BE 172 Spring 2018

Week VII: Hemorheology

Objective

To characterize the non-Newtonian flow properties of blood using preserved pig blood and a small diameter cylindrical tube. We will measure viscosity, hematocrit and calculate the oxygen carrying capacity of blood as a function of hematocrit.

Fluid Mechanics Fundamentals

The flow of any real fluid gives rise to tangential frictional forces which are called viscous forces. Consider a fluid filled space between two parallel plates, one is stationary and one is moving with a constant velocity u. A very thin layer of fluid adheres to the stationary plate; the velocity of this fluid layer is zero. A thin layer of fluid adheres to the moving plate; the velocity of this fluid layer is u (no slip boundary condition). The velocity gradient is uniform. The following relationship holds:

$$\tau = \mu \frac{du}{dy}$$

◎ ($ML^{-1}T^{-2}$) is the shear stress maintaining the flow, du/dy (T^{-1}) is the velocity gradient or shear rate between the two plates, and ◎ ($ML^{-1}\ T^{-1}$) is the coefficient of viscosity of the fluid. In c.g.s. unit the unit of viscosity is called a poise, in honor of Poiseuille.

$$1 \text{ poise} = 1 \text{ dyne-second/cm}^2$$

The viscosity describes a material property of the fluid being studied. Fluids in which the stress is always directly proportional to the shear rate, i.e. the viscosity ◎ is constant, are called Newtonian fluids. Water is a typical example. There are some fluids, particularly those with large constituent molecules in which the viscosity varies with the shear rate. Some fluids (e.g. cream) do not begin to flow until the shear stress exceeds a critical value (the yield stress) and behave like solids for smaller shears. Some fluids (e.g. silly putty) behave like a fluid if low shear stresses are maintained over a long period of time, but like a solid when large stresses of short duration are applied. These are examples of non-Newtonian fluids. Blood, over a certain range of stresses and shear rates, behave as a non-Newtonian fluid, exhibiting both a yield stress and shear dependent viscosity. In large arteries, blood is effectively Newtonian, but this is not the case in the micro circulation.

The basic equations governing the flow of a Newtonian, viscous, incompressible and homogeneous fluid can be approximated by the Navier-Stokes equations:

Equations of Continuity: $$\frac{\partial v_i}{\partial x_i} = 0$$

Equations of Motion: $$\rho \frac{Dv_i}{Dt} = \rho X_i - \frac{\partial p}{\partial x_i} + \mu \frac{\partial^2 v_i}{\partial x_k \partial x_k}$$

These equations represent conservation of mass and conservation of momentum. ◎ is the density of the fluid, x_i (i=1..3) are the rectangular Cartesian coordinates, v_i are the velocity components along the x_i axes, X_i is the body force per unit mass, p is the pressure and ◎ is the coefficient of viscosity. The repetition of an index in a term implies a summation with respect to that index over its range and is called a dummy index.

As part of your lab report, write out the above equations in their full length without the use of abbreviated index notation. The equation of motion can be interpreted as:

mass x acceleration = body force + pressure gradient force + viscous force

It is possible to rearrange the Navier-Stokes equations in a dimensionless form by normalizing each term with a characteristic velocity V and a characteristic length L. For the example of flow in a circular tube, V can be the mean flow speed and L the tube diameter. We can introduce the dimensionless variables as x◎ = x/L, u◎ = u/V, etc. It can then be shown that the dimensionless form of the Navier-Stokes equations has only one physical parameter in the form ◎VL/◎. This parameter is defined as the Reynolds number R_N. Consider two geometrically similar (same shape, different size) bodies in a moving fluid. The two flows will be identical in the dimensionless variables if R_N for the two bodies are the same. The Reynolds number is said to govern the dynamic similarity. This is an important consideration in the design of experiments because the dynamic similarity principle allows one to construct convenient size models and choose a fluid with appropriate density to match the R_N in real life situations.

Blood in the body is carried by a system of branching vessels that range in size from 1 cm in diameter in the aorta to 8 microns in diameter in the capillaries. The Reynolds number in these vessels ranges from 2,000 to less than 0.002. The physical interpretation of the Reynolds number is a ratio of the inertia forces to the viscous forces. For large R_N, the inertia forces are the dominant factors in the Navier-Stokes equations. For small R_N flow, the viscous forces are dominant.

The Navier-Stokes equations are difficult to solve, but there are situations in which the non-linear terms disappear and the solution can be obtained by standard methods. One particular example is the steady flow of an incompressible fluid in a horizontal circular pipe of small diameter, reasonable length, small Reynolds number, the flow is fully developed, and the end effects are negligible. The solution is the parabolic velocity profile of the Hagen-Poiseuille flow.

Based on Poiseuille's study of mechanics of the circulation in 1840, the following famous law for steady flow in a pipe remote from an entrance is derived:

$$\Delta p = \frac{8 \mu l}{\pi R^4} Q$$

This equation relates the flow rate Q (cm^3/sec) through the pipe with radius R (cm) to the pressure drop ∆p (dyne/cm^2) along the pipe length l (cm). We shall use this linear relationship in studying the blood flow through a circular tube.

