
j. Cross sectional area of the valve

2. Aortic valve stenosis

a. Preload - Preload refers to the initial stretching or filling of the heart's ventricles right before contraction. It is influenced by the volume of blood returning to the heart and plays a significant role in determining the force of contraction during systole.

Afterload - Afterload refers to the resistance the heart needs to overcome during systole to eject blood from the ventricles into the arterial system. This resistance is primarily determined by the arterial blood pressure.

b.



As the severity of aortic stenosis (AS) worsens, the left ventricle faces a greater challenge in pumping blood through the narrowed aortic valve. Consequently, during systole, the left ventricular pressure increases. To compensate for the obstruction and maintain sufficient cardiac output, the blood flow through the narrowed valve accelerates, leading to higher flow velocity across the aortic valve. As AS becomes more severe, the pressure-volume loop, representing the left ventricular pressure and volume during one cardiac cycle, shifts to the right and upward. This shift indicates that the left ventricle must work harder and expend more energy to overcome the stenosis and efficiently eject blood. In summary, increasing AS severity puts greater demand on the left ventricle, leading to higher pressures, accelerated flow, and increased myocardial energy expenditure.

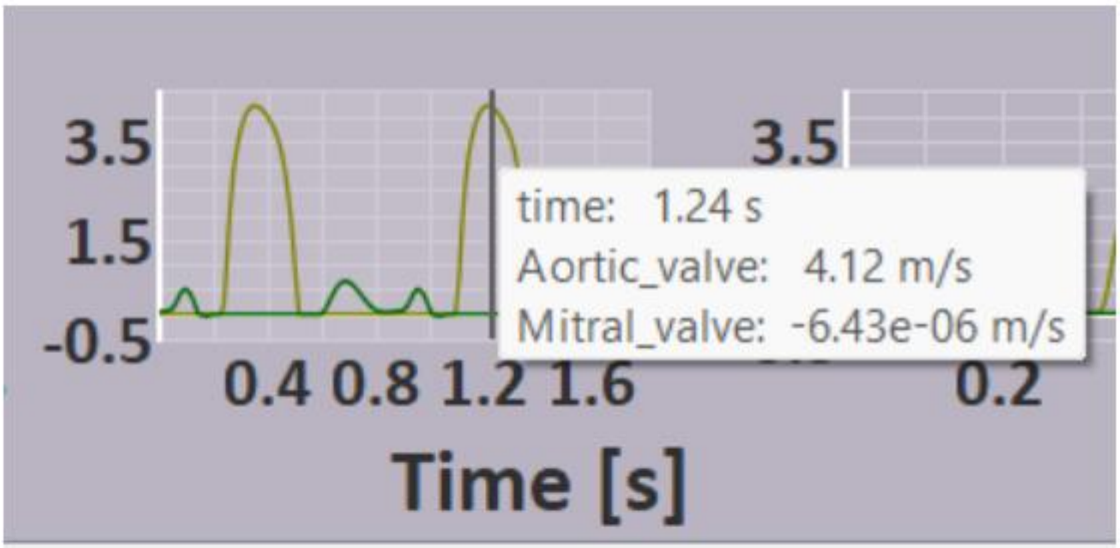
c. Aortic valve stenosis (AS) imposes a higher workload on the left ventricle. It increases preload by causing the ventricle to fill with more blood during diastole and raises afterload as the ventricle needs to exert more effort to pump blood through the narrowed valve during systole. These alterations impair the left ventricle's ability to effectively pump blood, resulting in a decline in cardiac output.

d. $Aortic\ blood\ pressure\ at\ the\ moment\ of\ maximal\ left\ ventricular\ pressure = 105\ mmHg$

$Maximal\ left\ ventricular\ pressure = 171\ mmHg$

$Pressure\ drop\ across\ stenotic\ valve = 171 - 105 = 66\ mmHg$

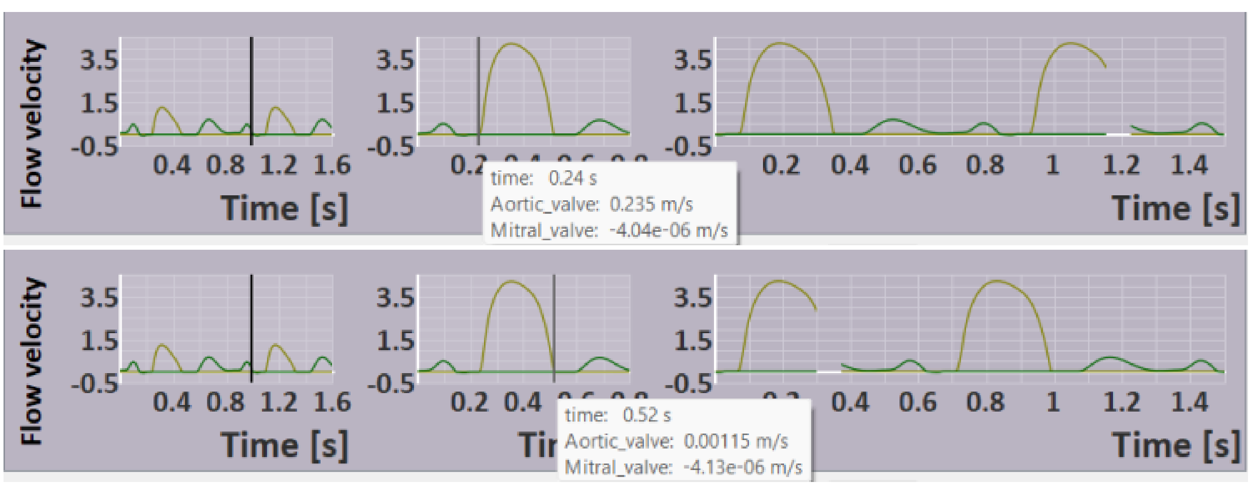
e.



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

$$\Delta p = 4 \times 4.12^2 = 67.8976\ mmHg$$

f.



Duration of ejection = 0.5s – 0.24s = 0.28s

g. Increase in external pump work = 6 x 20 x 20 = 2400 ml mmHg

h. 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.