Cardiovasculature: A Dynamic Sensing and Actuating System

Tzung Hsiai, MD, PhD

Cardiovascular Engineering Research Core
School of Engineering &
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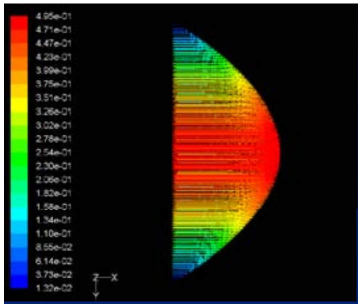
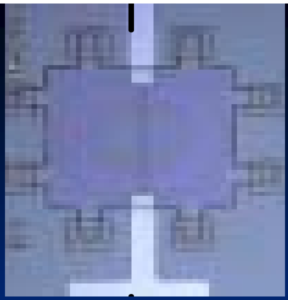
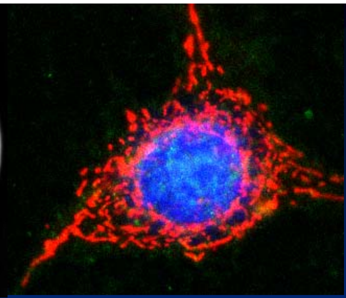
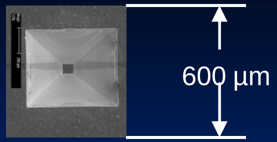
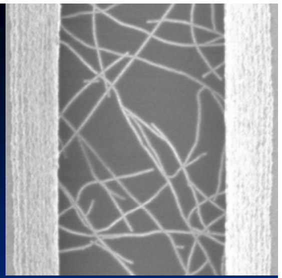
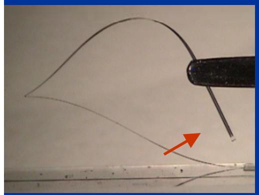



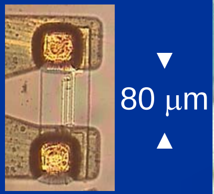



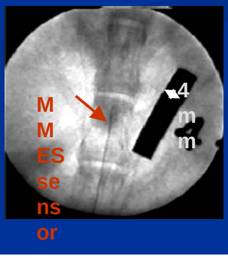


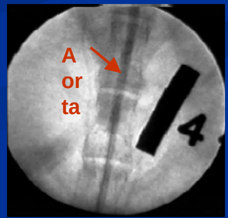
Objectives

- Introduce vascular systems
- Interface vascular dynamics with biology
- Translate vascular dynamics to in vivo models
- Bridge bioengineering, industry, and medicine







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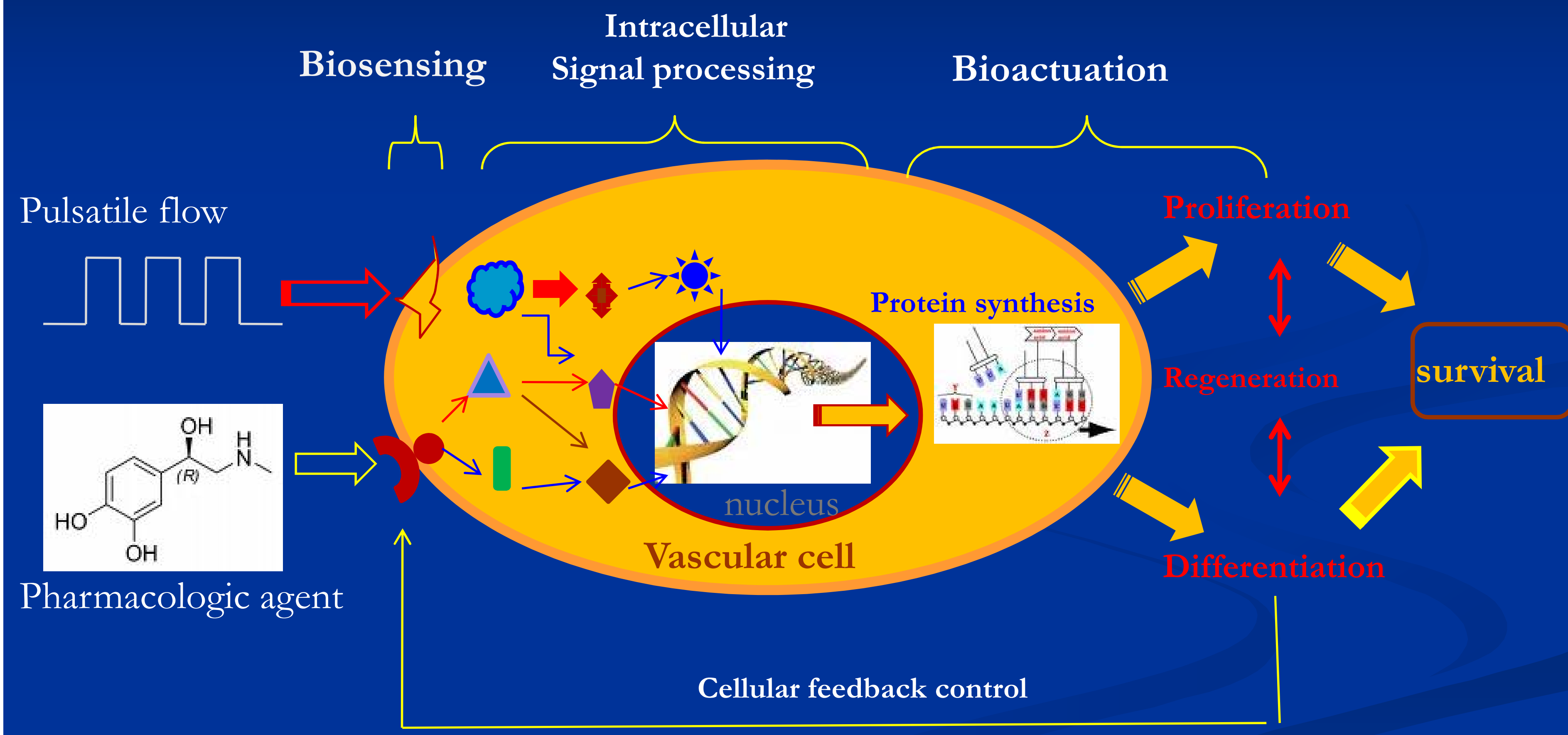
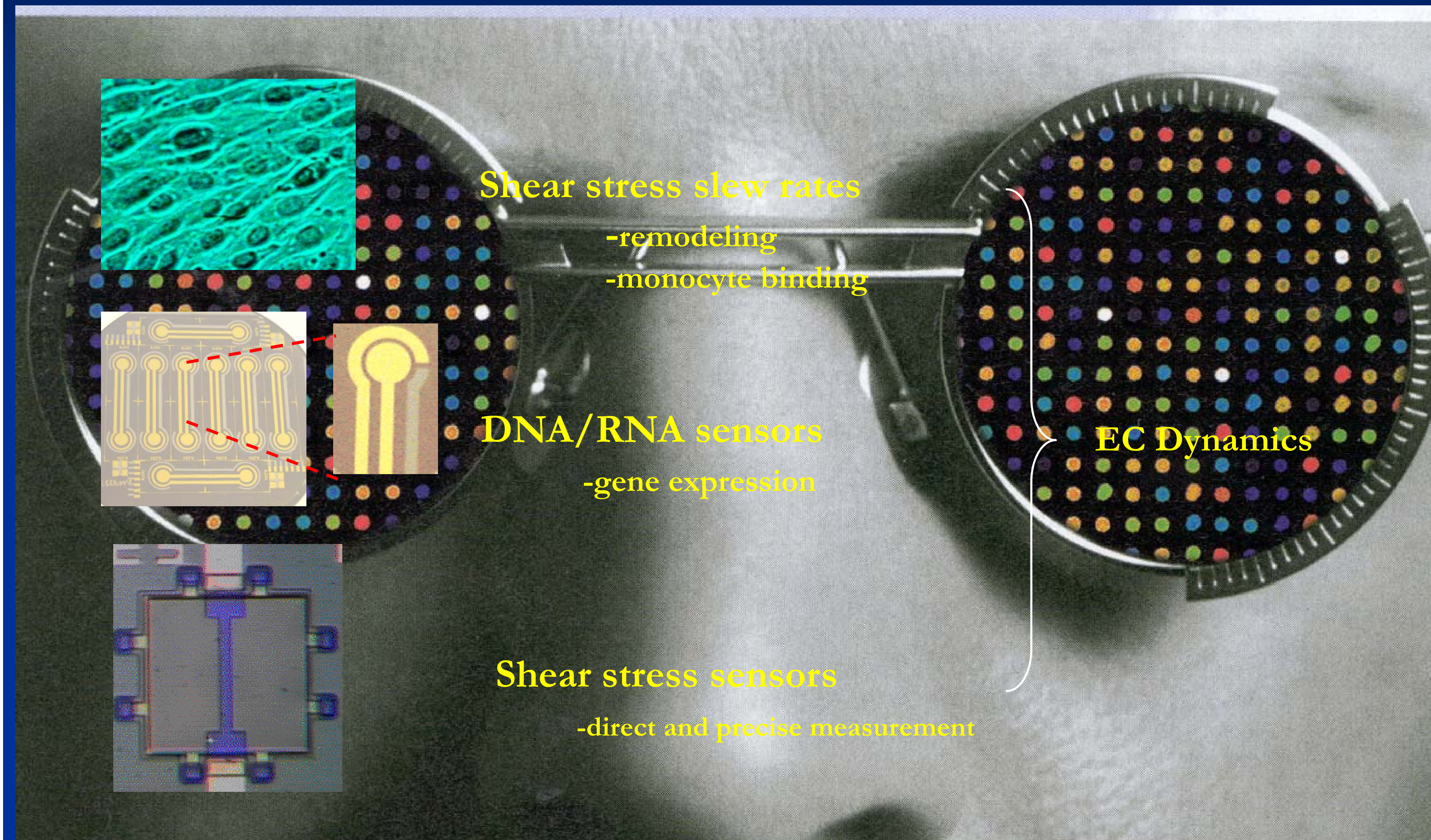
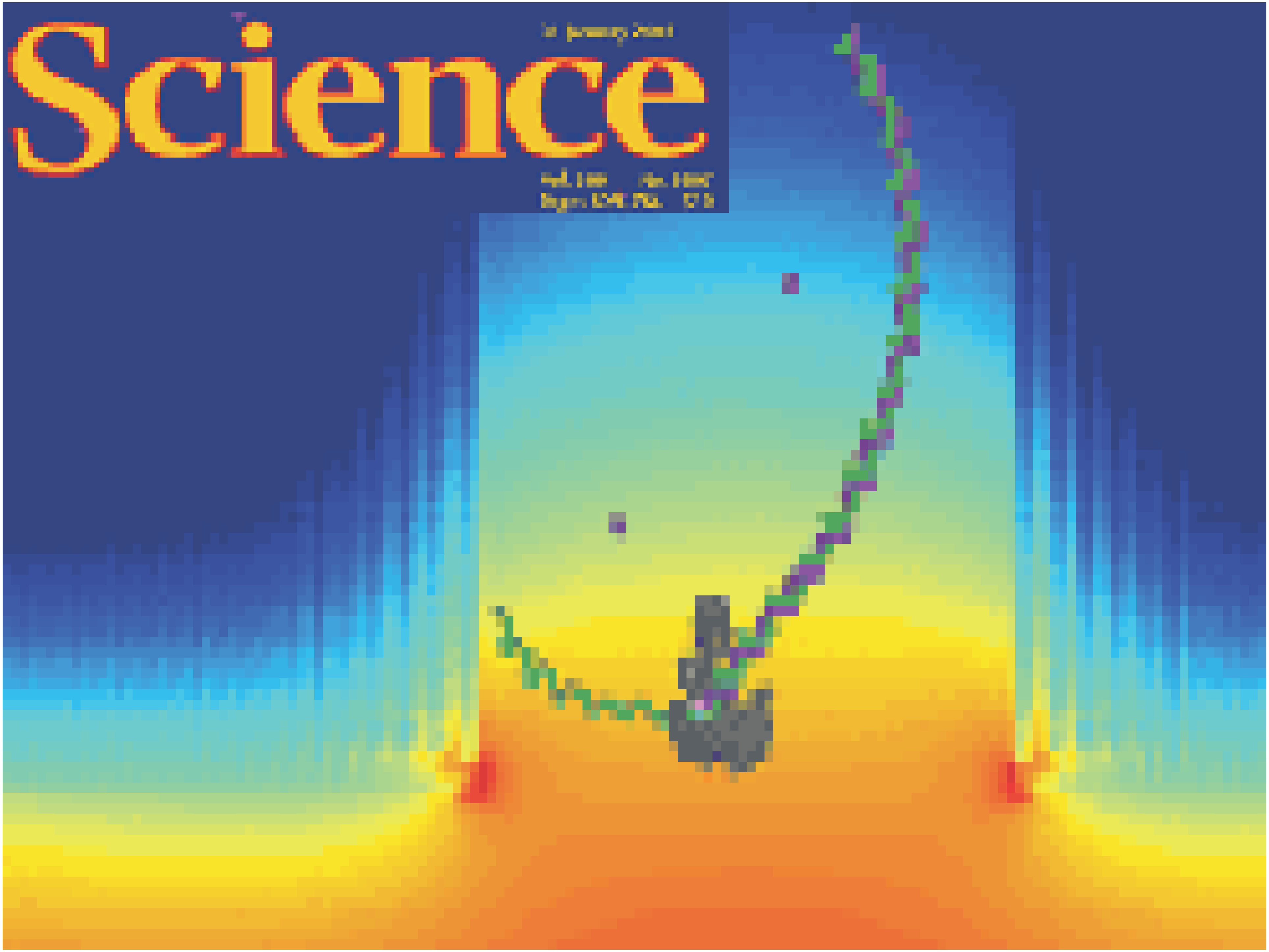
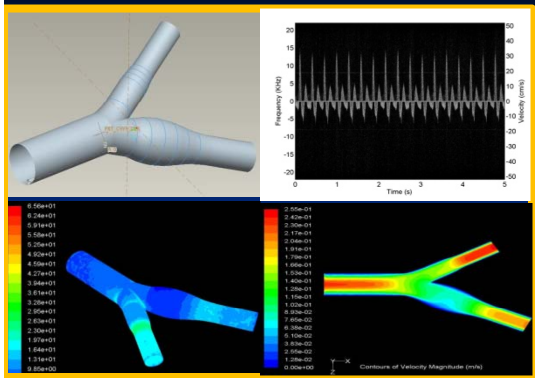


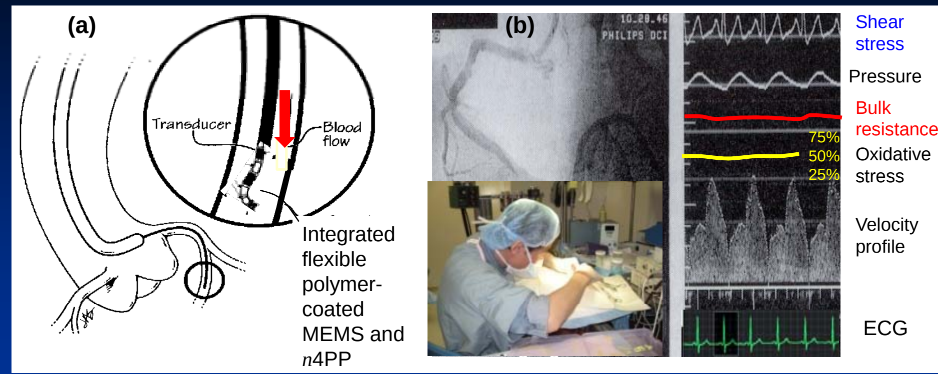
Biomedical Research in the Post-Genomic Era

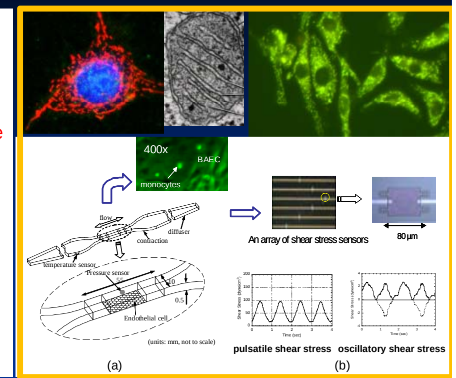



Science

Cardiovascular Engineering Research Core



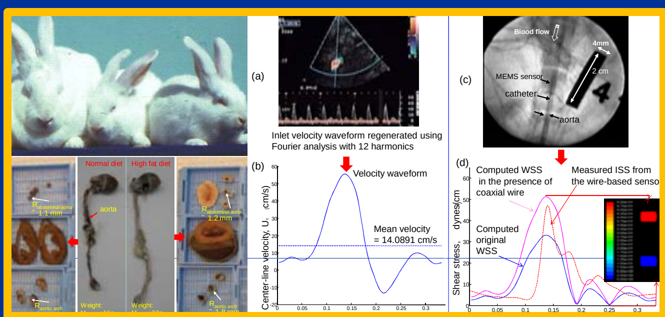




(1) Computational Fluid Dynamics

(2) Nanosensing of vascular oxidative stress and mechanically unstable plaque to predict acute coronary syndromes

(3) Mechano-transduction and vascular biology



(4) Rabbit model of atherosclerosis

Collaborators:

Fengzhu Sun, PhD, College LAS, USC
Ellen Lien, PhD, Children's Hospital Los Angeles, USC
Michael Kahn, PhD, Biochem & Molecular Bio, KSoM, USC
Mark Barr, MD, Cardiothoracic Surgery, USC
Fred A. Weaver, MD, Vascular Surgery, USC
Robert Kloner, MD, PhD, Good Samaritan Hospital, USC
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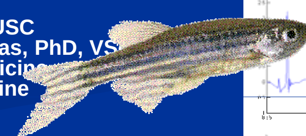
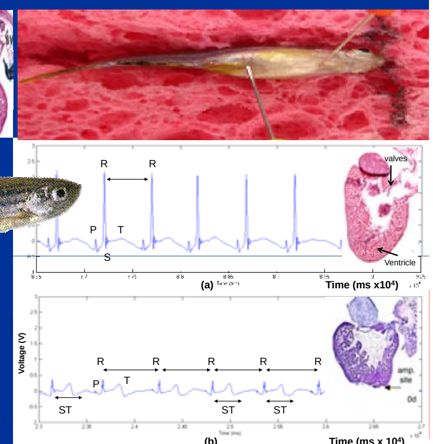
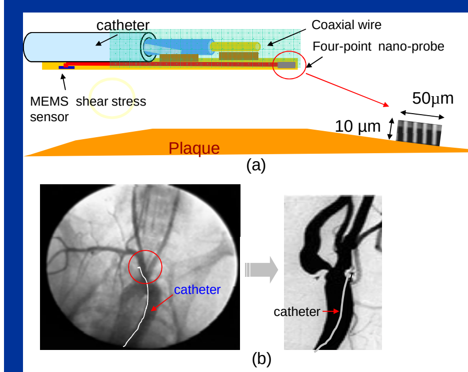
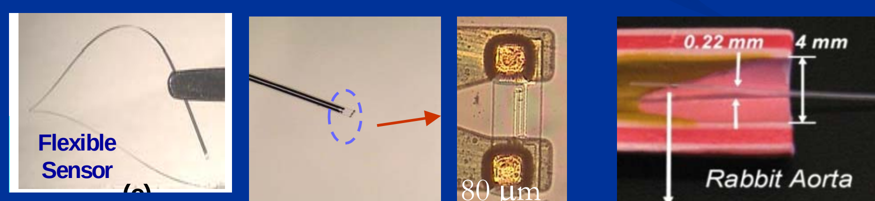
Joe Wu, MD, PhD, Stanford University School of Medicine
Julie Freishlag, MD, Johns Hopkins School of Medicine
Linda L. Demer, MD, PhD, UCLA School of Medicine
Judith Berliner, PhD, UCLA School of Medicine





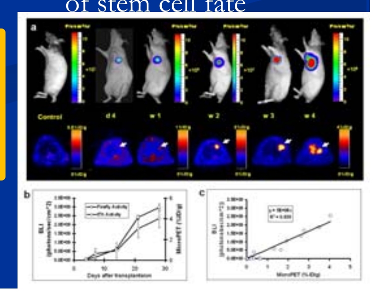
(7) Micro-ECG to monitor Zebrafish heart regeneration



