Fluid Mechanics CHEG 341
Department of Chemical and Biomolecular Engineering
University of Delaware Fall 2020
Mini-Project # 3

Project Statement: As experts in fluid dynamics, you are contracted by the Food and Drug Administration (FDA), who is updating guidelines for heart bypass surgery. You are tasked with understanding changes in blood flow which occur during coronary artery disease (CAD) and advising the FDA on your findings. The objective of this project is to model blood flow through a diseased heart with a stenosis and one that has undergone bypass surgery. You will create a report that will guide the FDA on whether the proposed surgery will result in blood flow similar to that of a healthy arterial system.

Learning Objectives:

- Simulate biological functions considering *in vivo* measurements and translating a real scenario into a simulation.
- Apply your knowledge of fluid dynamics to a health-related application
- Justify guidelines for the FDA based on a comprehensive analysis of several models.
- Translate your results into meaningful discussions and guidances.

Deliverable: You will prepare a brief written report detailing your results and recommendations to the FDA. A completed report will include the following components (see the rubric on the last page and in canvas for the exact grading details, summarized in the following):

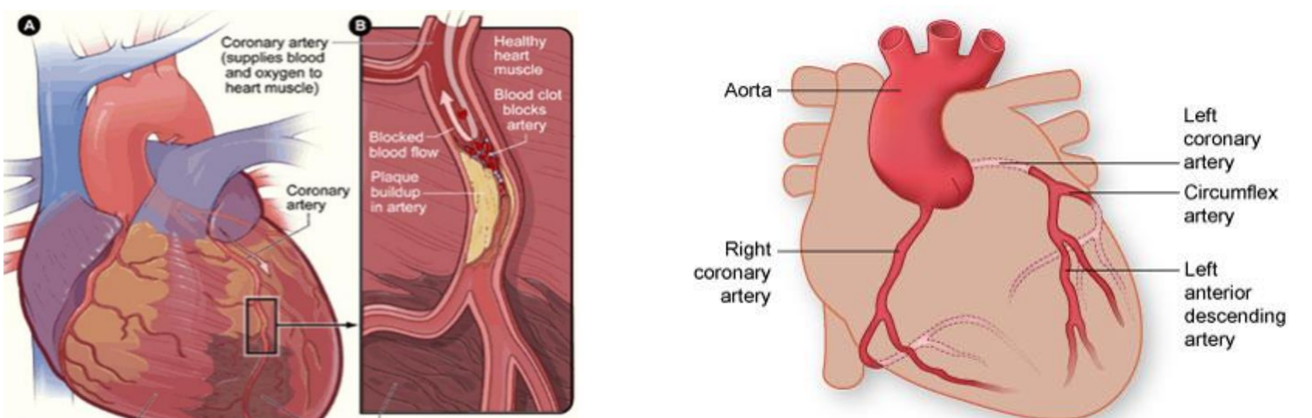
1. Title page. Single page with your name, project information, date submitted. Names of any collaborators should be included on the title page; however individual reports are expected
2. <u>Executive Summary.</u> A single paragraph briefly describing all of the enclosed components. Less than 1 pg.
3. <u>Introduction.</u> A brief introduction/objective statement to the problem (*do not* pull directly from project statement)
    - Must include clearly articulated health problem
    - Must include any background literature used in the report (*e.g.* background heart disease, artery dimensions, surgical intervention, what is known about flow through healthy and stenosed arteries…)
4. <u>Methods.</u> Systematically describe the technical methods you used to address the problem. Include any graphics of the geometries used and the technical details of how you performed the simulations. Include any calculations that are most critical for understanding the subsequent results. Since you are asked to perform computational fluid dynamics (CFD) calculations, include a brief overview of CFD by including some additional references,
5. <u>Results & Discussion.</u> Include your simulation results and describe what trends you observe, answering the specific questions listed in the report prompt.
    - Part I
        - Provide text descriptions of the simulation results and tables chosen.
        - Answer questions A-C with 1 paragraph each
    - Part II
        - Provide text descriptions of the simulation results and tables chosen.
        - Answer questions D-E with 1 paragraph each
6. <u>Conclusion and Recommendation.</u> Address the following with at least one paragraph for each point:
    - Summarize your findings
    - Include recommendations to the FDA for use of the bypass as simulated
    - Discuss limitations of your approach and results and next steps that might improve or elevate your results
    - Discuss utility of CFD models in understanding cardiovascular disease.
7. <u>References</u>
8. Appendices. Include an organized appendix (or appendices) with any important calculations, software outputs that are supplemental to the main results. This should be clearly annotated; do not just data dump.

