

Instructor's Digital Curriculum Resource-

For Techniques in Noninvasive Vascular Diagnosis-4th edition.

by Robert J. Daigle, BA, RVT, RVS, FSVU, FSDMS

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Chapter 9. Arterial Hemodynamics, Anatomy and Physiology

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Definitions for this chapter

- **Eddy flow**
 - Flow moving in an opposite direction to **mainstream flow**
- **"Plug" flow**
 - All blood cells are moving roughly at the same speed.
- **Parabolic flow**
 - Blood cells move progressively slower away from center stream and towards the wall.

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Arterial Hemodynamics

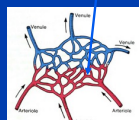
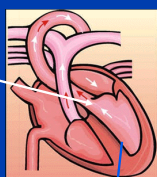
- **Energy gradient**
 - The energy level difference between two points
 - Must be present for fluid to flow from one point to another in a closed system
 - Fluid energy gradient is reflected in a pressure gradient.



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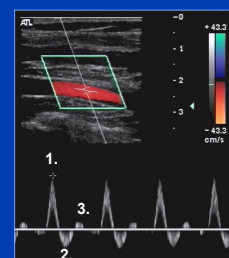
Pressure Gradient

- The highest pressure in the arterial system is in the left ventricle and thoracic aorta during systole
- The intra-arterial pressure in the distal vascular bed is lower during left ventricular contraction, so blood flows towards the vascular beds.



Normal peripheral arterial waveform

1. In systole, intra-arterial pressure is high, flow moves forward.
2. In diastole intra-arterial pressure is decreased and pressure distally is high (due to peripheral resistance); pressure gradient (& flow) reverses.
3. The third component is thought to be due to the elasticity of the arterial wall (rebounding).



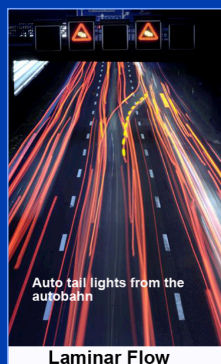
Popliteal artery

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Laminar Flow

- Laminar flow is streamline or pathline flow that occurs when a fluid (gas or objects) flows in parallel layers with no disruption between the layers, (picture a highway with cars traveling in discrete, parallel lanes).

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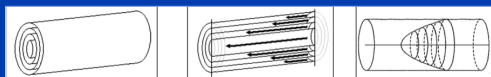
Laminar Flow



Non-laminar flow

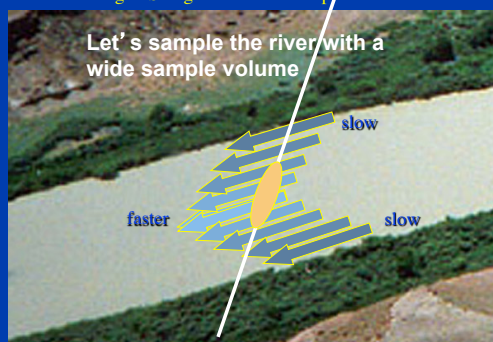
Friction

- The resistance of movement of one layer of blood against another layer or a wall
- The diameter of a vessel determines the amount of friction: the smaller the radius, the greater the friction and less amount of flow.



Long & Straight = laminar and parabolic

Let's sample the river with a wide sample volume

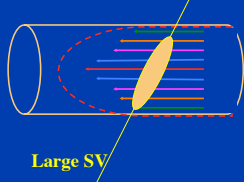


Animated.

