CIRCULATORY PHYSIOLOGY SECTION 5:
HEMODYNAMICS: HYDRAULIC FILTERS, FLOW, AND BLOOD PRESSURE[*]

Summary: The concepts of hydraulic filtering and blood pressure are discussed, as are the complexities of the inter-relationships between the factors that determine blood pressure.

I. Review of Pressure and Flow Relationships:

A. As with air in the lungs, flow between two points can generally be described according to the hydraulic version of Ohm's Law:

1. $$Q = \frac{\Delta P}{R}$$

where **Δ*P*** is the difference in pressure between two points in the circulation, ***Q*** is the volume that flows between these points and ***R*** is the total resistance to flow between those points.

B. This can be expanded to show more terms that are important to the determination of resistance:

2. $$R = \frac{(8 * \eta * L)}{(\Pi * r^4)}$$

where η is the viscosity, ***L*** is the length of the tube, and ***r*** is the radius of the tube. Thus, by substitution, we have the Poiseuille Equation:

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

Note the overwhelming effect of radius on the flow and the resistance.

C. Finally, we should keep in mind that total resistances along the vascular system are calculated by two different means, depending on whether they are in series or in parallel:

for series resistances:

4. $R_t = R_1 + R_2 + \ ... + R_n$

Notice that this is pretty much what is stated in equation #2: for a constant radius tube, as we add further lengths to this tube we expect the resistance to increase directly with the added length (and therefore greater total frictional contact between the tube and the fluid) and with the greater total internal resistance (due to friction between the particles in the fluid (viscosity).

For parallel resistances:

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5. $\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \ldots + \frac{1}{R_n}$

Thus, **as more and more resistances are added to each other in parallel, the total resistance decreases**. This should also be obvious since resistance the addition of channels of flow (resistances) in parallel creates more opportunities for fluid to flow and thus for a given pressure gradient, more fluid will flow if there are more channels (think of a bucket with a one 1" radius hole in the bottom vs. another bucket with twenty 1" radius holes. Obviously, for a given difference in pressure, the flow will be greater in the second example and by eq. #1 the resistance must be less.

II. Blood Flow through the arterial system:

A. The **HYDRAULIC FILTER CONCEPT**:

1. A hydraulic filter is a device that **converts pulsatile flow into smoother, more continuous flow.**

2. To a large degree the arterial system acts as a hydraulic filter -- the filtering is not perfect and remains pulsatile, nevertheless the pulses are greatly smoothed compared to what comes out of the heart.

3. Principle:

a. **Three factors are required for a hydraulic filter to operate**:

1. the **Vessel must be compliant, but not infinitely so**.

2. There **must be some resistance to flow** in the vessel.

3. **Fluid must be added to the vessel in amounts that exceed its RESTING CAPACITY** to hold fluid: that is, the addition of fluid must cause the vessels to expand.

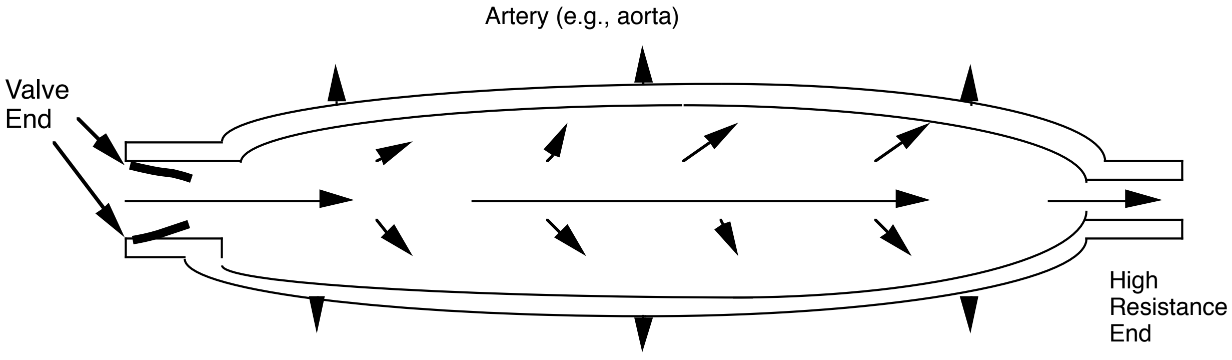
b. The addition of fluid in a volume that exceeds the resting capacity of the vessel at a rate that is greater than the rate at which the fluid can leave (determined by resistance) causes the vessel walls to expand elastically.

c. In this expansion, energy contained in the fluid is stored in the walls of the vessel.

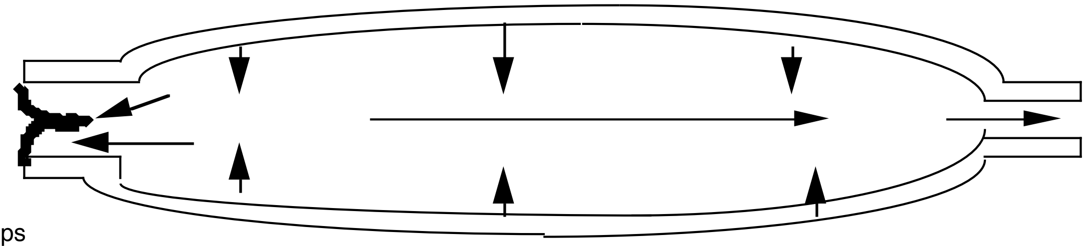
d. Of course, even while the vessel walls are still expanding, much fluid is still leaving through the end.

e. When the pump stops injecting fluid into the vessel, the stored energy in the vessels elastic walls is released and is used to keep the fluid under pressure and thereby continue the flow of the fluid out of the tube.

f. Thus, during the filling phase, the vessel stores some energy from the injected fluid. The remainder of this energy is used in the flow of some of the fluid out of the vessel. During the phase when the pump is relaxed, the energy stored in the vessel walls is used to keep the fluid pressurized and according to the flow equation, to keep fluid flowing.



