Department of Electronics and Telecommunications

University of Moratuwa

BM2012 Modelling and Analysis of Physiological Systems

Assignment 2

Analysis of cardiac physiology

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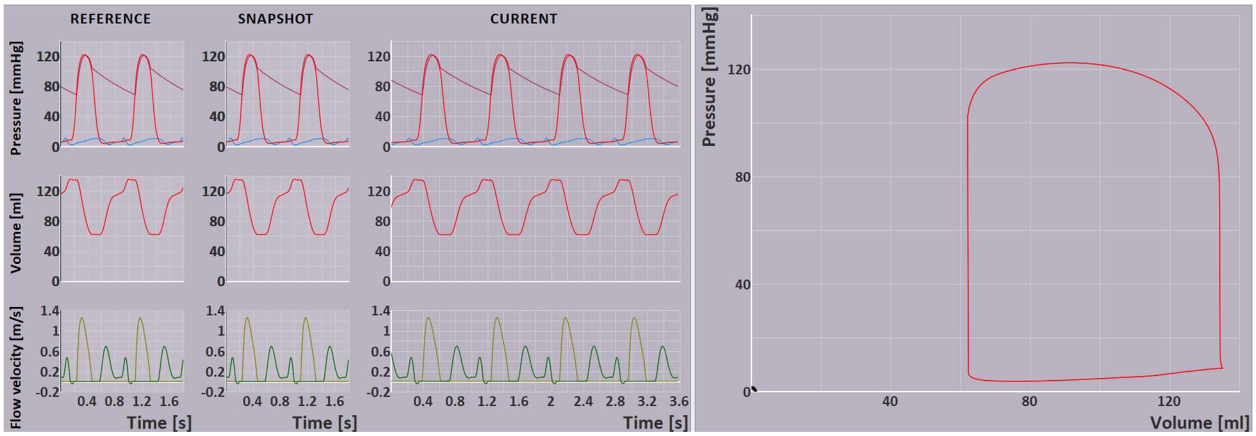
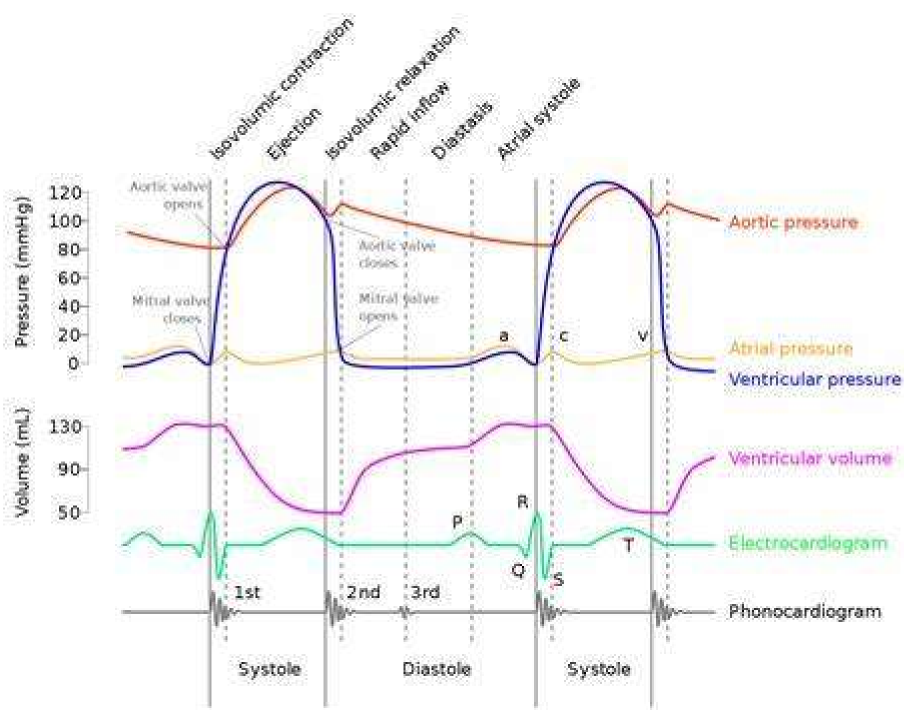
Normal Sinus Rhythm



Wiggers diagram:



Ventricular pressure and volume curve

Ventricular systole:

During ventricular systole, the volume within the ventricles decreases as blood is expelled from them. We can divide ventricular systole into 3 phases.

Phase 1 : Isovolumetric/isovolumic contraction

During this phase, the mitral valve remains closed, and the ventricles contract while preserving a consistent volume. Consequently, ventricular pressure increases while sustaining a steady ventricular volume.

Phase 2 : Ejection 1

In this phase, the pressure within the ventricle exceeds that of the aorta, prompting the opening of the aortic valve. Consequently, there is an increase in ventricular pressure concurrent with a reduction in ventricular volume as blood is ejected from the heart.