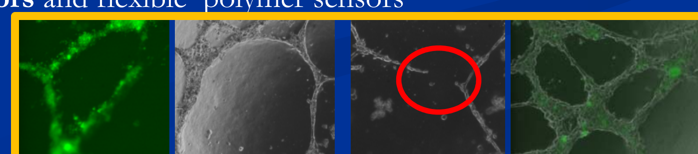


(6) MEMS shear stress sensors and flexible polymer sensors

(10) Molecular imaging of stem cell fate



(8) HAEC and tube formation

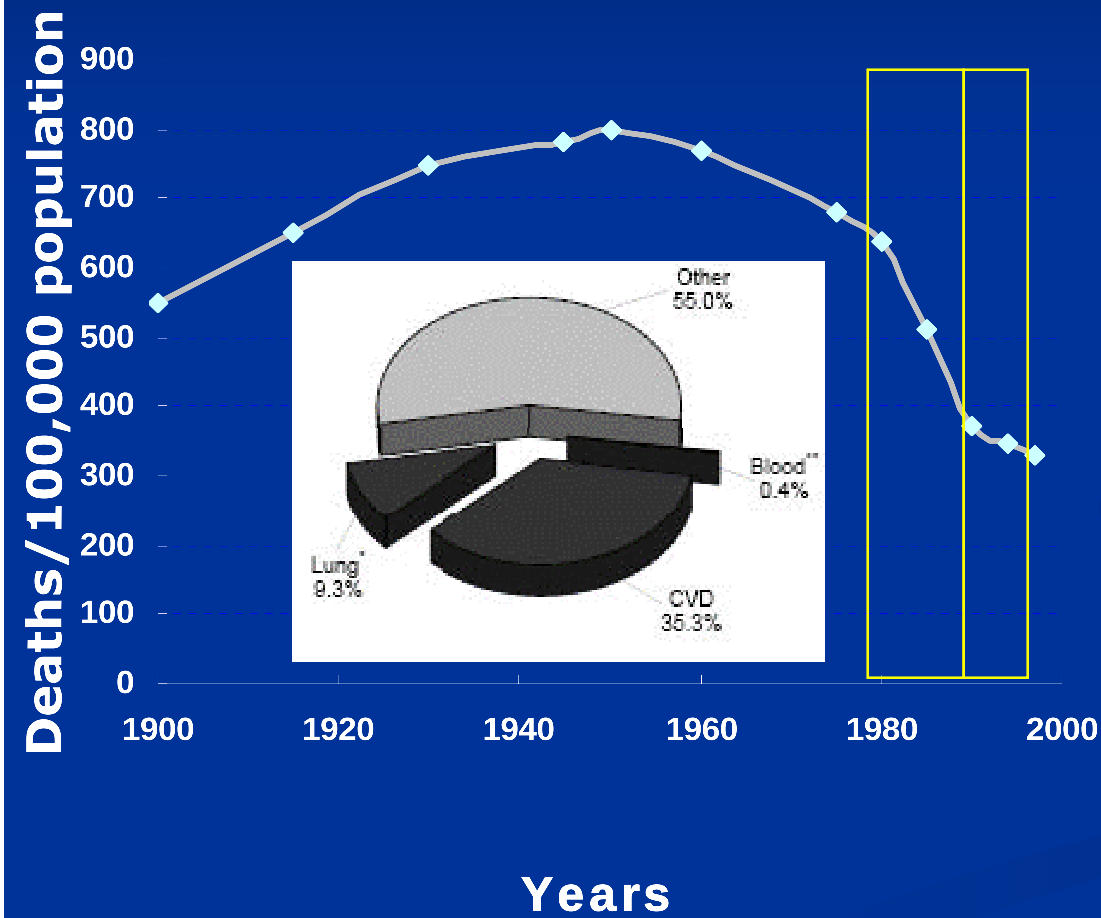


(5) Deployment of intravascular sensors in rabbit aortas

(9) Nano particles and environmental health

National Heart Lung and Blood Institute

Death Rates in Cardiovascular Disease: 35.3 % of all deaths in USA



Number of deaths for leading causes of death:

Heart disease: 631,636

Cancer: 559,888

Stroke (cerebrovascular diseases): 137,119

Chronic lower respiratory diseases: 124,583

Accidents (unintentional injuries): 121,599

Diabetes: 72,449

Alzheimer's disease: 72,432

Influenza and Pneumonia: 56,326

Nephritis, nephrotic syndrome, and nephrosis: 45,344

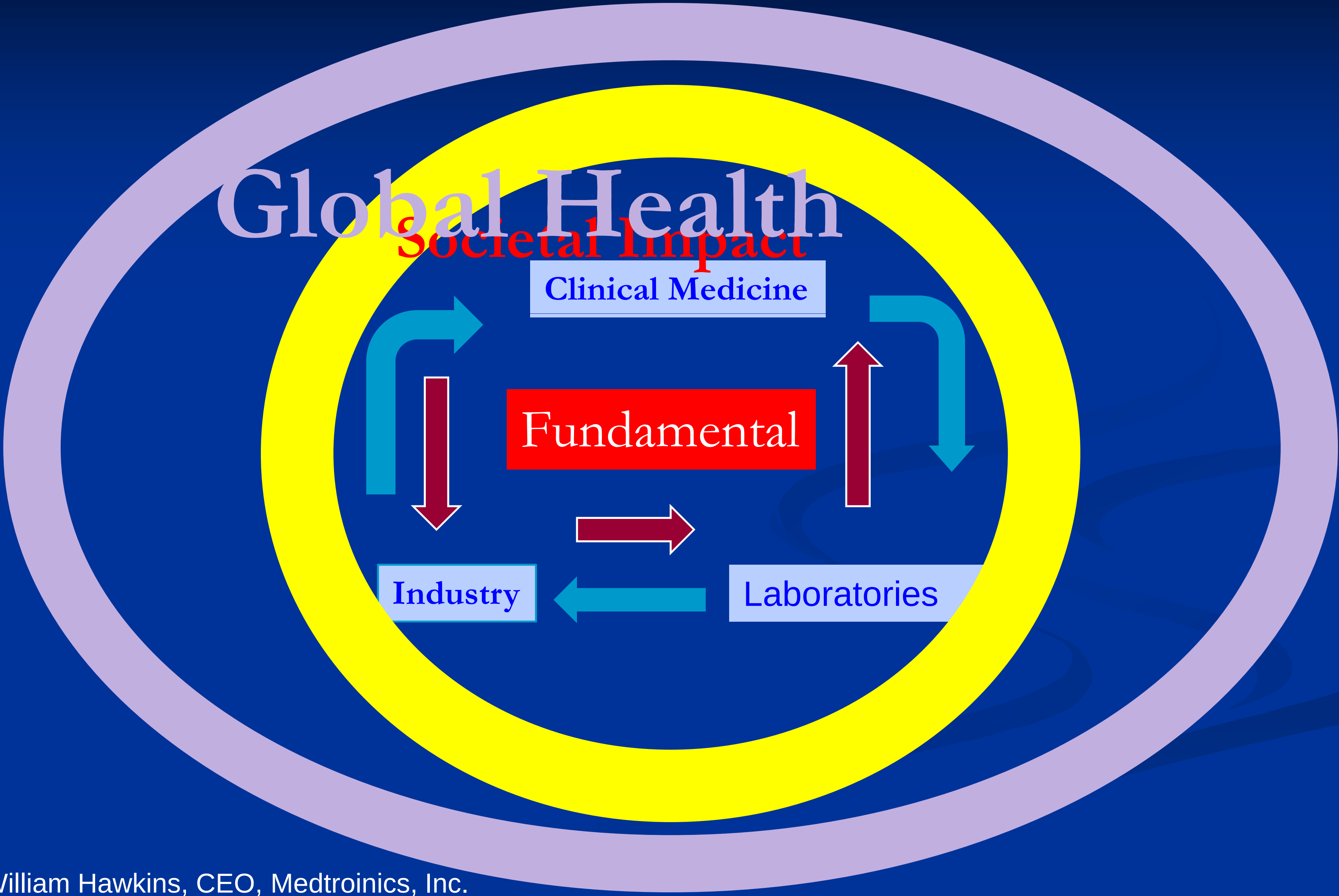
Septicemia: 34,234

Source: Deaths: Final Data for 2006, tables B, D, 7, 30

NIH NHLBI fact book, 2008

BMES2009

Three rivers of biology, engineering, and medicine

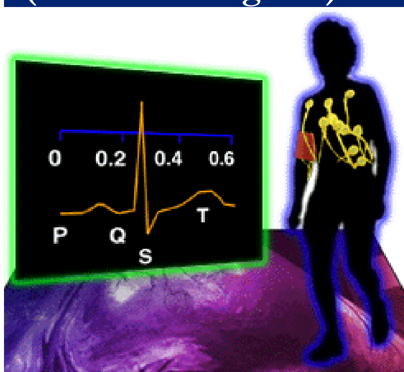


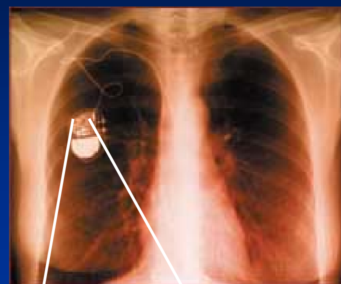
William Hawkins, CEO, Medtroinics, Inc.

Impact of Biomedical Research on Medicine

Macro →

ECG/EKG
(electrocardiogram)



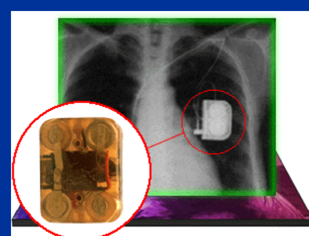


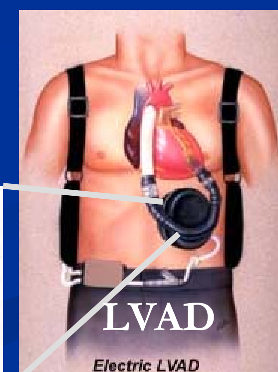
Chest X-Ray

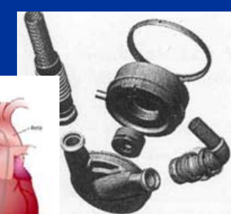
Echocardiogram

Imaging: MRI

Defibrillator







valves

A wide-open territory

Micro →

Molecular and nano approach to stem cell and regenerative medicine, tissue engineering, materials science, chemistry. Molecular biology, and alike.

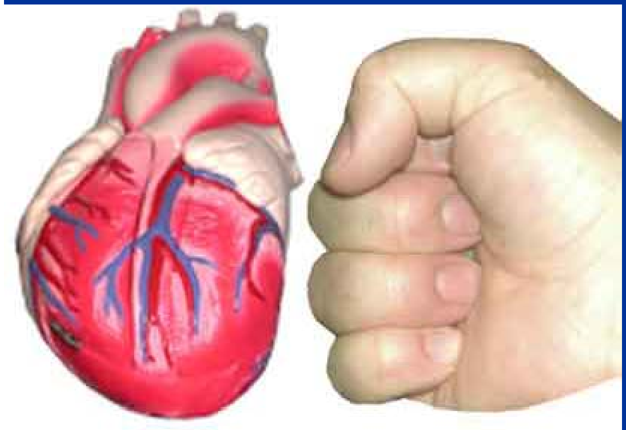
Nano → Biology, nanotechnology and nanophotonics

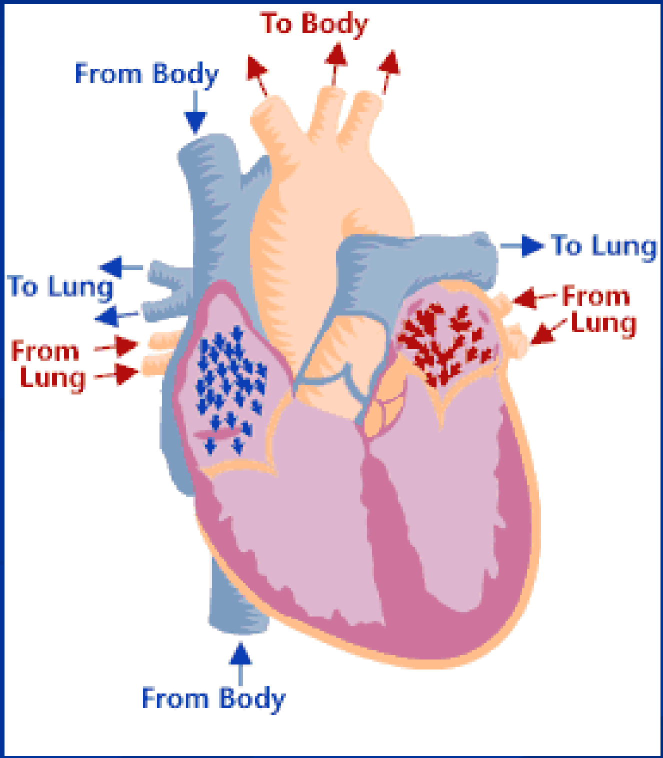
Dr. Hsiai's group at Edwards Lifesciences, Irvine, Ca.

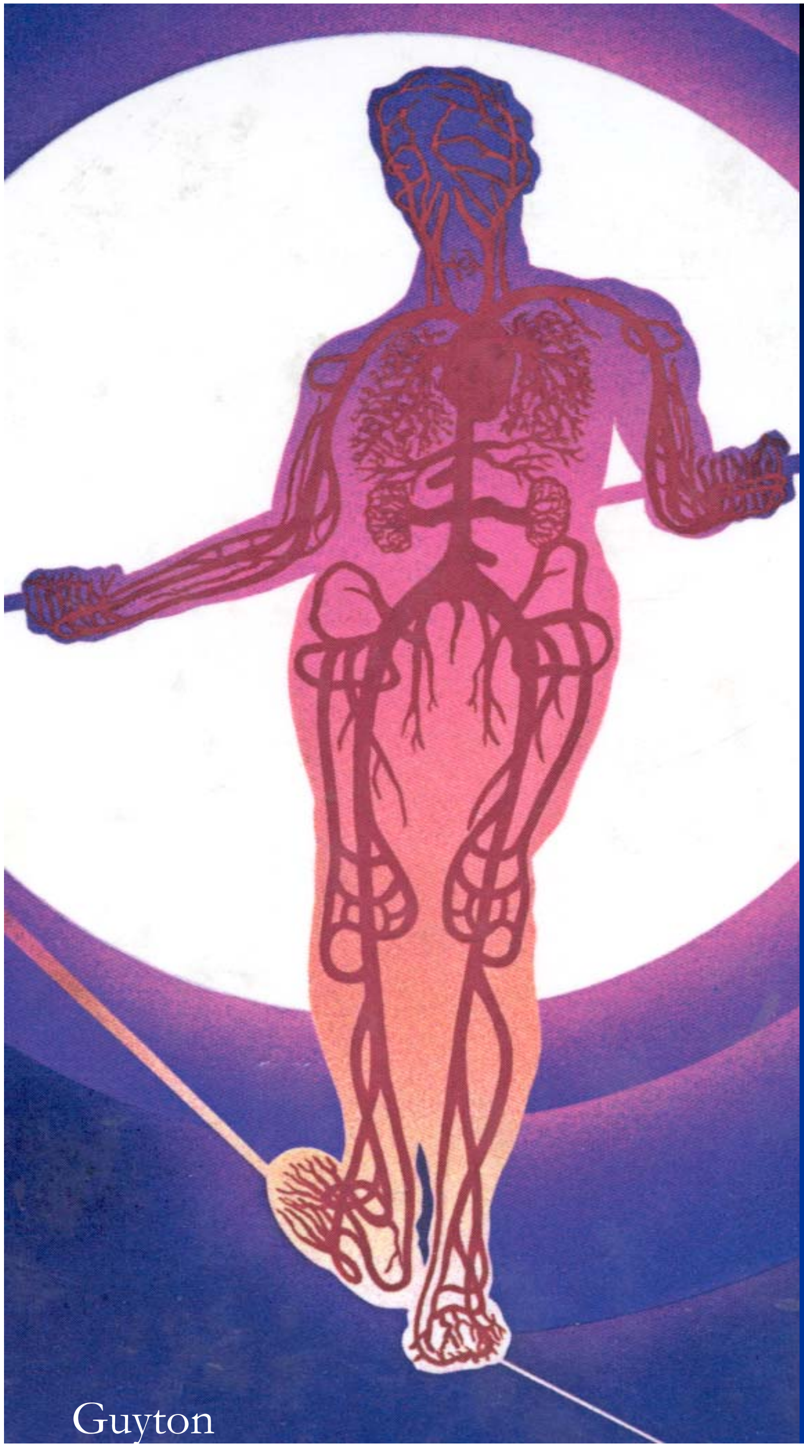
Objectives

- Introduce vascular systems
- Interface vascular dynamics with biology
- Translate vascular dynamics to in vivo models
- Bridge bioengineering, industry, and medicine

Vascular Dynamics







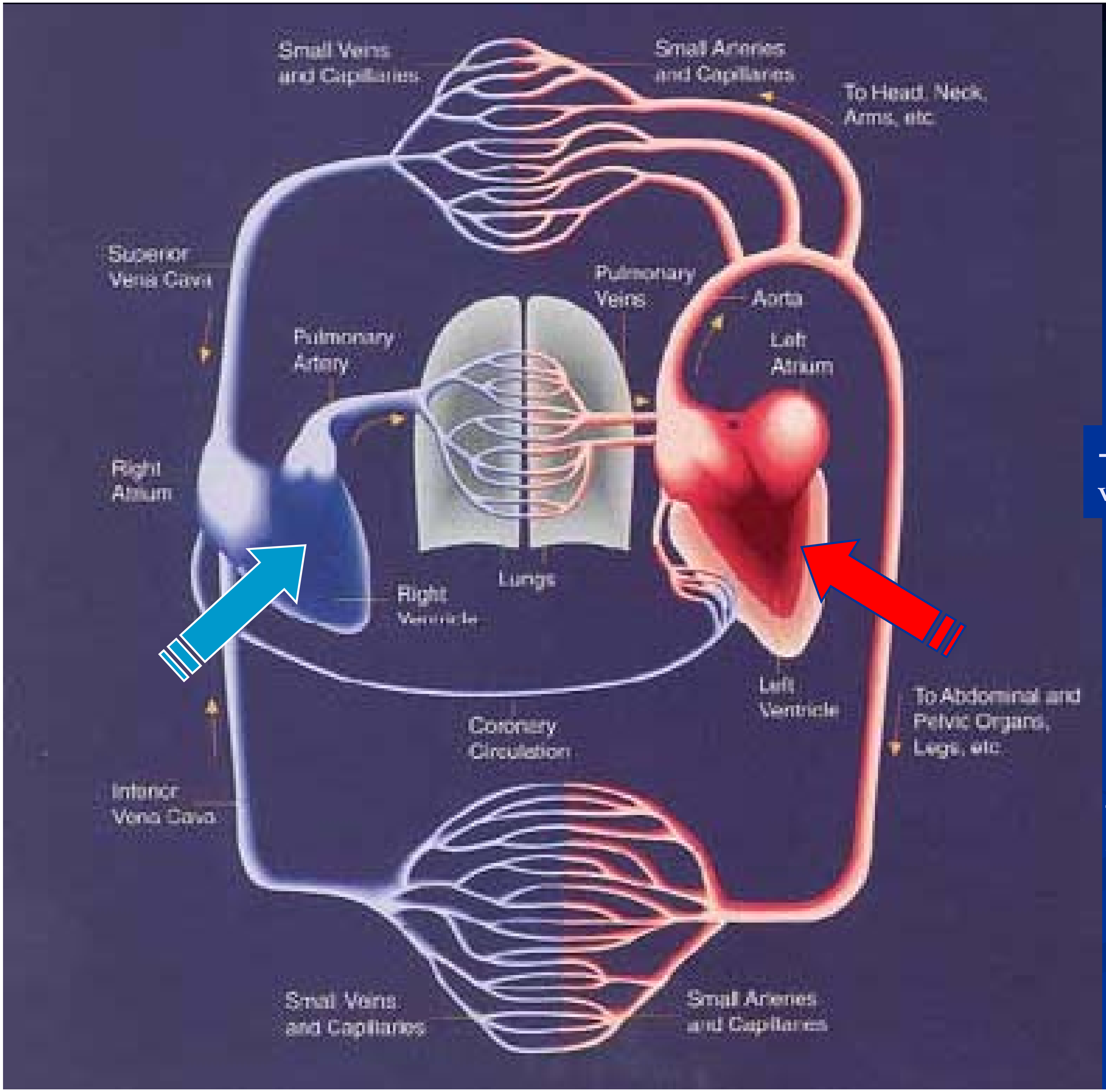
The Circuitry

Cardiovascular system

-a pump

-a series of distributing and collecting tubes

-an extensive system of thin vessels that permits rapid exchange of substances between the tissues and the vascular channels



