Hands On the Human Body! — March 24, 2002
Freshman Clinic II — Dr. Stephanie Farrell

THE CARDIOVASCULAR SYSTEM

OBJECTIVES

1. To measure cardiac output (blood flow rate) using the Indirect Fick Method
2. To measure blood pressure using a sphygmomanometer
3. To become familiar with the concepts of laminar flow, turbulent flow, and Reynolds number
4. To apply a mechanical energy balance to the circulatory system
    a. To explore hydrostatic effects
    b. To calculate the work of the heart
    c. To calculate frictional losses in the circulation system
    d. To investigate interconversion of kinetic energy and pressure

ENGINEERING PRINCIPLES

Various forms of energy are associated with a fluid flowing in a piping system, e.g., kinetic energy, potential energy, energy due to pressure changes, energy added by a pump, and energy lost through friction. The Law of Conservation of Energy allows us to write a mechanical energy balance on a fluid system:

$$\frac{1}{2\alpha}\Delta v^2 \quad + \quad g\Delta h \quad + \quad \frac{\Delta P}{\rho} \quad + \quad \hat{W} \quad + \quad \hat{E}_F \quad = 0 \tag{1}$$

Kinetic energy	Potential energy	Pressure energy	Work done by pump	Frictional losses

Where,

v = fluid velocity at a certain point in the system
α = 0.5 for laminar flow or 1.0 for turbulent flow. α accounts for the fact that the velocity is not uniform across the pipe cross section.
g = acceleration of gravity (981 cm/s^2)
h = elevation at a certain point in the system
P = pressure at a certain point in the system
ρ = fluid density
$\hat{W}$ =the work done by the system on the surroundings (per unit mass flow rate)
$\hat{E}_F$ = the friction loss from the system (per unit mass flow rate)

This mechanical energy balance is sometimes called the Extended Bernoulli Equation. This equation is frequently found in textbooks of Physics, Fluid Mechanics (ME, CE, and ChE), and Aerodynamics (ME).

In this lab we will investigate the different forms of energy in a fluid system. We will use the circulatory system as an example of fluid (blood) being pumped (by the heart) through a piping system (arteries and veins).

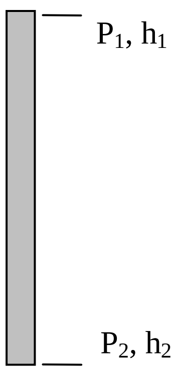
Measured Variables will be: blood pressure, elevation, blood flow rate.

Typical Values will be given for blood vessel diameter and blood pressure at certain points in the circulatory system. These values could be obtained only through invasive procedures.

Calculations will include: kinetic energy, pressure energy, hydrostatic pressure, work of the heart, and frictional losses in the circulation system. We will also see how kinetic energy and pressure can be interconverted, and we will use this to estimate the pressure rise in an aneurysm.

HYDROSTATICS OF THE CIRCULATORY SYSTEM

Hydrostatic pressure is the pressure exerted by a column of fluid. If the column of fluid has a height h and a density ρ, there will be a difference in pressure between the top of the column and the bottom of the column:



$$\Delta P = -\rho g \Delta h$$
$$P_2 - P_1 = \rho g (h_1 - h_2) \qquad (2)$$

Notice that if Equation 2 is solved for P_2, P_2 will be greater than P_1. This makes sense, since the column of fluid exerts a pressure downward toward the bottom. In the circulatory system, the pressure in the head is lower then the pressure in the feet (for a person standing upright).

Also notice that Equation 2 comes directly from the Mechanical Energy balance. Since the fluid in the column is static (i.e., not moving), there is no kinetic energy. Also because there is no motion, there is no energy loss due to friction. The fluid is not being pumped, so there is no pump work. Under these conditions, the mechanical energy balance reduces to Equation 2.