Phase 3 : Ejection 2

In this phase, ventricular pressure decreases until it reaches a level comparable to that of the aorta. Nevertheless, ventricular volume continues to decrease further during this phase.

Ventricular diastole:

During ventricular diastole, both ventricular pressure and volume decrease as the ventricles relax and fill with blood from the atria. We can divide ventricular diastole into 3 phases.

Phase 1 : Isovolumetric/isovolumic relaxation

During isovolumetric relaxation, the mitral valve remains closed, and the ventricles relax while maintaining a constant volume. Consequently, ventricular pressure decreases while sustaining a steady ventricular volume.

Phase 2 : Ventricular filling 1

During this phase, ventricular pressure drops below aortic pressure, also atrial pressure surpasses ventricular pressure allowing the mitral valve to open, resulting in blood flowing from the atria to the ventricles, thereby increasing ventricular volume.

Phase 3 : Ventricular filling 2

During this phase, atrial contraction occurs (atrial systole), further filling the ventricles with blood. Hence ventricular volume increases further.

Left atrial pressure curve.

The left atrial waveform consists mainly 3 waves:

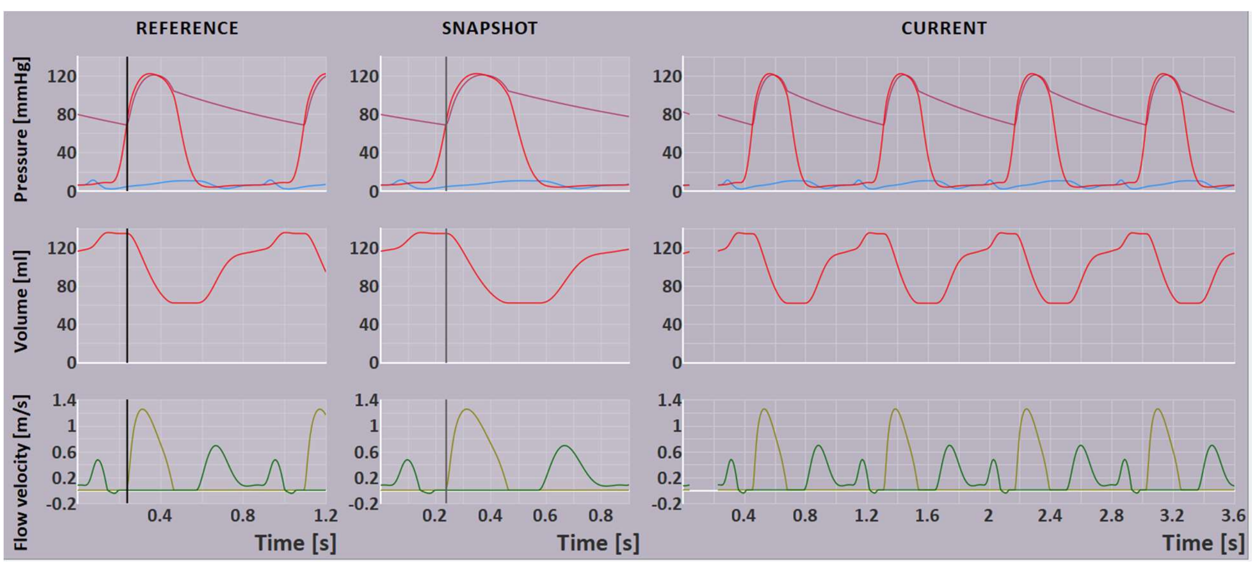
- a wave - indicates atrial contraction during the P wave, correlating with increased atrial pressure.
- c wave - follows the QRS complex, reflecting a slight pressure increase due to mitral valve bulging during ventricular contraction.
- v wave - occurs during ventricular diastole, signifying passive atrial filling as the mitral valve closes.

Aortic pressure curve.

The aortic pressure curve displays dynamic changes throughout the cardiac cycle:

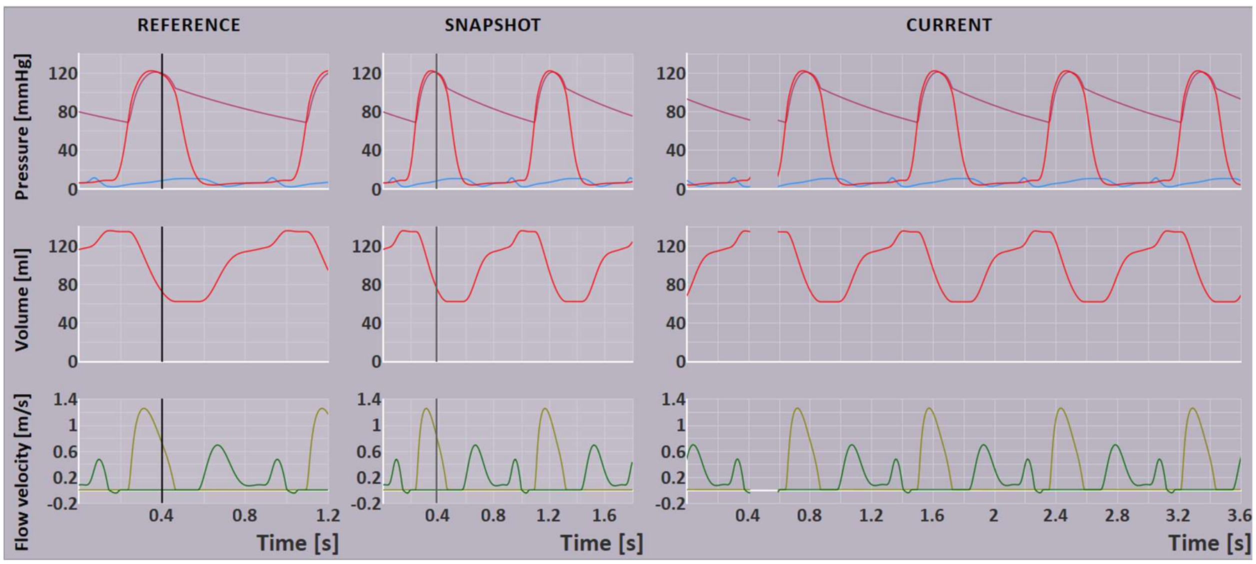
- Pressure rises during systole as blood is ejected into the aorta from the left ventricle.
- Peak pressure, occurring shortly after the onset of systole, represents the highest pressure reached during ventricular ejection.
- Following peak pressure, there is a gradual decline as ventricular contraction subsides and blood continues flowing into the systemic circulation.
- The dicrotic notch, a brief pressure rise, occurs immediately after the closure of the aortic valve, resulting from valve closure and arterial wall recoil.
- During diastole, aortic pressure further decreases as the ventricles relax and refill with blood, preparing for the next cardiac cycle.

a) Aortic valve opening:



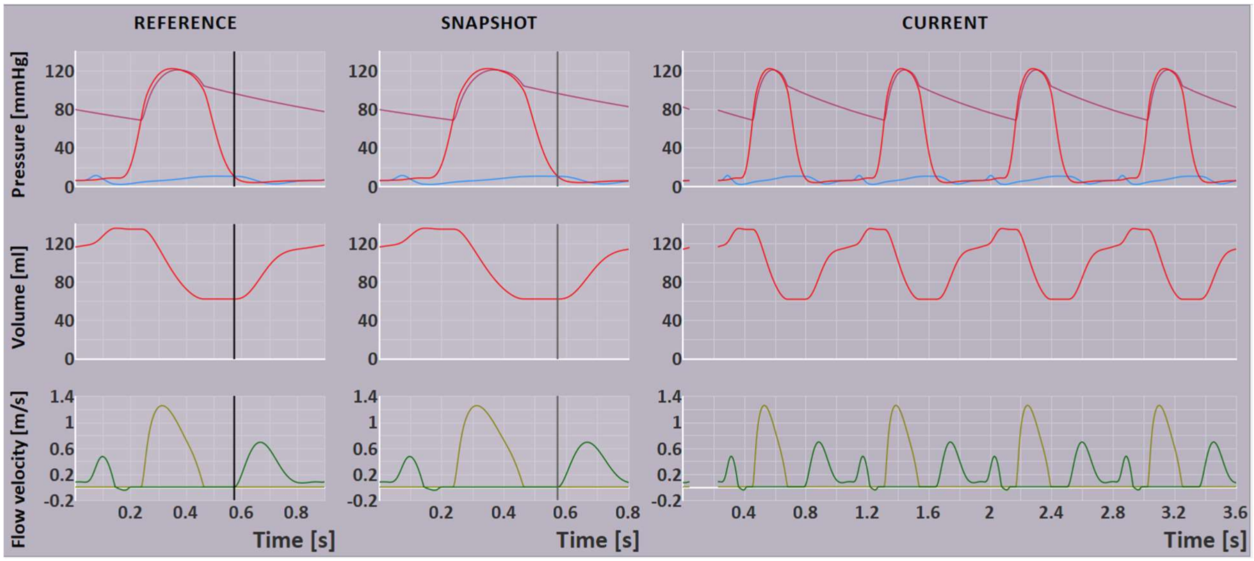
when the pressure in the left ventricle surpasses the pressure in the aorta, aortic valve opens in the direction of aorta and allows blood to be ejected from the left ventricle into the aorta. The moment of aortic valve opening can be visualized in the above graphs. It occurs at the point where the left ventricular pressure and the aortic pressure coincide, followed by a subsequent moment where the aortic pressure exceeds the left ventricular pressure. This transition marks the initiation of aortic valve opening, facilitating the ejection of blood from the left ventricle into the aorta.