-Pulsatile flow

-Laminar flow

-Viscous/frictional resistance

-Right vs left ventricular wall thickness

-Arterial resistance: Aorta vs. capillaries

-Capillaries: Resistance in parallel

-surface area: Aorta vs. capillaries

Law of Continuity of Flow

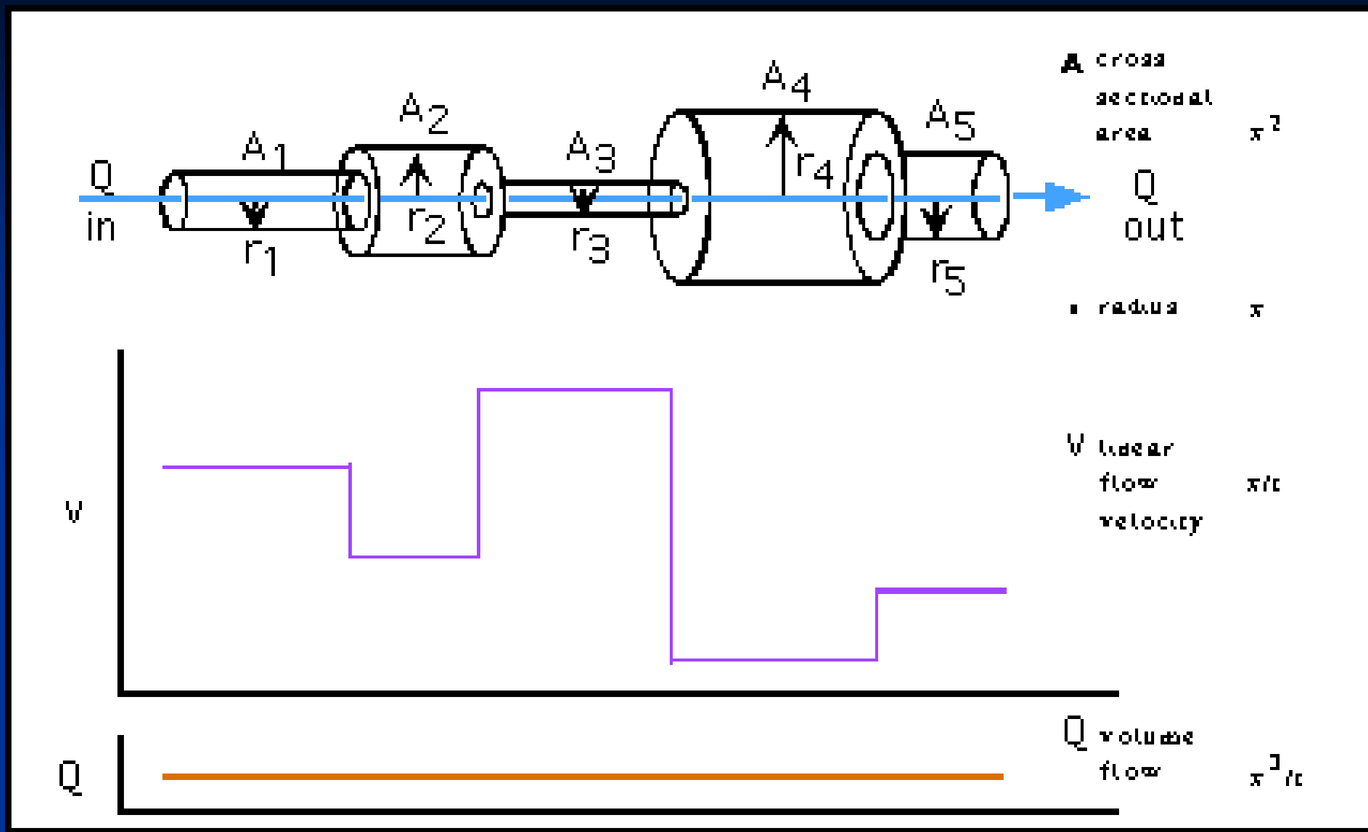
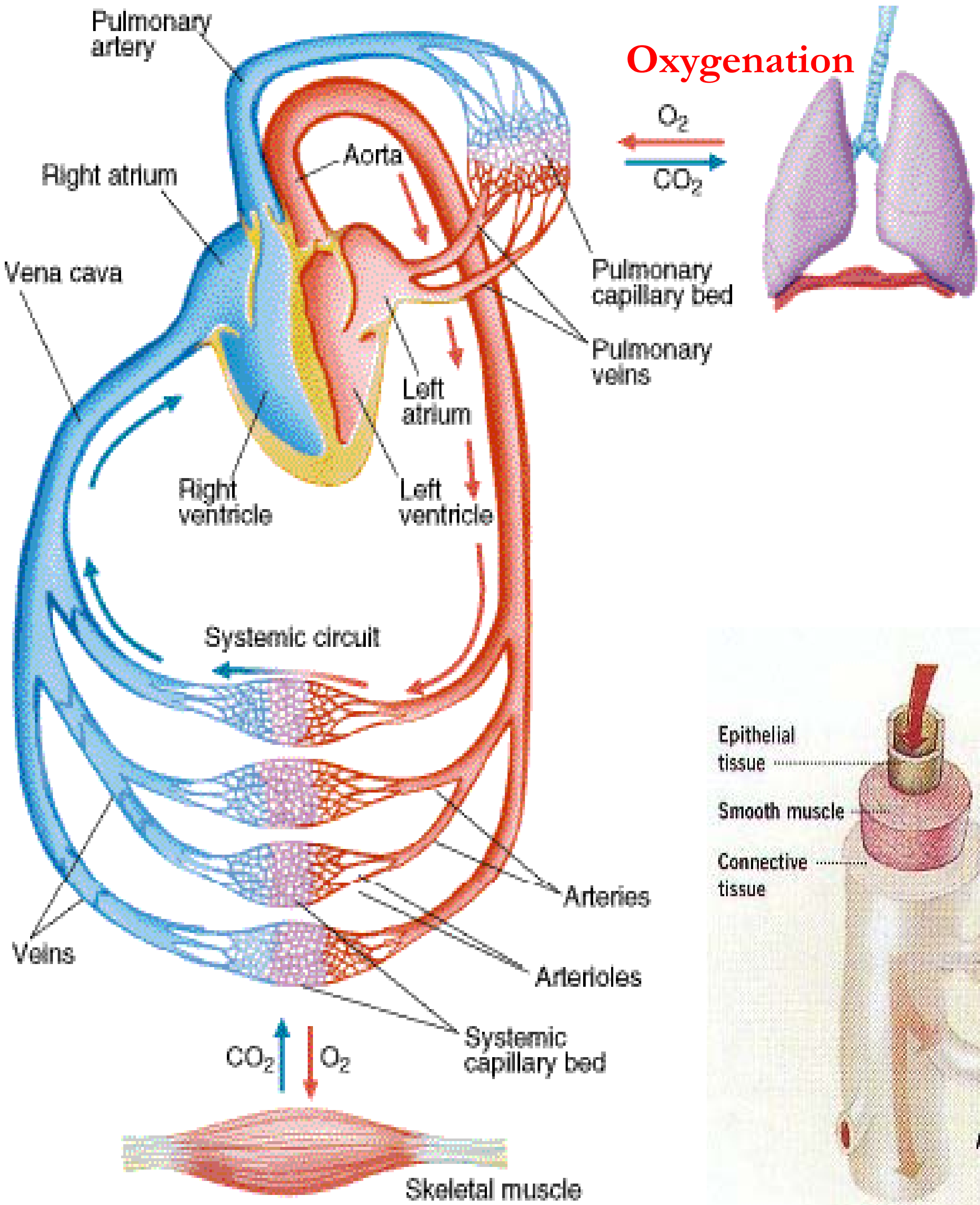


Figure 2

Blood flow in vessels of different sizes is constant in each segment of a given cross-sectional area regardless of the magnitude of that area. If vessels run side by side (in parallel), the flow will be additive. When one vessels lead one directly into another (in series), what flows in is what flows out:

$$Q_{total} = Q_1 + Q_2 = (V_1A_1) + (V_2A_2) = Q_{in} = Q_{out}$$



Compositions of vessel wall

-Endothelial cells

-Intima (collagen fibers)

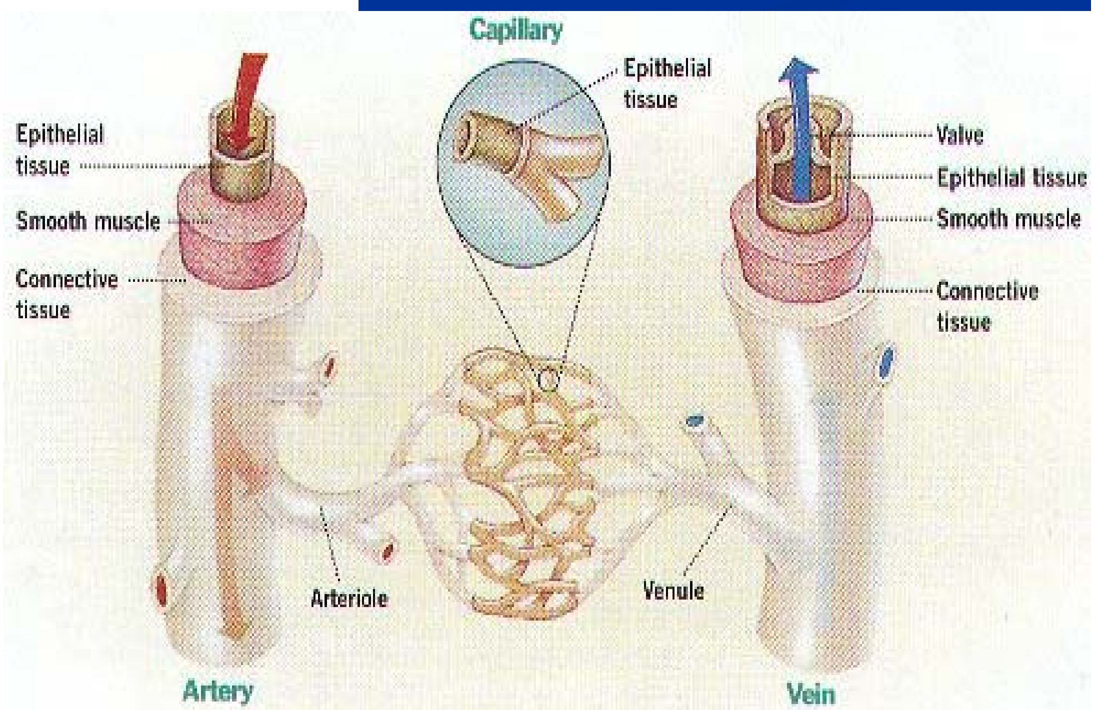
-Elastic laminar (arteries)

-smooth muscle cells (arteries vs. veins)

-tunica media

-adventia

-vaso vesorum



Navier-Stokes Equations
3-D unsteady flow

Coordinates: (x,y,z)

Velocity Components: (u,v,w)

Time : t

Density: ρ

Total Energy: Et

Pressure: p

Stress: τ

Heat Flux: q

Reynolds Number: Re

Prandtl Number: Pr

Continuity:

$$\frac{\partial \rho}{\partial t}+\frac{\partial(\rho u)}{\partial x}+\frac{\partial(\rho v)}{\partial y}+\frac{\partial(\rho w)}{\partial z}=0$$

X – Momentum:

$$\frac{\partial(\rho u)}{\partial t}+\frac{\partial(\rho u^2)}{\partial x}+\frac{\partial(\rho uv)}{\partial y}+\frac{\partial(\rho uw)}{\partial z}=-\frac{\partial p}{\partial x}+\frac{1}{Re_r}\left[\frac{\partial \tau_{xx}}{\partial x}+\frac{\partial \tau_{xy}}{\partial y}+\frac{\partial \tau_{xz}}{\partial z}\right]$$

Y – Momentum:

$$\frac{\partial(\rho v)}{\partial t}+\frac{\partial(\rho uv)}{\partial x}+\frac{\partial(\rho v^2)}{\partial y}+\frac{\partial(\rho vw)}{\partial z}=-\frac{\partial p}{\partial y}+\frac{1}{Re_r}\left[\frac{\partial \tau_{xy}}{\partial x}+\frac{\partial \tau_{yy}}{\partial y}+\frac{\partial \tau_{yz}}{\partial z}\right]$$

Z – Momentum

$$\frac{\partial(\rho w)}{\partial t}+\frac{\partial(\rho uw)}{\partial x}+\frac{\partial(\rho vw)}{\partial y}+\frac{\partial(\rho w^2)}{\partial z}=-\frac{\partial p}{\partial z}+\frac{1}{Re_r}\left[\frac{\partial \tau_{xz}}{\partial x}+\frac{\partial \tau_{yz}}{\partial y}+\frac{\partial \tau_{zz}}{\partial z}\right]$$

Energy:

$$\frac{\partial(E_T)}{\partial t}+\frac{\partial(uE_T)}{\partial x}+\frac{\partial(vE_T)}{\partial y}+\frac{\partial(wE_T)}{\partial z}=-\frac{\partial(up)}{\partial x}-\frac{\partial(vp)}{\partial y}-\frac{\partial(wp)}{\partial z}-\frac{1}{Re_r Pr_r}\left[\frac{\partial q_x}{\partial x}+\frac{\partial q_y}{\partial y}+\frac{\partial q_z}{\partial z}\right]$$

$$+\frac{1}{Re_r}\left[\frac{\partial}{\partial x}(u\,\tau_{xx}+v\,\tau_{xy}+w\,\tau_{xz})+\frac{\partial}{\partial y}(u\,\tau_{xy}+v\,\tau_{yy}+w\,\tau_{yz})+\frac{\partial}{\partial z}(u\,\tau_{xz}+v\,\tau_{yz}+w\,\tau_{zz})\right]$$

Navier-Stokes Equation:

Newtonian fluids of constant density and viscosity

At steady flow — Hydrostatic equilibrium — An ideal fluid

$$\rho\left(\frac{\partial v}{\partial t} + \mathbf{v}\cdot\nabla\mathbf{v}\right) = -\nabla p + \mu\nabla^2\mathbf{v} + \mathbf{f}$$

Transient Inertial force + Convective initial force = Pressure force + Viscous force + Body Force =ρg

For pulsatile flow, compare the transient inertial force term with the viscous force term:

$$\frac{inertia}{viscous} = \frac{\rho\omega U}{\mu U L^{-2}} = \frac{\rho\omega L^2}{\mu} = \frac{\omega L^2}{\nu}$$ = a frequency parameter called the Stokes' number

The square root= $$\alpha = N_w = \frac{D}{2}\sqrt{\frac{\omega}{\nu}}$$ = Womersley's number

In aorta: α in a man ~20, in a dog~14, a cat ~8 and a rat ~3

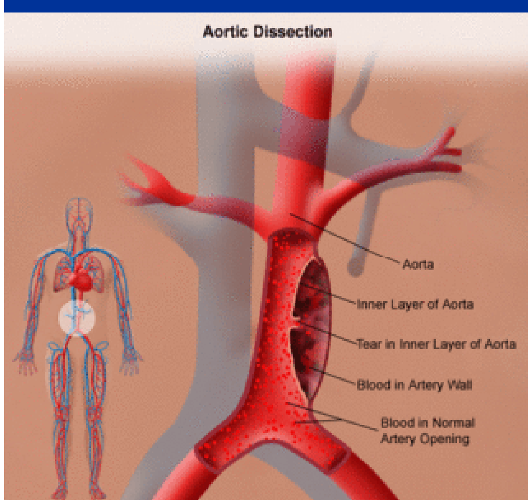
Reynolds number

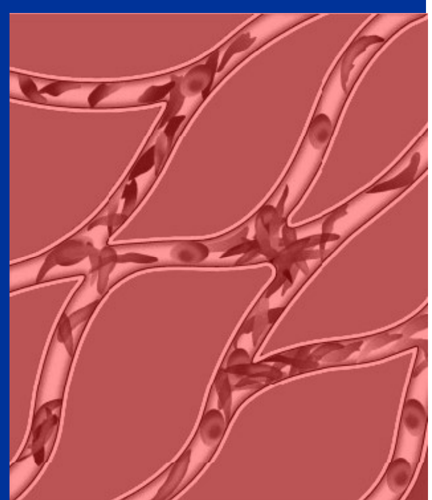
Compare convective inertial force with the viscous force terms:

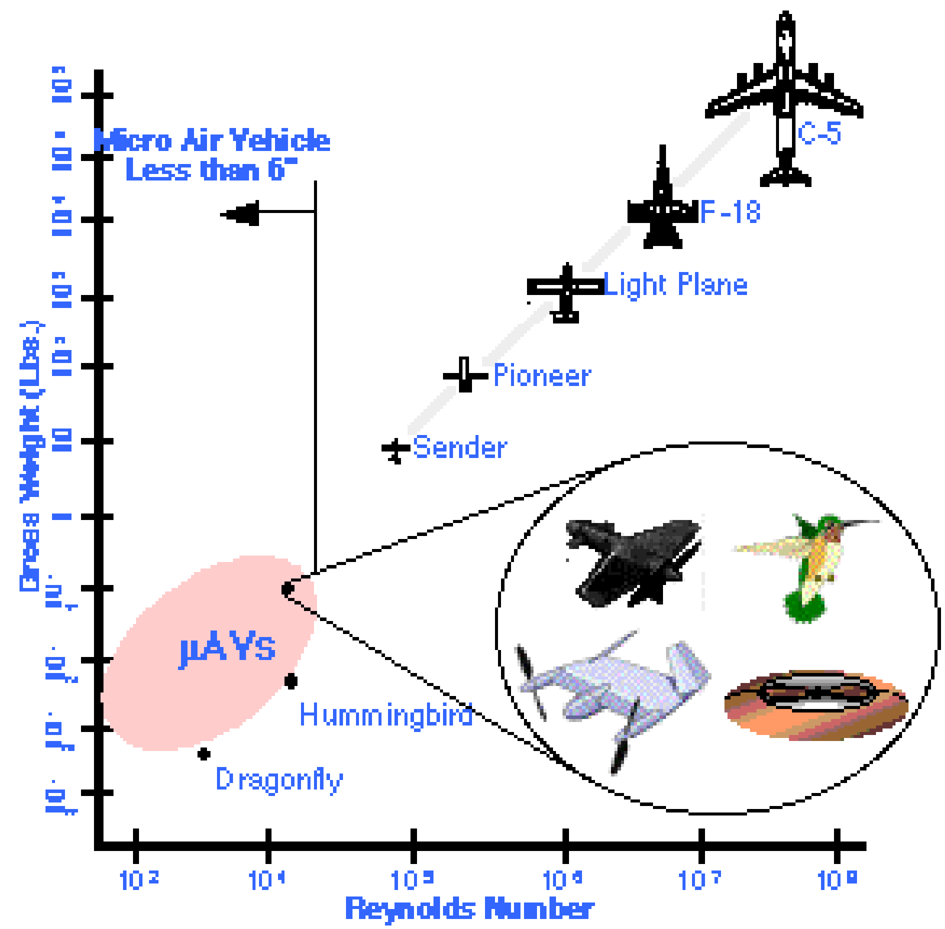
$$\frac{inertia}{viscous} = \frac{\rho U^2}{\mu U / L} = \frac{\rho U L}{\mu} = \text{Re}\,ynolds$$

A large Re #: a preponderant inertia effect.
A small Re #: a predominant viscous force effect.