As more blood enters (left) than can leave via the high resistance (rigth), the walls expand elastically and the tension in them is approximately equal and opposite to the blood pressure. Put another way, some of the energy in the blood (as pressure) is used to do work on the walls of the vessel to expand it elastically. Most of this energy is stored.



Heart stops pumping, valve is closed the higher pressure in the artery relative to the heart.

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The pressure in the blood is no longer greater than in the arteral wall; as a result, the walls rebound elastically and keep the pressure of theblood high (essentially returning the energy to the blood). The result is that flow out of the artery continues even though no blood is being added to the artery by the heart. The pulsitile flow of the heart has become more less so, although it certainly is not steady.

4. Hydraulic filters are also referred to as **WINDKESSEL VESSELS** (a German word). Windkessels are the old type of hand-pumped fire engines that converted a pulsatile inflow into a smooth outflow.

B. HYDRAULIC FILTERING AND CARDIAC WORK

1. To increase our understanding of both the flow of blood and also the energy demands on the heart, we will examine the work that a pump (e.g., a heart) does when it is attached to different types of vessels.

2. As an approximation, we can calculate the mechanical work of the heart as:

$$W = \int_{t=0}^{t=1} PdV \tag{6}$$

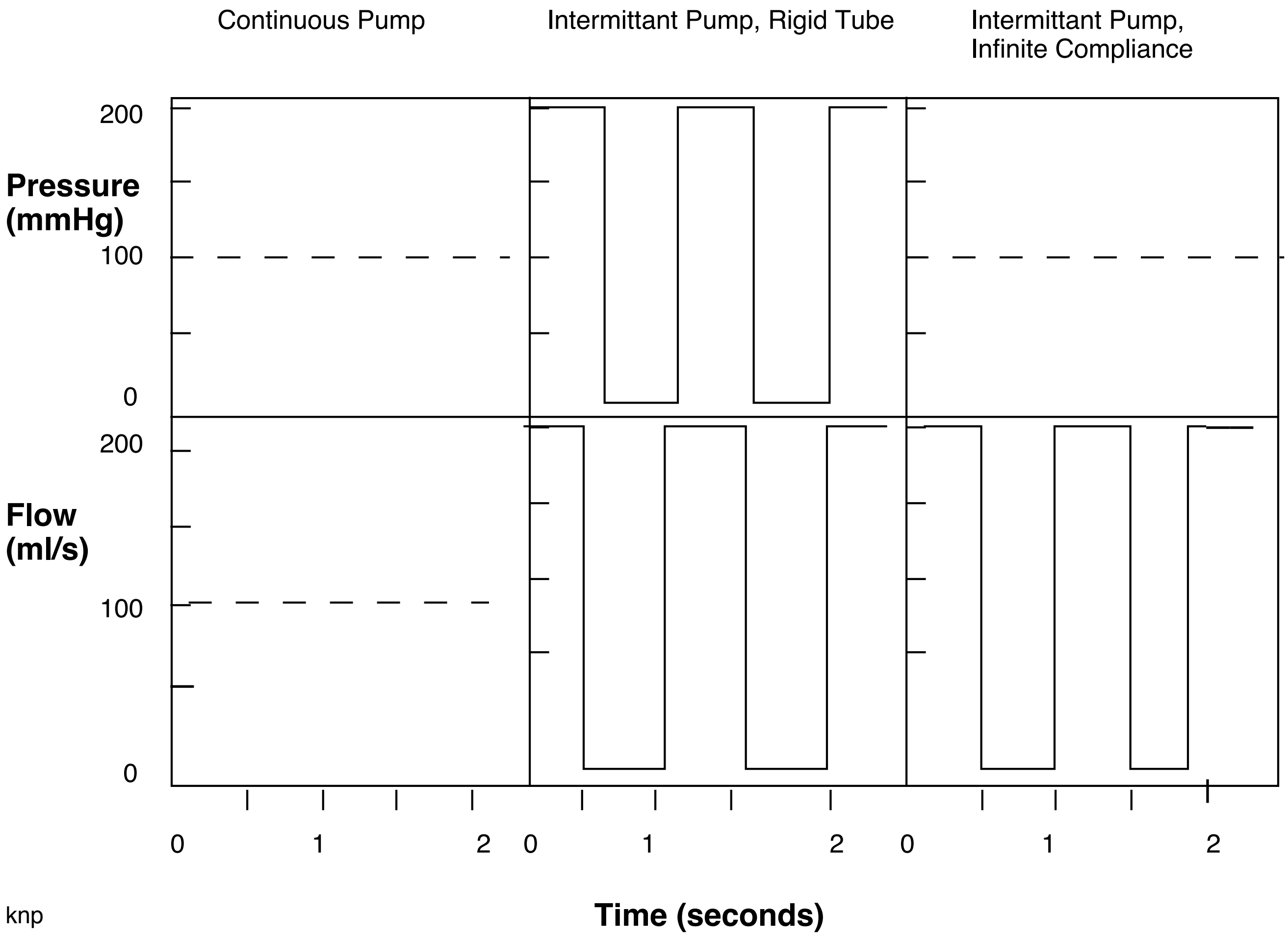
where ***W*** is work, ***P*** is pressure and ***dV*** is the increment in volume pumped. The times of integration, ***t*** = 0 and ***t*** = 1 will be taken as the start to the finish of a complete cardiac cycle; that is from one beat to another (see figure below). (Note that this is an approximation since it ignores inertial costs involved with pulsatile pumping).