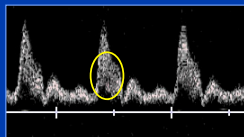
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Spectral waveforms are affected by:

- Sample volume size and position



Large SV

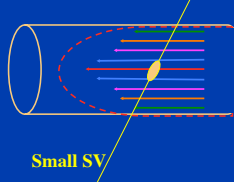


Wide spectrum-
spectral broadening

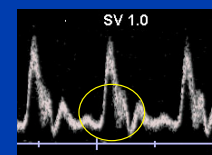
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Spectral waveforms are affected by:

- Sample volume size and position



Small SV

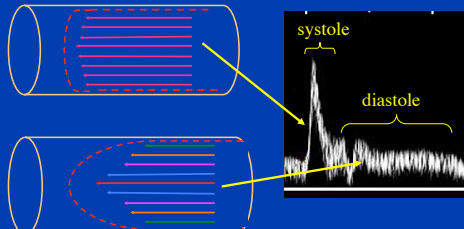


narrow spectrum-
minimal spectral broadening

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"Plug flow" occurs during flow acceleration; "lanes of traffic" have similar velocity.

SYSTOLE = "plug" flow, narrow spectrum



DIASTOLE = parabolic flow, wider spectrum

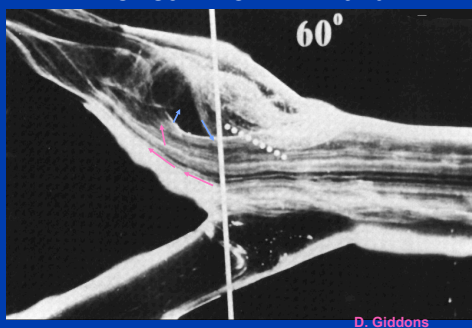
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Non-laminar Flow

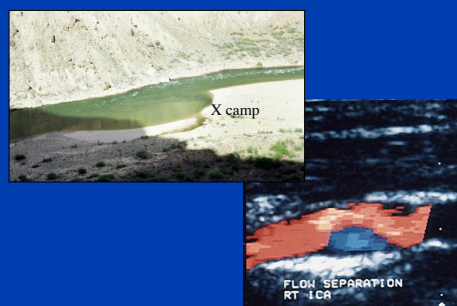
Helical Flow and Flow Separation

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Helical Flow in Bulb



Eddy Flow Separation



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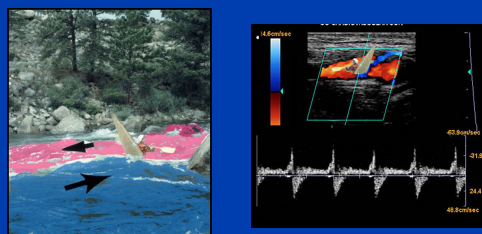
**Flow separation:
playing the seams!**

Kayaks like to "play" in the "eddy line" on line of flow separation

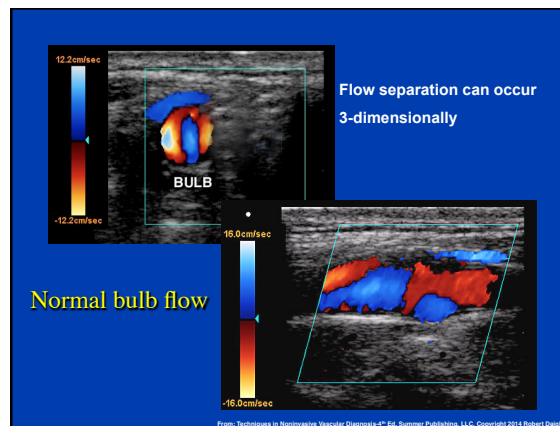
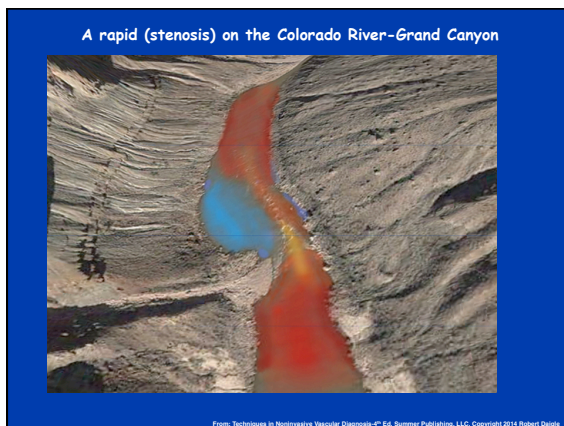


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Think of this kayak as a sample volume; we'd see flow in both directions on the spectral display



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Viscosity

- The property of fluid that resists flow
- A friction that exists between adjacent layers of fluid or a wall
- The higher the viscosity, the higher the resistance to flow

Molasses

Motor Oil

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Viscosity

- Water has low viscosity compared to blood
- The viscosity of blood is directly proportional to hematocrit
 - The higher the hematocrit, the higher the viscosity
- Viscosity is often represented by the greek letter " η " (ETA).

