ORGANIZATION OF THE CARDIOVASCULAR SYSTEM

Systems Biology: Tissue and Organ function block
Lecture 14
10/31/08 1:30-3:00pm
Ruben Mestril, PhD. rmestri@lumc.edu, 327-2395
Reading Assigment: L.S. Costanzo, Physiology 3E, Chap. 4 p. 111-121.

LEARNING OBJECTIVES

1.- Understand the relationship between pressure, flow, and resistance (Ohm's law).
2.- Understand the relationship between pressure, radius and viscosity (Poiseuille's law).
3.- Define viscosity (Poiseuille's law).
4.- Explain the effect of tube diameter and hematocrit on relative viscosity.

REVIEW QUESTIONS

1.- Determine how is the blood flow in each of the following conditions? Explain your answers.
 a) Pressure gradient increased.
 b) Vessel diameter reduced.
 c) Hematocrit reduced.
2.- Select the condition where turbulent flow is more likely to occur.
 a) Small or large vessels
 b) Low or high blood velocities
 c) Low or high hematocrit
3.- Predict what will happen with a given laminar flow through a cylindrical tube with a fixed driving pressure, if the radius is reduced by half. Explain your answer.

ORGANIZATION OF THE CARDIOVASCULAR SYSTEM

1. Evolution of the Circulatory System.

The requirement of a circulatory system is an evolutionary consequence of the increasing size and complexity of multicellular organisms.

In complex organisms, a circulatory system provides a steep concentration gradient for nutrients and waste products.

The functional roles of the circulatory system are:

a) Distribution of nutrients
b) Chemical signaling
c) Heat dissipation
d) Host defense

The circulatory system of humans consists of the three following basic functional elements:

a) Pump (**heart**)
b) Circulating liquid (**blood**)
c) Set of conducts (**vessels**).

2. Circulatory System Overview.

It is divided into major circulation and minor circulation.

Characteristics of the major:

1) Systemic circulation.
2) High pressure system.
3) Begins in the left ventricle.
4) Derives from the aorta.
5) Contains renal and mesenteric circulations.
6) Blood flow auto-regulates in many regions.

Characteristics of the minor:

1) Pulmonary circulation.
2) Low pressure system.
3) Begins in the right ventricle.
4) Derives from the pulmonary artery.
5) Blood flow auto-regulation does not play a major role.