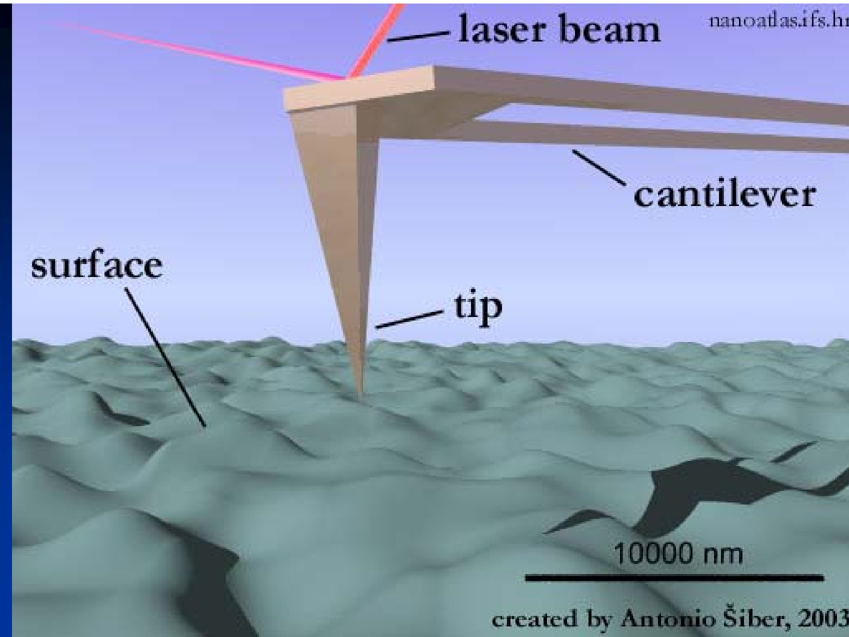
Re # in aorta: 2,000-3,000
Re # in capillary: 0.001 to 0.01





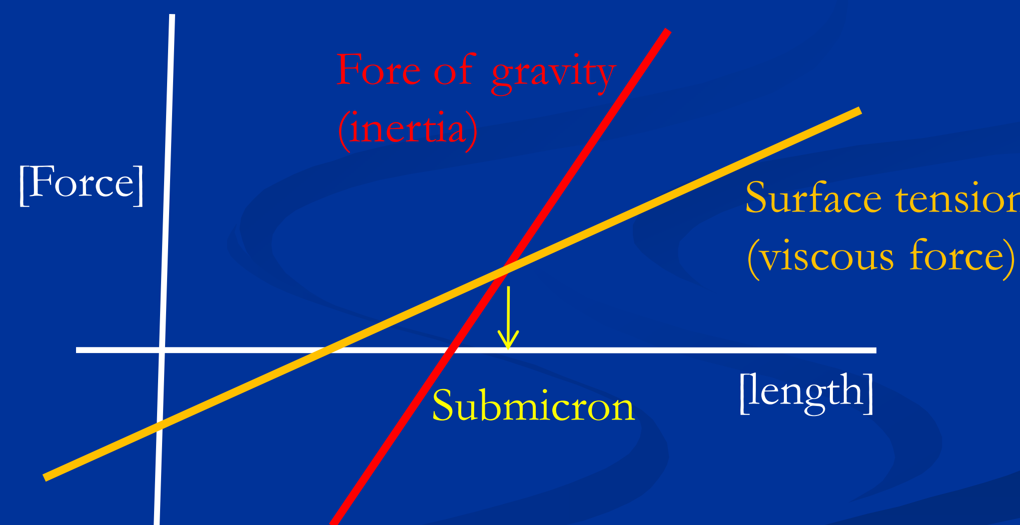


Paradigm shift in the micro- and nano-scale dynamics

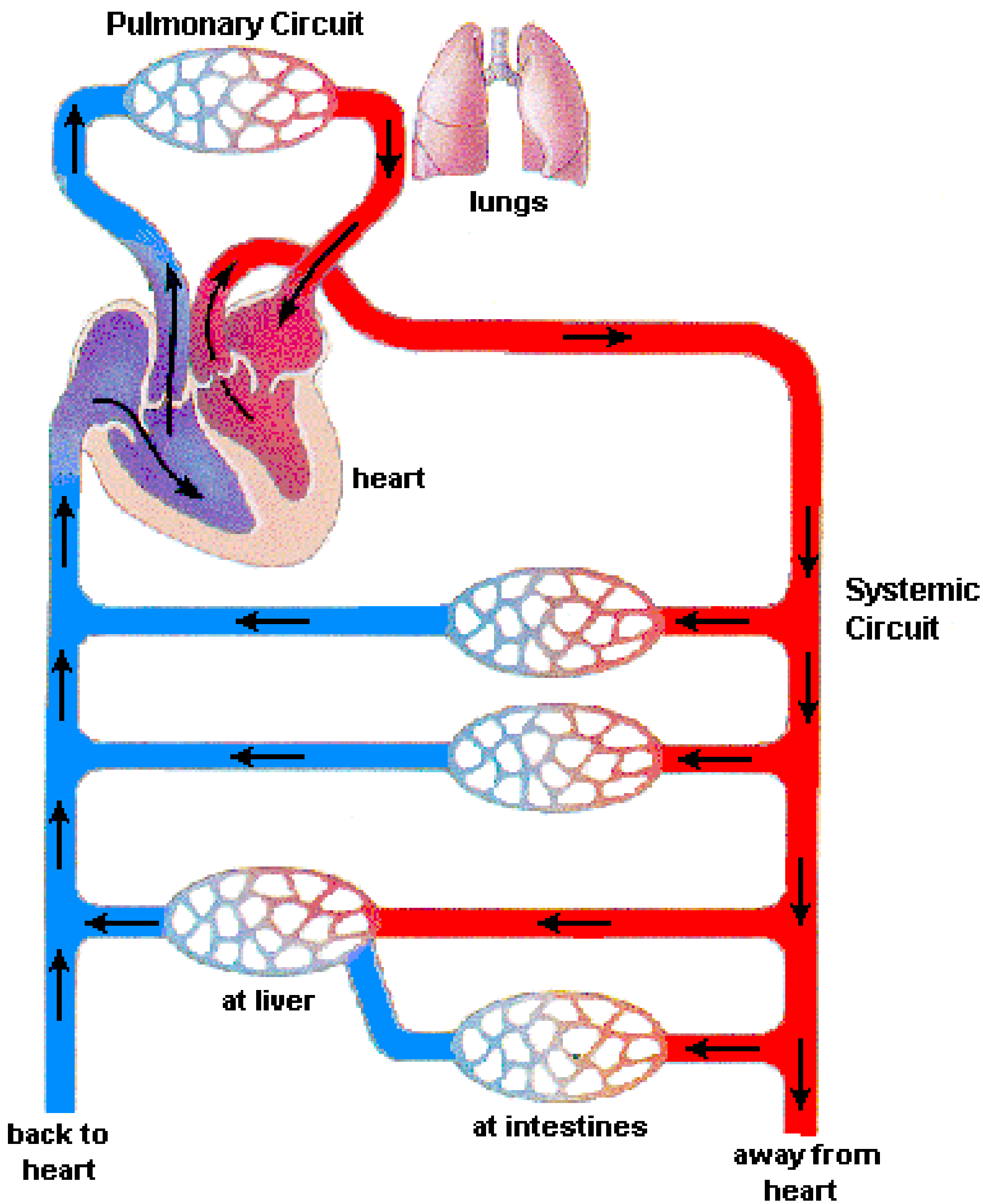


Key points

- Semiconductors
- MEMS
- Microfluidics
- Gene Chips
- MEMS cardiovascular sensors
- Nanotechnology
- Nanotubes
- Quantum dots
- Green fluorescent protein
- Optics/molecular imaging
- Biodefense
- Nanotoxiciyy



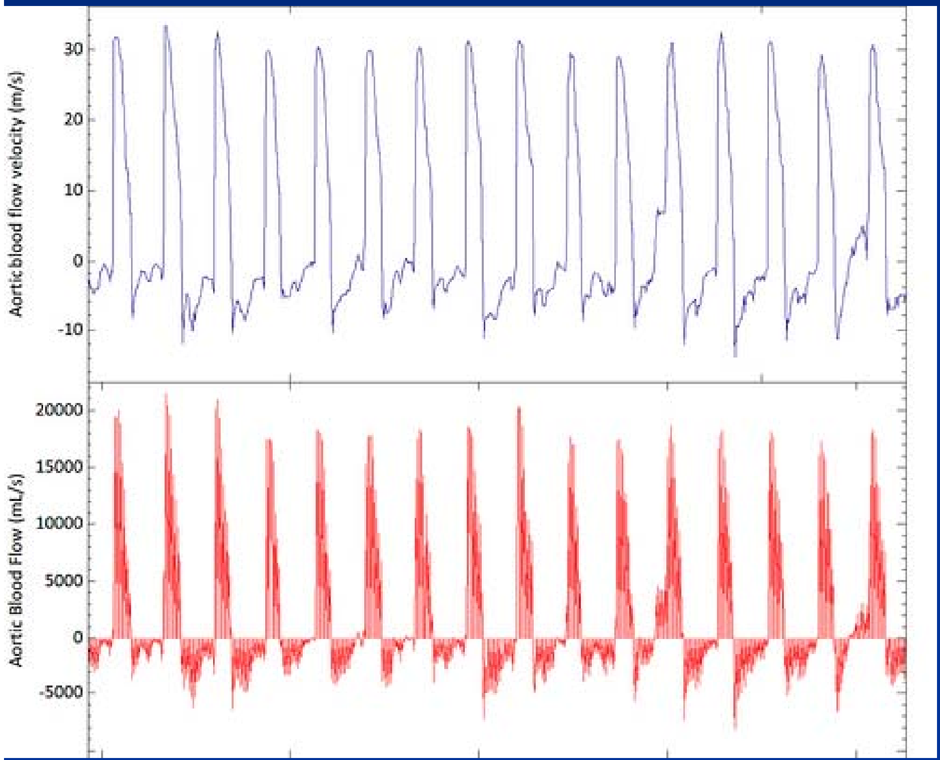
$$\frac{inertia}{viscous} = \frac{\rho U^{2}}{\mu U / L} = \frac{\rho UL}{\mu} = \mathrm{Re}\ ynolds$$

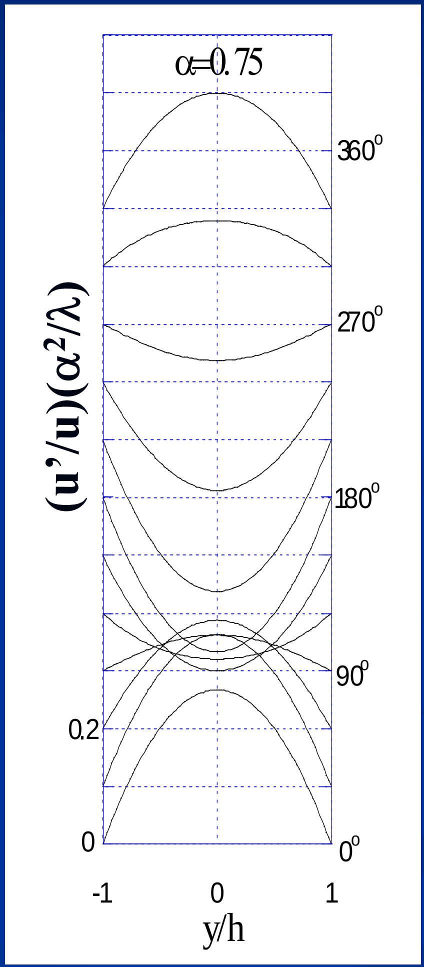


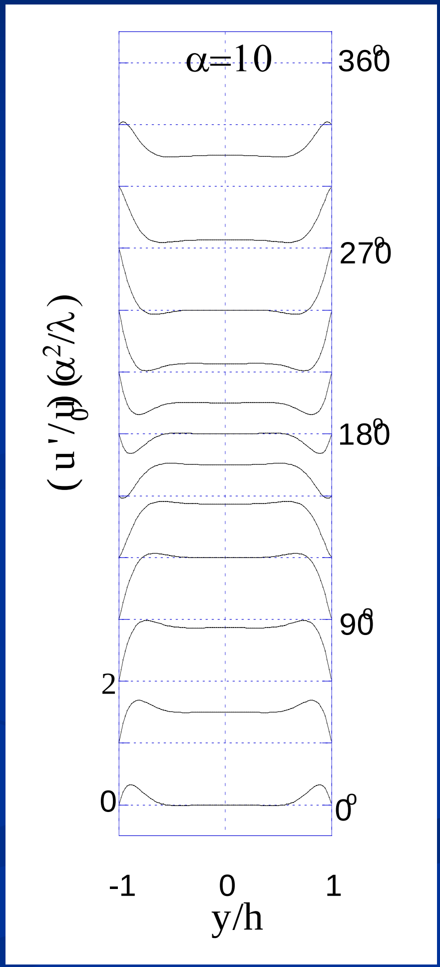
Reynolds numbers:
- aorta
- arterioles
- capillaries
- veins