Low viscosity

RED BLOOD CELL

High viscosity

INCREASE IN RED CELL VOLUME AND HEMOGLOBIN

Viscosity Contributes to Parabolic Flow

- Layers "drag" against one another

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Turbulence

- As flow streams increase in velocity, a point is reached when laminar flow is disrupted. Flow becomes chaotic with small eddies and cross-currents.
- The flow speed at which turbulence occurs depends on:
 - Density of the fluid.
 - Viscosity.
 - Diameter of the vessel.

Turbulence alongside cruise ship as ship speed increases

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Turbulence

- The Reynolds Number (Re) is used to describe when turbulence is likely to occur.

$$RE = \frac{\text{average flow} \times \text{density} \times \text{tube diameter}}{\text{viscosity}}$$

- Turbulence occurs when the Reynolds number meets or exceeds approximately 2000.
- In blood, density and viscosity are fairly constant, so velocity and vessel diameter are the most influential factors for turbulence.

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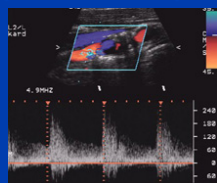
Turbulence

- An increase in flow speed increases the Reynolds number.
- An increase in vessel radius increases the Reynolds number.
- Turbulence also occurs distal to a stenosis in a vessel.
- On spectral Doppler, turbulence is demonstrated as a broadening of the spectral waveform and a filling of the spectral envelope.

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Turbulence

- Distal to maximum stenosis, velocities decrease and laminar flow is disrupted- turbulence occurs
- Turbulence is irregular motions of fluid elements; Cross-currents, eddy's etc



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Inertia



- The property that causes a fluid or object to resist a change in direction or speed
- Objects at rest tend to remain at rest...

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Inertia

- objects in motion tend to remain in motion
- Friction, viscosity, and resistance are the foes of inertia



Space Station in motion

Poiseuille's Law Pressure-Flow-Resistance

- Poiseuille's Law
 - Predicts flow in a cylindrical vessel
 - Describes relationship between
 - pressure
 - length
 - radius of a tube
 - viscosity
 - flow

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Poiseuille's Equation

$$Q = \frac{\Delta P \pi r^4}{8nL}$$

Q = flow
 ΔP = pressure gradient
 π = pi (3.14)
 r^4 = radius of vessel, 4th power
 n = viscosity
 L = length



Resistance Equation

- Because resistance (R) depends on viscosity and the radius, the formula can be rewritten:

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

If viscosity increases, resistance increases
 As radius decreases, resistance increases
 As length increases, resistance increases

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Poiseuille's Law of Hemodynamics simplified relationship of:

$$\Delta P = Q \times R \quad \text{or} \quad R = \frac{\Delta P}{Q}$$

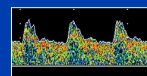
ΔP = Pressure
 Q = Flow
 R = Resistance

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Poiseuille's Law in Exercise



Exercise,
high flow demand



- Vasodilation in arterioles
- Decreased resistance
- Increased flow
- No change in distal pressure



Arteriole
Vasodilation

$$Q \uparrow \times R \downarrow = P \text{ no change}$$

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An often-used analogy to Poiseuille's is Ohm's Law

$$E \text{ (energy)} = I \text{ (current)} \times R \text{ (resistance)}$$

$$Q \text{ (flow)} = P \text{ (pressure)} \times R$$

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Blood volume change over stenosis impacts distal perfusion

