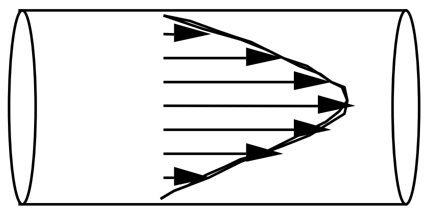
General Biology 2 -- The Flow of Fluids in Tubes*

I. Laminar and Turbulent Flows

A. Overview. When a fluid flows through a tube (or across a surface, there are two general flow types, laminar (the most common in the body) and turbulent.

B. Laminar Flow – this is the "ideal" flow type. Each particle in the fluid moves at a constant distance and in parallel to the walls of the tube or surface. The particles in the center of the tube (farthest from the walls) move the most rapidly. The particles in contact with the walls move the least. Thus, if we cut the tube lengthwise and looked at the velocities of the particles we would see the following:



where the vectors indicate the direction and velocity of particles in different parts of the tube and the curved line at the arrowheads indicated the general velocity profile (highest in center lowest at edges.) Thus, for the entire tube, the profile of particle velocities will look like a cone – slowest on the edges and faster as we move towards the center. Thus, particles in tubes do not flow everywhere at the same velocity.

1. The fact that flow is slow at the edge of the tube is significant – this means that the fluid undergoing diffusion with tissues (blood nearest the walls of a capillary moves most slowly and this gives more time for diffusion to occur (more about this later.)

2. Why the velocity profile? This has to do with friction.

a. Friction of the fluid with the walls of the tube. The magnitude of this effect is governed by the area of the tube wall.

b. Internal friction of the fluid – **viscosity**. Viscosity is a measure of the difficulty particles have sliding past each other without interacting. The more viscous, the more interaction (friction) – the more one particle tends to influence another.

c. We will return to a discussion of these factors shortly when we see Poiseuille's equation below.

3. In most blood vessels most of the time, blood flow is laminar. The main places where it is **not laminar is around constrictions such as valves**.

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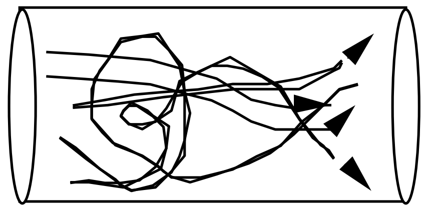
C. Turbulent flow. In this case, particles move in highly irregular paths. They interact extensively with each other and with the walls of the tube. Here is a diagram:



Turbulent flow can arise at a number of places -- for instance anywhere a vessel opens or shuts, makes a sharp bend or undergoes a large decrease in diameter.

II. Variables of Concern in Circulations:

A. **Pressure, *P*,** – force/area, usually given as mmHg or kPa

B. **Volume, *V* or *q*,** given as liters or some subunit (e.g., dl or ml)

C. **Particle velocity, *v*,** given is m * s^{-1}. The discussions above in the laminar vs. turbulent flow section dealt with particle velocity.

D. **Volume velocity**, $\dot{Q}$, given as liters/sec or minute. This is the flow through a tube past a particular point per unit of time. **We have already seen volume velocity when we considered cardiac output.**

III. Laminar flow in tubes

A. Pressure and volume velocity

1. Pressure is a measure of energy per unit volume. It has units of force/area (note this is dimensionally the same as energy/ volume.) Thus, when fluids move down total pressure gradients, they are also moving down an energy gradient.

2. For any ideal fluid's movements:

1. $\dot{Q} \propto \Delta P$

where ΔP is the pressure difference between two points between which flow occurs. Changing this relationship to an equation, we have:

3. $\dot{Q} = G * \Delta P$ -- know this equation

where *G* is the conductance. Conductance is the inverse of resistance, *R*:

4. $R = \frac{1}{G}$ -- know this equation

and so, by substitution:

5a,b. $\dot{Q} = \frac{\Delta P}{R}$ -- or-- $R = \frac{\Delta P}{\dot{Q}}$ -- know these equations

Note that this equation is essentially identical to Ohm's Law used in electricity (for those of you who have electricity in a physics class.)

B. Resistance and flow. Experiments by the French physician **Poiseuille** established that resistance (*R*) to flow in smooth tubes can be described by the following equation:

6. $$R = \frac{8 * \eta * L}{\Pi * r^4} = 20.37 * \frac{\eta * L}{r^4} = k * \frac{\eta * L}{r^4}$$

where ***r*** is the radius of the tube, η is the viscosity of the fluid (see above), ***L*** is the length of the tube, and ***k*** is a constant equal to 8 * η / π. Thus:

- the longer the tube, the more resistance;
- the smaller the radius, the more resistance.
- Resistance is much more strongly dependent on radius than length since radius is raised to the fourth power.

If we substitute equation 6 into equation 5a we end up with **Poiseuille's equation**:

7a. $$\dot{Q} = \frac{(\Delta P * \Pi * r^4)}{(8 * \eta * L)}$$

7b. $\dot{Q} == \frac{\Delta P * r^4}{k * \eta * L} \quad (i.e., \frac{\Delta P}{R})$ -- know this equation (the more complicated one.)

IV. More About Resistance

A. In the vascular system tubes are constantly changing radius (for instance, think about going from arteries to capillaries.) They are also constantly dividing (tree-like into smaller more numerous branches – arteries to capillaries) and then re-joining into fewer larger diameter vessels (capillaries to great arteries.) How do we determine the overall resistance to flow in such a complex system?

B. How do we determine the overall resistance of a **single vessel that constricts or widens in different places.** Each place where the radius changes has a different resistance (see eq. 6 above). **These different resistances are in series with respect to each other** (think back to series elastic elements in muscles). In such a case, the total resistance (R_t) is:

8. $R_t = R_1 + R_2 + \ ... + R_n$ -- know this equation

Notice that this is pretty much what is stated in equations 7 a and b: for a constant radius tube, as we add further length to this tube we expect the resistance to increase directly with the added length (because of greater total frictional contact between the tube and the fluid and with greater internal resistance due to friction between the particles in the fluid (viscosity).)

C. What about cases where a vessel divides into two? The two paths that emerge from one are termed parallel paths and therefore these resistances are parallel resistances. Their total resistance is given by:

9. $$\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \ ... + \frac{1}{R_n}$$ -- know this equation

Thus, **as more and more resistances are added to each other in parallel, the total resistance of the combined parallel paths decreases**.
If you have trouble with this idea, consider the following. Resistance is in the inverse of conductance (eq. 4). A conductance is a path for a fluid to travel through. If I provide more paths, I provide more total conductance and a fluid will flow more quickly. For instance, image a barrel of water. A single 1 cm hole in the bottom provides one path for water to leave. If I now add a second 1 cm hole to the bottom, the conductance has been doubled (resistance has been cut in half) and flow will double.

Note: you only need to understand the general principle of series and parallel resistances – you will not need to solve networks of resistances in this course (as you would need to do in physics.)

V. Pressure, Volume, Work and Energy. If pressure is energy per volume, then work is:

10. $$W = E = \int_{v_1}^{v_2} P dV$$ -- know this equation

so **if, for example, the pressure required to move a certain amount of blood must be increased due to an increase in resistance, the work will increase**.

Note: The work required to a certain volume of fluid through a certain resistance is far greater in turbulent flow than laminar flow.