Additionally, the completed report must include the following formatting components

- Times New Roman or Arial Font size 11; single or 1.5 spacing
- Title page with three lines: your name, Mini-Project #3, the date submitted (collaborator names on line 4)
- Page numbers in the bottom right corner of the footer (Times or Arial Font)
- Document has less than 5 glaring grammatical errors
- Section headers (#ed above) should be bolded. Subheaders bolded & italicized

- Any figures, equations, calculations, schematics that appear in the main report should be professional level figures and created with a computer. Anything appearing in the Appendix can be images of handwritten calculations.
- Any equations used must be listed and formatted in the document (using a computer). They must be numbered sequentially
- Results should be summarized in graphs and tables. These should also be numbered sequentially, beginning with #1 in the main text.
    - Figures/Tables should be mentioned in the narrative. Each mention should be bolded. Example: "*The height of fluid in the tank was calculated using Eq. 4 and varies with time, as plotted in **Figure 2**.*"
    - Every Figure/Table must be accompanied by a descriptive caption
    - Figures/Tables should be inserted either as "floating" objects (off to the side of the text) OR in line immediately following the first mention and appear next to the first mention
- References to any outside sources **<u>must be</u>** included and mentioned in appropriate places in the text. These must be included in the main text using superscripts, beginning with #1, and corresponding to the full citation listed in the Reference section at the conclusion of the report. Follow the ACS style guide for reference formatting: https://pubs.acs.org/doi/full/10.1021/acsguide.40303

Detailed Description: The heart is an extraordinary organ that pumps blood via the blood vessels to provide nutrients to the ten trillion cells of the body. The work of feeding the cells can never stop. In that sense, the heart is an extraordinary pump; it operates 24/7 for an average lifetime of 78 years and it circulates an average of 5 liters per minute of blood! The heart also feeds itself and receives its own supply of blood from the coronary arteries. There are two major coronary arteries that branch off from the aorta: the left coronary artery (**LCA**) –also known as left main artery (**LM**)**-** and the right coronary artery (**RCA**), which feed blood to the left and the right side of the heart, respectively. The LM bifurcates into the left anterior descending (**LAD**) artery and the left circumflex artery (**LCX**). These arteries and their topology in the human heart are shown in ***Figure 1*** below. Despite the technological advancements in the medical field, the most common heart disease, coronary artery disease (CAD), remains the leading cause of death in the US. This occurs when plaque builds up on the inner walls of the arteries (atherosclerosis), leading to a reduction in the diameter of a vessel, an effect formally known as stenosis (see ***Figure 1***, right). This leads to a decrease in coronary blood flow and an inadequate supply of oxygen to the heart muscle.



A. **B.**

Figure 1. Relevant physiology. A. Depiction of a stenosis in a heart artery. B. Diagram of the arteries of the heart.

Key Background Information: You have been provided with two CAD files with anatomically accurate dimensions of the left coronary arteries: length of the coronary arteries are 0.9 cm, 2.7 cm and 1.06 cm for the LM, LAD and LCX, respectively. The inlet diameter is 4.0 mm (D_0=4.0 mm) while at outlets 1 and 2 the diameter is 1.75 mm and 2 mm, respectively (D_1=1.75 mm, D_2=2 mm). The first CAD file has a stenosed (narrowed) LM artery bifurcation that is 90% occluded; the second CAD file has a stenosed LM artery bifurcation with a bypass. These are depicted in ***Figure 2***.