Blood flow volume change over a fixed stenosis
impacts distal perfusion

Flow scenario #1- Low flow

Flow volume 55 ml/min

Minor pressure drop,

hypothetical P 120 mmHg pressure 100 mmHg



hypothetical P 120 mmHg pressure 30 mmHg

Flow scenario #2- High flow

Flow volume 800 ml/min

Major pressure drop

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Bernoulli's Principle

- Potential energy is stored energy (slingshot retracted)
- Kinetic energy is energy of motion and work (slingshot rock flying)



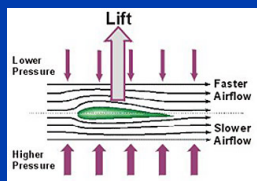
Bernoulli's Principle gets us off the ground!

- The total energy at one location must equal all the total energy of another location
- Total energy = potential energy + kinetic energy

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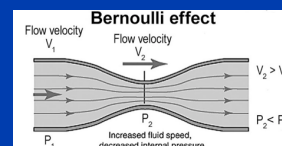
Bernoulli Effect

- "the pressure of a fluid (liquid or gas) decreases as the speed of the fluid increases.
- Within the same fluid (air), high-speed flow is associated with low pressure, and low-speed flow is associated with high pressure.



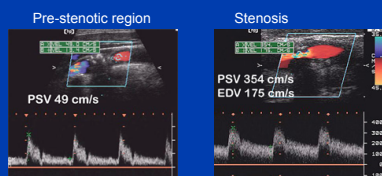
Applied Bernoulli's Effect

- A 75 % area reduction (50% diameter, if circumferential) will cause a velocity increase, and a distal pressure decrease
- Velocity increases as the area decreases.



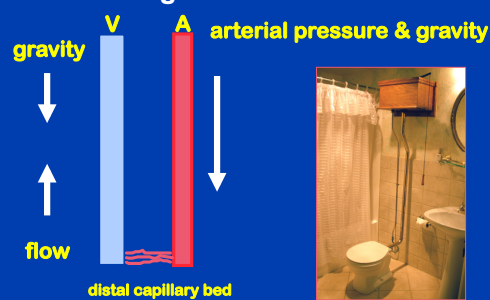
Effects of stenosis on flow characteristics

- By measuring either the velocity or the increase in velocity we can estimate percent of arterial stenosis
- The greater the narrowing, the faster the velocity



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Hydrostatic pressure: The weight of a column of fluid.



Hydrostatic pressure model!

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World's Tallest Man

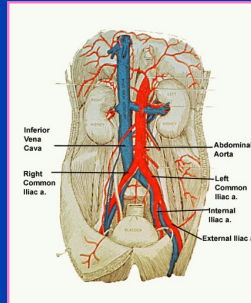
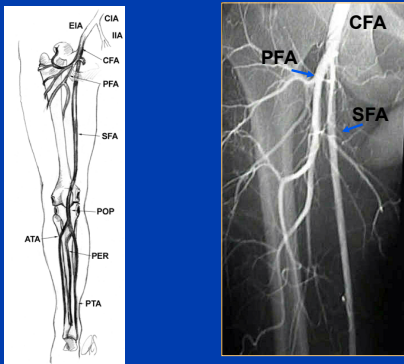
Hydrostatic pressure:

22 mmHg for each 12" of vertical distance below heart

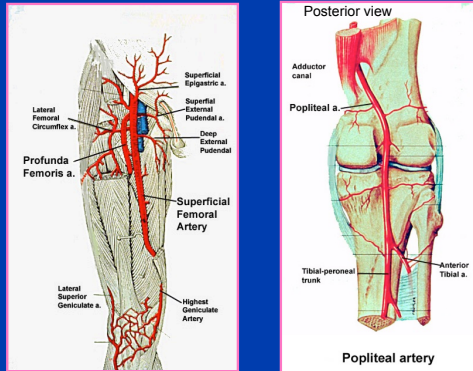
Hydrostatic pressure estimate: 120 mmHg

At 7 feet, 9 inches tall, Bao Xishun is the world's tallest man

Arterial Anatomy of Lower Extremities.