Womerley's number:
- aorta
- arterioles
- capillaries
- veins

Velocity Profiles of Pulsatile Flow:
$\propto = 0.75$ vs. 10

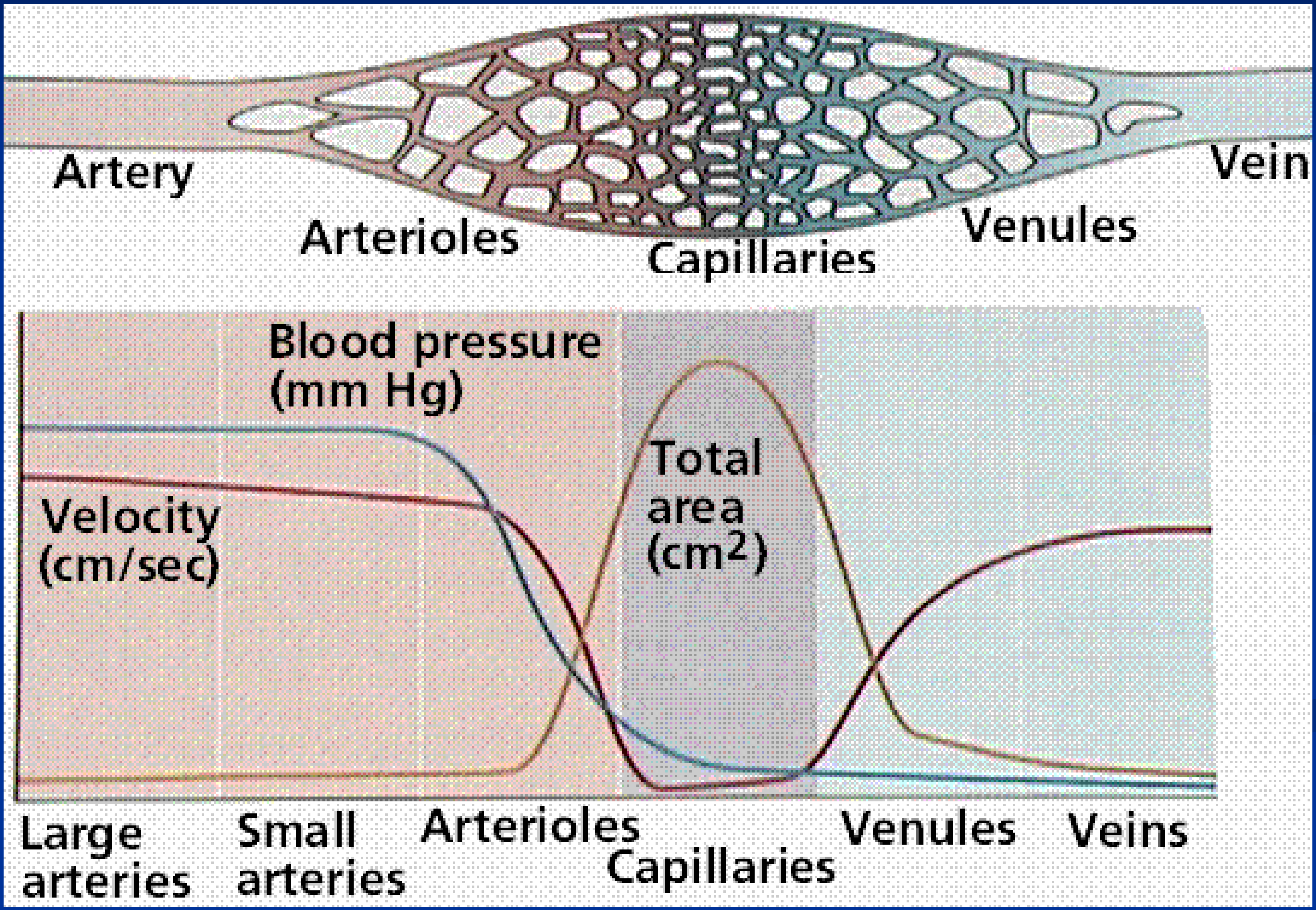




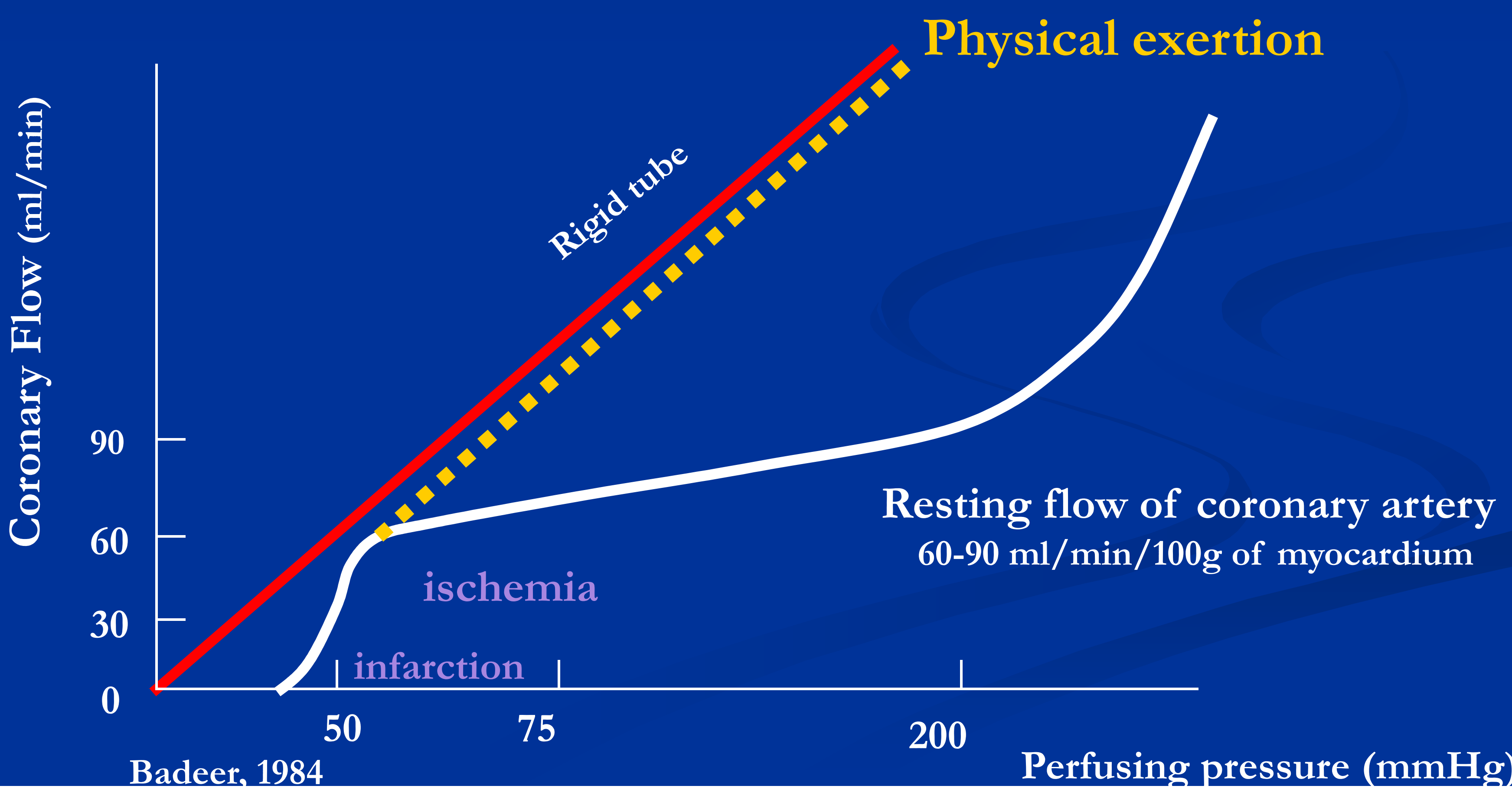


Womersley, J of Physiol, and SK Cho

Blood Pressure



Rigid tube vs. Coronary vascular bed

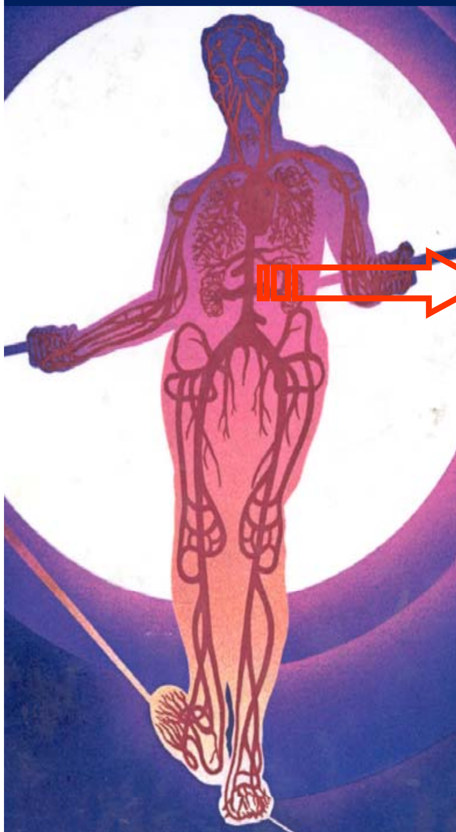


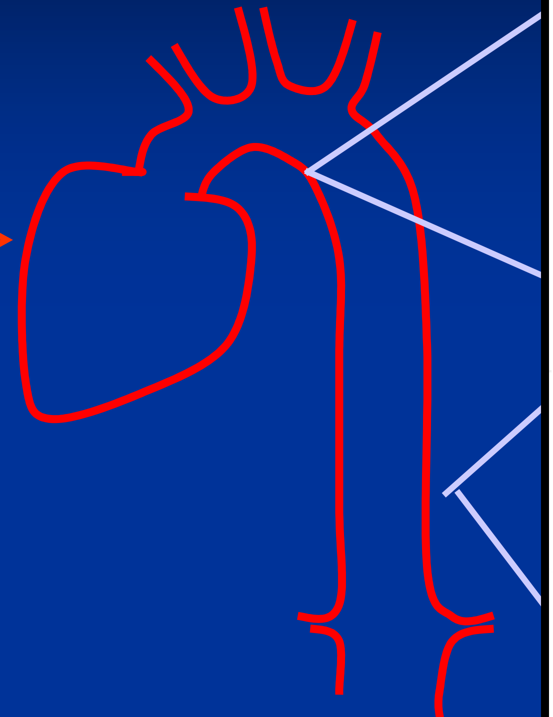
Badeer, 1984

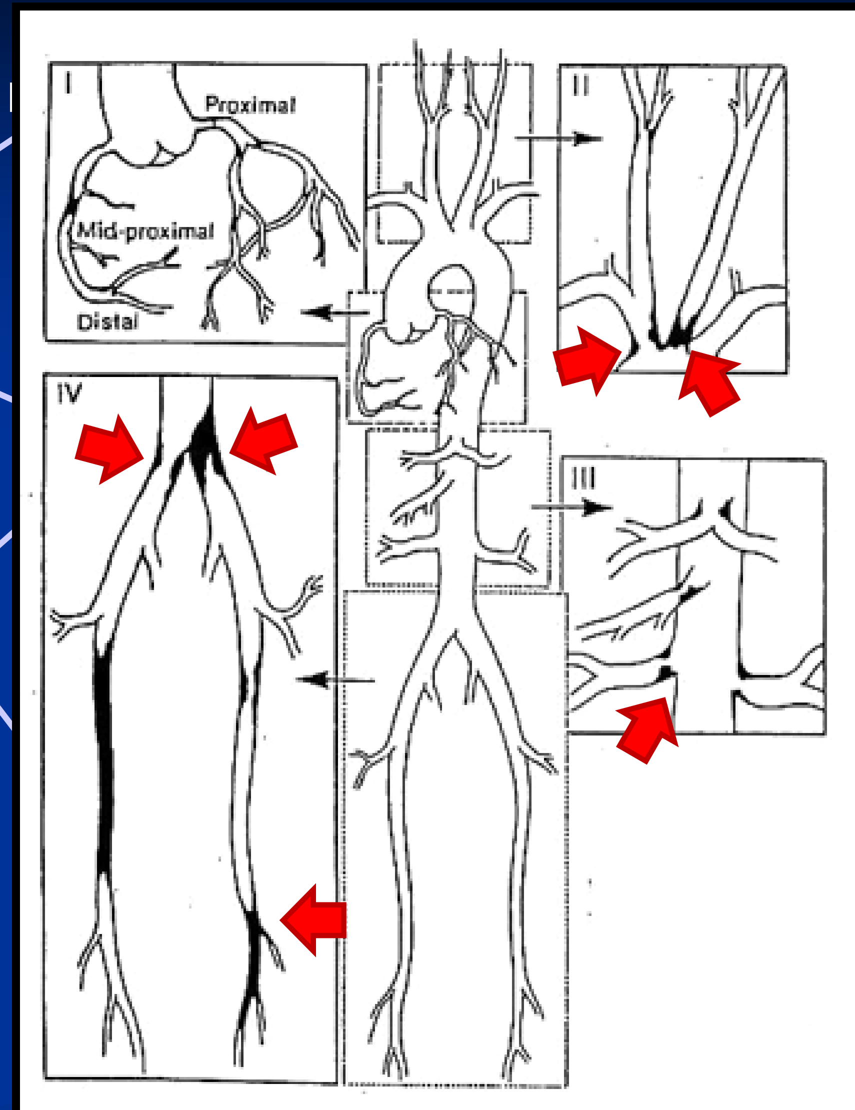
Objectives

- **Introduce vascular systems**
  - Inertia vs. viscous force
- Interface vascular dynamics with vascular biology
- Translate vascular dynamics to an in vivo model
- Bridge bioengineering, industry, and medicine

Interplay between Hemodynamics and Vascular Biology

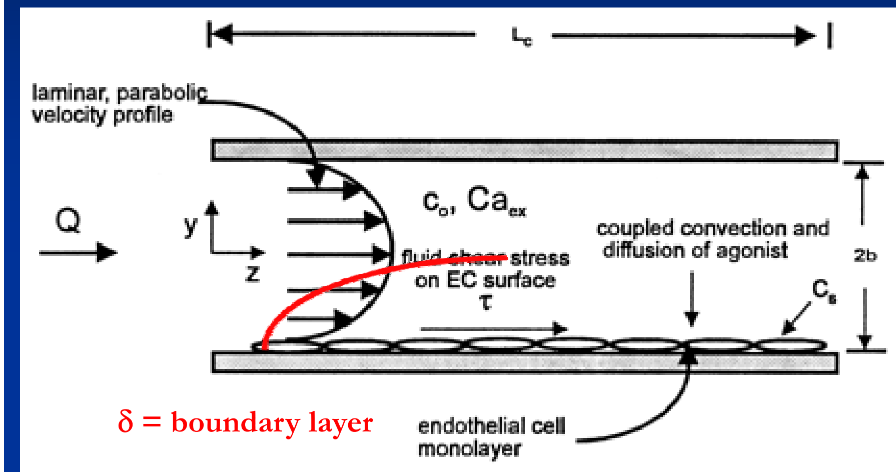






Shu Chien, John Cook, John Frango, Scott Simon, R. Narem, M. Gimbrone, P. Davies, L. McIntyre ,
Don Giddens, David Ku, C. Taylor, C. Zarins

Atherosclerosis and Hemodynamics



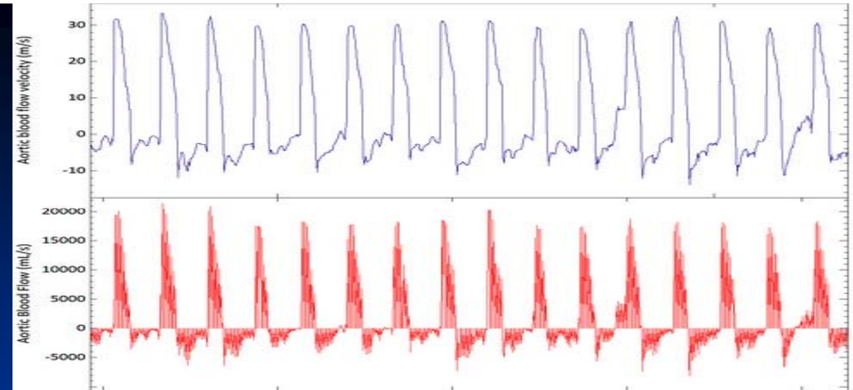
Navier-Stokes Equation

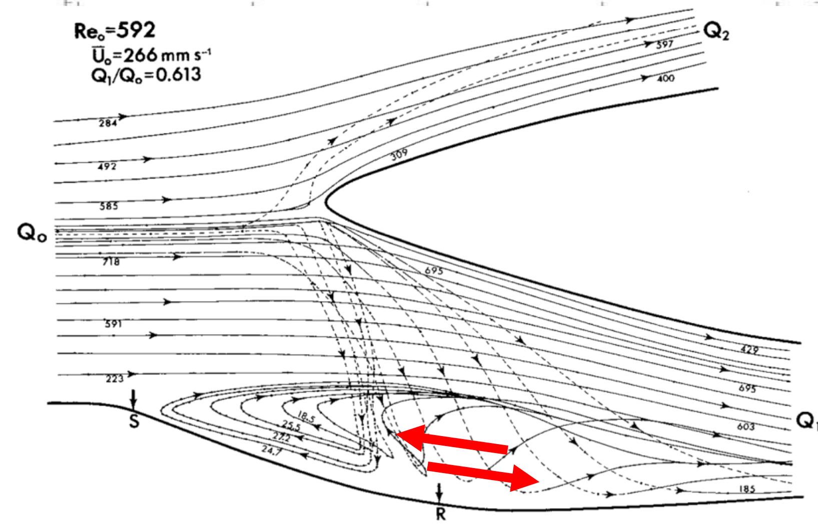
$$\rho\left(\frac{\partial v}{\partial t} + \mathbf{v}\cdot\nabla\mathbf{v}\right) = -\nabla\rho + \mu\nabla^2\mathbf{v} + \mathbf{f}$$

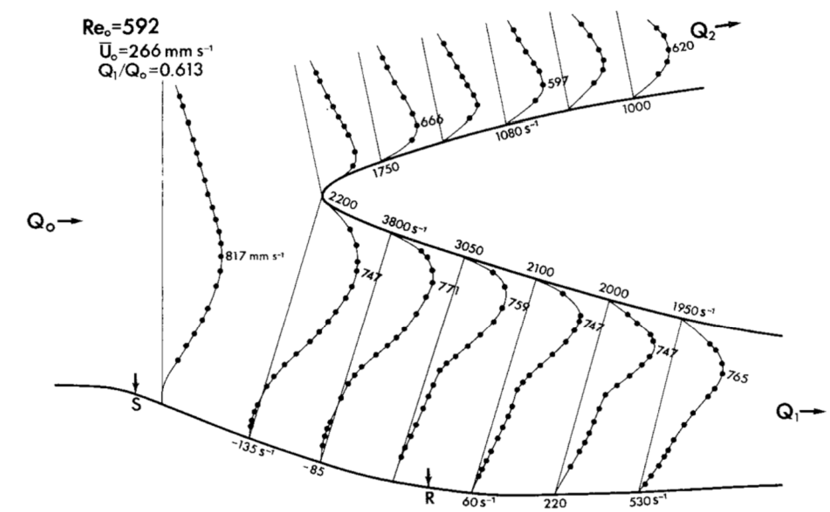
Transient inertial force | Convective initial force | Pressure force | Viscous force | Body force

$$\frac{\partial\tau}{dt} = 0, \alpha \leq 1, Re < 1000$$

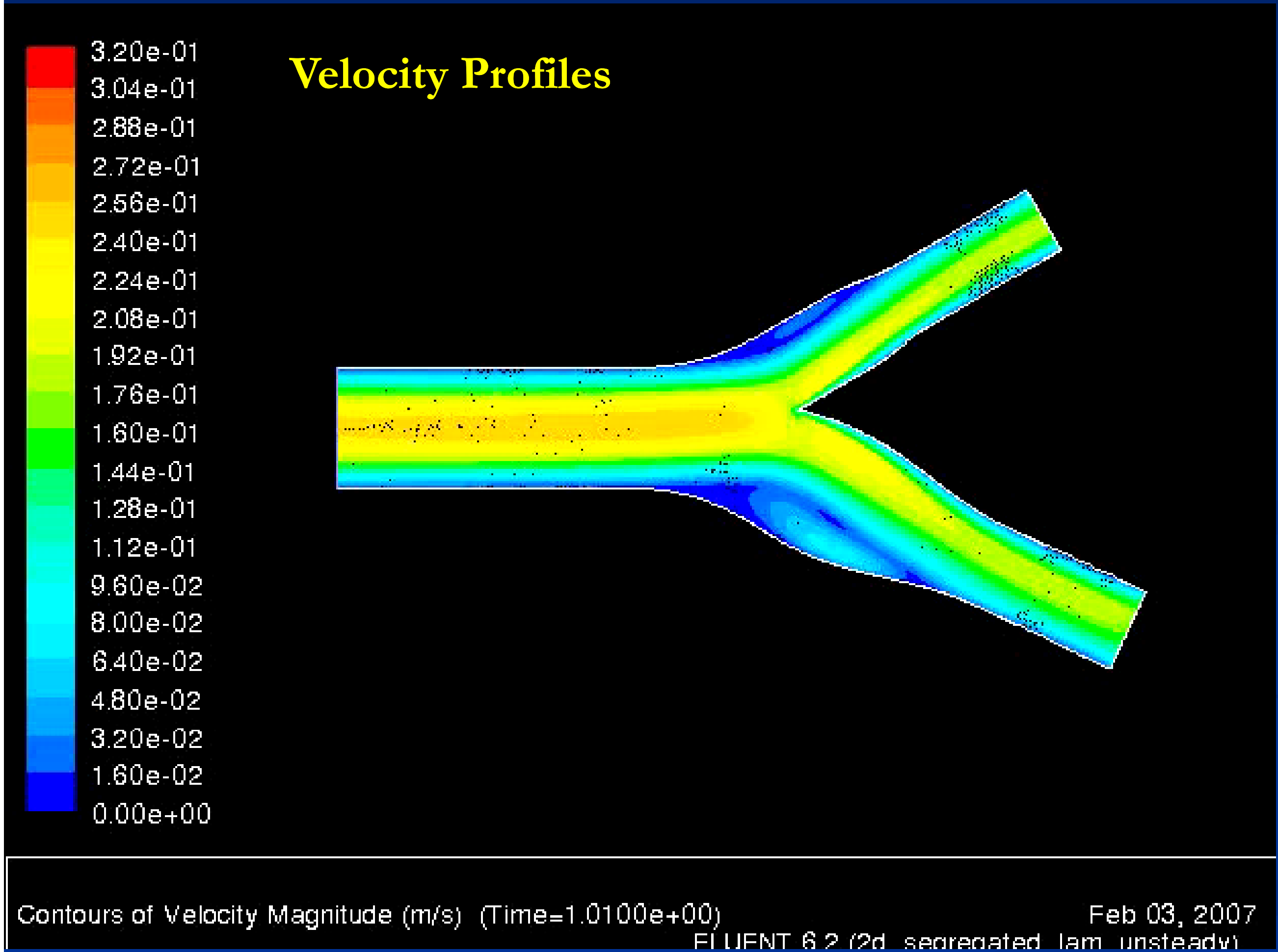
$$\tau_w = \mu\frac{\partial u}{\partial y}\bigg|_{y=0}$$

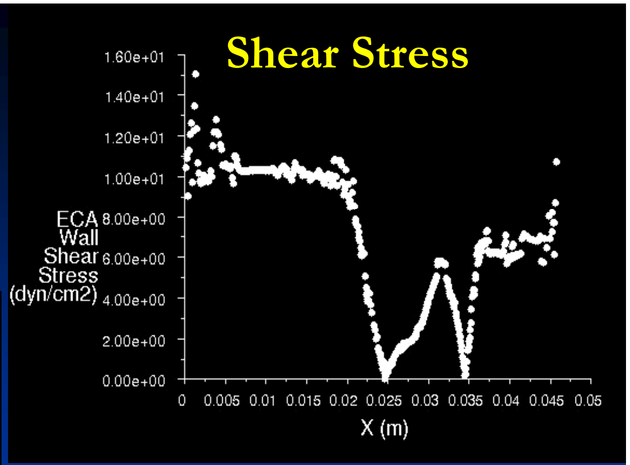


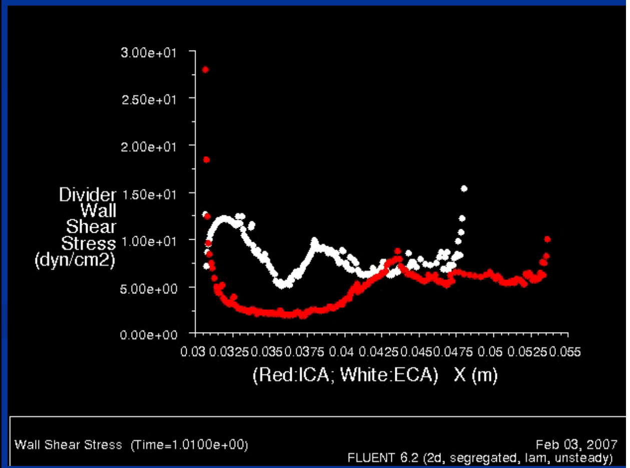


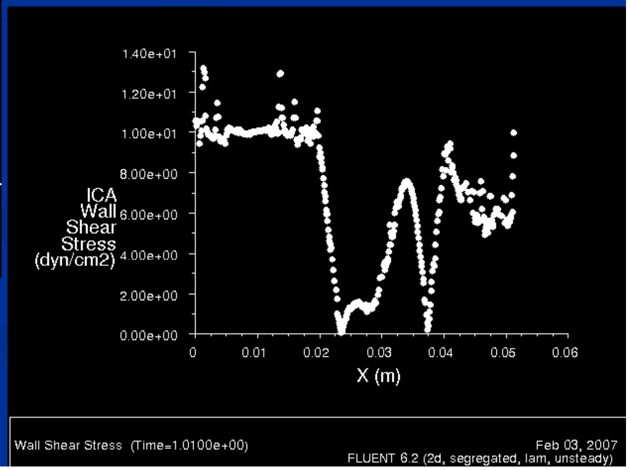


Unsteady State CFD of Human Carotid Artery

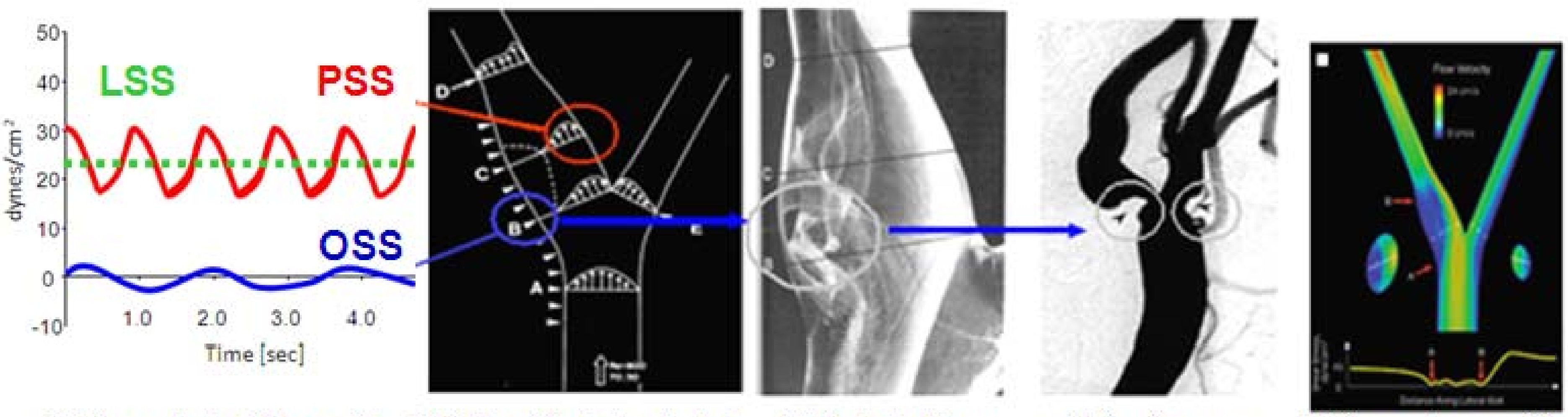






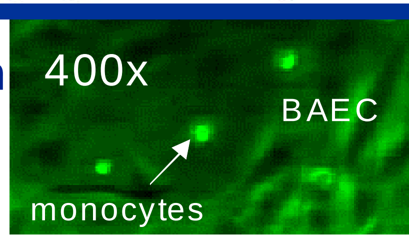


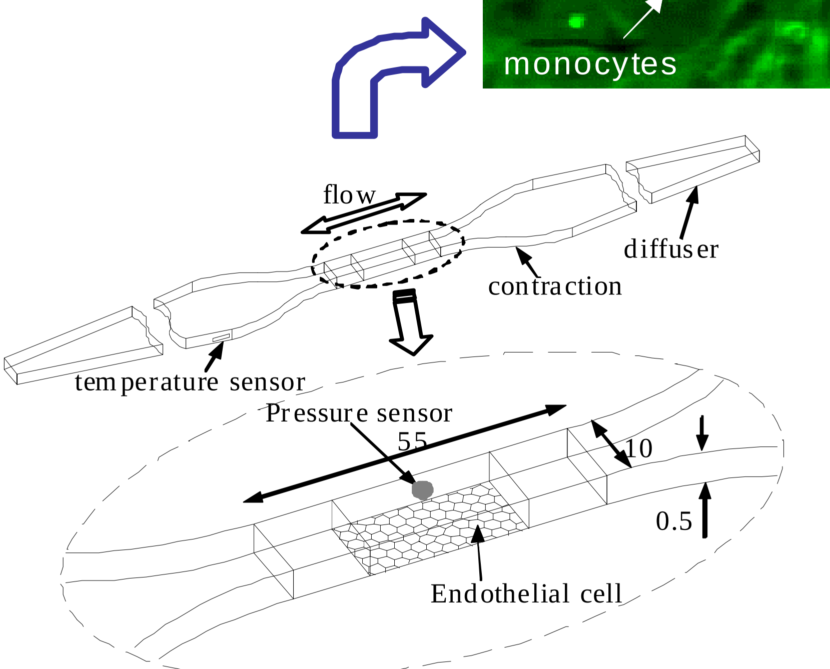
Ai, Hsiai, et al. Am J Physiol: Cell. 2007