Aortic valve closing:



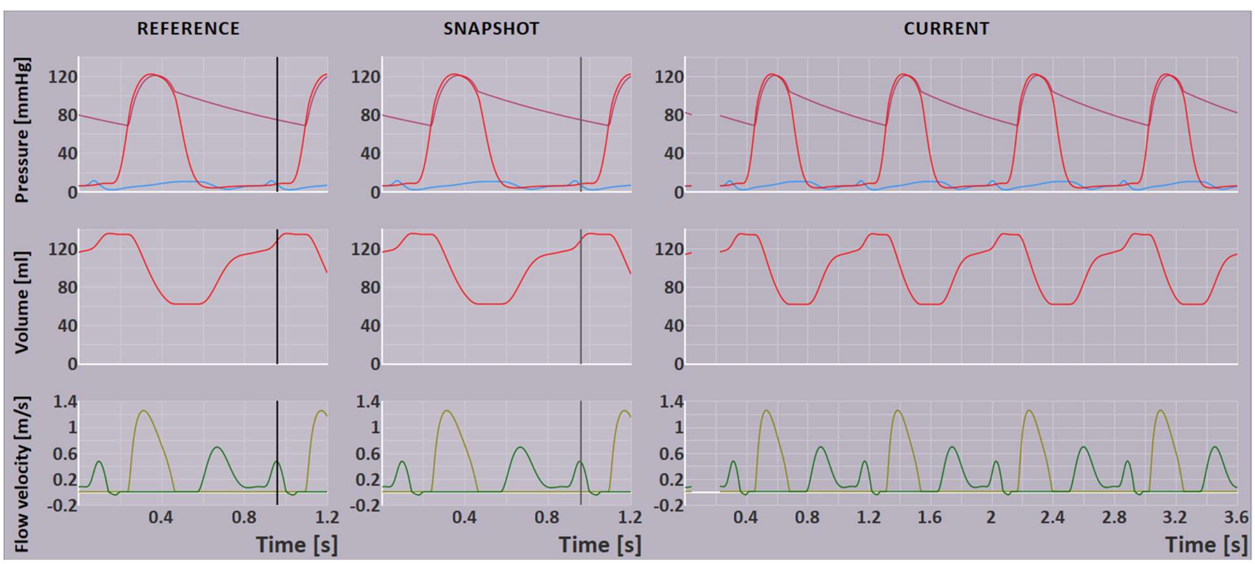
Aortic valve closing occurs during the cardiac cycle when the pressure in the left ventricle falls below the pressure in the aorta. This pressure gradient causes the aortic valve to close, preventing the backflow of blood from the aorta into the left ventricle. The moment of aortic valve closing can be visualized in the above graphs. It occurs at the point where the left ventricular pressure and the aortic pressure coincide, followed by a subsequent moment where the aortic pressure decreases below the left ventricular pressure. This transition marks the initiation of aortic valve closing, preventing backflow.

b) Mitral valve opening:



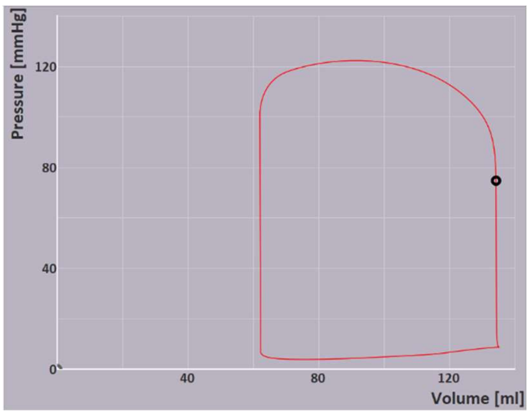
Mitral valve opening occurs when the pressure in the left atrium exceeds the pressure in the left ventricle. This pressure gradient causes the mitral valve to open in the left ventricular direction, allowing blood to flow from the left atrium into the left ventricle during ventricular diastole. From the above graphs, we can identify this point by observing when the left atrial pressure increases above the left ventricular pressure while the volume of the left ventricle begins to increase.

Mitral valve closing:

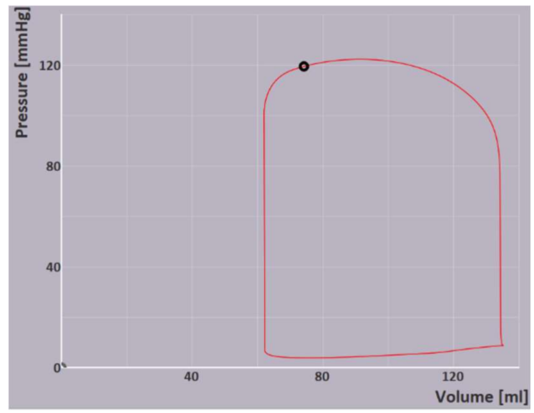


Mitral valve closing occurs during the cardiac cycle when the pressure in the left ventricle surpasses the pressure in the left atrium. This pressure gradient causes the mitral valve to close, preventing the backflow of blood from the left ventricle into the left atrium. The moment of mitral valve closing can be observed in the graphs by identifying the point where the left ventricular pressure exceeds the left atrial pressure, marking the initiation of mitral valve closure and ensuring the unidirectional flow of blood through the heart.