Here are the examples, in graphical format:

! NOTE: TO MAKE THE VALUES USED IN THE EXAMPLE BELOW COMPARABLE, ALL OF THE NUMBERS WERE SELECTED TO GIVE A CONSTANT TOTAL PUMP OUTPUT OF **100 ml/s.**

REALIZE THAT THE GRAPHS OF FLOW ARE FLOW OUT OF THE HEART INTO THE VESSEL (I.E., CARDIAC OUTPUT), NOT FLOW FROM THE VESSEL.

ALSO, NOTE THAT WE WILL ASSUME THAT THE TERMINAL RESISTANCE IS THE SAME IN ALL OF THESE VESSELS AND THAT IT IS FAIRLY LOW.



3. **Example #1**: Assume that we have a **NON-PULSATILE PUMP** pushing fluid **through a tube of infinite elastance (rigid).**

    a. Further assume that:

        1. **Cardiac output is constant (non-pulsatile) at 100 ml/s**
        2. **Pressure is constant at 100 mm Hg**.

    b. The work done will be 10,000 mmHg * ml/s, or about 1.3 J.

4. For **example #2**, let's assume that we now have a **pulsatile pump**. In addition, assume that:

    a. The vessel walls have **INFINITE ELASTANCE**, that is, they are **RIGID TUBES**.

    b. The will **last for 1/2 of the total pump cycle of 1 s, therefore systole lasts 1/2 s**.

    c. For there to be a cardiac output of 100 ml/s where flow only occurs for 1/2 s., the flow rate from the pump must be 200 ml/s for that 1/2 s (i.e., 100 ml/s).

d. Therefore according to the flow equation (#1), the pressure during the period when blood is flowing out of the heart must be two times that in the first case above (since the R is the same in both cases but all the flow occurs in half the time).

1. Therefore, P = 200 mm Hg and Flow from the heart = 200 ml/s

2. Over the first 1/2 s (the pumping phase, the work done would be 40,000 mm Hg * ml/(0.5 s), over the entire cycle the work would be 20,000 mmHg*ml/s or 2.6 J.

Thus, we can see that the work is twice that of a non-pulsatile pump acting with the same vascular system (tube).

5. For **example #3**, assume that we once again have a pulsatile pump, except this time assume that the vessel is a **WINDKESSEL VESSEL** that has **INFINITE COMPLIANCE**. This is obviously an ideal situation, but basically what it means is that energy in the fluid will be stored in the vessel **SUCH THAT THE PRESSURE IN THE VESSEL REMAINS CONSTANT NO MATTER HOW MUCH FLUID HAS BEEN ADDED**.

a. Once again, **all flow from the pump will occur during the 1/2 s that the pump is contracting.**

b. However, the **pressure in the artery will remain constant**.

1. During the time that blood is added, the walls of the vessel balloon outward and are loaded elastically. This keeps the pressure lower than it would be in a rigid tube where the blood is forced into a constant, small volume (as in example #2 above).

2. When the pump ceases adding blood into the vessel, the walls now move inward, in the process maintaining their pressure on the blood and keeping the pressure constant.

3. (Note that this implies very unusual compliant properties -- in a real artery the pressure would decrease as blood drains off and increase as the blood is added.)

c. Thus, the pressure remains constant at 100 mm Hg for the entire time. The Flow is 200 ml/(0.5 s) or 100 ml/s over the whole second. Thus the work that the heart must do is 10,000 (mm Hg * ml)/s or about 1.3 J.