Rheology of blood

Blood is the fluid that nurtures life, contains many enzymes and hormones, various blood cell components (red blood cells, white blood cells, platelets), knows when to flow and when to clot, and transports oxygen and carbon dioxide between the lungs and the cells of the tissues. The flow properties of blood are determined by hematocrit (blood cells concentration), plasma viscosity, red blood cell aggregation and deformability, and blood vessel wall properties. The rheology of normal blood varies with the shear rate. As the shear rate is increased, deformation, orientation and aggregation of the red blood cells lead to reduction of the blood viscosity, i.e. whole blood exhibits shear thinning. Blood viscosity measurement is high at low shear rate, where red cells aggregation is the dominant feature. At higher shear rate, the viscosity decreases because the aggregation begins to break up and the red cells participate by elongation, orientation and deformation.

There are various types of viscometer for measuring blood viscosity. The capillary viscometer method that we will use in this experiment is the simplest to use but it can be the most difficult to interpret particularly due to the non-Newtonian nature of the blood. Some complications that can enter into the analysis are: 1) unless the tube is carefully washed and dried or a new tube is used for each measurement, there will be some carry over effects due to the adherence of a thin film of fluid on the inner wall; 2) if the measuring tube is fed from a reservoir, entrance conditions can affect the character of the flow for some distance downstream, and for whole blood, may influence the concentration distribution and even the actual concentration; 3) the meniscus effects in small tubes may cause a significant pressure head loss; 4) using blood, the shear rate varies from zero at the center of the tube to a maximum at the wall non-linearly.

In addition to the above considerations, one major factor that will affect the blood viscosity measurement is the problem of blood handling and storage. The blood used in this experiment will be drawn from a swine meat-packing facility. The initial drawing process can affect the shape of the red blood cells. Since the blood will be stored, anticoagulation agents and anti-bacterial agent will be introduced. These can further affect the pH, crenation and hemolysis of red cells, and alter the blood's mechanical properties. The drawn blood will be stored in the refrigerator at 4°C.

Prelab Questions

1. Briefly describe 2 methods for measuring viscosity, and why the can be used to measure blood viscosity.
2. Assume you have a 10-feet tube of inner diameter 2 mm filled with water and connected to a pressure head 2 feet high at one end, how much fluid (in theory) drips out the other end in 1 minute?

3. Find in the references or literature, what are normal wall shear stresses on arterioles, capillaries, and venules. Define and justify the size of the vessels you are using to calculate the wall shear stresses.
4. Can the internal roughness of the blood vessels affect the head of pressure loss due to friction? How does ratio between the roughness and the internal diameter of the blood vessel affect the average flow? Briefly explain your answers.

Equipment

- Ring stand with fluid reservoir
- Capillary tube and connecting tubing
- Fluid collection chamber
- Force transducer
- Labview computer acquisition program
- Blood sample
- Two plasma expanders (Low and high viscosity)

Experimental Procedure: 4 parts

1) Find the diameter of the capillary tube utilizing Poiseuille's equation with a fluid of known viscosity, water.
2) Measure the viscosity of whole blood with the capillary tube. Vary the pressure head and measure flow to calculate the viscosity. Plot viscosity against flow to observe the non-linear characteristics of blood.
3) Change hematocrit by mixing blood with the plasma expander. Determine the blood viscosity for each hematocrit. Determine the effect of the plasma viscosity in blood viscosity.
4) Calculate the effective oxygen carrying capacity of blood as hematocrit varies. Effective oxygen carrying capacity is defined as the product of flow rate times the corresponding hematocrit for a given pressure head. The results are the basis of rate processes for the clinical use of hemodilution. (*you can do this part with your results out of the lab*)

Part 1 You will be given a piece of polyethylene (PE) tubing of unknown internal diameter. Measure the length of the tube, straighten it out and mount it horizontally on the work bench. Set up the driving pressure head, fill it with water and connect one end of the PE tube to it as shown in Figure 1. Use the square plastic container to raise the ring stand so that you can catch the fluid as it drips near the edge of the table. The fluid shown dripping in Figure 1 should be at the edge of the table top, and the fluid catching mechanism/force transducer mounted on the ring stand on top of the plastic container.

