1. Introduction

The aim of this lab is to give you a better understanding on how pressure and flows are correlated in the cardiovascular system. The lab is separated into three parts. In the first part you will model the pressure and flows in the aorta. The second part covers the relation between pressures and flows in the left ventricle. In the last part you will investigate the effects of different catheter configurations on the measured pressure signal.
All models in this lab are based on the analogy of electrical and hydraulic systems, which was introduced in the lectures about the vascular system and the cardiac pump.

2. Preparations

Before the lab, you are required to **read this lab manual** and **answer the preparatory questions**. Responses to the preparatory questions should be submitted to Lisam latest on Monday before the lab at 23:59. To do the lab remotely, you need to have a computer with MATLAB and the following add-ons installed:
Simscape Electrical
Simscape
Simulink

3. Preparatory Questions

1. Explain the terms compliance, inertance and resistance from a pressure system point of view. What are the equivalents in mechanics/electronics? Motivate.
2. Which Elements are used in the 4-Element Windkessel model? Which physiological phenomena do they represent?
3. What are preload and afterload? What leads to changes in these conditions?
4. Why is it difficult to accurately measure the blood pressure signal in the body using a fluid filled catheter?
5. How do the following properties affect a pressurized system in relation to dampening and resonance frequency: a catheter of large diameter, a rigid catheter, a long catheter?

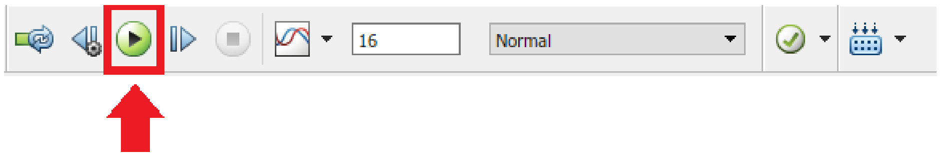
4. Pressure model data

Download the folder Pressure Lab folder from Lisam.

4.1 Windkessel Model

5.1.1 2 Element Windkessel

1. Open the file TwoElementWindkessel.slx. Double-click on the boxes “Compliance” and “Resistance 1”. These boxes are marked red, since the parameters C1 and R1 are not define yet
2. What is the input to the model? What is the output?
3. Run the script “loadParameters.m” to load the parameters.
4. Now you can click on “Run” button in Simulink to run the simulation.



5. Double-click on the icon "Pressure Plot" to see the simulated pressure curve
6. How high are systolic pressure, diastolic pressure and pulse pressure?

5.1.2 The aging process

1. With age, the vessels in the body become stiffer. Which parameter in the Windkessel model characterizes the stiffness of the vessel?
2. Change this parameter so that you simulate the cardiac system of an older person. (Enter "ParameterName" = "YourNewValue" into the Command Window in Matlab. Now you see the new value in the Workspace) Run the Simulink simulation again and look at the pressure curve. How did systolic pressure, diastolic pressure and pulse pressure change?
3. If there is time, try different values for the parameters and see, how they change the pressure curve.

5.1.3 Other Windkessel models

1. Close the "ElementWindkessel" window and open "WindkesselModelComparisson.slx"
2. What are the differences in the Windkessel models?
3. Run the script "loadParameters.m" again, so that your workspace contains the original values
4. Run the Simulink simulation "WindkesselModelComparisson" and open the pressure plot.
5. How do the different elements of the windlessel models influence the pressure curve?
6. The pressure output from the 4-element Windkessel model is being saved in the file "Pressure.mat". Keep this file, it will be used in the Catheter model.

4.2 Heart Model

In this part of the lab you will learn how pressure and flow behave in the left ventricle. The task uses a Matlab script with different code sections, separated by "%%". You can run the code sections individually by clicking "Run Section" or entering "Crtl" + "Enter" on the keyboard.

1. Run the first 2 sections of the HeartModel_1.m script ("load Parameters" and "Show flow curves")
2. Which of the curves you see is the ventricular inflow curve and which is the ventricular outflow curve? How long is Systole and how long is Diastole?
3. In the workspace you find the variables "AVflow" (flow through the aortic valve), "MVflow" (flow through the mitral valve) and "EDV" (End-Diastolic volume). With these parameters, you can calculate the volume of the left ventricle over time by using the conservation of mass:
$$\frac{dV}{dt} = Q_{in} - Q_{out}$$
Where Q_{in} is the inflow and Q_{out} is the outflow.
4. Run the section "plot volume curve"
5. Run the section "plot Elastance curve"
6. The time-varying elastance of the left ventricle describes the relationship between the pressure and the volume of the left ventricle:
$$E(t) = \frac{p(t)}{V(t)}$$
Use this equation to calculate the left ventricular pressure in the section "calculate pressure curve".
7. Run the section "HeartModel_2.m" to create a pressure-volume loop
    a. How does the Stroke vol, EDV and ESV change with changing preload/afterload?
    b. How does the pressure curve change?
    c. How does the PV look change and why?

4.3 Catheter Model

1. When designing a Catheter, which parameters can you influence? What are reasonable values for these parameters?

2. Implement the missing equations in the Matlab script:

$$R = \frac{8\,\eta\, l}{\pi\, r^4} \quad L = \frac{\rho\, l}{\pi r^2} \quad f_n = \frac{1}{2\pi\sqrt{L\,C}} \qquad \gamma = \frac{R}{2}\sqrt{\frac{C}{L}}$$

$$f_{res} = f_n\sqrt{1-\gamma^2}$$

3. To measure the pressure signal from task 5.1 though a catheter, you have 4 catheters available:

Catheter Number	*Inner Radius [mm]*	*Length [m]*	*Compliance*
#1	1	0.5	1e-10
#2	1.5	1	1e-11
#3	1	1	1e-14
#4	1	0.5	1e-13

   Create a frequency response plot for each catheter, which shows the amplitude of the output signal for different frequencies. As an input to the catheter, use a sinus curve that you can create with the SinusInput.m script. Modify the parameter freq on the script, run it, run the catheter simulation and analyze the measured output. Create the plot using the file CatheterComparisonTemplate.xlsx. (You can ask the lab assistant for help on how to do this task)

4. Which catheter do you think is best suited to measure the pressure in the aorta?

5. Copy the file Pressure.mat that was created in part 5.1 to the 3_catheter folder and define it as an input to the catheter. Run the model for each catheter and check the pressure output. To view the Input and Output curve in one plot, click on View/Layout…, Mark one square blue and click.
   Is the catheter you chose in 4. best suited to measure the signal?