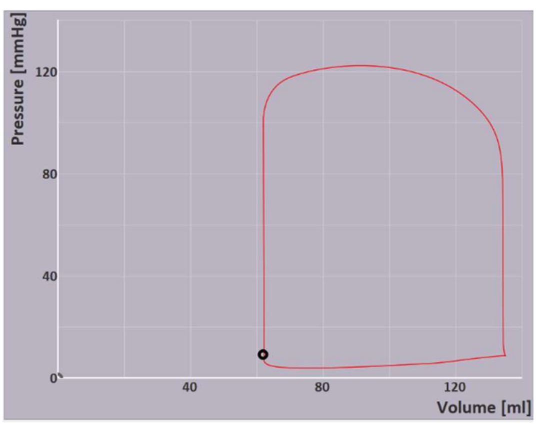
c)



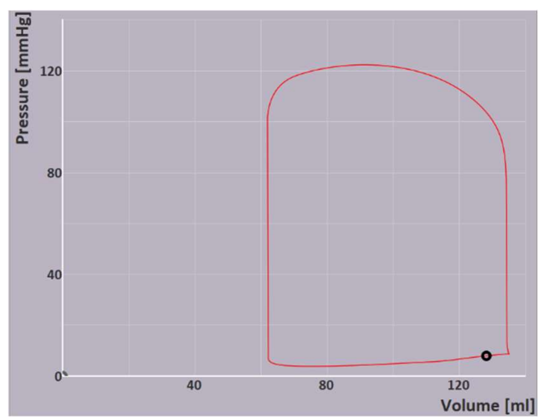
1- aortic opening



2-aortic closing



3-mitral opening



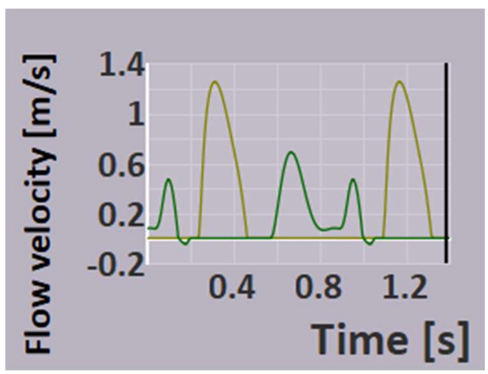
4-mitral closing

d) A - Filling
B - Isovolumic contraction
C - Ejection
D - Isovolumic relaxation

e)

The aortic valve exhibits a single hump in its flow velocity pattern because it exclusively opens when the pressure within the left ventricle exceeds that of the aorta. This mechanism ensures a continuous and uniform flow of blood from the left ventricle into the aorta.

Conversely, the mitral valve demonstrates a flow velocity pattern characterized by two humps. This attribute arises from the valve's passive opening, influenced by the pressure discrepancy between the left atrium and left ventricle. When the pressure in the left atrium surpasses that of the left ventricle, the mitral valve opens, permitting blood to enter the ventricle. However, the presence of two leaflets in the mitral valve may induce fluttering or vibration during blood flow, resulting in the dual-hump pattern. The initial hump corresponds to the rapid inflow of blood upon valve opening, while the subsequent hump signifies the closure of the valve and the slower outflow of blood from the left atrium into the ventricle.



f)

Fast (Steep) Increase in Atrial Pressure:

This occurs during the isovolumetric contraction phase of the cardiac cycle.

Electrical depolarization of the atria initiates atrial muscle contraction. As the atria contract, the pressure within the atrial chambers increases rapidly. This force pushes more blood flow across the open atrioventricular (AV) valves, leading to a swift flow of blood into the ventricles.

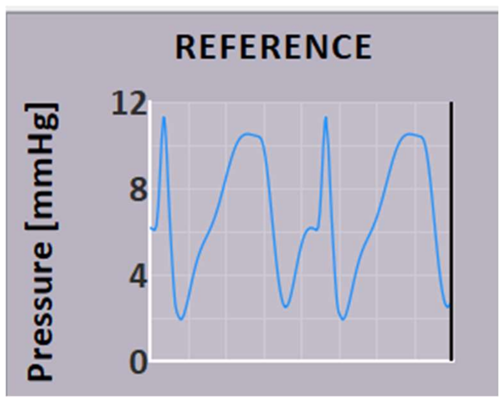
ECG Waveform Correspondence - P wave

Slow Increase in Atrial Pressure:

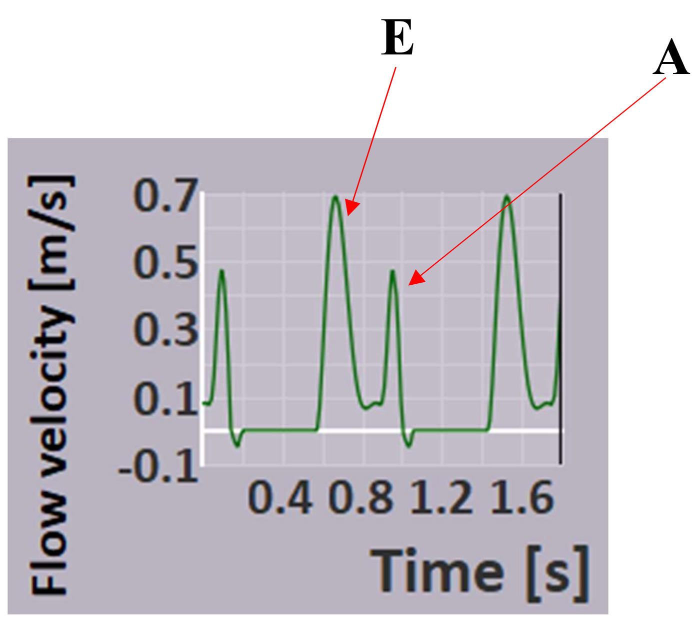
This occurs during the filling phase of the cardiac cycle.

In diastole (heart relaxation), both the atria and ventricles are relaxed. Blood flows from the vena cava and pulmonary veins into the right and left atria, respectively. The ventricles gradually fill with blood at a decreasing rate until their pressure equals that in the veins. At the end of diastole, the atria contract (atrial systole), squirting a small amount of extra blood into the ventricles. This additional blood increases the ventricles' pressure, making it higher than that in the atria. As a result, the atrioventricular valves (mitral/tricuspid) close.

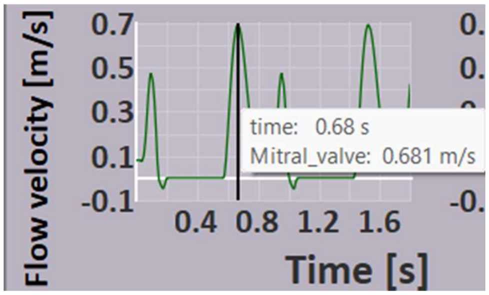
ECG Waveform Correspondence: T wave

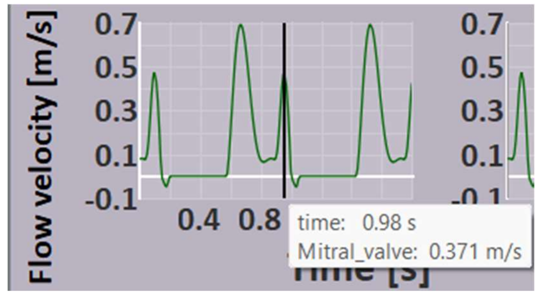


g)



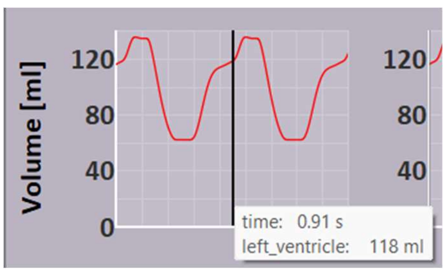
h)

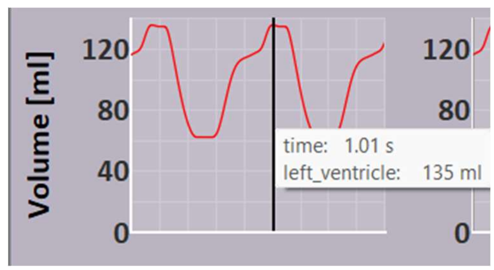


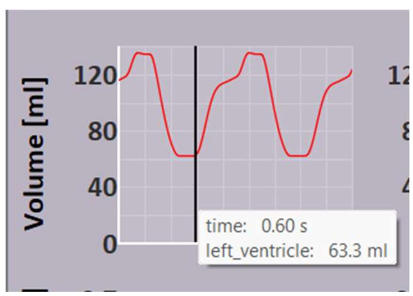


$$\frac{E}{A} = \frac{0{\cdot}681}{0.371} = 1 \cdot 836$$

i)







Due to passive filling = 118 – 63.3 = 54.7 ml

Due to active filling = 135 – 118 = 17 ml

j)