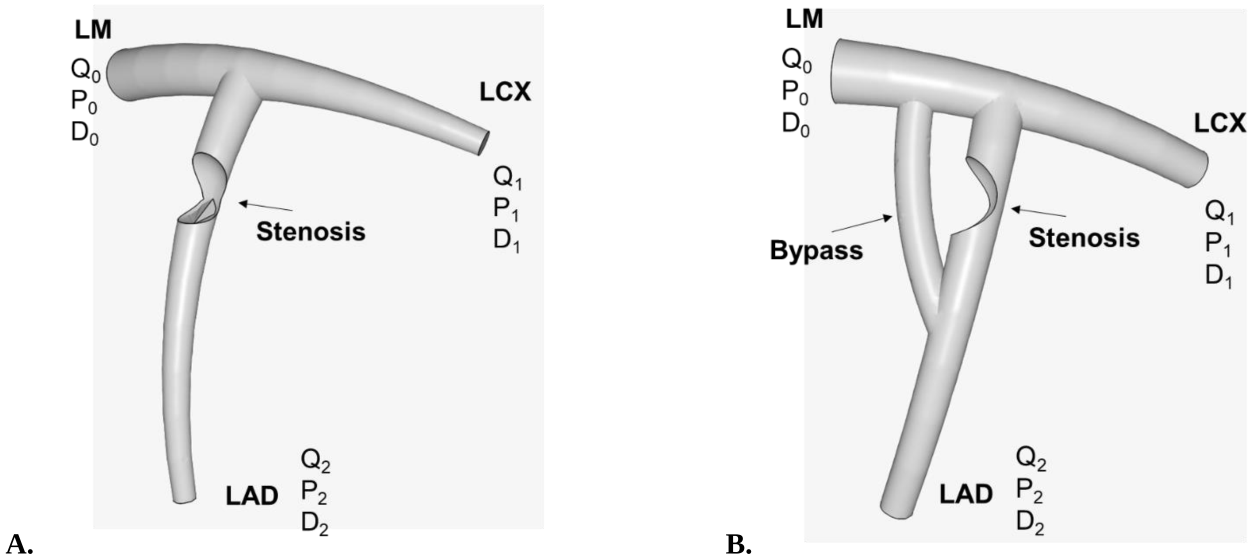


Figure 2. Depiction of provided CAD files. A) Stenosis and B) bypass.

The heart processes 5 L/min of blood and the pressure at the heart is 100 mm Hg (P_{LM}=P_0=100 mm Hg). The pressure in the capillaries, the smallest vessel in the human body, is a constant P_c = 2000 Pa. The reported pressure values (P_{LM}, P_0, P_C) are all relative in comparison to the atmospheric pressure, *i.e.* gauge pressures. Under resting conditions, 5% of that flow rate is used to feed the heart muscle, half of which is the inlet flow rate to the LM, Q_{LM}(=Q_0). For this project, we will be assuming blood to be incompressible with a density of 1060 kg/m^3 and Newtonian with a dynamic viscosity of 3.5 cP.

Even using sophisticated software, we can only focus on a limited component of the whole arterial network. Nevertheless, we need to somehow account –even approximately- for the impact that the rest of the vasculature has on the flow under investigation. We need to take into consideration the pressure drop that results from the large number of vessels that exist between the LCX/LM arteries and the capillaries in the rest of the body. We will do that by using a resistance-model approach; similar to circuits where the resistance R of an object is defined as the ratio of voltage across it (V) to current through it (I); here, we are defining the resistance R of a network of vessels to be the ratio of pressure drop between the outlet of the artery (*e.g.* LAD) and the capillaries, P_1-P_c, to the volumetric flow rate through the specific network, Q_1. This resistance is a constant, no matter how the flow changes in the LM bifurcation. Based on this information we can develop the following two equations for resistance:

$$R_{LAD} = \frac{|\Delta P|}{Q} = \frac{|P_C - P_{LAD}|}{Q_{LAD}} = constant$$

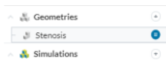
$$R_{LCX} = \frac{|\Delta P|}{Q} = \frac{|P_C - P_{LCX}|}{Q_{LCX}} = constant$$

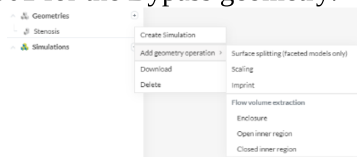
Even though the geometry of our problem consists only of the arteries LM, LAD and LCX (and not the capillaries or any other vessels in between), the output of the simulation (Q_1,P_1,Q_2,P2) should always satisfy the conditions set by R_1 and R_2.