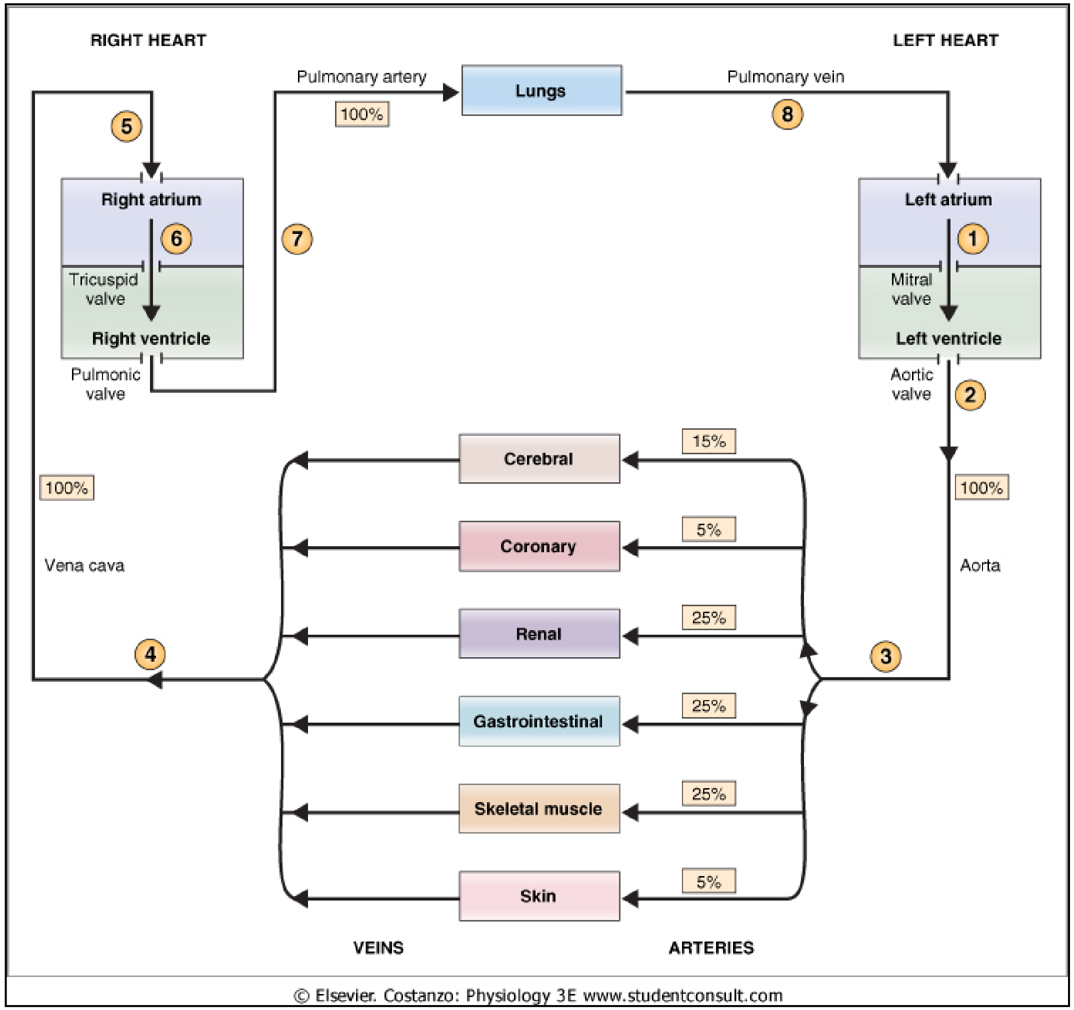

Figure 4-1 A schematic diagram showing the circuitry of the cardiovascular system. The arrows show the direction of blood flow. Percentages represent the percent (%) of cardiac output. See the text for an explanation of the circled numbers.

HEMODYNAMICS

Hemodynamics refers to the principles that govern blood flow in the cardiovascular system. Therefore, the concepts of flow, pressure, resistance and capacitance apply to blood flow to and from the heart within the blood vessels.

Blood Vessels

- Arteries – Their function is to deliver oxygenated blood to the organs. They are thick-walled structures with extensive development of elastic tissue, smooth muscle and connective tissue. They receive blood directly from the heart and are under the highest pressure in the vasculature. Constriction is mediated by α_1-adrenergic receptors while relaxation is mediated by β_2-adrenergic receptors.

- Capillaries – Thin-walled structures lined with a single layer of endothelial cells, surrounded by a basal lamina. They are the site where nutrients, gases, water and solutes are exchanged between blood and tissues.

- Venules and veins – Thin-walled structures composed of endothelial cells and a modest amount of elastic tissue, smooth muscle and connective tissue, permitting them to have a high capacitance (capacity to hold blood volume).