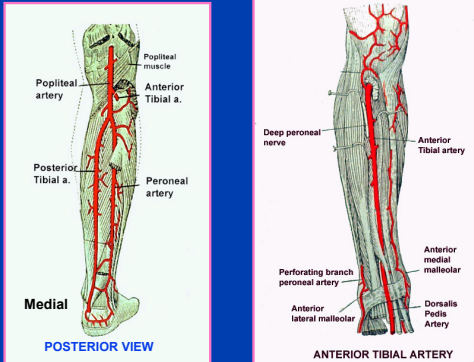



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Posterior view

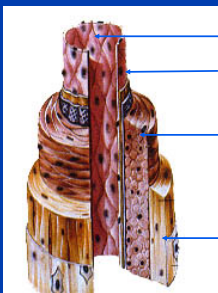
Popliteal artery



POSTERIOR VIEW

ANTERIOR TIBIAL ARTERY

Arterial Wall Anatomy



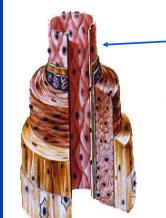
Endothelial lining

Intima

Media

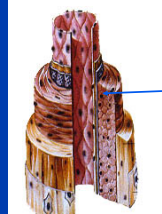
Adventitia

The Intima: the inner-most layer



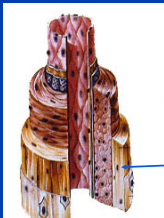
- **Intima**
- Consists of one layer of endothelial cells supported by an internal elastic lamina.
- Endothelium
 - Single cell layer that lines the inner surface of the artery. and
 - In contact with the intraluminal moving blood. It provides the following functions:
 - Permeability
 - Antithrombogenic
 - Vasoreactivity

The Media: the middle layer



- **Media**
- Consists primarily of smooth muscle cells
- Allows rhythmic changes in the arterial size that occurs during cardiac cycle.
- Collagen is also found in this area of the wall structure
- The external elastic membrane lies between the media and the adventitia

The Adventitia: the outer layer

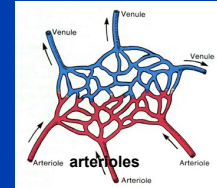


- Contains connective tissue and collagen
- Contains the vasa vasorum; tiny blood vessels that supply the artery wall.

Adventitia

Capillaries

- The smallest vessels in the circulatory "tree".
- Small arterioles lead into the single-cell wall capillary beds.
- Venules carry blood back into the venous drainage system.



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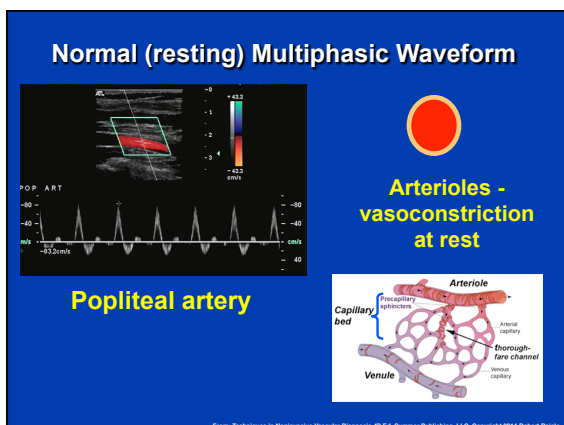
A hemodynamic primer- lower arterial.

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Blood flow in the lower extremities is controlled by:

- Cardiac output
- Intraluminal wall resistance
- Arterial wall compliance
- Dynamics of arteriolar vasoconstriction and vasodilation in the distal vascular beds

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Low demand

Blood flow in the extremities is ruled by DEMAND.

High demand

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Low demand

- Vasoconstriction in distal arterioles.
- Arteriovenous shunting in muscle capillary beds.
- **Not much blood flow to skeletal muscles.**
- Large blood volume exists in viscera and cerebral distributions.
- High resistance in flow from aorta to arterioles.

