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Analysis of Cardiac Physiology

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BM 2102 Modelling and Analysis of Physiological Systems

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1 Introduction

Cardiac physiology is the study of the function and behavior of the heart. It involves understanding the mechanisms and processes that enable the heart to pump blood throughout the body, delivering oxygen and nutrients to various organs and tissues. In order to analyze cardiac physiology, various parameters and measurements are taken into consideration. This report considers about simulating normal cardiac rhythm and rhythm during aortic valve stenosis for identifying the changes in the parameters caused by the stenosis.

2 Normal Sinus Rhythm

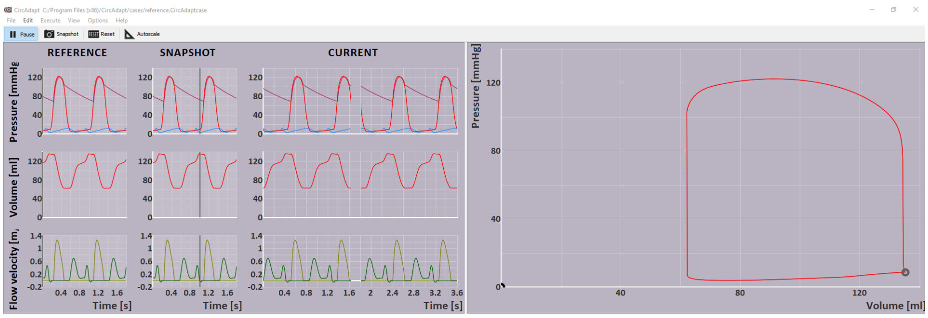

Figure 1: Snapshot of CircAdapt Simulator v1.1.0

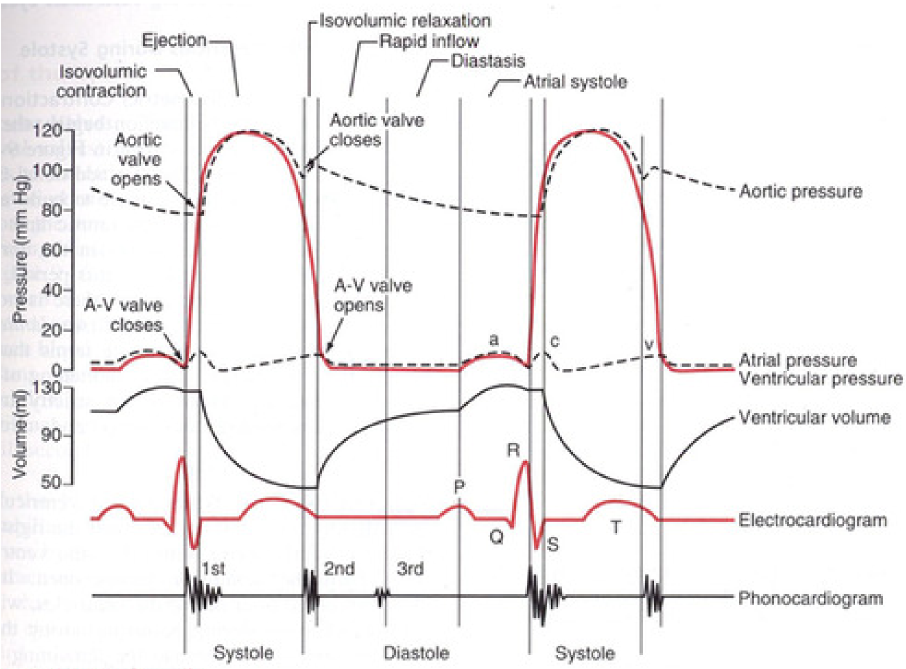

FIGURE 9–5

Events of the cardiac cycle for left ventricular function, showing changes in left atrial pressure, left ventricular pressure, aortic pressure, ventricular volume, the electrocardiogram, and the phonocardiogram.

Figure 2: Wiggers Diagram for a normal person

a.

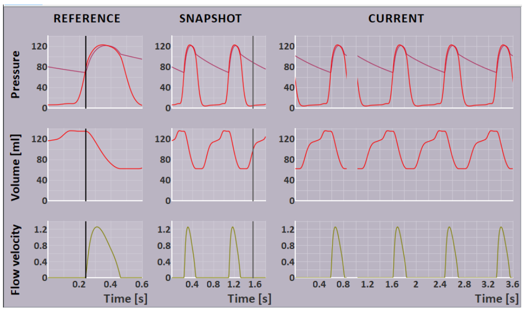

Figure 3: opening lines of the aortic valve.