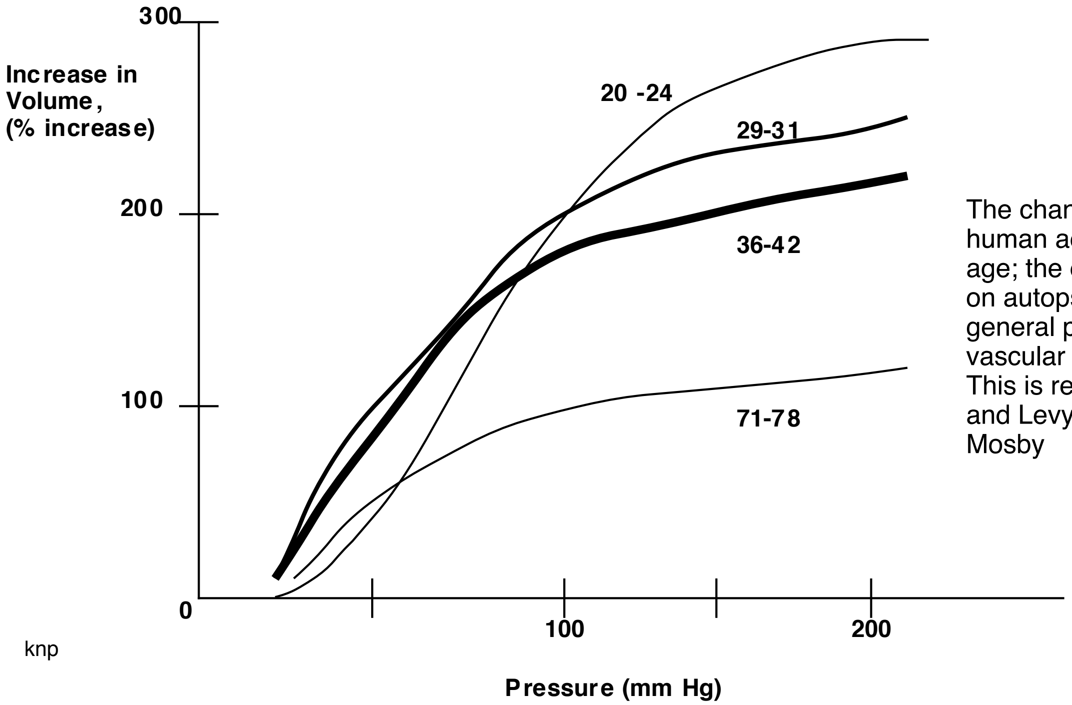
6. In summary, we can see that the use of a compliant artery actually decreases the amount of work that a pulsatile pump such as the heart needs to do over time when compared to the situation where the arteries are rigid. Also, the maximal pressure needed to pump a given amount of blood is less.

a. realize that situations 2 and 3 are both extremes, neither of which is actually what occurs in real organisms.

b. However, these point out the fact for a given cardiac output, that the more compliant the artery, the less work a pulsatile heart needs to do and the lower the pressures that will be needed to pump the blood.

C. Arterial Elasticity:

1. Arteries and other blood vessels show compliance just like other biological materials. If we plot the **STATIC VOLUMES vs. PRESSURE** curves for vessels we get curves as are shown below. Note that these particular curves show that the compliance changes with age, generally decreasing.



The changes in compliance in human aortas as a function of age; the data were obtained on autopsy and suggest the general pattern of changes in vascular complaince with age. This is re-drawn from Berne and Levy, *Physiology,* 1983, Mosby

2. Compliance itself is (as always) defined as **ΔV/ΔP**. In vascular physiology, we often speak of **CAPACITANCE** instead of compliance. The terms are synonymous.

3. As usual, when the compliance (capacitance) curves for arteries are taken under dynamic conditions that approximate those found in typical filling cycles in arteries, the curves are somewhat different than those seen in static conditions.

a. this is due to the **VISCO-ELASTIC PROPERTIES** of the arteries: that is, their ability to internally re-arrange themselves during periods of continued stress.

b. Generally, due to visco-elastic properties, the compliance must be described in terms of change in **VOLUME, PRESSURE and RATE OF CHANGE**.

III. ARTERIAL BLOOD PRESSURE

A. General terminology:

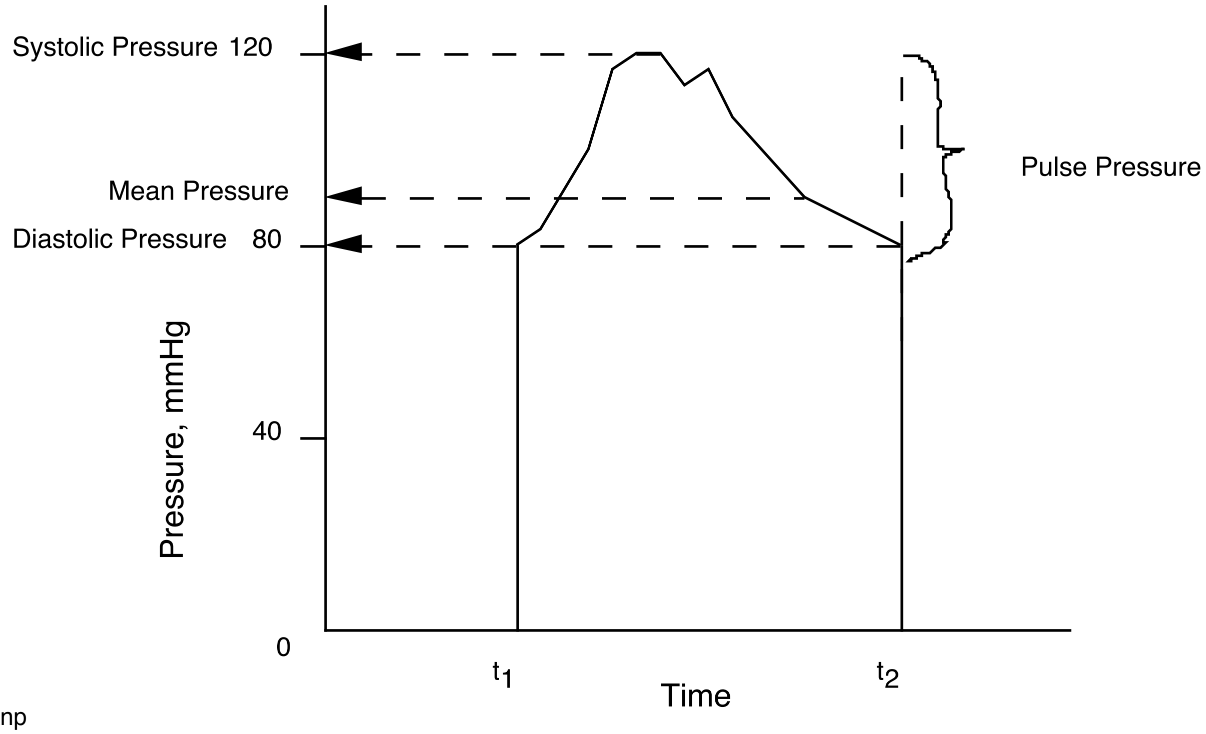
1. **Systolic pressure**: the highest pressure measured in a vessel, it does not necessarily correspond to the time when the ventricles generate maximum force.