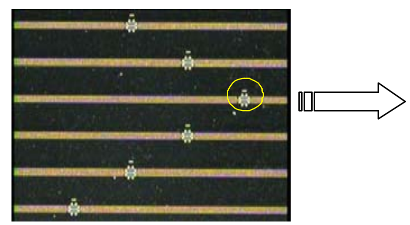
(a) Reconstructed flow profiles (b) 2-D profile at steady stats (c) Disturbed flow (d) Angiograms (e) Shear stress profile

Dynamic Flow System

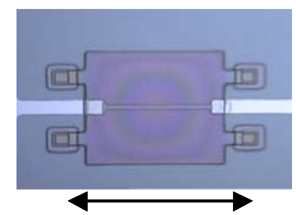




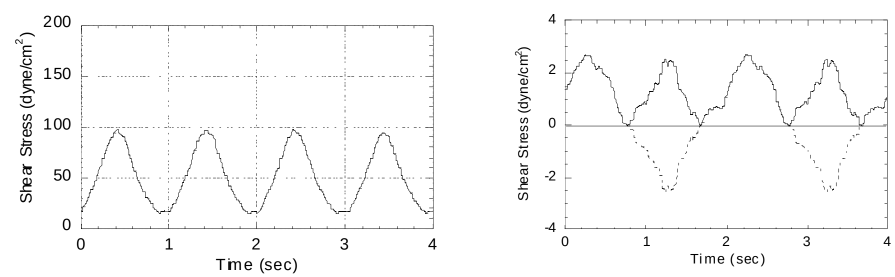
(units: mm, not to scale)



An array of shear stress sensors

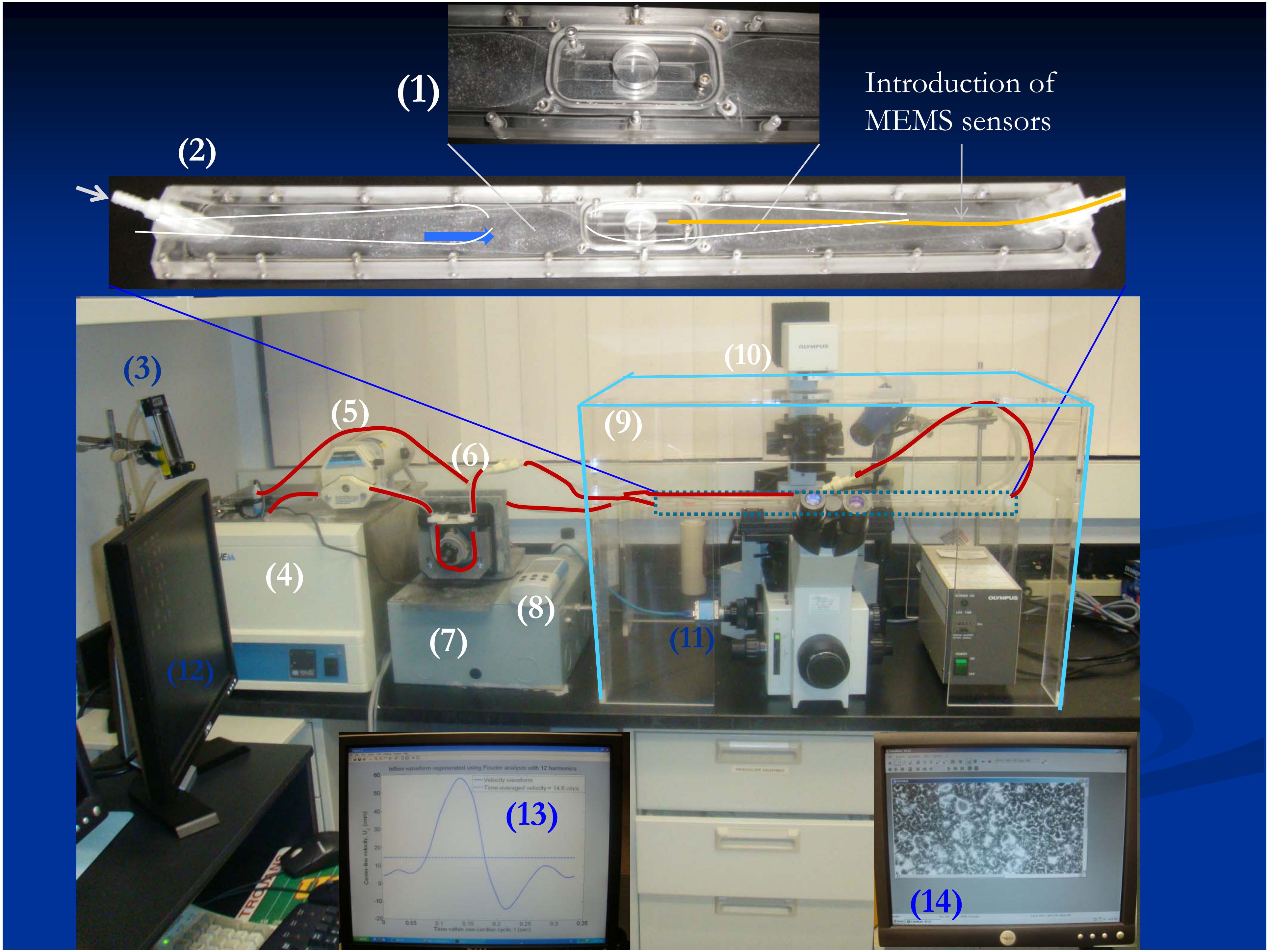


80 µm



pulsatile shear stress **oscillatory shear stress**

Hsiai, et al, FASEB, 2003



(1)
Introduction of
MEMS sensors
(2)
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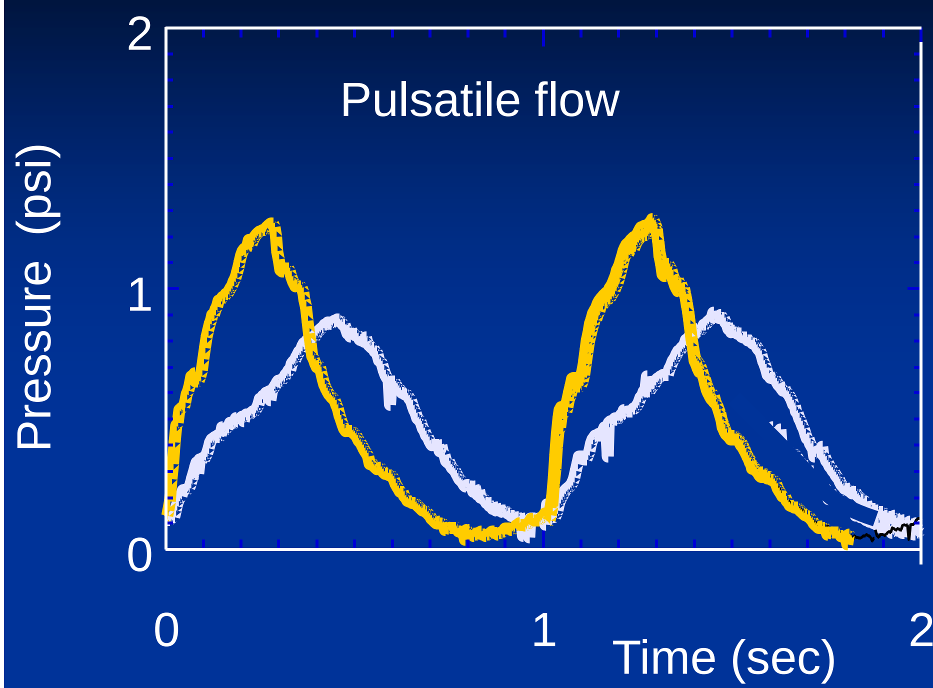
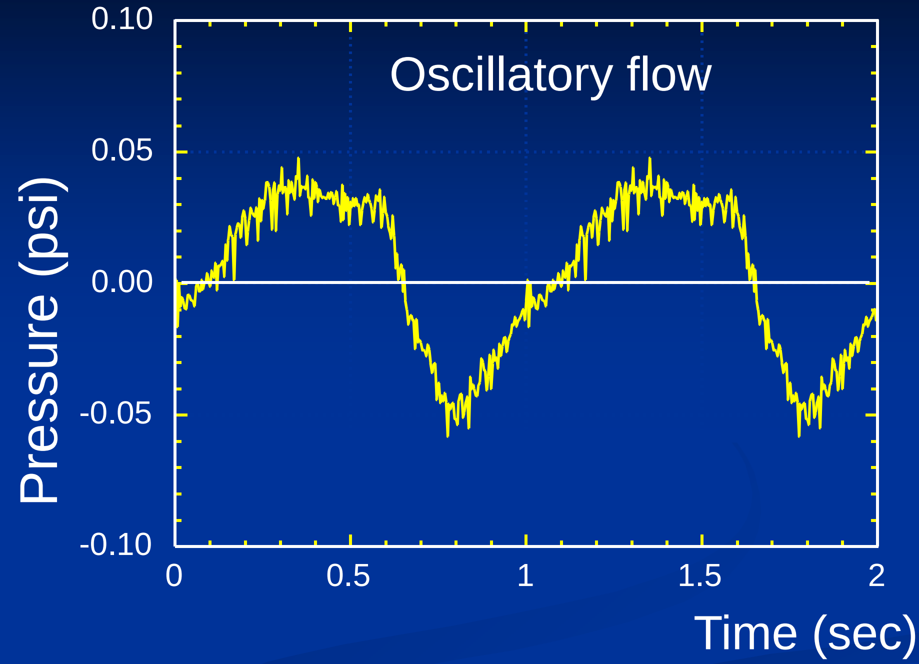
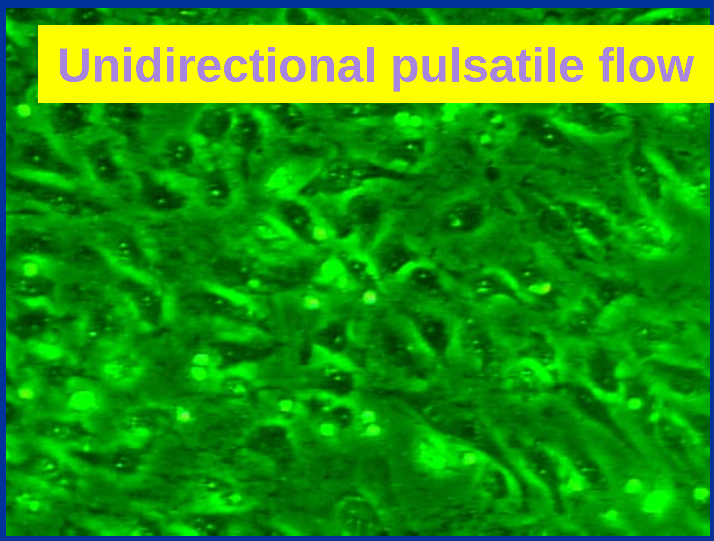
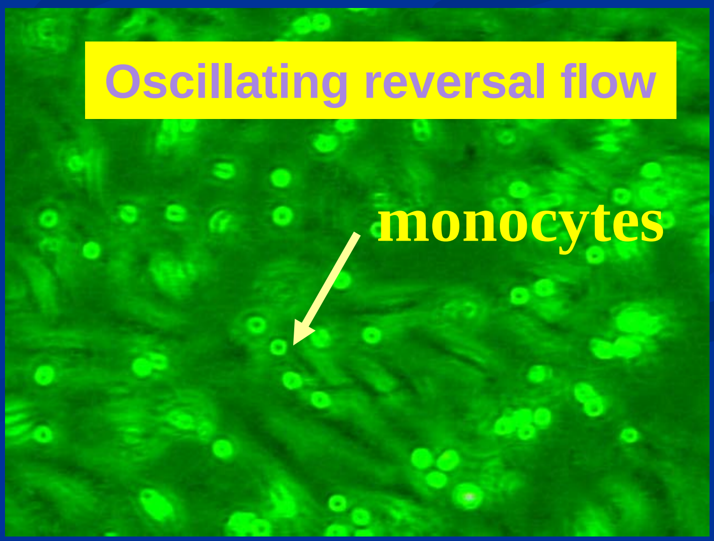
(14)

Monocyte Attachment to Endothelial Cells



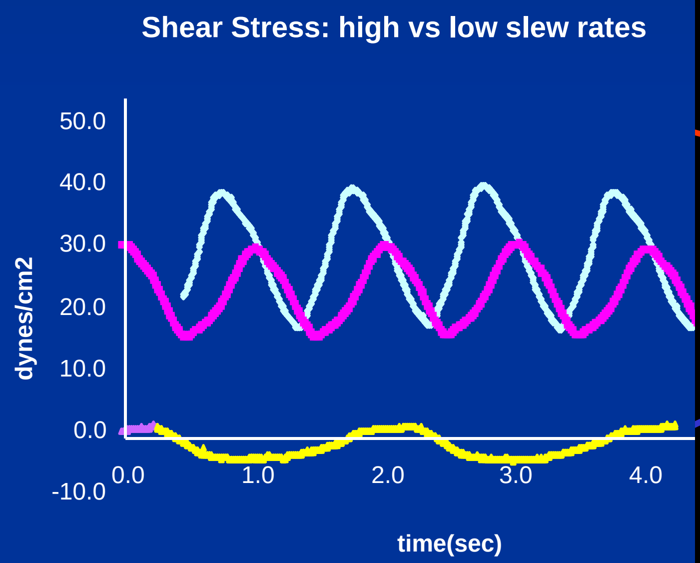


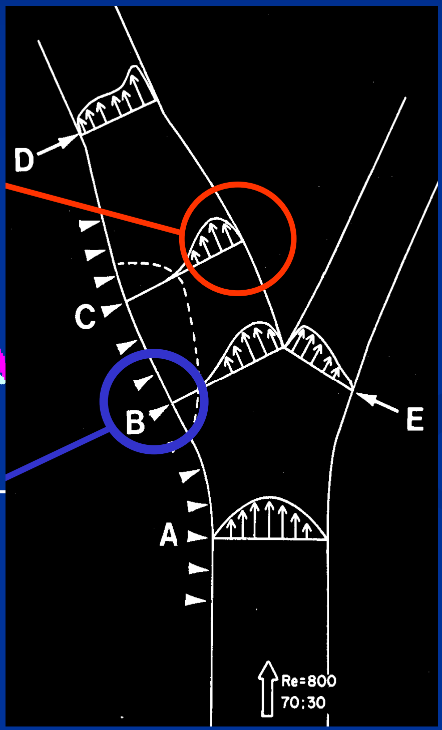


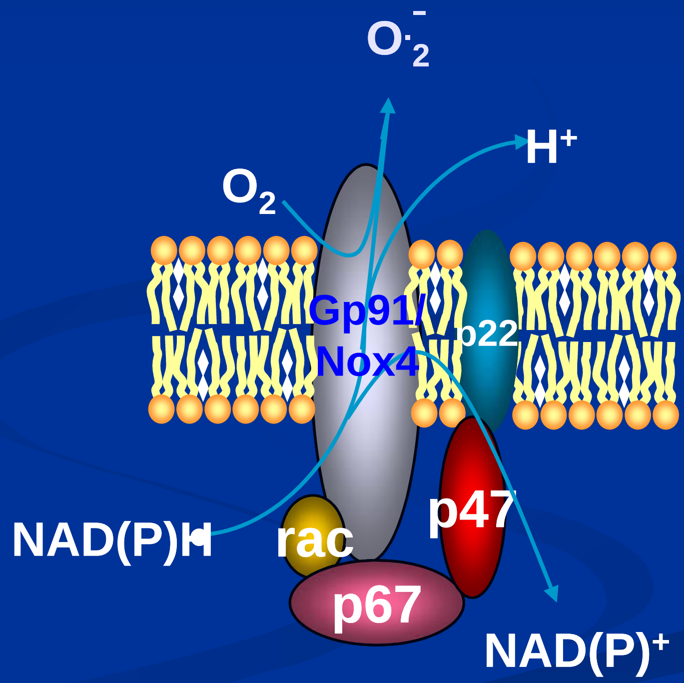


Hsiai et al. ATVB 2002

Shear stress induces NADPH oxidase system





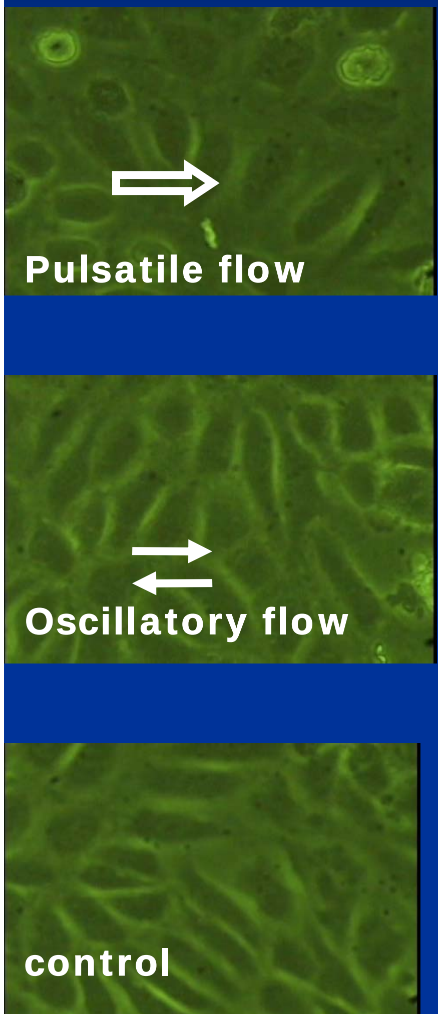


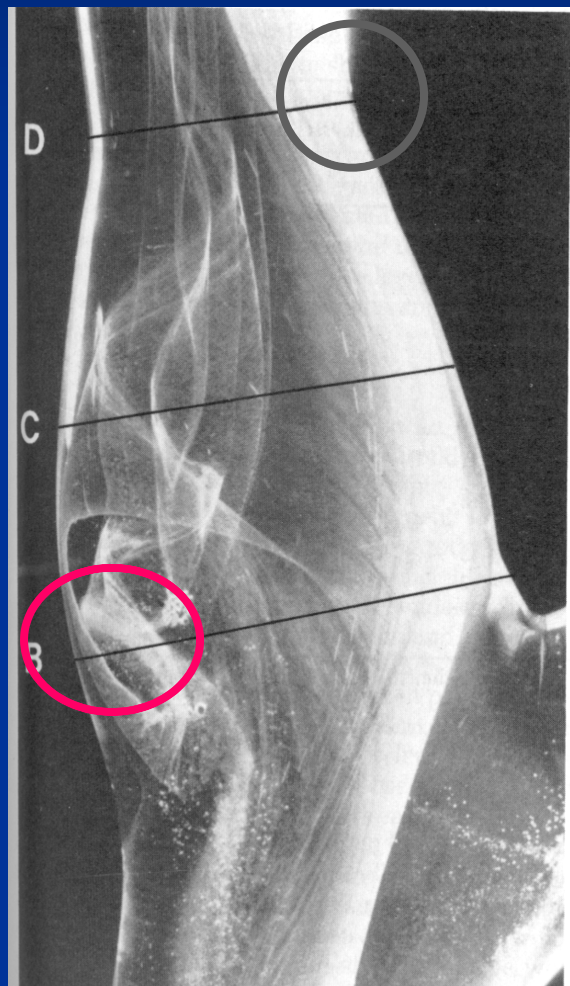
$$NADPH + O_2 \xrightarrow{\text{NADPH oxidase}} NADP^+ + O_2^{\cdot -} + H^+$$