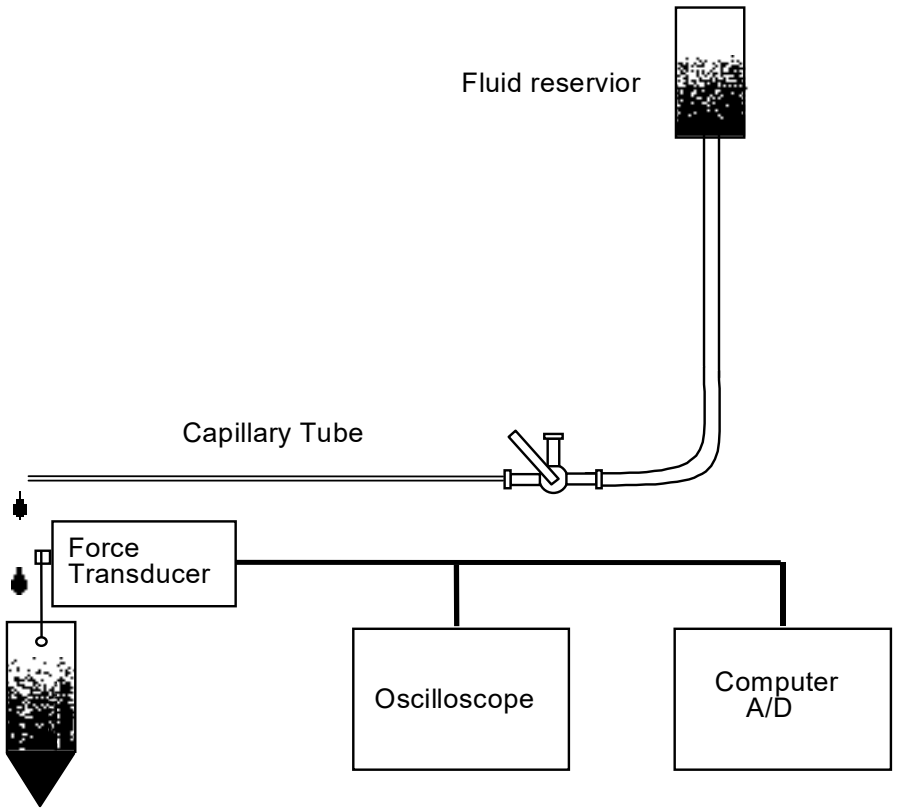

Figure 1: Experimental Setup

In order to determine the radius of the tube we make use of Poiseuille's formula. We will use the viscosity of water as the known fluid. Since viscosity is dependent on temperature you will need to find the room temperature. The following table relates viscosity of water to temperature:

Temperature (°C)	Viscosity (centipoise)
18	1.0559
20	1.0050
22	0.9579
24	0.9142
26	0.8737
28	0.8360
30	0.8007

Referring back to Poiseuilleís equation:

$$\Delta p = \frac{8\mu l}{\pi R^4} Q$$

◎P is determined from the hydrostatic pressure head (check your units), the length of the tube has been measured, the viscosity of water was found from the table, and the flow rate Q (ml/min) is determined by weighing the amount of water collected as a function of time using a force transducer. To find Q, acquire the force signal on the Labview computer system as a function

of time for at least ***10 seconds (****after the flow has reached steady state)*, and include at least one plot of the raw signal (mass vs. time) in your report. Use a fitting procedure to determine flow rate from the raw signal, and include an error estimate of the fit. With the above information you should be able to determine R. Make ***3 measurements*** and take the average to give the estimated radius of the tube.

Part 2 After determining R, measure the hematocrit of the whole blood by micro-tube centrifugation. Then proceed to measure the viscosity of the whole blood by varying the pressure head and measuring flow (as described in Part 1). Make measurements at ***3 pressure levels*** and note the non-linear nature of the pressure flow curve. Take ***3 measurements*** (and average them) at each pressure level. Calculate viscosity and plot viscosity versus flow.

Part 3 Change the hematocrit of the blood by diluting it with the low viscosity plasma expander (LVPE) to obtain a total of ***3 different hematocrits*** ranging from that of whole blood to about 14%. Verify each hematocrit with the micro-centrifuge. Determine blood viscosity using the procedure in part 2 for each hematocrit and note the change in non-Newtonian behavior as a function of hematocrit. You can use 1.06 as the specific gravity of blood and 1.0 as the specific gravity of plasma expander.

Part 4 Change the hematocrit of the whole blood by diluting it with the high viscosity plasma expander (HVPE) to the lowest hematocrit measured in part 3. Verify the hematocrit with the micro-centrifuge. Determine blood viscosity using the procedure in part 2. Note the effect of plasma viscosity in the non-Newtonian behavior of the blood viscosity.

Part 5 The rate of oxygen delivery to tissues is equal to the product of the blood flow and the arterial blood oxygen content. The arterial blood oxygen content is mainly that carried within the hemoglobin in the red cells and is proportional to the hematocrit. Thus, the effective oxygen carrying capacity can be defined as the product of the flow rate times the corresponding hematocrit at a given pressure head. Generate a plot of the effective oxygen carrying capacity vs. hematocrit. Normalize the effective oxygen carrying capacity such that the value for whole blood is 1. In your write-up, discuss the applicability of hemodilution, and how does it affect blood oxygen delivery.

Report

From now on there will not be specific requirements given for the reports. Use your previous experiences and current handout to determine what details and discussion points should be included in the reports.