PUMP WORK

A pump does work *on a fluid flow system* by increasing the pressure of the fluid in the pipe. We can calculate the work done on the fluid by the pump, as the pump raises the pressure of the fluid. The pump does not increase the velocity or the elevation of the fluid, hence the kinetic energy change and the potential energy change are zero. Frictional losses are negligible in the pump also. For the pump, the mechanical energy balance reduces to:

$$\frac{\Delta P}{\rho} + \hat{W} = 0 \qquad (3)$$

Both Equation 1and Equation 3 are written on a *unit mass basis (e.g., per kilogram).* To find the *total rate of work* of a pump (or pumping power), we must multiply the equation by the mass flow rate (equal to the volumetric flow rate divided by density, Q/ρ):

$$-\dot{W} = Q\Delta P \tag{4}$$

In Equation 4, $\dot{W}$ is the pumping power. This equation can be used to determine the rate power (rate of work) of the heart, as it pumps blood at a flow rate Q. Notice that the rate of work should be negative, the heart does work on the fluid (a positive term in the mechanical energy balance indicates that the fluid is doing work on the surroundings).

INTERCONVERSION OF KINETIC ENERGY AND PRESSURE

Consider a short segment of a horizontal pipe through which a fluid flows. There is no change in elevation within this section of pipe, so the potential energy change is zero. There is no pump within the segment of pipe, so the pump work is zero. The frictional energy losses in the short pipe are also negligible. The mechanical energy balance reduces to:

$$\begin{aligned} \frac{1}{2\alpha}\Delta v^2 + \frac{\Delta P}{\rho} &= 0 \\ \frac{\rho}{2\alpha}\left(v_2^2 - v_1^2\right) &= P_1 - P_2 \end{aligned} \tag{5}$$

In a fluid flow system, a velocity change would be due to a narrowing or widening of the pipe diameter as shown in Figure 1. When the pipe diameter narrows, the fluid velocity increases. This causes the pressure of the fluid to decrease.. As we can see from Equation 5, when the velocity changes, the fluid experiences an accompanying change in pressure. A wider pipe (increase in cross sectional area) causes the velocity to *decrease*. Notice that if the *velocity decreases, the pressure increases*!

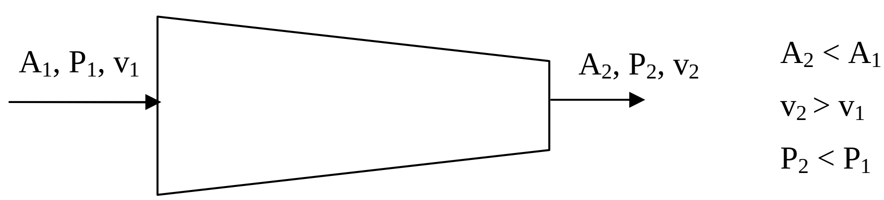
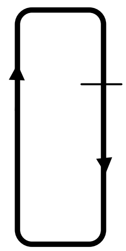


Figure 1. When the pipe diameter narrows, the fluid velocity increases. This causes the pressure of the fluid to decrease.

FRICTION LOSSES IN A PIPING SYSTEM

In the circulatory system, the heart pumps the blood through an entire piping circuit and back to the starting point at the heart. When we consider the entire circuit, there is no net change in elevation (because the fluid comes back to the starting point); there is no net change in kinetic energy, and no net change in pressure. (Although at different points in the circuit, the fluid may experience changes in kinetic energy, pressure energy, or hydrostatic pressure.)

Considering the entire circuit, the mechanical energy balance reduces to:



$$\hat{W} + \hat{E}_F = 0 \tag{6}$$

Figure 2. The complete flow circuit.

In other words, the reason the pump must do work on the system is to overcome frictional energy losses in the piping system. The work of the pump is equal to the frictional loss in this situation.