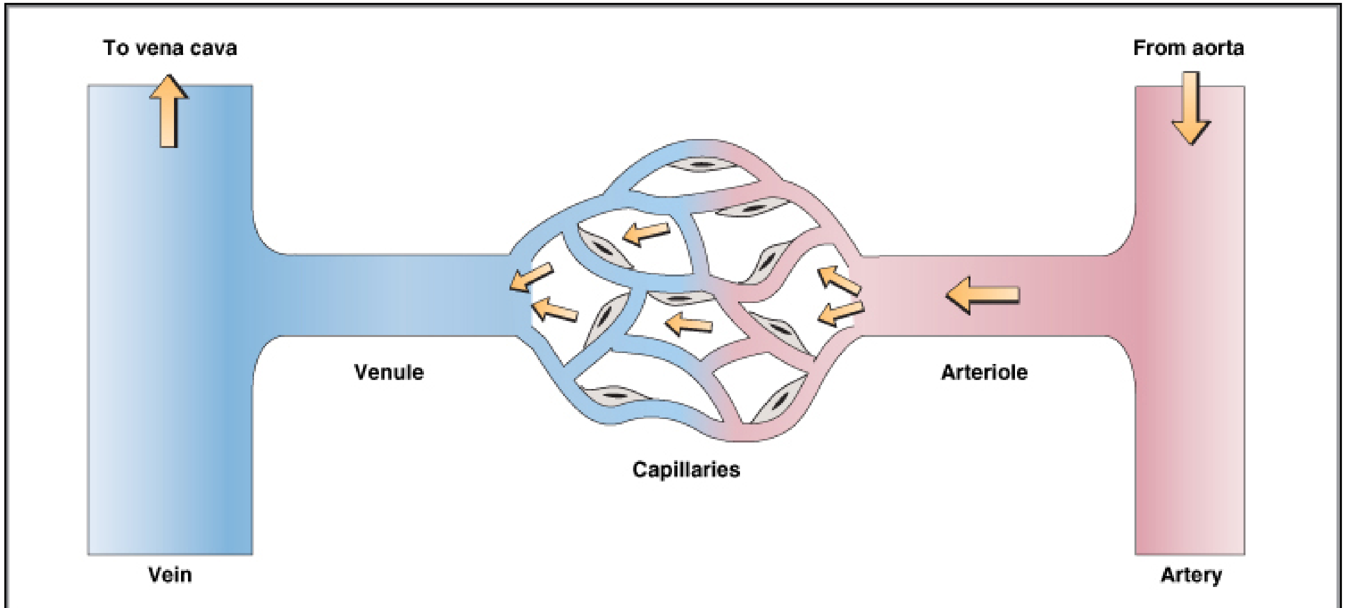

Figure 4-2 Arrangement of blood vessels in the cardiovascular system.