2. **Diastolic pressure**: the minimum pressure measured in a vessel, usually in the arterial system, this pressure is recorded just before the ventricles start to eject blood.

3. **Mean Arterial Pressure**: the average arterial pressure over a complete cardiac cycle.

a. this can most accurately be measured by taking the area under the curve for blood pressure:

(please see next page)



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7. $$P_a = \frac{\int_{t_1}^{t_2}(P_o dt)}{(t_2 - t_1)}$$

b. However, it can be **approximated** as about the diastolic pressure plus 1/3 of the difference of the systolic minus the diastolic pressure. Mathematically:

8. $$\overline{P_a} = P_d + \frac{1}{3}(P_s - P_d)$$

where $\overline{P_a}$ is the mean arterial pressure, P_S is the systolic pressure, and P_d is the diastolic pressure. The reason for the use of 1/3 the difference between systolic and diastolic pressure should be obvious from the diagrams above.

B. Blood Pressure: an overview and model.

1. Blood pressure is a complex phenomena that involves the following elements: arterial capacitance (compliance), resistance to outflow of blood from the artery into capillaries, and the amount of blood that is pumped into the arterial system per unit time.

2. Let's consider a simple and familiar model that will help us understand blood pressure:

a. Assume that you have a typical garden hose that is attached to a spigot that can be turned on and off. At the other end of the hose is a nozzle whose degree of opening can be varied (like a typical garden spray attachment).

b. By analogy, the hose is an artery

1. It has a certain capacitance. As we add water at greater and greater rates (rates that exceed the ability of the water to leave the hose) the hose's walls will be pushed outward. Likewise, they

will store some of the force by which the water was pumped into the hose in their walls. Hoses of different compliances will be distorted to different degrees by water pressure -- this will vary from a rigid tube to a completely compliant vessel.

2. Arteries are compliant, but are also relatively stiff when compared to much more compliant vessels such as veins.

c. By analogy, the spigot is the heart. If we turn it on and off, it will inject water into the hose at high pressures. If it injects water at greater rates than the water can leave the nozzle end, the hose expands. In the most extreme case, when the pressure in the hose equals that at the spigot, water input will stop.

d. The adjustable nozzle is the equivalent of the **ARTERIOLES**, which are sometimes also referred to as the **RESISTANCE VESSELS**.

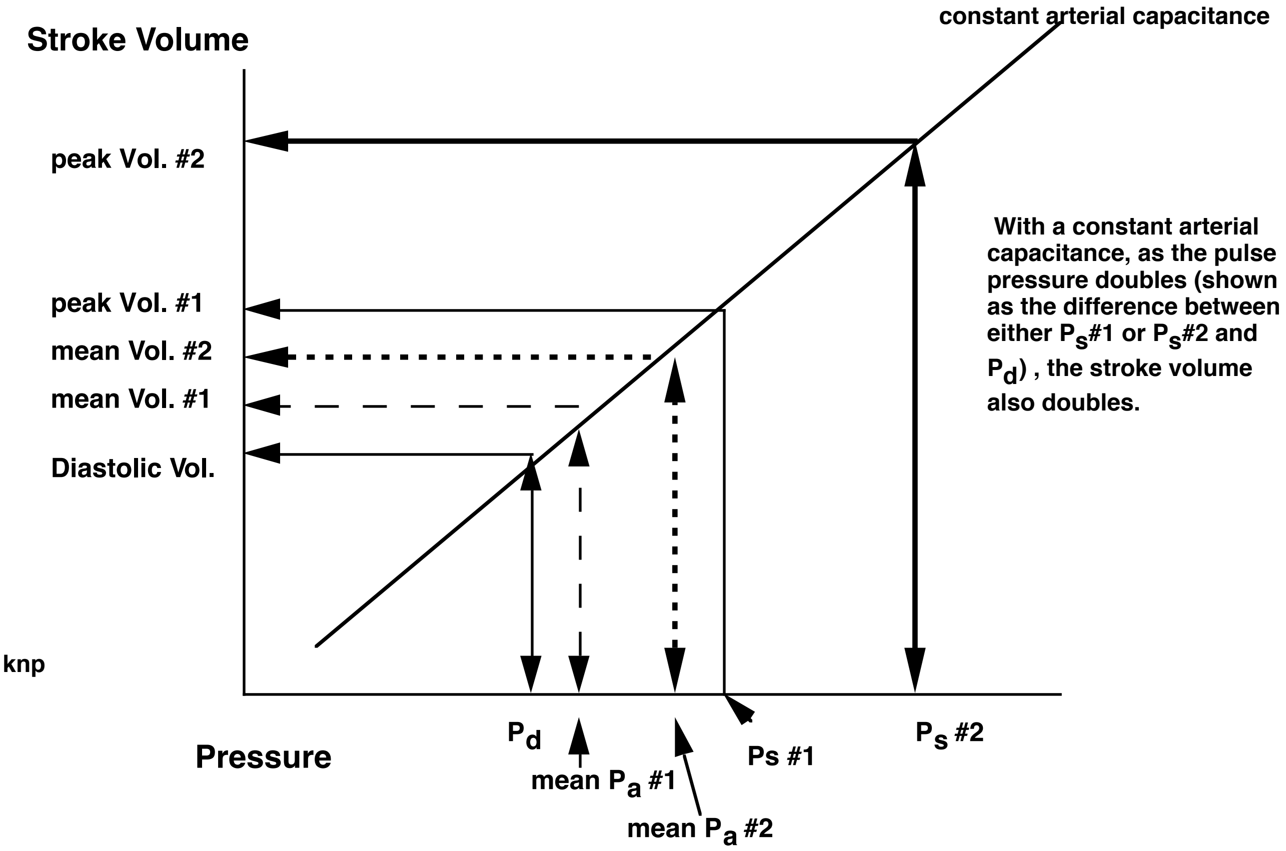
1. This is the part of the system that controls what is called **PERIPHERAL RESISTANCE**. The greater this resistance, the greater the difficulty that blood has leaving the arteries.