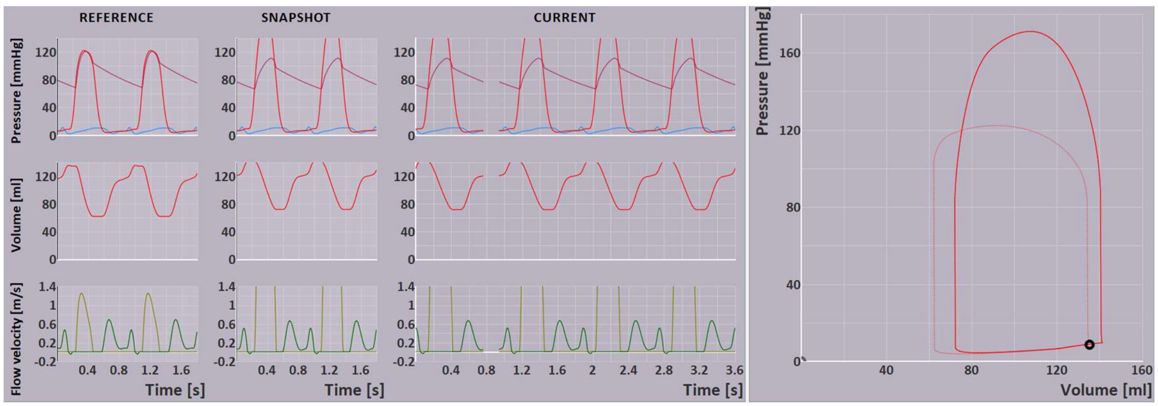
Cross sectional area of the valve.

Aortic Valve Stenosis

a)

- Preload - Preload is the volume of blood that the ventricle can hold during diastole, which is the relaxation phase of the cardiac cycle. It represents the stretch experienced by the cardiac myocytes due to the filling of blood in the ventricles.
- Afterload - Afterload refers to the pressure that the heart must work against during ventricular contraction (systole) to eject blood into the circulation. Specifically, it represents the load that the heart faces as it pushes blood out of the ventricles against the resistance of the arterial system.

b)



The pressure-volume loop, a graphical representation of left ventricular pressure and volume changes over the course of a cardiac cycle, provides valuable insights into the physiological consequences of worsening AS. With increasing severity of stenosis, the pressure-volume loop shifts towards the right and upwards. This shift signifies an augmented workload for the left ventricle, as indicated by the increased area enclosed by the loop. Consequently, the heart must expend more energy to overcome stenosis and effectively pump blood, highlighting the strain imposed on the myocardium.

As aortic stenosis (AS) worsens, the left ventricle encounters escalating challenges in ejecting blood through the increasingly narrowed aortic valve. This increased resistance necessitates a more vigorous contraction of the left ventricle, resulting in elevated left ventricular pressure during systole. Additionally, to compensate for the valve narrowing and maintain adequate blood flow, the velocity of blood passing through the constricted opening accelerates.

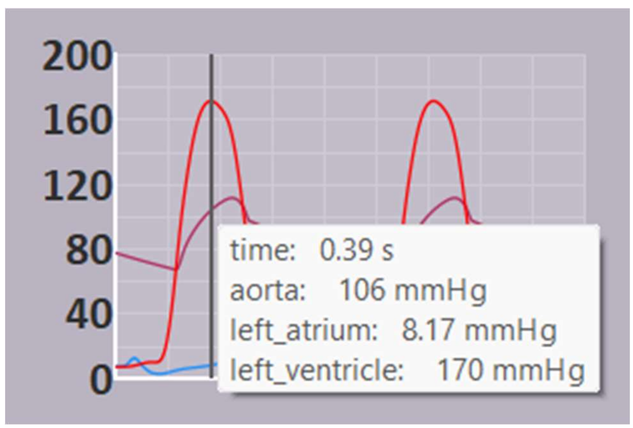
c)

Afterload represents the resistance the left ventricle must overcome to eject blood into the aorta. With AS, the narrowed valve increases afterload as the heart works harder to push blood through the restricted opening.

The preload of the left ventricle slightly increases because of aortic valve stenosis. This is caused by the increased afterload leading the left ventricle to contract harder. As a result, more blood is pumped into the ventricle during diastole, leading to a modest increase in preload.

Increased afterload in aortic valve stenosis creates greater resistance for the heart to pump blood out of the left ventricle and into the aorta. As a result, the heart requires increased energy and effort to eject blood into the systemic circulation, which can lead to decreased cardiac output over time.

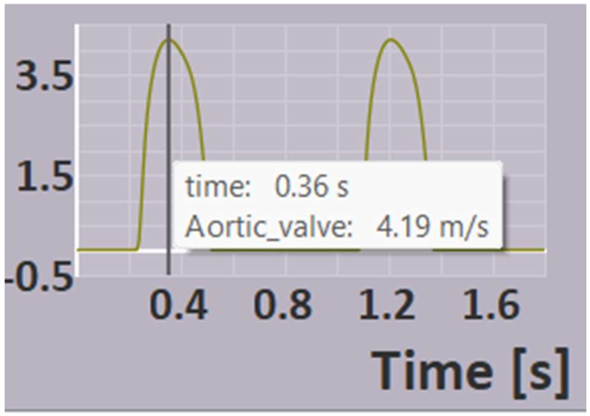
d)



Maximum left ventricle pressure = 170 mmHg

Aorta pressure when maximum ventricle pressure occurs = 106 mmHg

Pressure drop across stenotic aortic valve = 170 mmHg - 106 mmHg = 64 mmHg e)