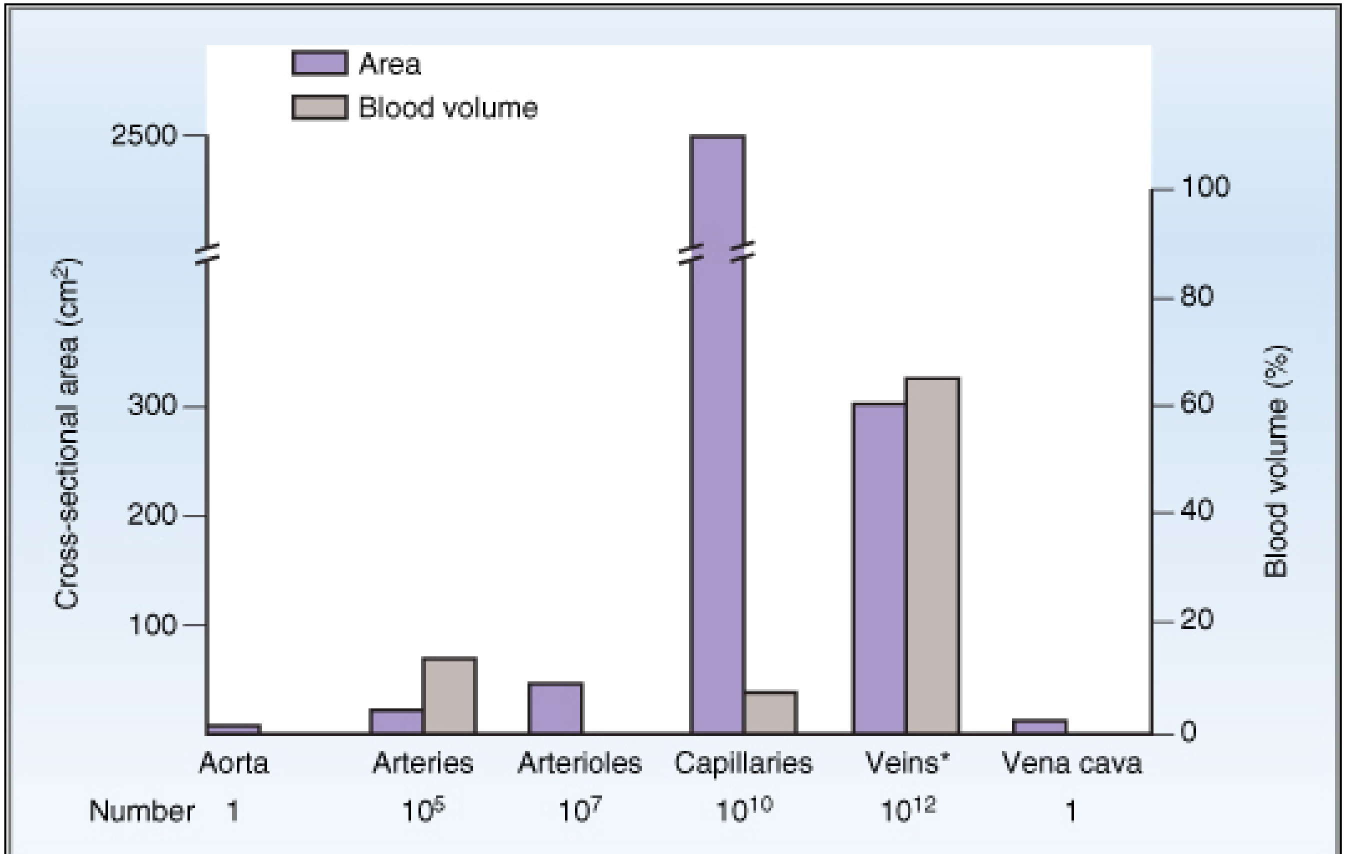

Figure 4-3 Area and volume contained in systemic blood vessels. The blood vessels are described by the number of each type, total cross-sectional area, and percentage (%) of blood volume contained. (Pulmonary blood vessels are not included in this figure.) *Total number includes veins and venules.

VELOCITY OF BLOOD FLOW

$$v = Q/A$$

Where:

v = velocity of blood flow which is linear velocity and refers to the rate of displacement of blood per unit time (cm/sec).

Q = flow which is volume flow per unit of time (ml/sec). In cardiovascular system equal to cardiac output.

A = area which is the cross sectional area of a blood vessel or group of blood vessels (cm^2).

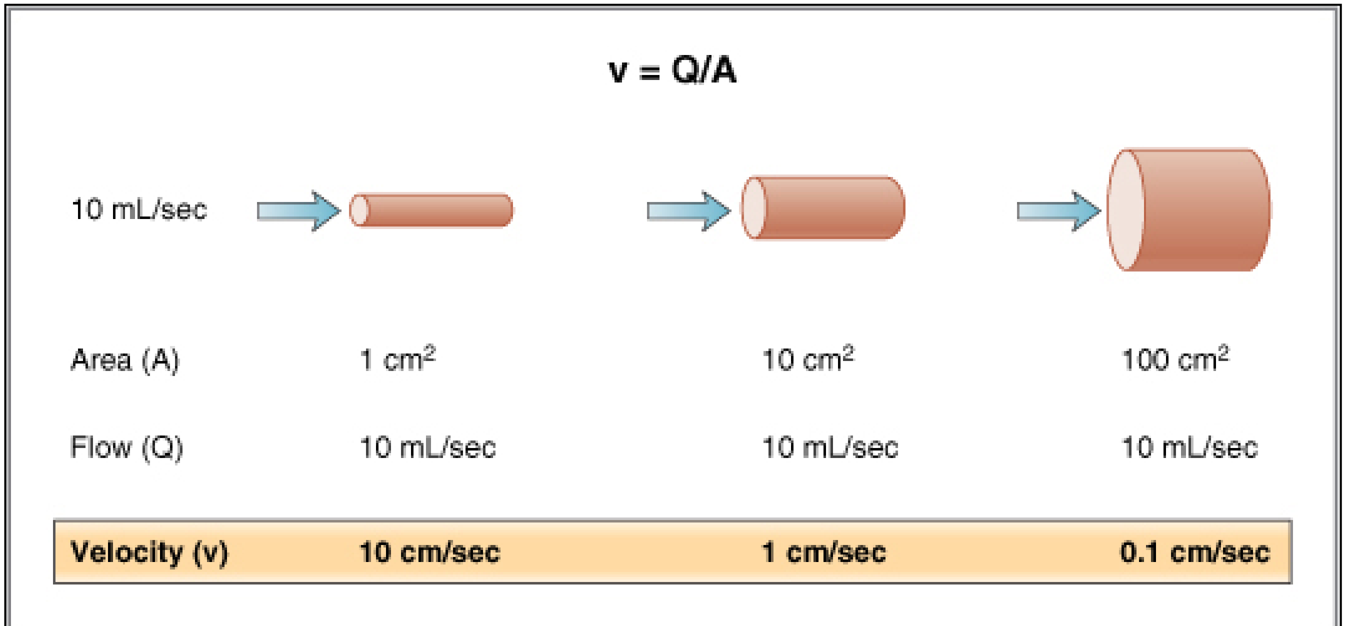

Figure 4-4 Effect of the diameter of the blood vessel on the velocity of blood flow.