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Exercise Creates “Demand” !

High demand

- **Muscles need O₂, metabolites, and removal of metabolic waste, including CO₂, lactic acid, etc.**
- **Mild exercise = mild demand**

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Arterioles and Flow

Arterioles in lower extremities are vasoconstricted at rest

Arterioles vasodilate during exercise, ischemia, chemical-emotional stimulation, Etc.

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The “Triggers” for Vasodilation

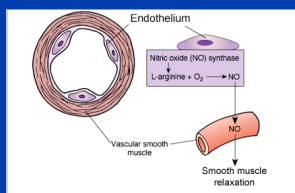
- **Low oxygen tension in tissue**
- **Increased CO₂ levels in tissue**
- **Increase in lactic acid**
- **Epinephrine from adrenal medulla**
- **Increased potassium ions**

Arteriole Vasodilation

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The “Triggers”

- Endothelium-mediated nitric oxide (NO) causes smooth muscle cells to relax
- Increased blood flow = increased amt. NO

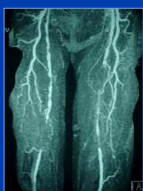


Heavy exercise creates heavy demand

- Maximum arteriole vasodilation
- 100% of capillaries open
- A-V shunts close
- Heart rate and cardiac output increases
- Shunting of blood from viscera to muscles
- Dermal vasoconstriction

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Patients with Occlusive Disease



- During exercise, vasodilation “triggers” occur:

- Decrease O₂
- Increase lactic acid
- Increase in tissue CO₂
- Increase epinephrine
- Increase in Nitric Oxide
- Decrease in distal pressure

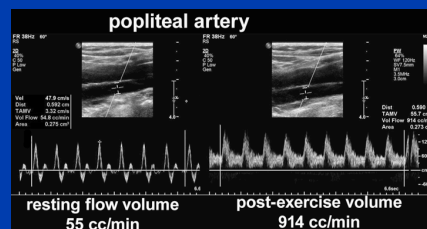
But, no increase in flow distally.

$$Q \begin{matrix} \text{no change} \\ \text{or decrease} \end{matrix} \times R \downarrow = \downarrow P$$

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Exercise

- Flow volume increases to lower extremity vascular beds



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Poiseuille's Law of Hemodynamics simplified relationship of:

$$\Delta P = Q \times R$$

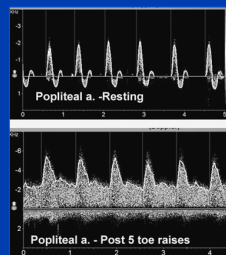
$$\Delta P = \text{Pressure}$$

$$Q = \text{Flow}$$

$$R = \text{Resistance}$$

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Popliteal Artery: pre & post 5 toe raises.



In normals, ankle pressure following exercise remains about the same as before exercise.

$$Q \uparrow \times R \downarrow = P \text{ no change}$$

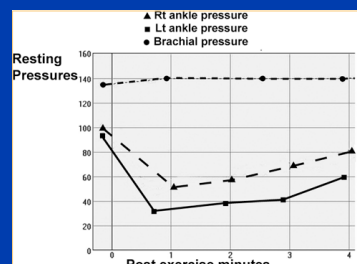
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Distal Pressure

1. $Q \uparrow \times R_{\text{no change}} = \uparrow P$
2. $Q \uparrow \times R \downarrow = P_{\text{no change}}$
3. $Q_{\text{no change or decrease}} \times R \downarrow = \downarrow P$

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Post-exercise Pressure Graph



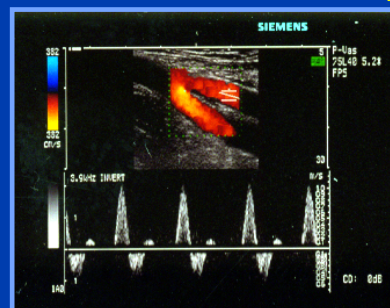
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Various flow patterns that can occur with occlusive disease.