Greindling, Hsiai, et al. Circ Res 2003

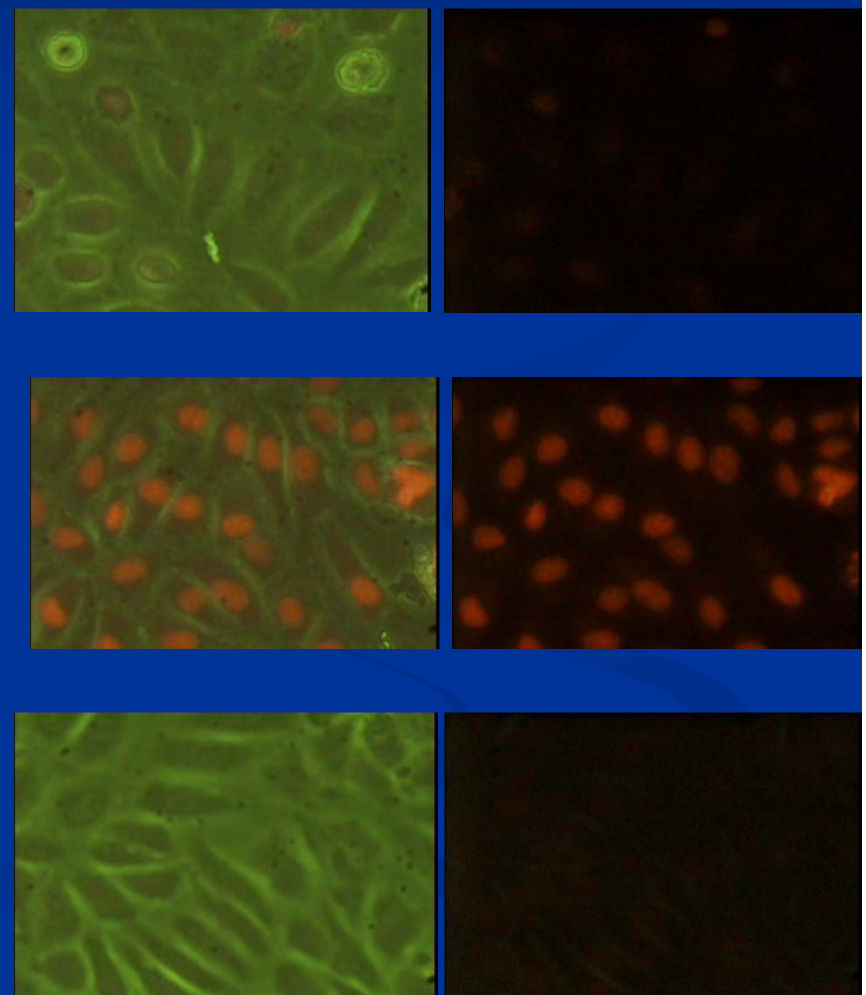
Shear Stress and Vascular Oxidative Stress

Dihydroethidium Bromide for $O_2^{\cdot -}$





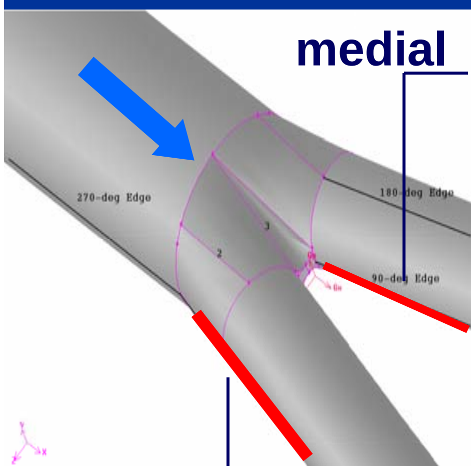
Ku, Gidden, Zarins



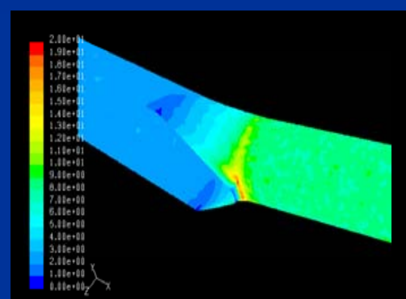
Hsiai et al, Circ Res. 2003

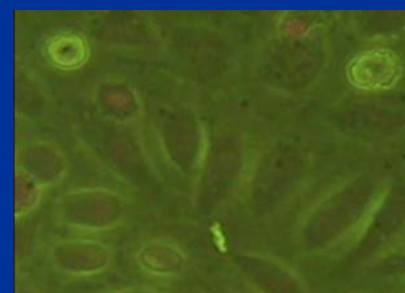
Spatial variations in shear stress and vascular oxidative stress

LDL oxidation and nitration

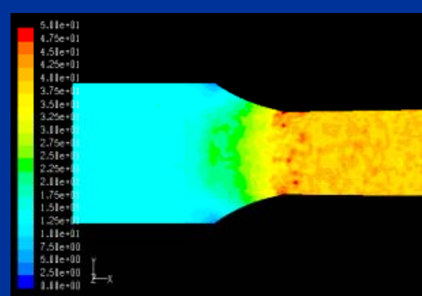


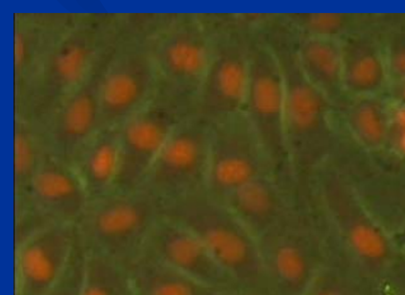
lateral





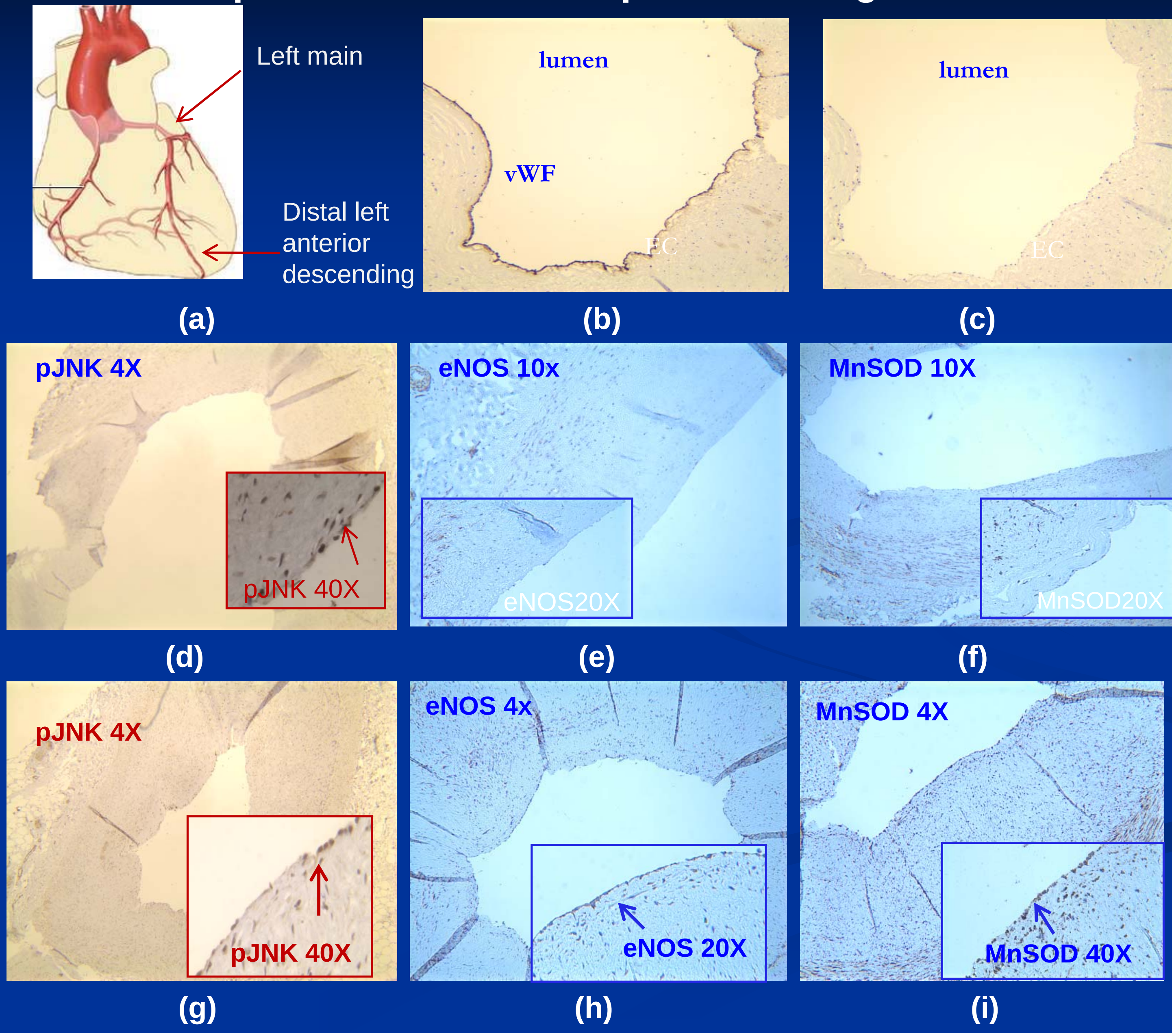
↑ eNOS
↓ Nox4
↓ O_2-·
↑RNS/ROS





↓ eNOS
↑ Nox4
↑ O2-.
↓RNS/ROS

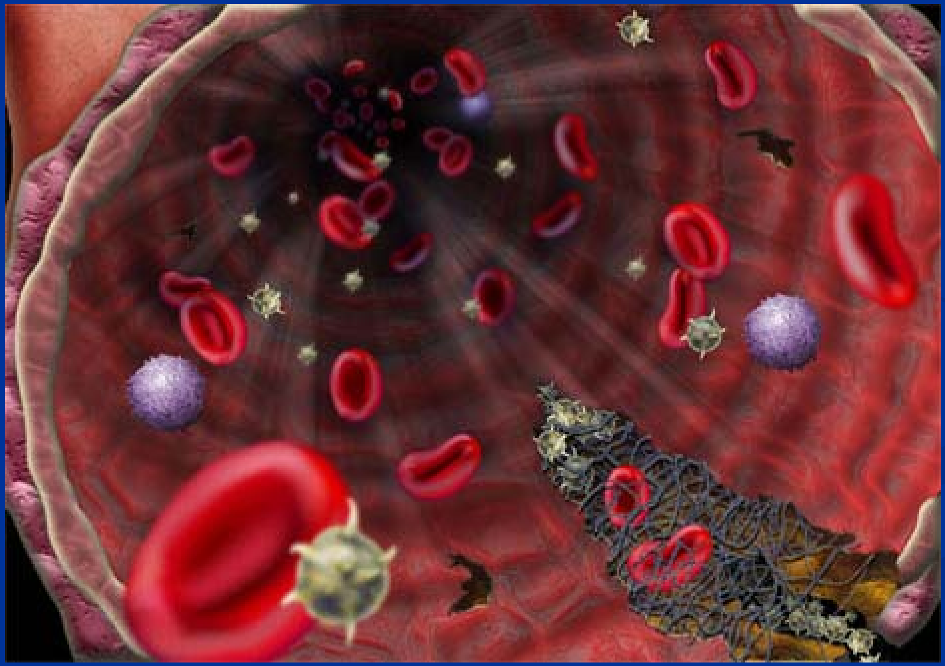
JNK activation and antioxidant expression in the athero-prone versus athero-protective regions



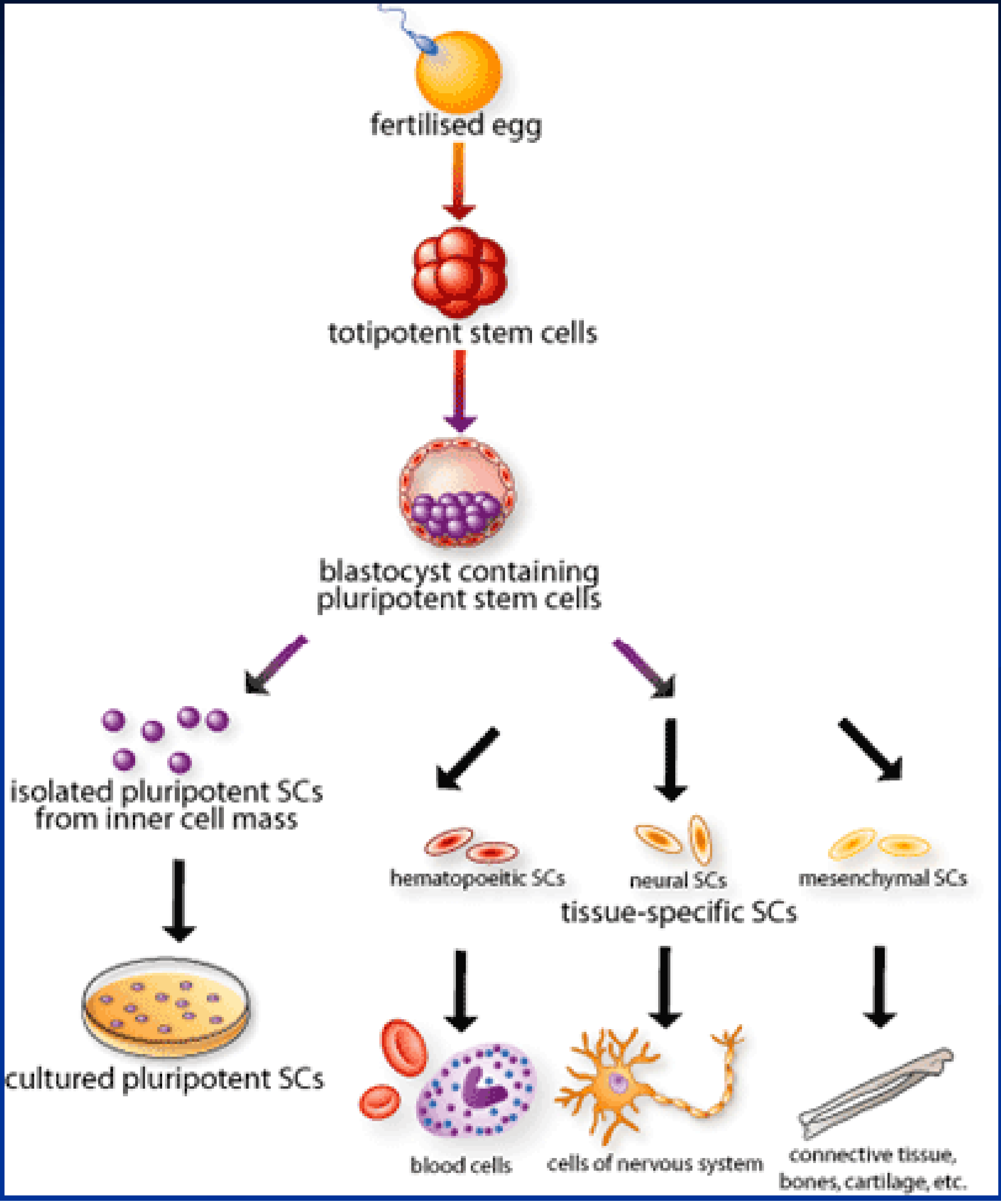
Hemostasis

In response to blood vessel injuries, the blood under three process to stem the flow of blood:

1. Vasoconstriction (endothelium, smooth muscle cells)
2. Platelet aggregation, and
3. Blood coagulation (coagulation cascade)

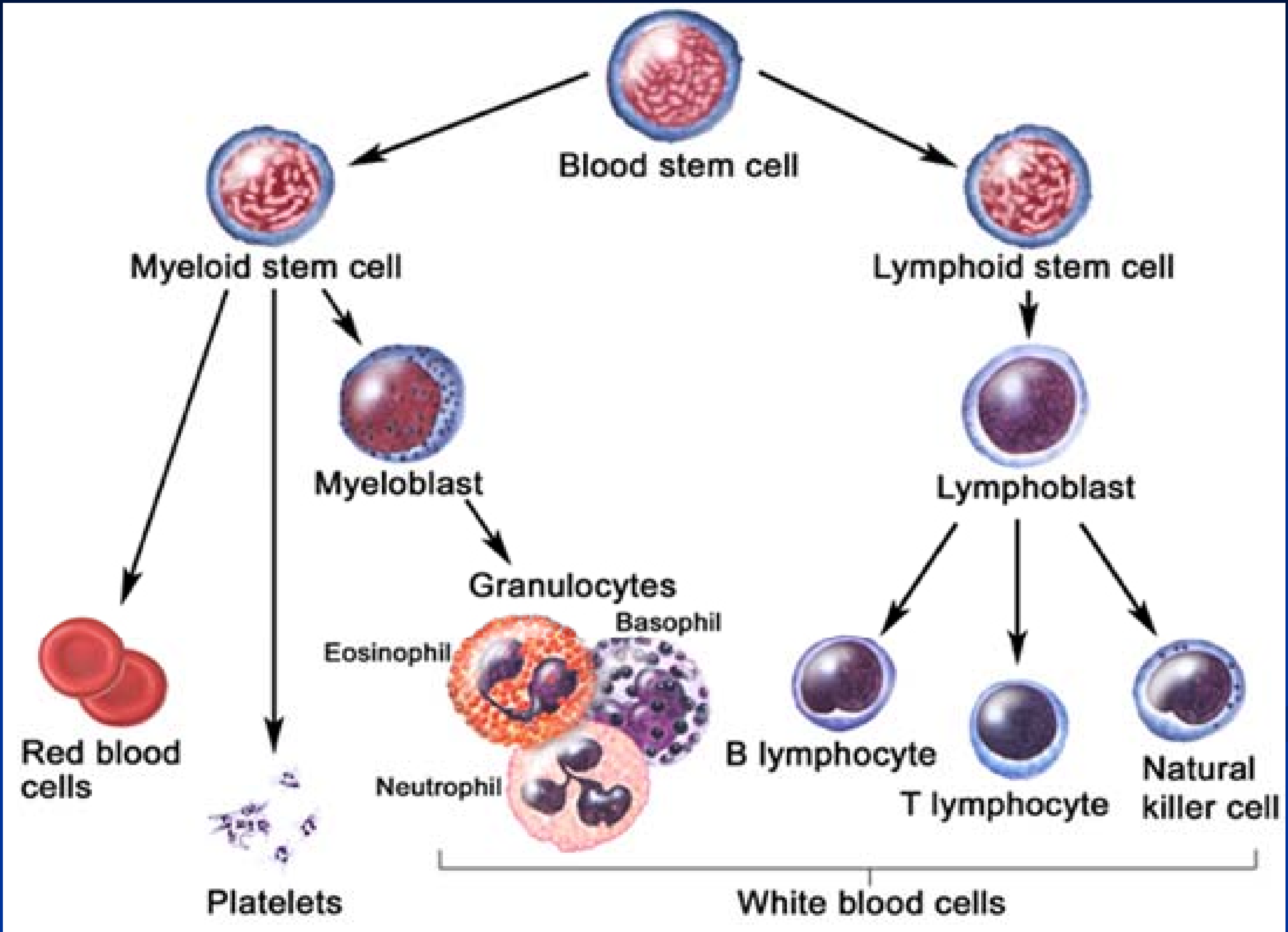


Stem Cells

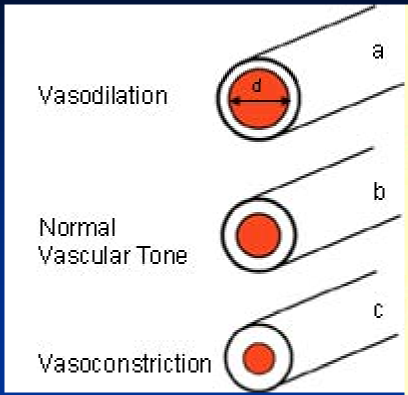


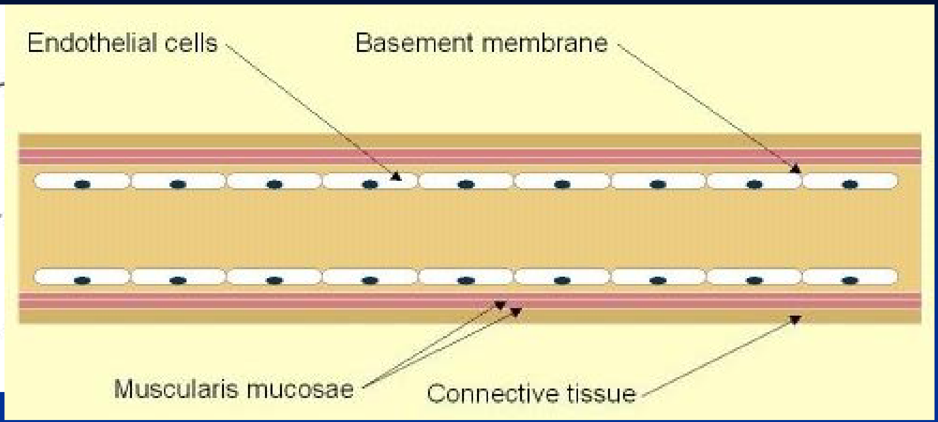
fertilised egg
totipotent stem cells
blastocyst containing pluripotent stem cells
isolated pluripotent SCs from inner cell mass
cultured pluripotent SCs
hematopoeitic SCs
neural SCs
mesenchymal SCs
tissue-specific SCs
blood cells
cells of nervous system
connective tissue, bones, cartilage, etc.