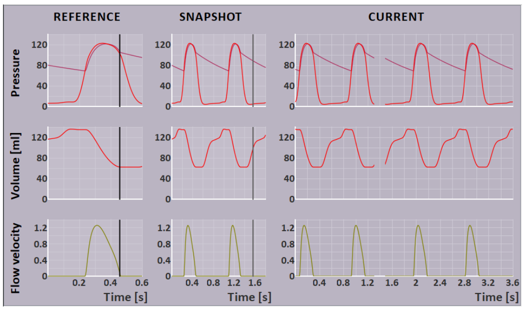

Figure 4: closing lines of the aortic valve.

Aortic Valve Opening

Aortic Valve opens during ventricular systole, when left ventricular pressure passes the pressure in the aorta. As it is a passive process the pressure gradient between these two compartments determines the opening and closing of the aortic valve. Reference column in Figure 3 corresponding to the beginning of the aortic valve opening. In the same time left ventricular volume starting to drop as blood starting to flow out of the heart from left ventricles through aorta. Opening of aortic valve signifies the beginning of the ejection phase, where the blood is pumped out of the heart to the rest of the body.

Aortic Valve Closing

Aortic valve closes during ventricular diastole, when left ventricular pressure drops below the pressure in the aorta. As it is a passive process the pressure gradient between these two compartments determines the opening and closing of the aortic valve. Reference column in Figure 4 corresponding to the beginning of the aortic valve closing. In the same time reduction of left ventricular volume stopped as blood flow out of the heart stops. Closing of aortic valve signifies the end of the ejection phase, where the blood is pumped out of the heart to the rest of the body.

b.

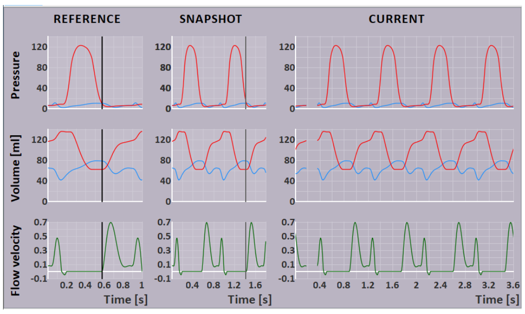

Figure 5: opening of the mitral valve.

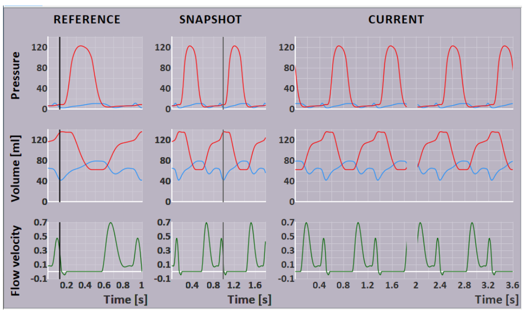

Figure 6: closing of the mitral valve.

Mitral Valve Opening

Mitral valve controls the blood flow between left atrium and left ventricle. It opens in the direction of the left ventricle. When pressure of the left atrium exceeds left ventricular pressure the mitral valve opens in two phases namely early diastole(passive filling) and late diastole(active filling due to atrial contraction). Reference column in Figure 5 corresponding to the beginning of the mitral valve opening. After opening left atrium volume decreases and left ventricular volume increases due to blood flow.

Mitral Valve Closing

When closing of the mitral valve occours left atrium volume is at its minimum due to contraction in late diastole. Left ventricular pressure is just above the atrial pressure. Reference column in Figure 6 corresponding to the beginning of the mitral valve closing of the mitral valve which can be confirm by flow velocity through mitral valve.

c.

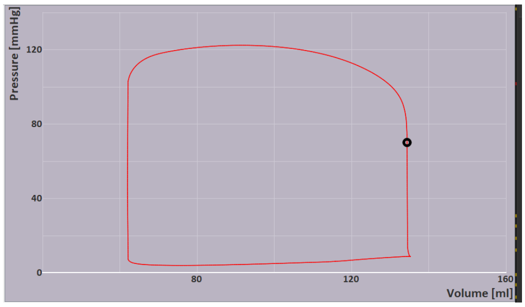

Figure 7: opening of the aortic valve.