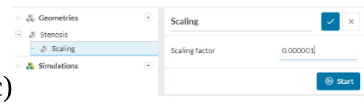
Simulation Tasks and Questions:

<u>Part I</u>

1. Simulate physiological conditions for a Stenosis and Bypass geometry. Leave default settings unless indicated in A-D below.
   i. Upload the provided Stenosis and Bypass model geometries in Simscale. Scale the models by a) hovering over the geometry file such that the options button appears, b) hovering over "Add geometry operation" such that the dropdown menu appears, select "scaling" and c) scale by a factor of 0.000001 **(1e-6)** for the Stenosis geometry and a factor of 0.001 for the Bypass geometry.



(a)


(b)


(c)

   ii. Create two Incompressible simulations based on the scaled geometries.
   iii. For both simulations, add the material as Water but change the values for density to 1060 kg/m^3 and viscosity to 3.3E-6 m^2/s to mimic that of blood.
   iv. For both simulations, include the following Boundary Conditions: Set the outlet conditions to be zero gauge pressure at the LAD and LCX faces. Set the inlet volumetric flow rate to be 2.083E-6 m^3/s by selecting the velocity inlet condition, changing the Velocity Type to "Flow Rate", and changing the Flow Rate Type to "Volumetric".
2. Create a table like the Table below for the Stenosis and Bypass simulations and report the average values you obtain for the simulation. You will not be able to find explicit values due to the geometry and will need to estimate the values to the best of your ability using simscale. (Note the numbers indicated in the table below are NOT the expected results, merely representative of the sorts of values we want to see reported out). Round pressure values to the nearest ten Pascals (*i.e.* 93 Pa would be rounded to 90 Pa) and round velocity to the nearest thousandths (*i.e.* 0.12823 m/s would be rounded to 0.128 m/s). You will need to calculate the Reynold's number, Blood Pressure (absolute pressure based on simulation output for relative pressure), and resistance (see above equations).

TABLE
Healthy Arterial System: Data and Simulation Results

Location	LM	LAD	LCX
Relative Pressure	105 Pa	0 Pa (BC)	0 Pa (BC)
Volumetric Flow Rate	2.080×10^{-6} m^3/s	5.589×10^{-7} m^3/s	1.522×10^{-6} m^3/s
Velocity	0.1837 m/s (BC)	0.1779 m/s	0.3364 m/s
Reynolds Number	211.4	107.8	255.2
Blood Pressure	13332 Pa	13227 Pa	13227 Pa
Resistance	--	1.983×10^{10} kg/m^4 s	7.280×10^{9} kg/m^4 s

3. Create appropriate figures in order to visualize the important velocity and pressure from your simulation. You will likely want to illustrate regions of max and min values using either cutting planes or isosurfaces. Simulation results and regions of interest should be clearly labeled and described in your report. Each figure should be accompanied by descriptive text in the main report, as well as a caption.

Questions to answer in Part I results/discussion section: (A-C should be addressed in three individual paragraphs following the description of your figures)

A. How do your values for relative pressure, volumetric flow rate, and velocities compare in the three arteries between the stenosis and bypass simulations? Write a brief paragraph discussing each of these values, referring to your result figures.
B. While Simscale does not provide a read-out for shear stress, using your knowledge of fluid dynamics, where would you expect areas of high and low shear stress in each simulation? How do these compare (*i.e.* would there be more or less shear stress in one case or another)? Write a brief paragraph discussing this and why that

might be important to the patient. *Hint- what might happen to the plaque in regions of high shear? How do the geometries of these vessels relate to other flows we've discussed in class?*

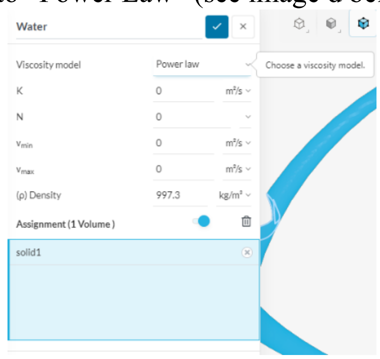
C. How does the information obtained in your simulation of these two cases provide important information about bypasses? Make one statement guiding the FDA for or against the bypass as modeled. If against, make one suggested change (diameter of bypass, location, etc). If you are for it, state the most compelling reason for why you support the bypass as proposed.

<u>Part II. Choose *ONLY ONE* of the two alternative scenarios below:</u>

Scenario I. Simulate blood as a non-Newtonian Fluid.