Sample Problem:

A man has a cardiac output of 5.5 L/min. The diameter of his aorta is estimated to be 20 mm, and the total surface area of his systemic capillaries is estimated to be 2500 cm^2.

What is the velocity of blood flow in the aorta relative to the velocity of blood flow in the capillaries?

Answer:

Total blood flow (Q) = cardiac output (in this case 5.5 L/min)

Cross-sectional area of capillaries = 2500 cm^2

Cross-sectional area of aorta = $\pi r^2 = 3.14 \text{ x } (10mm)^2 = 3.14 \text{ cm}^2$

$v_{capillaries}$ = Q/A = 5.5 L/min / 2500 cm^2 = 5500cm^3/min / 2500cm^2 = <u>2.2 cm/min</u>

v_{aorta} = Q/A = 5500cm^3/min / 3.14 cm^2 = <u>1752 cm/min</u>

Hemodynamic Principles.

A. Ohm's Law.

1. Blood flow is directly proportional to the pressure gradient.
2. Blood flow is inversely proportional to the resistance
    a) Resistance is directly proportional to the vessel length.
    b) Resistance is inversely proportional to the radius.

$$I = \frac{\Delta V}{R} \qquad \text{Ohm's Law} \qquad Q = \frac{\Delta P}{R}$$

where:

Q = Flow (ml/min)
ΔP = Pressure difference (mm Hg)
R = Resistance (mm Hg/ml/min)

Sample Problem:

Renal blood flow is measured by placing a flow meter on a woman's left renal artery. Simultaneously, pressure probes are inserted in her left renal artery and left renal vein to measure pressure. Renal blood flow measured by the flow meter is 500 ml/min. The pressure probes measure renal arterial pressure as 100 mm Hg, and renal venous pressure as 10 mm Hg.

What is the vascular resistance of the left kidney in this woman?

Answer:

$$Q = \Delta P/R$$

solving for R:

$R = \Delta P/Q$ = (100 mm Hg – 10 mm Hg)/ 500 ml/min = 90 mm Hg/500 ml/min = <u>0.18 mm Hg/ml/min</u>

RESISTANCE TO BLOOD FLOW

Blood vessels and blood itself constitute resistance to blood flow. The relationship between resistance, blood vessel diameter (or radius) and blood viscosity is described by the Poiseuille equation:

$$R = \frac{8\ \eta\ l}{\pi\ r^4}$$

Where:

R = resistance

η = viscosity of blood (directly proportional to resistance)

l = length of blood vessel (directly proportional to resistance)

r^4 = radius of blood vessel raised to the fourth power (inversely proportional to resistance)

Sample Problem:

A man suffers a stroke caused by partial occlusion of his left internal carotid artery. An evaluation of the carotid artery using magnetic resonance imaging (MRI) shows a 75% reduction in its radius.

Assuming that blood flow through the left internal carotid artery is 400 ml/min prior to the occlusion, what is blood flow through the artery after the occlusion?

Answer:

From the Poiseuille equation: $R = \frac{8 \eta 1}{\pi r^4}$ where resistance is inversely proportional to radius

Since radius is decreased 75%, only $1/4^{th}$ of the radius is left, then $1/(1/4)^4$ = 256-fold increase in resistance.

And since blood flow is: $Q = \Delta P/R$, flow will be decreased by 1/256 or 0.39% of original value

That is 0.39% of 400 ml/min or 1.56 ml/min

SERIES AND PARALLEL RESISTANCES

Series resistance

In this case, the total resistance of the system arranged in series is equal to the sum of the individual resistances.