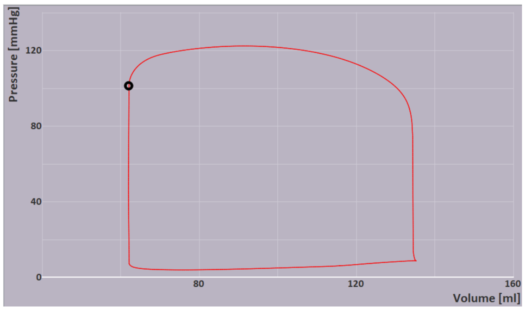

Figure 8: closing of the aortic valve.

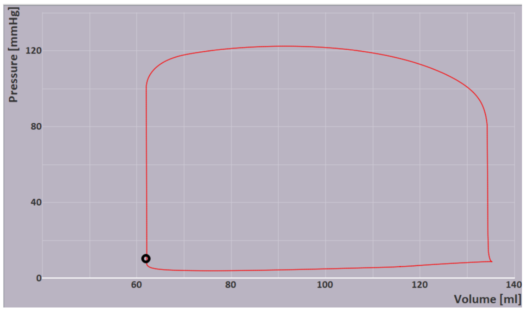

Figure 9: opening of the mitral valve.

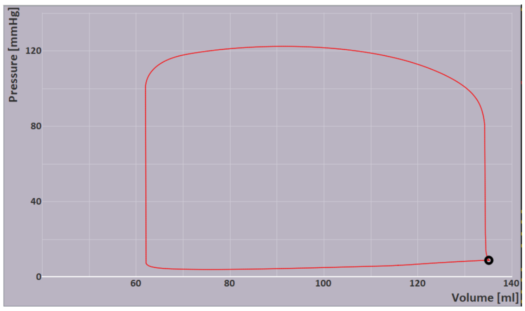

Figure 10: closing of the mitral valve.

d.

- **A:** Filling
- **B:** Isovolumic Contraction

- **C:** Ejection
- **D:** Isovolumic Relaxation

e.

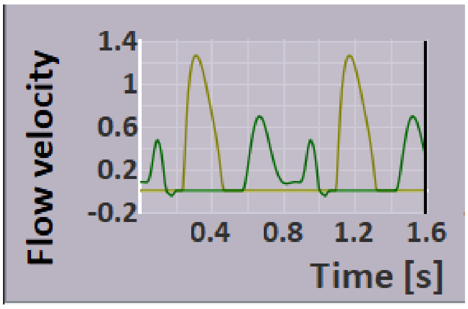

Figure 11: Mitral and aortic flow

Flow velocity in the aorta varies over the cardiac cycle. During systole, the mean velocity rises to a peak, then it falls during diastole. This pattern is repeated with each squeezing pulse of the heart. The highest velocities are found at the exit of the valve during systole. This results in a single-hump velocity pattern.

The mitral valve controls the inflow of blood from the left atrium to the left ventricle. The flow across the mitral valve is characterized by two distinct phases during the cardiac cycle. The first phase is the early diastolic filling which is a passive filling phase. The second phase is the late diastolic filling which is an active filling phase due to atrial contraction.

f.

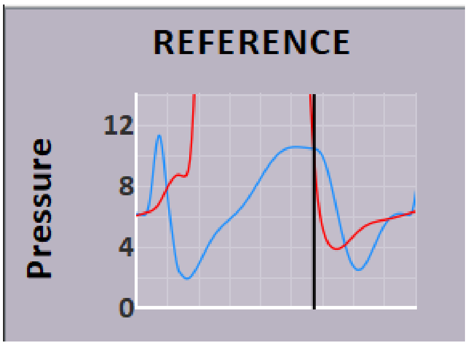

Figure 12: Mitral and aortic flow
Blue color represents left arterial pressure

Fast Increase: During atrial systole. Where atrial wall contracts and eject blood into ventricle. In ECG waveform P wave demonstrate that fast increase in atrium.

Slow Increase: It occurs with the atrial filling while AV valve closed due to the increased volume in the atrium This occurs during the ventricular systole, so it is correspond to the QRS complex in ECG waveform.

g.