Cardiac output and distal resistance are the 2 most important factors

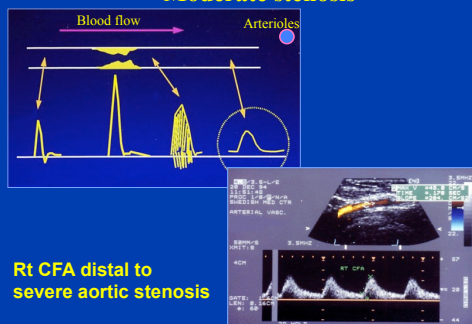
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Normal multiphasic waveform; high resistance due to vasoconstriction distally



Various flow/waveform scenarios in PAD

Moderate stenosis



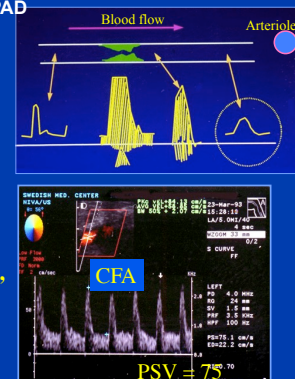
Rt CFA distal to severe aortic stenosis

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Various scenarios in PAD

Severe disease

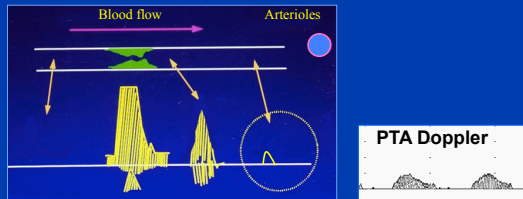
Left SFA occlusion, no iliac disease



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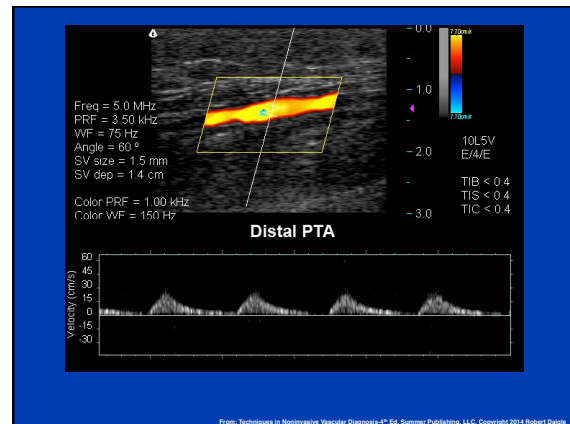
Various scenarios in PAD

Very Severe disease



Insufficient diastolic pressure to maintain flow

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Waveform Morphology

- Used to judge the present or absence of disease
- Affected primarily by the state of vasoconstriction/dilation in arterioles of the distal vascular beds.
- Arterio-venous fistulas can affect proximal flow.

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Risk Factors for PAD

- Familial –generic component
- Cholesterol >240 mg/dl
- Hypertension
- Diabetes mellitus
- Severe obesity
- Elevated triglycerides

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Risk Factors for PAD

- LDL > 160 mg/dl
- Depressed fibrinolytic system
- Tobacco abuse
- Increased oxidation of LDLs

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Arterial Symptoms of Occlusive Disease

- Mild arterial disease
 - Pt. is asymptomatic (ASX)
 - Not hemodynamically significant.
 - May have abdominal bruit
 - With exercise, a mild decrease in ankle pressure.
 - Athero disease may be seen on ultrasound exam, but no flow reduction.

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Arterial Symptoms

- **Moderate disease**
 - Asymptomatic at rest
 - Intermittent claudication:
 - pain, fatigue or cramping in the calf, thigh or buttock with exercise. Symptoms are relieved by rest. Claudication is brought about by a transient ischemic event in the muscles.
 - This is the most common symptom of peripheral arterial disease.