Parallel resistance

In this case, the total resistance is less than any of the individual resistances

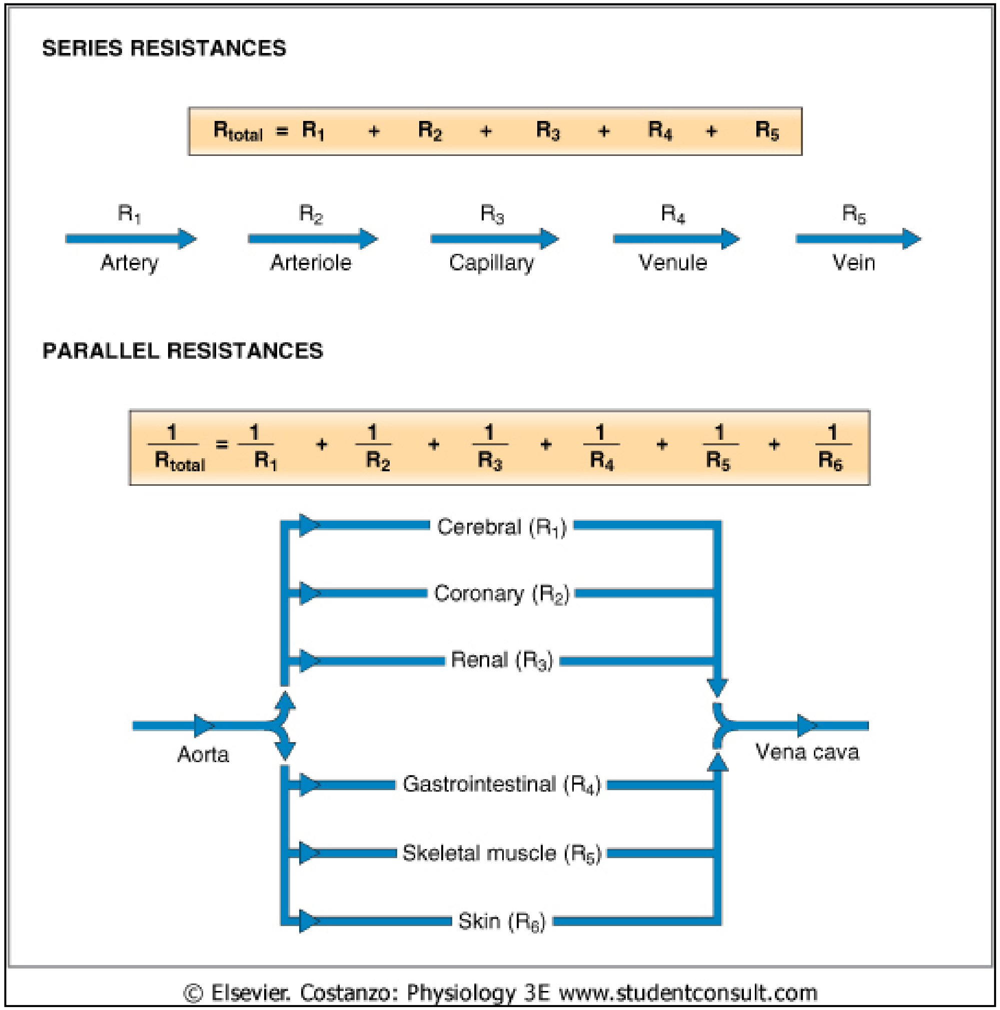

Figure 4-5 Arrangements of blood vessels in series and in parallel. The arrows show the direction of blood flow. R, Resistance (subscripts refer to individual resistances).

LAMINAR FLOW

1. Shear stress: Resistance to movement between laminae (pressure).

2. Shear rate: Relative velocities between laminae (velocity of blood flow):

In a blood vessel the shearing laminae of blood are not planar but concentric cylinders that move with different velocities. The inner most cylinder moves with the highest velocity, while the outermost cylinder moves at the slowest velocity. The resulting velocity profile is a parabola with the maximum velocity at the central axis. The lower the viscosity, the sharper the parabolic distribution.