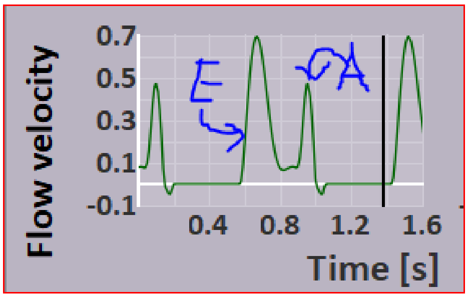

Figure 13: Labeled E and A waves

E-wave - Diastolic filling of the left ventricle is characterized by an early passive filling phase
A-wave - Late active filling phase that results from atrial contraction

h.

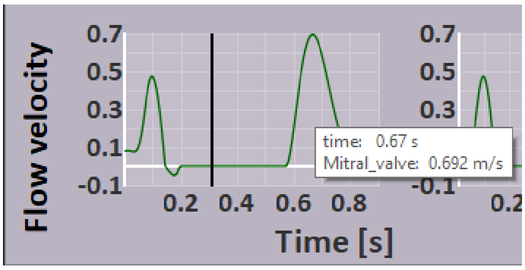

Figure 14: Peak value of the A wave.

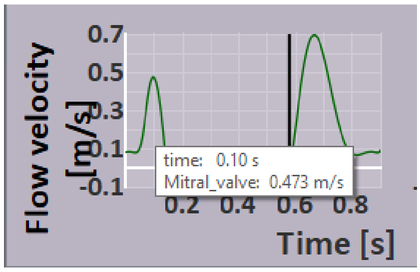

Figure 15: Peak value of the A wave.

$$\frac{E}{A} ratio = \frac{0.691}{0.473} = 1.461 \tag{1}$$

i.

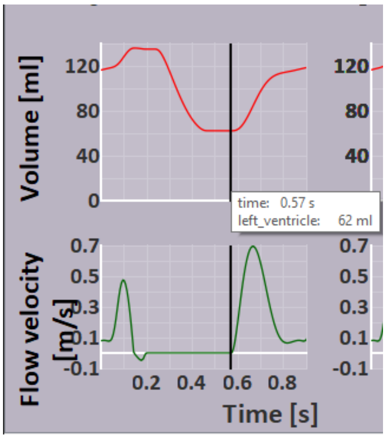

Figure 16: Left ventricular volume at the beginning of E wave.

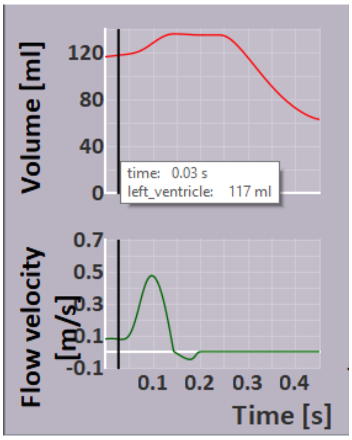

Figure 17: Left ventricular volume at the beginning of A wave.

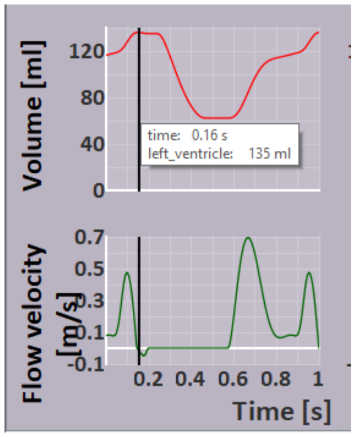

Figure 18: Left ventricular volume at the end of the A wave.

Due to passive filling = 117 - 62 = 55ml
Due to active filling = 135 - 117 = 18ml

j.

We need to know average opening area of the valve in order to convert flow velocity in to the volume flow rate

3 Aortic Valve Stenosis

a.

Preload: Preload, also known as the left ventricular end-diastolic pressure (LVEDP), refers to the volume of blood in the ventricle at the end of diastole, just before contraction which is known as end diastolic volume. It represents the amount of ventricular stretch at the end of diastole.

Afterload: Also known as the systemic vascular resistance ,refers to the resistance that the heart must overcome to open the aortic valve and push the blood volume out into the systemic circulation. It's essentially the pressure against which your heart has to pump that blood.

b.