Repeat analysis from part I in both the stenosis and bypass using a non-Newtonian model for blood (steps below). Follow these steps to use a non-Newtonian viscosity model:

A. Under the material name, click the default viscosity model "Newtonian" to make appear the drop-down menu for viscosity models. Change the model to "Power Law" (see image d below).



(d)

B. Enter the following constants: K = 0.98 m^2/s, N=0.708, v_{min} = 0, v_{max} = 1.88E-5 m^2/s.

Questions to answer in Part II results/discussion section: (D-F should be addressed in three individual paragraphs following the description of your new figures)

D. How do your values for relative pressure, volumetric flow rate, and velocities compare in the three arteries between the stenosis and bypass simulations in the non-Newtonian simulation? Write a brief paragraph discussing each of these values, referring to your result figures.
E. What makes blood a non-Newtonian fluid? Perform your own research to learn about the properties of blood and include references on how blood can be modelled.
F. Compare the Newtonian to the non-Newtonian simulations. How different are the results? Is one approach more accurate than the other? Why?

Scenario II. Repeat Part I at a higher volumetric flow rate.

Repeat analysis from part I in both the stenosis and bypass using a higher volumetric flow rate. Change your boundary conditions such that inlet volumetric flow rate is 2.7E-6 m^3/s by selecting the velocity inlet condition, changing the Velocity Type to "Flow Rate", and changing the Flow Rate Type to "Volumetric".

Questions to answer in Part II results/discussion section: (A-C should be addressed in three individual paragraphs following the description of your figures)

D. How do your values for relative pressure, volumetric flow rate, and velocities compare in the three arteries between the stenosis and bypass simulations to your previous simulation? Write a brief paragraph discussing each of these values, referring to your result figures.
E. What might make the volumetric flow rate of a person increase to this amount? Perform your own research to learn about blood flow and how it changes across individuals and heart rates.
F. Compare the first lower volumetric Newtonian simulations to the higher volumetric flow rate simulation. How different are the results? Is one approach more accurate than the other? Why?

Rubric: This is the rubric that will be used to grade your project. Only the items listed below will be considered when evaluating the project. A completed assignment must have all of the items confirmed as complete; thus a "no credit" in any one of the items will mean a no credit for the project. Use the listed items as a checklist prior to submission to make sure that you receive credit for the assignment.

Overall Report

	Complete	**No credit**
Title page with your name, class section, date submitted and Mini-Project #2		
Executive summary is only 1 pg with at least >=1 sentence about each section		
Formatting is correct (times/arial 11, correct pg 1 header, footer all pages, sections bold, subsections bold/italics)		
Less than 5 glaring grammatical errors found		
Equations, Figures, Tables formatted appropriately and computer generated		
References included and formatted correctly in main text and the concluding reference section		
Introduction includes background information on cardiovascular diseases and stenosis		
Methods section included and describes approach for Parts I and II results		

Results & Discussion

	Complete	**No credit**
Part 1 has the two requested tables for stenosis and bypass simulations with Location, Relative Pressure, Volumetric Flow Rate, Velocity, Reynold's Number, Blood Pressure, and Resistance provided with reasonable values provided		
Part 1 has appropriate velocity and pressure figures for both stenosis and bypass simulations indicating any regions of interest		
Part 1 has appropriate velocity and pressure results clearly discussed in the text		
Part 1 A-C questions each answered with a paragraph		
Part 2 has one of two scenarios included		
Chosen part 2 has the two requested tables for stenosis and bypass simulations with Location, Relative Pressure, Volumetric Flow Rate, Velocity, Reynold's Number, Blood Pressure, and Resistance with reasonable values provided.		
Chosen Part 2 has appropriate velocity and pressure figures for both stenosis and bypass simulations indicating any regions of interest		
Chosen Part 2 has appropriate velocity and pressure results clearly discussed in the text		
Part 2 D-E questions each answered with a paragraph		

Conclusions & Recommendations

	Complete	**No credit**
>=1 paragraph summarizing findings		
>=1 paragraph summarizing recommendations to the FDA for use of the bypass as simulated		
>=1 paragraph summarizing limitations of the work		
>=1 paragraph summarizing use of CFD models in understanding cardiovascular disease (in this work and other references)		