HOMEWORK

To be turned in on the due-date: (1) Lab notebook page, (2) calculations and (3) answers to follow-up questions. The calculations should be neatly written on engineering paper (show all steps and show units throughout your calculations). The answers to the follow-up questions should be typed. Also hand in your evaluation/feedback form for this lab.

Calculations

1. Hydrostatic Pressure
   a. Draw a stick figure depicting the positions of your blood pressure measurements. Indicate the elevation (relative to heart level) of each position.
   b. Calculate the average pressure at each point (P_1 at level 1 and and P_2 at level 2)

   $$BP_{avg} = \frac{\text{systolic} + 2 * \text{diastolic}}{3}$$

   c. Using the heart-level measurement as (P_1, h_1) predict the blood pressure at the second position ((P_2, h_2) using Equation 2.

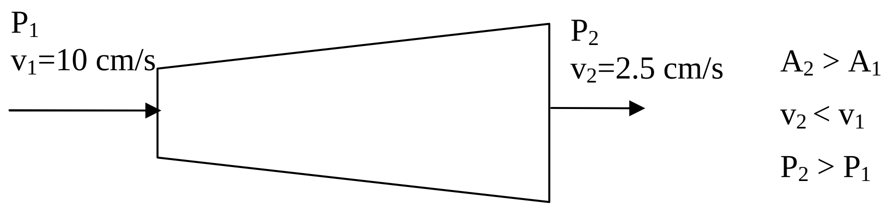
   The density of blood, $\rho = 1.056$ g/ml[1]. The following conversion factor will be necessary: 7.5×10^{-4} (mm Hg)=1 g/(cm s^2).

   d. Compare the value of P_2 obtained in part b to your measured value.
2. Pump work
   a. Using Equation 4, calculate the rate of work of the heart. The heart raises the pressure from $P_1 \approx 0$ mm Hg to P_2 = your measured value. Use the conversion factor 7.5×10^{-4} (mm Hg)=1 g/(cm s^2) to obtain your answer in (g cm^2)/s^3
   b. Convert your answer for part (a or b) to kcal/hr. Use the conversion factor 1 (g cm^2/s^3) =8.6×10^{-8} kcal/h.
   c. The Mechanical efficiency of the heart is about 10% [1]. Calculate the actual energy expenditure required to maintain the heart's pumping action. (Hint: use the definition of efficiency that you used in the metabolism module).

3. Kinetic Energy

    a. Using Equation 5, calculate the pressure in an aneurysm. An aneurysm is a bulge in an artery due to a weak wall.

    In the normal artery, the average velocity of blood flowing in the arteries is 10 cm/s. For the normal pressure P_1, use your average blood pressure that was calculated in Question 1 (normal elevation).The aneurysm causes a bulge – the diameter doubles, causing the velocity to decrease to 25% of the original velocity.



    b. Recalculate (a) for the case where the cardiac output increases 3 times due to exercise. This causes the velocity to increase to 30 cm/s in the normal artery and 7.5 cm/s in the aneurysm.

Follow-up Questions

1. If a small aneurysm developed in an artery, the local pressure increases, pushing outward against the artery wall. What will this do to the size of the aneurysm? What effect will this change in aneurysm size have on the pressure on the aneurysm?
2. In your own words, describe how the Streamliner Artificial Heart works (see Streamliner link on course website. Cite this reference and any others that you use). One paragraph is enough.
3. A VAD is a ventricular assist device. In your own words, describe how a VAD works. When was the first totally implantable LVAD procedure performed? (See State of the Art link on course website. Cite this reference and any others that you use).
4. In your own words, describe the ABioCor Artificial Heart. Comment on the function, materials, power source, and who could benefit. (See link to Abiocor on course website, then click on ABioCor Replacement Heart, then click on FAQ. Cite this reference and any others that you use).
5. How much power do you think must be supplied to the ABioCor Artificial Heart? Explain.

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[1] Cooney, David O., Biomedical Engineering Principles, Marcel Dekker, Inc., NY, 1976.