Precentage of Stenosis	Peak aortic flow velocity	Peak left ventricular pressure
Normal	1.25 ms-1	122 mmHg
5%	1.35 ms^{-1}	122 mmHg
10%	1.45 ms^{-1}	124 mmHg
15%	1.5 ms^{-1}	124 mmHg
20%	1.55 ms^{-1}	126 mmHg
25%	1.6 ms^{-1}	126 mmHg
30%	1.7 ms^{-1}	126 mmHg
35%	1.8 ms^{-1}	128 mmHg
40%	2.0 ms^{-1}	128 mmHg
45%	2.1 ms^{-1}	130 mmHg
50%	2.3 ms^{-1}	132 mmHg
55%	2.5 ms^{-1}	135 mmHg
60%	2.7 ms^{-1}	140 mmHg
65%	3.0 ms^{-1}	145 mmHg
70%	3.3 ms^{-1}	150 mmHg
75%	3.7 ms^{-1}	160 mmHg
80%	4.2 ms^{-1}	170 mmHg

Table 1: Variation of peak aortic flow velocity and peak left ventricular pressure with the percentage of stenosis.

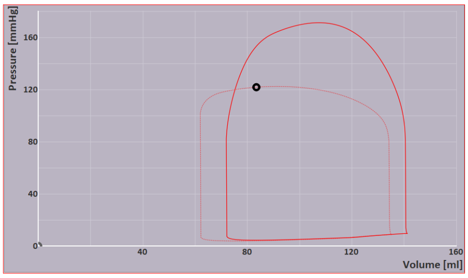

Figure 19: Pressure volume relation for 80% of stenosis

c.

Aortic valve stenosis is a condition where the opening of the aortic valve is narrowed. This narrowing can have significant effects on the heart's function, particularly on the preload and afterload of the left ventricle, and consequently, the cardiac output.

Preload: Reduced, The narrowing of the aortic valve increases the resistance to blood flow in to the left ventricle. This results in a decrease in the amount of blood that fills the left ventricle during diastole, reducing the ventricular pressure causes to reduction of preload.

Afterload: Increased, The increased resistance to blood flow out of the left ventricle due to the narrowed aortic valve increases the afterload on the left ventricle.

Cardiac Output: Stenosed aortic valve compromise the blood flow to the aorta reducing the stroke volume(amount of blood pumped out of the heart during each contraction). So the cardiac output is reduced due to the redused preload and the increased afterload.

d.

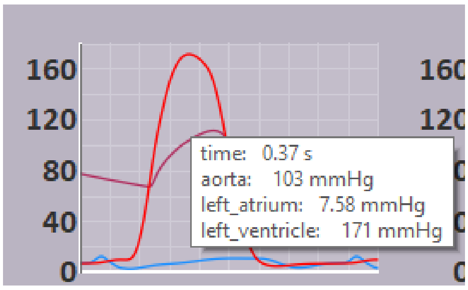

Figure 20: Ventricular and aortic pressure values for(80%) aortic stenosis

Maximum left ventricular pressure = 171 mmHg
Aortic blood pressure = 103 mmHg
Pressure drop across aortic valve = 68 mmHg

e.

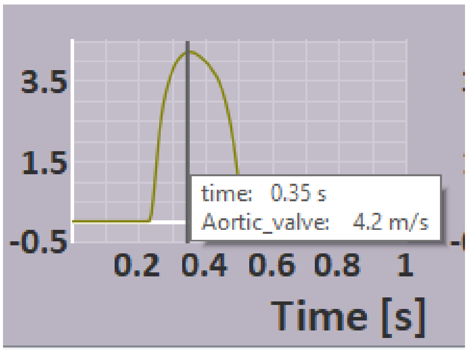

Figure 21: Aortic flow maximum velocity for (80%) aortic stenosis

$$\Delta P \approx 4v^2 \tag{2}$$
$$\Delta P \approx 4 \times (4.2)^2 \tag{3}$$
$$\Delta P \approx 70.56mmHg \tag{4}$$

Answers are approximately equal. So the equation is valid for the estimation of the maximum pressure across the valve.

f.