2. The value of the peripheral resistance of the arterioles can be changed via the action of the autonomic nervous system and also certain local controllers of perfusion.

3. Obviously, the peripheral resistance will influence all types of blood pressure: an increase in peripheral resistance will decrease outflow and will cause the arteries to expand more and the pressure to become higher. This is the same thing you notice with our garden hose as you close the valve (increase the resistance) and the hose expands outward.

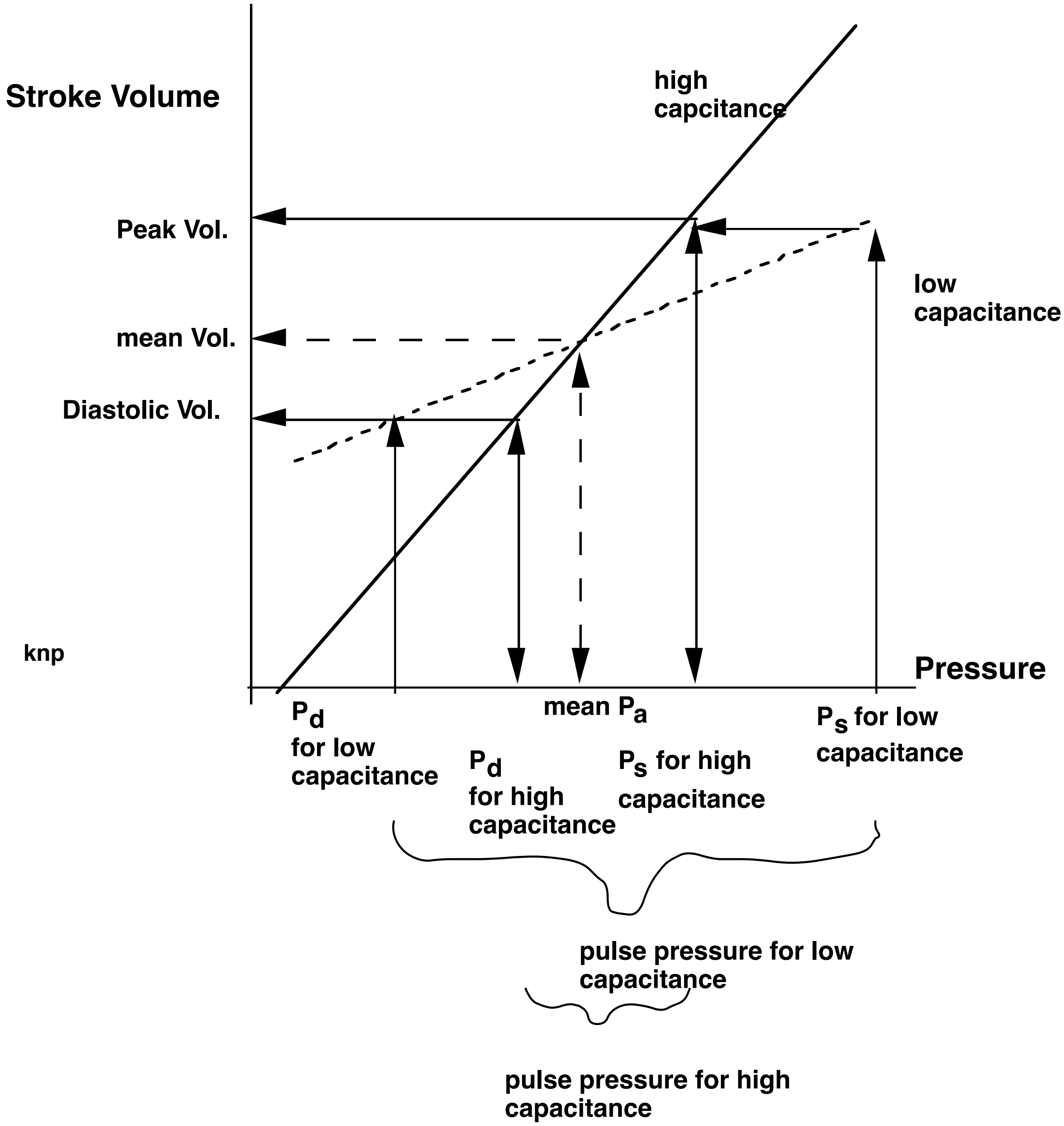
C. PULSE PRESSURE or DRIVING FORCE:

1. The **pulse pressure (driving force)** for the movement of blood is essentially the difference between the systolic and diastolic pressures. This is the difference between a measure of the pressure the heart must work against (diastolic pressure) and a measure of the force of contraction of the heart (systolic pressure). Obviously, the more this force exceeds the diastolic pressure (per unit time), the more blood will be ejected.



2. However, **an increase in the mean arterial pressure does not necessarily reflect an increase in the driving force or the stroke volume**. For example, if blood pressure increases from 110/60 (driving force = 50 mean art. P = 75) to 150/100 (driving force = 50, mean arterial P = 115) there has been no increase in the blood ejected.

3. A capacitance (compliance) plot can also be used to show the effects of changes in arterial capacitance on pulse pressure and stroke volume:



The important thing to note from this graph is that **<u>in order to keep a constant stroke volume</u>**, ***<u>if capacitance decreases, the pulse pressure must increase</u>***. This has important consequences related to disease states that you should think about.

D. Total Resistance in the Systemic Circulation:

1. We can estimate the resistance of the entire systemic circulation by looking at the difference between the mean arterial pressure and the mean pressure of the right atrium. Notice that we use mean pressures since these represent the average pressures over an entire cardiac cycle and their differences the average driving pressure to move blood.

2. Thus, by eq. #1:

9. $$\dot{Q} = \frac{(\overline{P_a} - \overline{P_{ra}})}{R}$$

Since P_{ra} is usually near 0, we can re-write this equation and solve for R:

10. $$R = \frac{(\overline{P_a} - \overline{P_{ra}})}{\dot{Q}} \cong \frac{\overline{P_a}}{\dot{Q}}$$

with the units of R normally given as ((mm Hg * min) / L). (Notice that R is essentially a proportionality constant between pressure and flow rate).

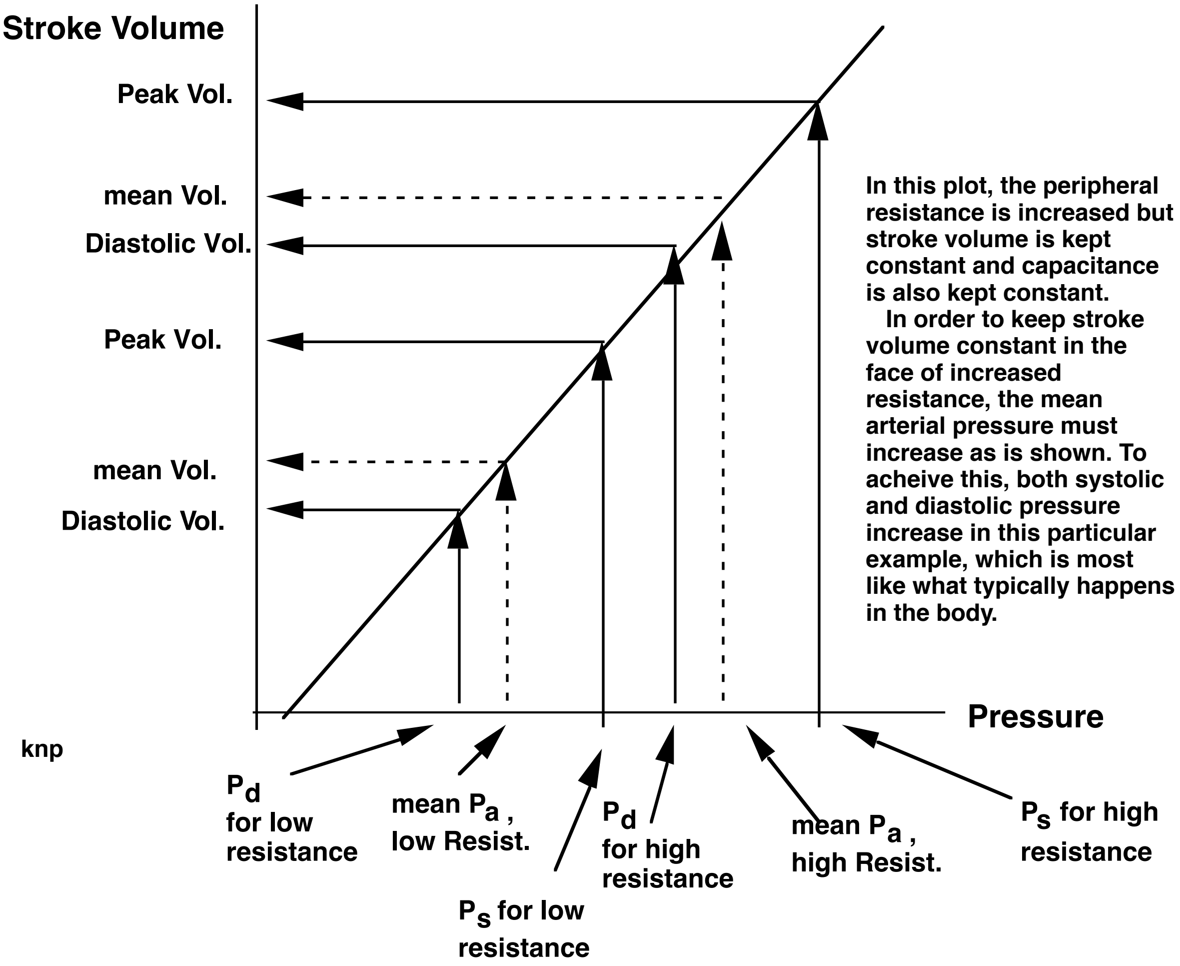
2. Effects of changes in peripheral resistance on the blood pressure.