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Severe Disease

- **Night pain in feet- toes**
 - relieved by dependency
- **Dependant rubor**
 - Redness, light purple or deep red-violet color that develops on the foot when it hangs in a dependent position

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Severe Disease

- Ischemic rest pain in feet and toes
- Non-healing wounds on feet/toes
- Ulceration on lower leg or foot
- Tissue necrosis, gangrene



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Arterial Pathology

- **Atherosclerosis (ASO)**
- **Peripheral arterial disease (PAD) - ASO in the legs**
- **Thrombosis (preceded by ASO)**
- **Thrombo-emboli**

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Blue Toe Syndrome

- **Thrombo-emboli with resulting areas of cyanosis**



AKA, "trash foot"

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Arterial Pathology

- **Aneurysm**
 - AAA
 - Popliteal



Popliteal artery aneurysm

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Other Arterial Pathology

- **Buerger's disease** – small vessel thrombosis- "fixed" occlusive disease
- **Raynaud's syndrome** - small vessel vasospasm
- **Pulsatile masses** - aneurysms & pseudoaneurysms
- **Arteritis**
- **Arterial-venous fistulas (AVF)**

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Entrapment Syndromes; structures that extrinsically pinch or constrict arterial flow.

- **Popliteal artery entrapment**- **claudication-like symptoms**.
- **Nutcracker syndrome**- **renal vein entrapment syndrome**.
- **Median arcuate syndrome**- **compression of the celiac axis**.

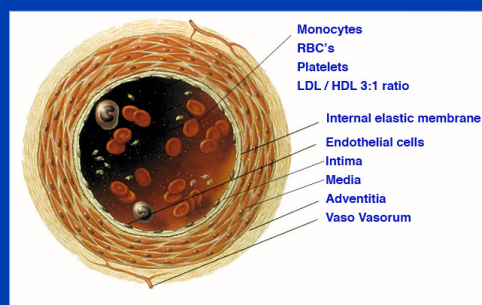
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Entrapment Syndromes; structures that extrinsically pinch or constrict arterial flow.

- **SMA syndrome**-compression of the **superior mesenteric artery**.
- **Thoracic outlet syndrome**- **compression of the subclavian or axillary artery**

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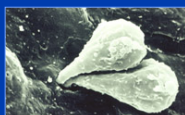
Normal Artery



Atherosclerotic process

1. Early Athero: Injury

- **Endothelial injury** (due to increase in LDL, hypercholesterolemia, etc.
- **Deposition of LDL into intima**
- **Recruitment of lymphocytes, monocytes (inflammation response)**



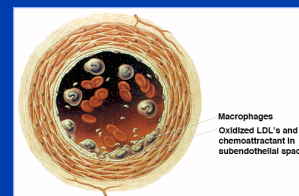
Electron microscope-monocyte invading the endothelium.

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Atherosclerotic process

2. Inflammatory Response

- **Monocytes in intima become macrophages**
- **Macrophages ingest lipids, lipoproteins**
- **Macrophages become foam cells.**
- **Fatty streak forms.**



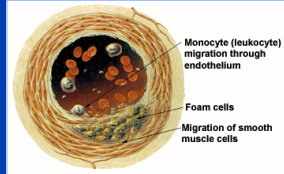
Early Atherosclerosis

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Atherosclerotic process

3. Atheromatous Thickening- Plaque Formation

- Migration/proliferation of smooth muscle cells from media
- Neovasculature supplies plaque, feeds LDL and macrophages
- Fibromuscular cap formation



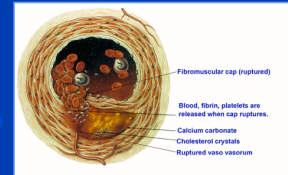
Plaque Formation

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Atherosclerotic process

4. Advanced Athero- Late changes

- Cell necrosis
- Scar tissue formation (fibrosis)
- Macrophage lysis
- Intraplaque hemorrhage
- Rupture of fibrous cap
- Ongoing inflammatory process



Advanced Atherosclerosis

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