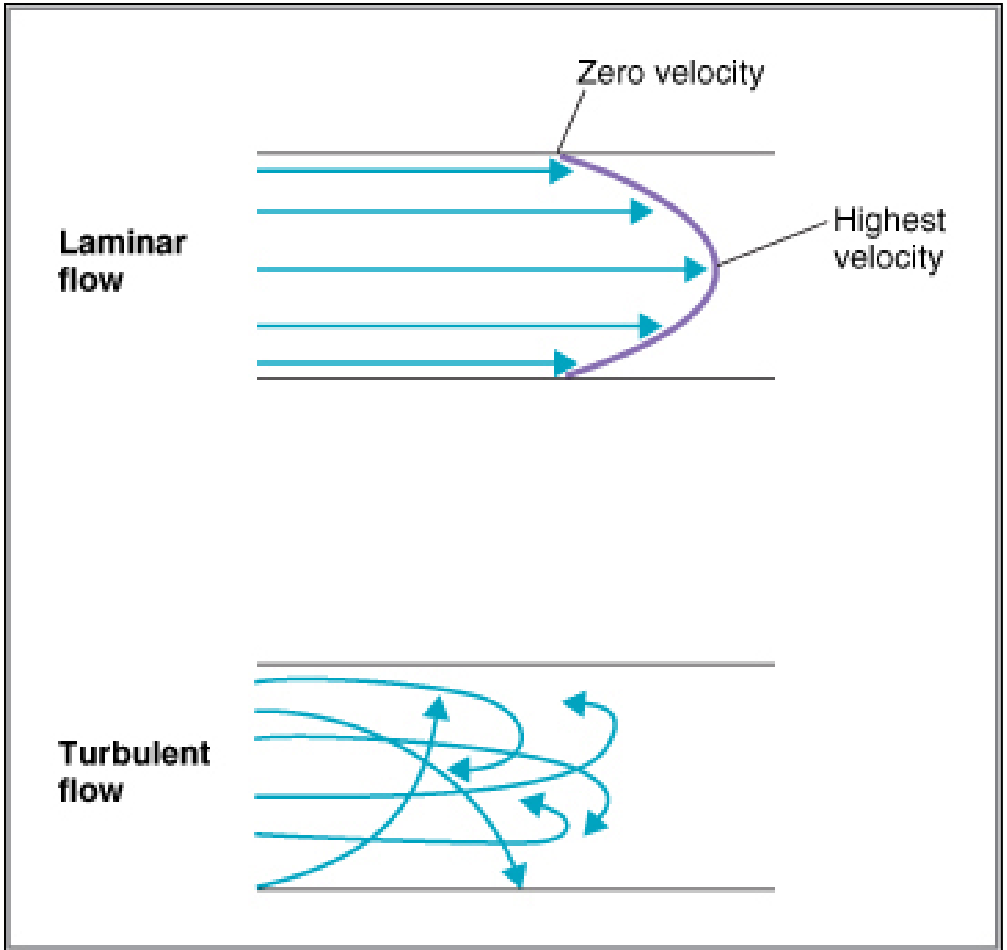

Figure 4-6 Comparison of laminar flow to turbulent blood flow. The length of the arrows shows the approximate velocity of blood flow. Laminar blood flow has a parabolic profile, with velocity lowest at the vessel wall and highest in the center of the stream. Turbulent blood flow exhibits axial and radial flow.

Laminar vs. Turbulent blood flow.

1. Laminar flow: fluid moves in parallel concentric layers (laminae) within a tube.

2. Turbulent flow: disorderly pattern of fluid movement; non-laminar.
a) murmurs & bruits
b) damage to endothelial lining
c) thrombi

3. Reynold's number: Dimensionless number indicating propensity for turbulent blood flow; the higher the Reynold's number (>3000), the greater chance for turbulent blood flow to develop.

$$NR = \frac{\rho\, d\, v}{\eta}$$

where

NR = Reynold's number
ρ = Density of blood
d = Diameter of blood vessel
v = Velocity of blood flow
η = Viscosity of blood

4. Determinants: tube diameter (D), velocity (v), density (ρ), viscosity (η).

Common clinical situations that affect hematocrit concentration and vessel diameter:

a) relative viscosity decreases progressively as hematocrit concentration decreases; ex:
Anemia - low hematocrit - relatively low viscosity (increases Reynold’s number)- produces turbulence.

b) narrowing of the diameter of the blood vessel causes increase in blood velocity; ex:
Thrombi – blood clot narrows blood vessel diameter – increase in blood velocity (and in Reynold’s number) – produces turbulence.