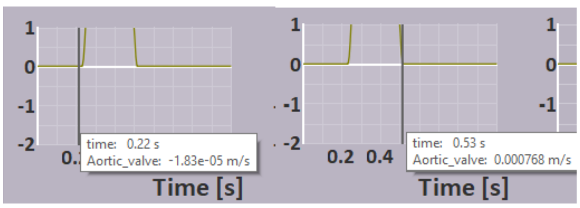

Figure 22: Duration of ejection for (80%) aortic stenosis

Duration of ejection = 0.31s

g.

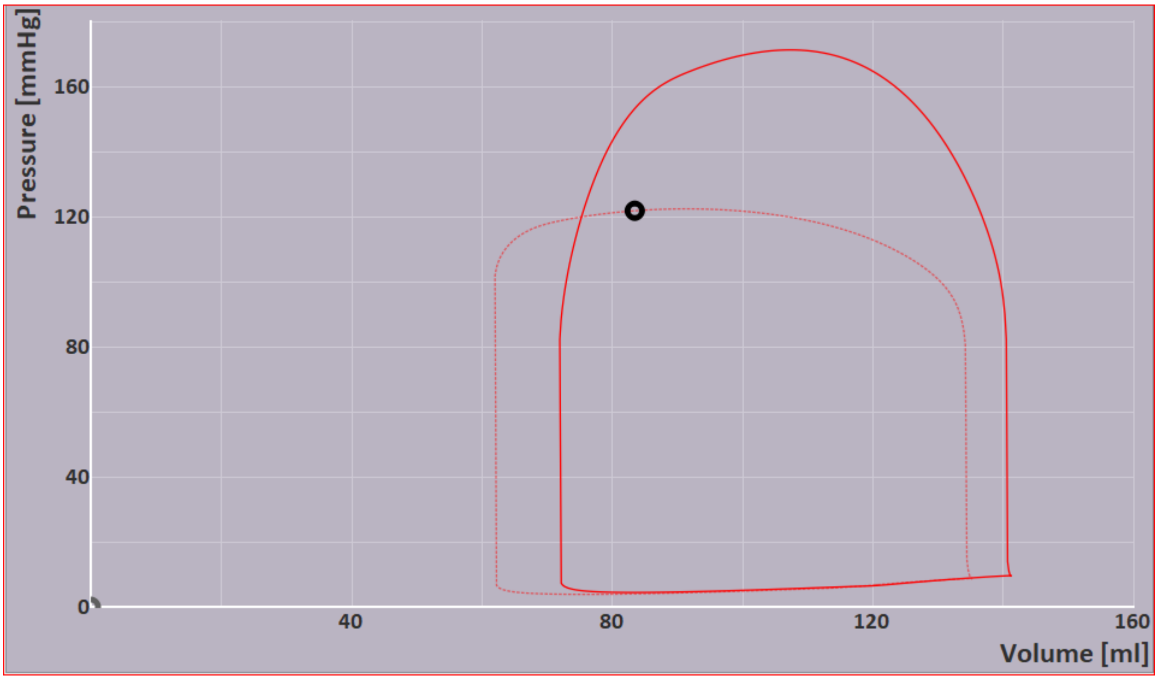

Figure 23: Pressure volume relation for 80% of stenosis

$$\text{Area under the curve when have 80\% stenosis} \approx 24$$
$$\text{Area under the curve under normal healthy conditions} \approx 20$$
$$\text{Area increase} \approx 4 \text{ squares} \approx 1600 \text{ ml mmHg} \tag{5}$$

h.

The myocardial tissue of the left ventricle will adapt in several ways to be able to generate the chronically increased pump work caused by conditions like aortic stenosis (AS). These adaptations are part of the process of cardiac remodeling. Here are some of the main adaptations

- **Myocyte hypertrophy:** Individual cardiac muscle cells (myocytes) increase in size (hypertrophy) to generate more force during contraction. This is primarily achieved through an increase in the synthesis of contractile proteins such as actin and myosin
- **Increased Contractility:** The left ventricle adapts by increasing its contractile strength.Improved contractility allows the heart to generate more force during systole, reducing the impact of afterload.

Initially afterload may decrease. A stronger and more efficient left ventricle can pump against the same pressure with less effort, effectively reducing afterload. However, chronic remodeling can lead to excessive stiffening of the heart muscle (fibrosis). This increased stiffness can ultimately reduce the ventricle's ability to relax fully, leading to higher afterload with the time.