a. If peripheral resistance increases and cardiac output is to remain the same, the mean arterial pressure must increase according to equation #10 above. This is commonly achieved by an increase in both the systolic and diastolic pressures.

b. The reason for this particular pattern is that a higher resistance will tend to result in:

1. greater average filling of the arteries since a higher pressure is needed to force the blood out of the arteries (due to the higher resistance).

2. This is reflected in a higher diastolic pressure. Then, to keep the cardiac output the same, systolic pressure must also rise so that mean arterial pressure rises.



In this plot, the peripheral resistance is increased but stroke volume is kept constant and capacitance is also kept constant.
In order to keep stroke volume constant in the face of increased resistance, the mean arterial pressure must increase as is shown. To acheive this, both systolic and diastolic pressure increase in this particular example, which is most like what typically happens in the body.

E. Cardiac Output and Blood Pressure:

1. We can write a simple equation that describes the change in volume of the arterial system based on its inflow of blood from the heart and outflow via the arterioles:

11. $$\frac{dV_a}{dt} = Q_I - Q_O$$

where Q_i is the inflow of blood (cardiac output) into the arteries and Q_O is the outflow, both in Vol./time and $\frac{dV_a}{dt}$ is the rate of change of the arterial volume.

2. **Now, let's look at how the blood pressure changes when the cardiac output suddenly increases (as in exercise) but the resistance remains constant**:

a. Assume that originally the cardiac output was 5 L/min., the arterial outflow was also 5 L/min. and the mean arterial pressure was 100 mm Hg. Thus, the peripheral resistance is 20 mm Hg * min / L.

b. Now assume that the cardiac output is instantaneously doubled to 10 L/min. Assume that the peripheral resistance remains the same, as does the compliance.

1. The blood pressure must increase since there is more blood going in (10 L/min) than is flowing out (5 L/min).

a. Since *R* is constant and flow inward has increased, the pressure required to cause the flow has increased:

12. $$\Delta P = R * Q$$

b. Realize that a non-steady state exists: the initial outflow conditions (5 L/min) still exist while an increased inflow is occurring. To increase this inflow, the pressure of the pump must be increased.

? Draw a graph that shows the changes (qualitatively) in in-flow , out-flow, mean pressure, arterial volume, and arterial elastic force (given as a rebound pressure) with respect to time for the scenario outlined above.

c. This increased in-flow under higher pressures increases the pressure in the artery. Notice that it also causes the artery to expand and some of the energy is stored in compliant walls of the arteries.

d. With time, the pressure will build in the artery due to the greater filling and elastic rebound pressure in the artery walls. As a result the outflow will increase, also according to eq. #1.

2. According to eq. #9, the mean arterial volume will increase since the mean arterial pressure has increased.

a. This increase will stop when Q_O once again equals Q_i, the mean pressure at which this will occur will be determined by eq. #8 for the situation where Q = 10 L/min.

b. Notice that the mean pressure where flow equilibrium is reached is determined entirely by the *Q* and *R*.

c. On the other hand, the rate at which the new **mean pressure** is reached is determined by the **capacitance, *C***. Obviously, if *C* is very low, the rate of pressure change will be very great and vice versa. If you have trouble visualizing this, go back to the model of the rigid vs. compliant tube.

! Notice that this discussion deals with the effects of changes in volume and capacitance on mean arterial pressure, not on pulse pressure (as was considered earlier). In fact, as capacitance decreases the pulse pressure must become greater.

? Two important effects of atherosclerosis are:
(i) a decrease in capacitance and
(ii) an increase in peripheral resistance.
What are the important differences, independent of changes in resistance, on the blood pressure in terms of rest and exercise states in normal vs. atherosclerotic individuals? Discuss systolic, diastolic and mean arterial pressures.
? If one also factors in resistance changes, what differences would emerge between normal and atherosclerotic individuals?

? Another version of the questions above: Atherosclerosis results in less complaint, narrower arteries. What are the effects of atherosclerosis on: R, dP/dt, Q, P_a, pulse pressure (driving force), systolic and diastolic pressures? Tie all of this together into a unified answer.
What will be the differences, if any, in the blood pressure changes for a normal vs. atherosclerotic person in going from rest to exercise?