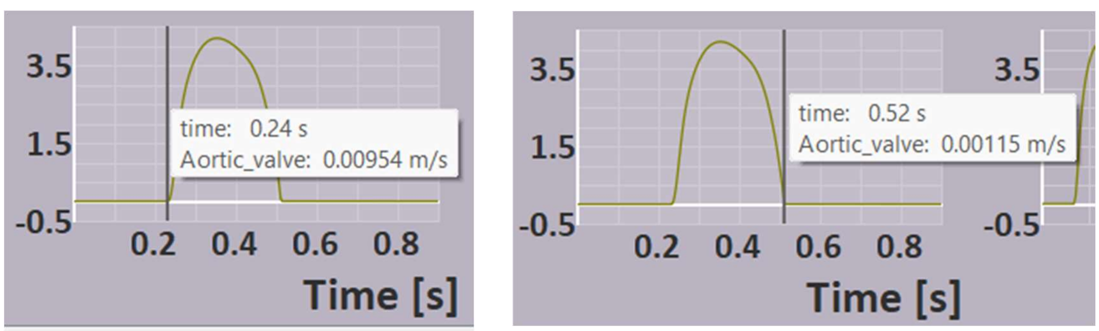
$$\Delta P \approx 4v^2$$

$$\Delta P \approx 4 \times 4.19^2$$

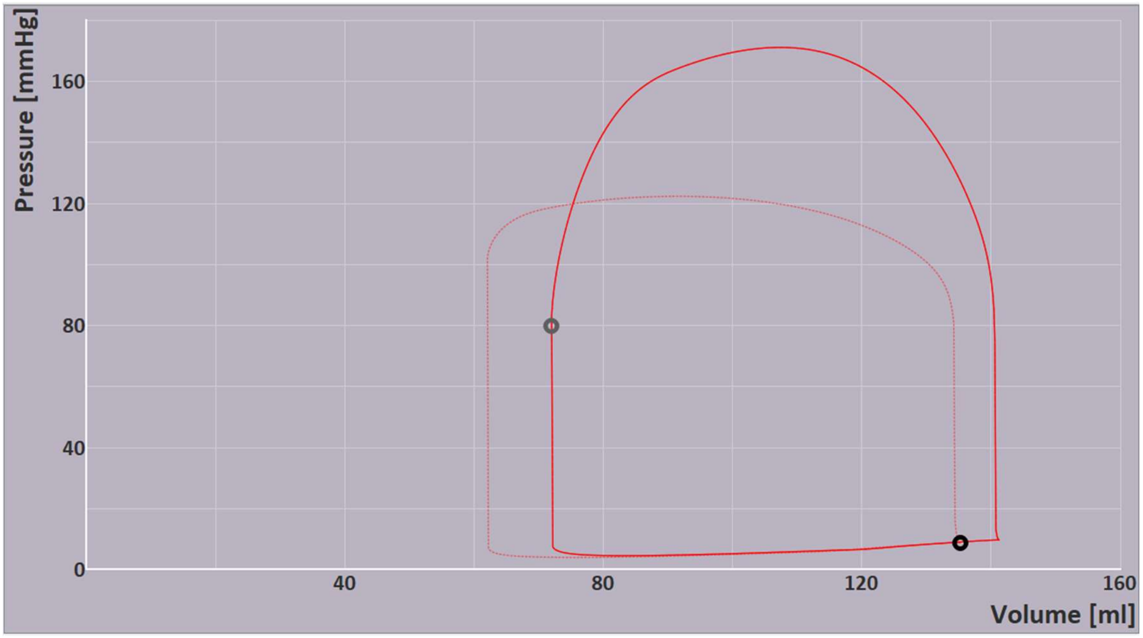
$$\Delta P \approx 70.224\ mmHg$$

Answer is little bit greater than previous value.

f)



Duration of ejection = 0.52 s - 0.24 s = 0.28 s g)



Number of squares before 80% AS ≈ 20

Number of squares after 80% AS ≈ 26

Difference ≈ 6 squares

external pump work ≈ 6×20×20

≈ 2400 mlmmHg

h)

In response to aortic valve stenosis (AS), the myocardial tissue of the left ventricle adapts through myocardial hypertrophy. This process involves enlarging individual cardiac muscle cells (cardiomyocytes) and thickening the left ventricular wall. Myocardial hypertrophy enables the ventricle to generate greater contractile force, overcoming the increased afterload associated with AS and maintaining cardiac output. Additionally, increased contractility and compliance help maintain preload levels during diastole. These adaptations collectively support the heart's function despite the challenges posed by aortic valve stenosis.

As a result of these adaptations, the left ventricle experiences an increase in wall tension (afterload). This occurs because the ventricle generates more force due to the augmented muscle mass and improved contractility. Additionally, the afterload further rises as the ventricular walls experience increasing strain.