COMPLIANCE OF BLOOD VESSELS

Compliance of a blood vessel describes the volume of blood the vessel can hold at a given pressure**.**

Compliance is expressed by the equation:

$$C = V/P$$

where

C = Compliance (ml/mm Hg)

V = Volume (ml)

P = Pressure (mm Hg)

Therefore, compliance describes how volume of blood contained in a vessel changes for a given change in pressure ($\Delta V/\Delta P$).

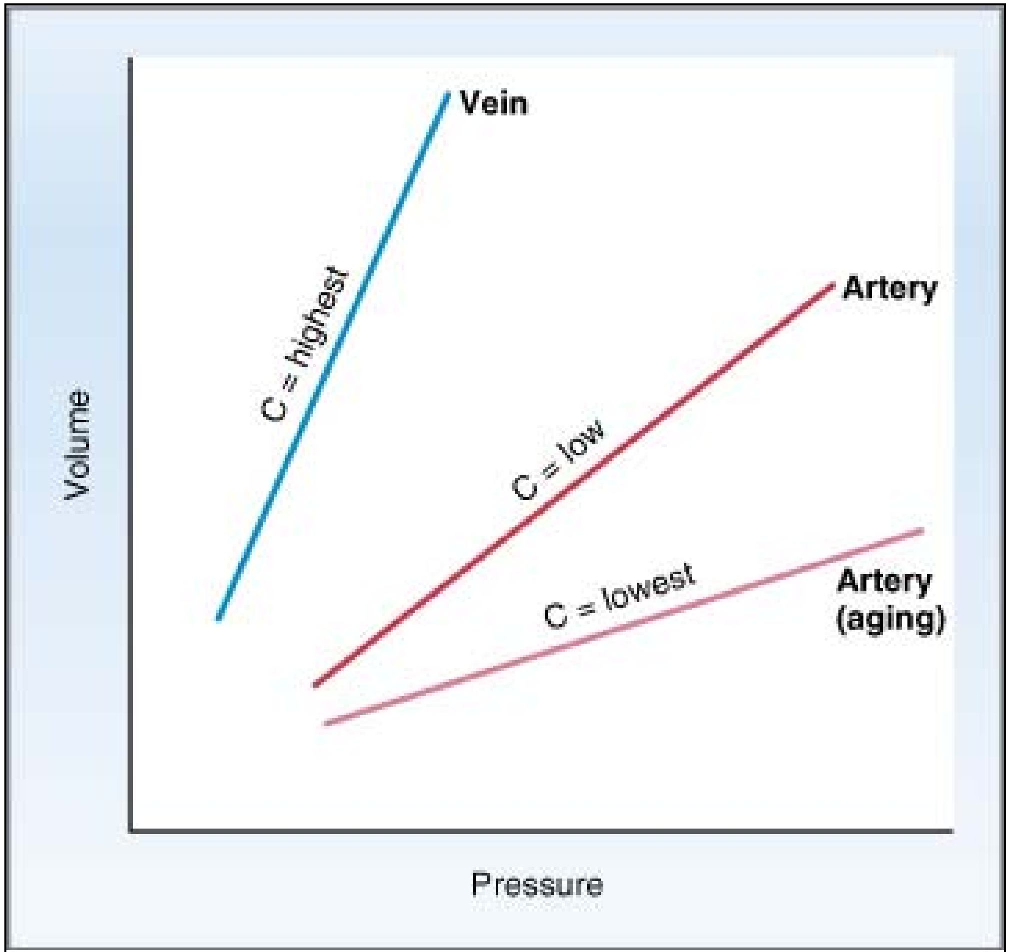

Figure 4-7 Capacitance of veins and arteries. Volume is plotted as a function of pressure. The slopes of the curves are capacitance (C).

COMPLIANCE IN THE AGING ARTERY

During aging the arterial wall becomes stiffer, less distensible and less compliant.

Therefore, at a given arterial pressure the arteries hold less blood or in order for the aging artery to hold the same volume of blood, arterial blood pressure will need to be higher.

This is exactly what happens among the elderly who develop high arterial blood pressure precisely due to a decrease in arterial compliance.