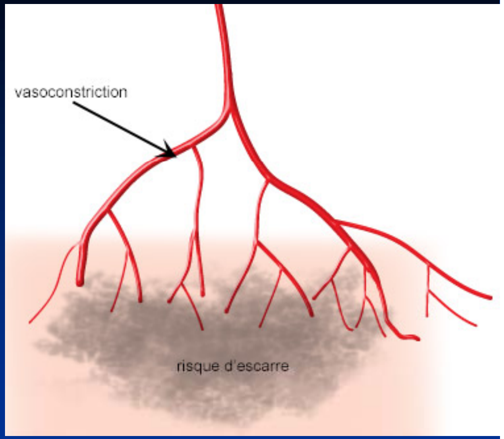
Part I: Blood cells



Vasoconstriction



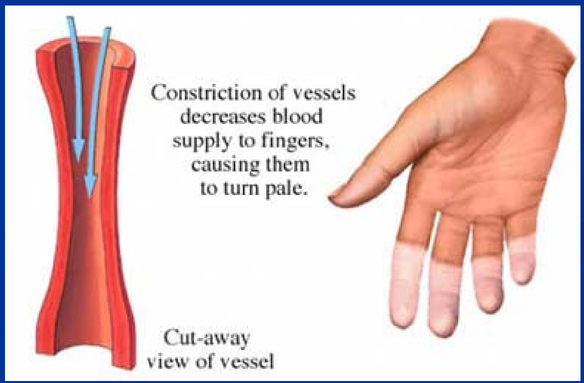




-Injury to a blood vessel elicits a contractile response by the vascular smooth muscle, resulting in a narrowing of the vessel.

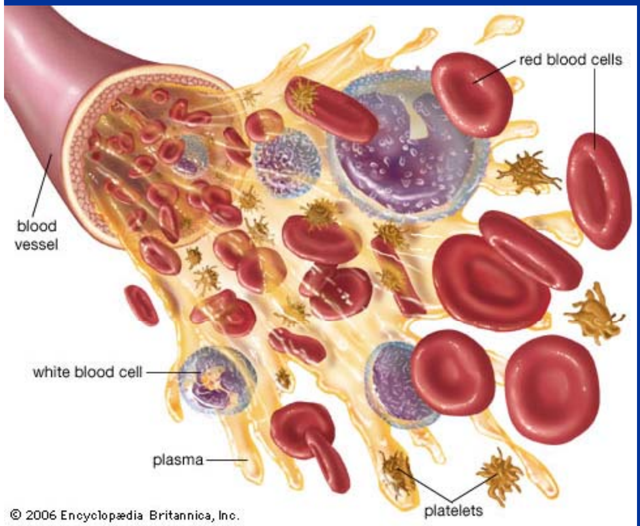
-Vasoconstriction in severed arterioles or small arteries can completely obliterate the lumen of the vessel to stop blood flow.

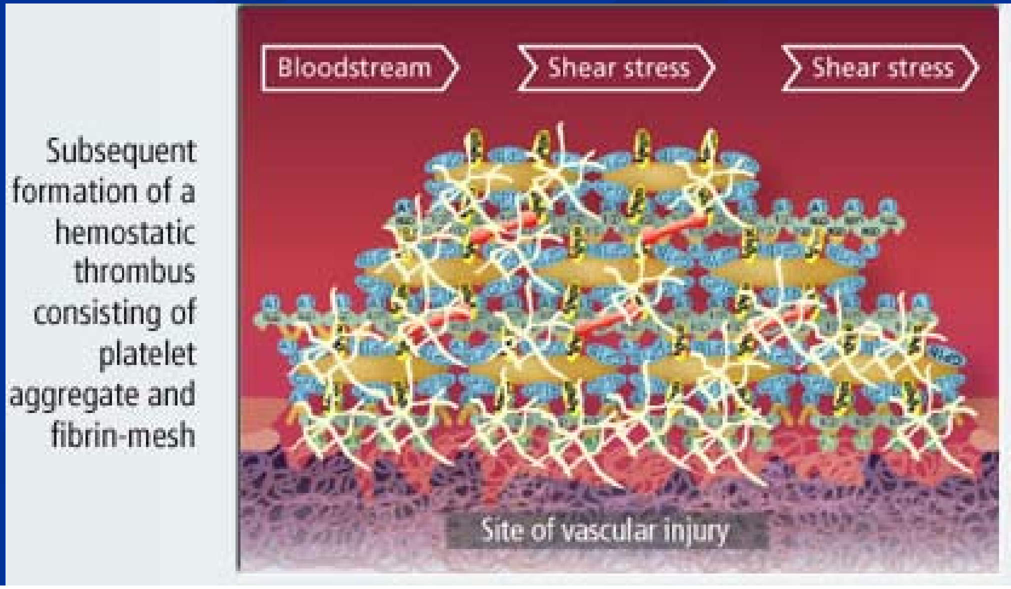
-The contraction of the vascular smooth muscle is induced by direct mechanical stimulation (GTP, increased in intracellular calcium, etc.) as well as by mechanical stimulation of perivascular nerves.



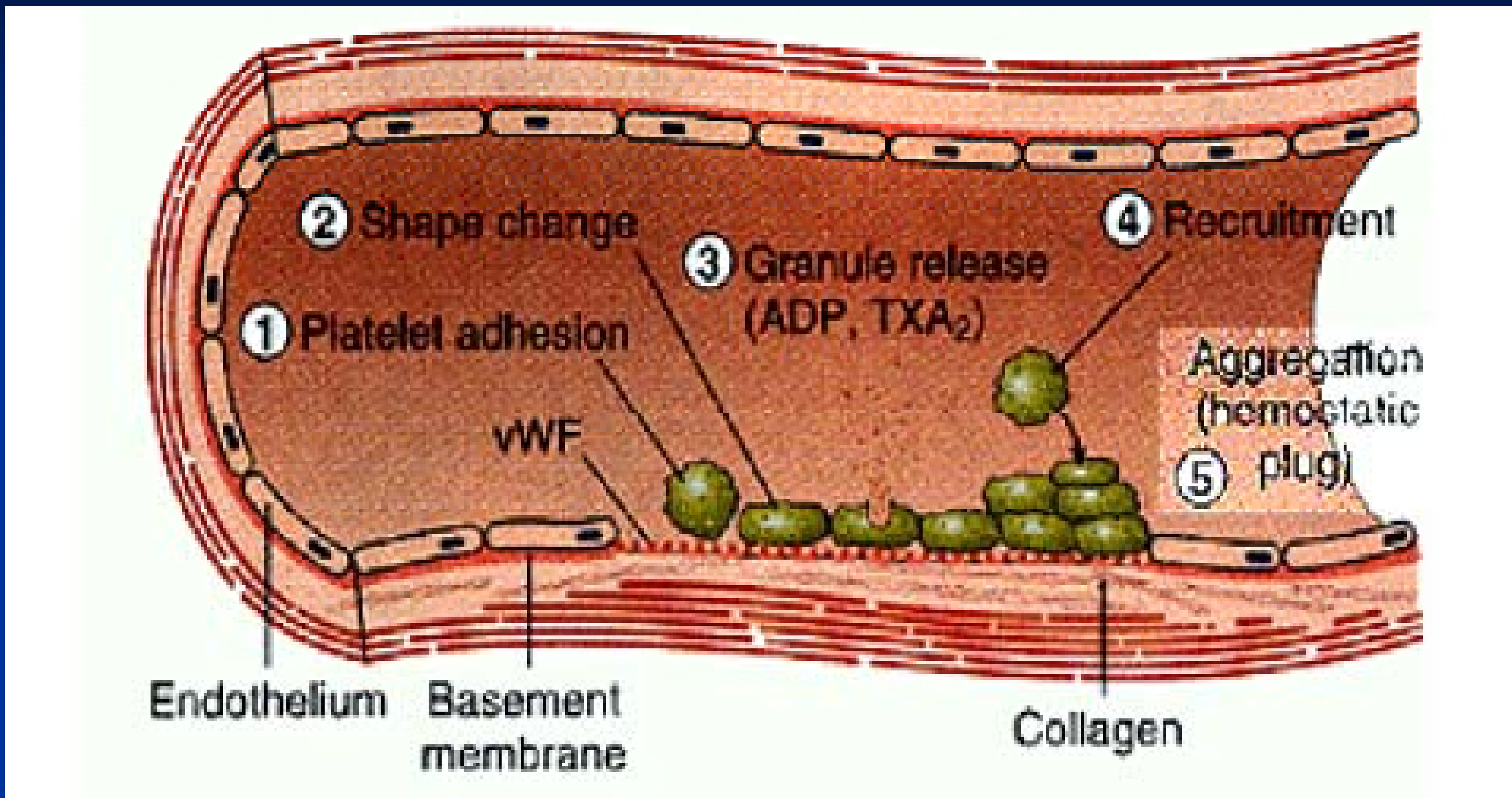
Hemostasis

- Following injury to a blood vessel, all of the systems are activated.
- The hemostatic process is divided into 2 components;
  - primary hemostasis
    - Primary hemostasis depends upon the response of the platelet and blood vessel wall to the injury. When the small blood vessels are injured, blood platelets adhere and aggregate at the site of injury, reducing and finally arresting bleeding.
  - secondary hemostasis
    - Secondary hemostasis starts when the cascade system of coagulation is activated by substances released at the time of blood vessel injury.



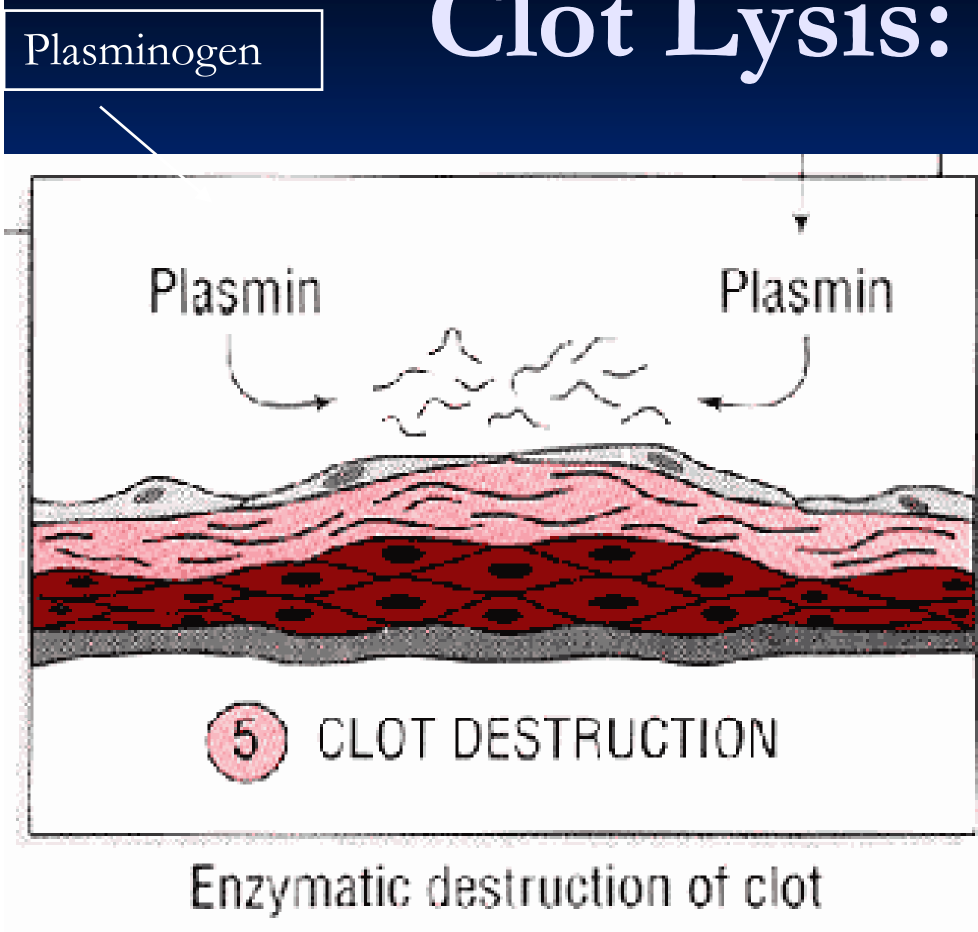


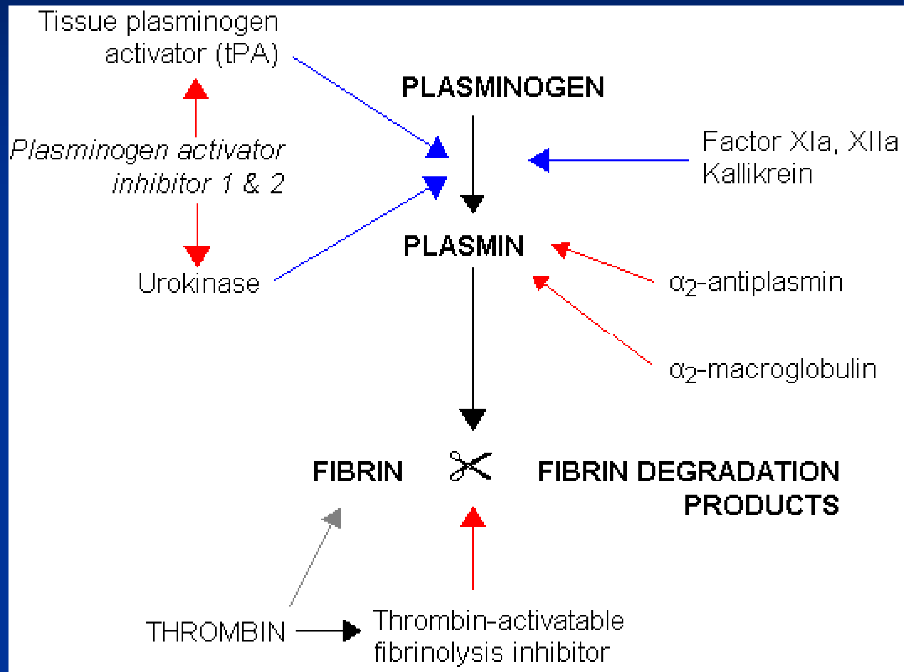
Primary Hemostasis



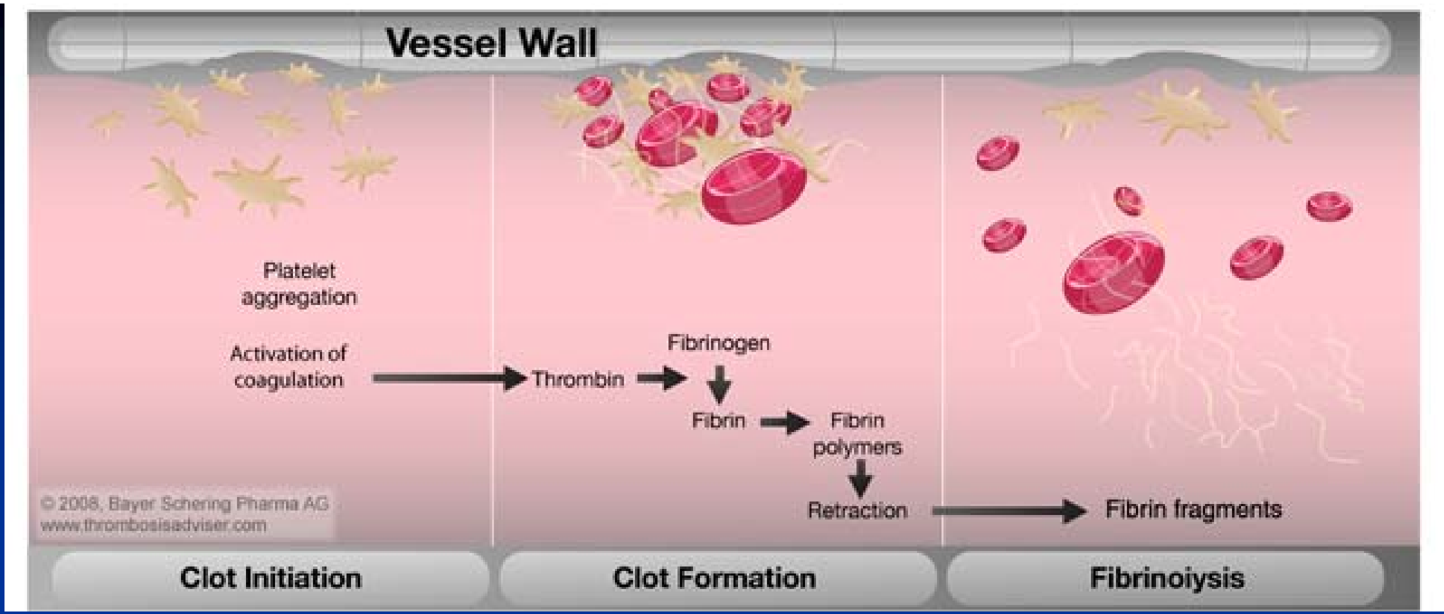
Primary hemostasis depends upon the response of the platelet and blood vessel wall to the injury. When the small blood vessels are injured, blood platelets adhere and aggregate at the site of injury, reducing and finally arresting bleeding.

Clot Lysis: fibrinolysis





The last stage of coagulation is fibrinolysis, which is the dissolution and localization of a fibrin clot. These functions are carried out by enzymes and their inhibitors. A disruption or breach of the fine balance of this fibrinolytic system can result in bleeding or thrombosis.



Fibrinolysis is mediated by activation of plasminogen to plasmin.

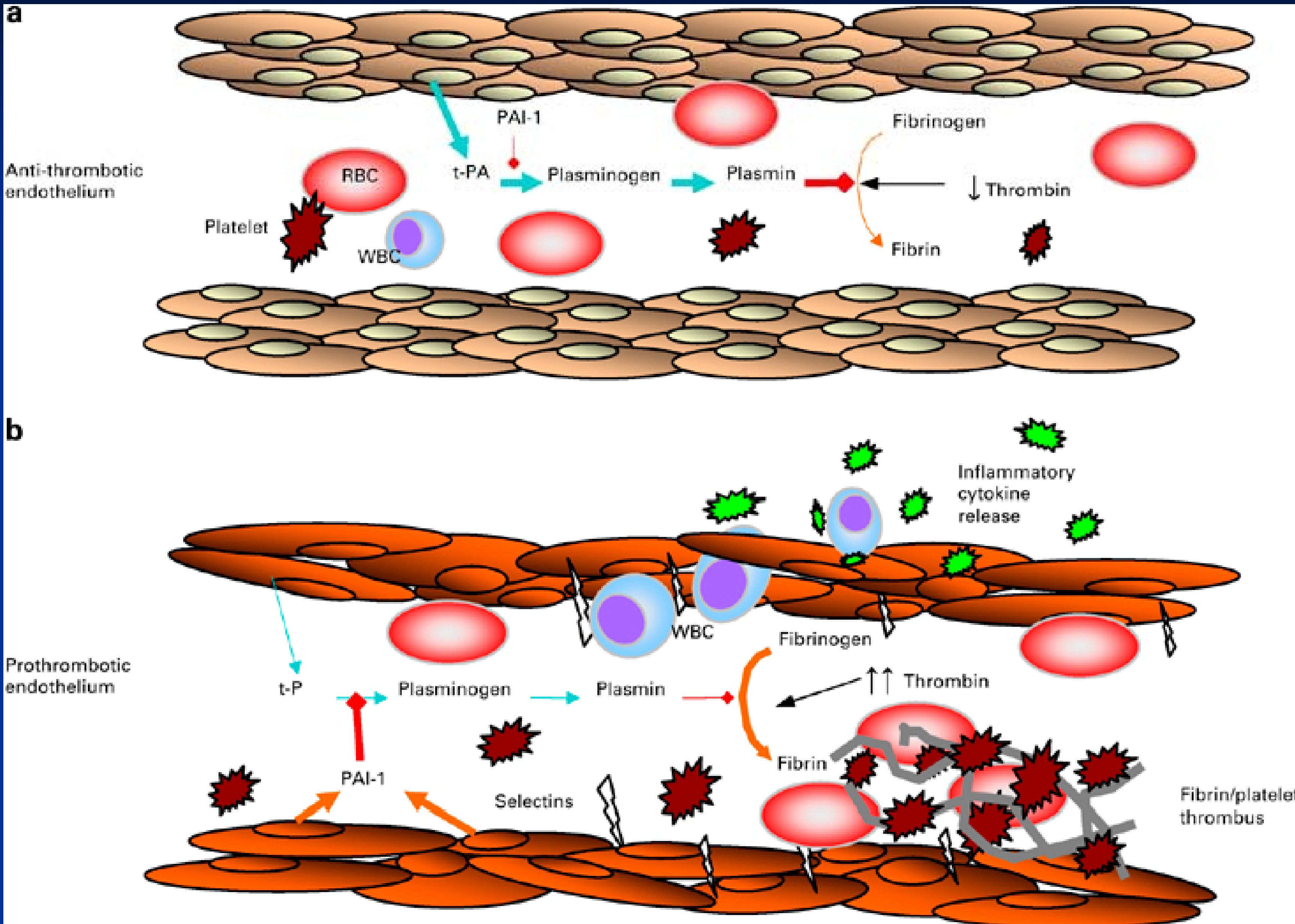
This is accomplished by:

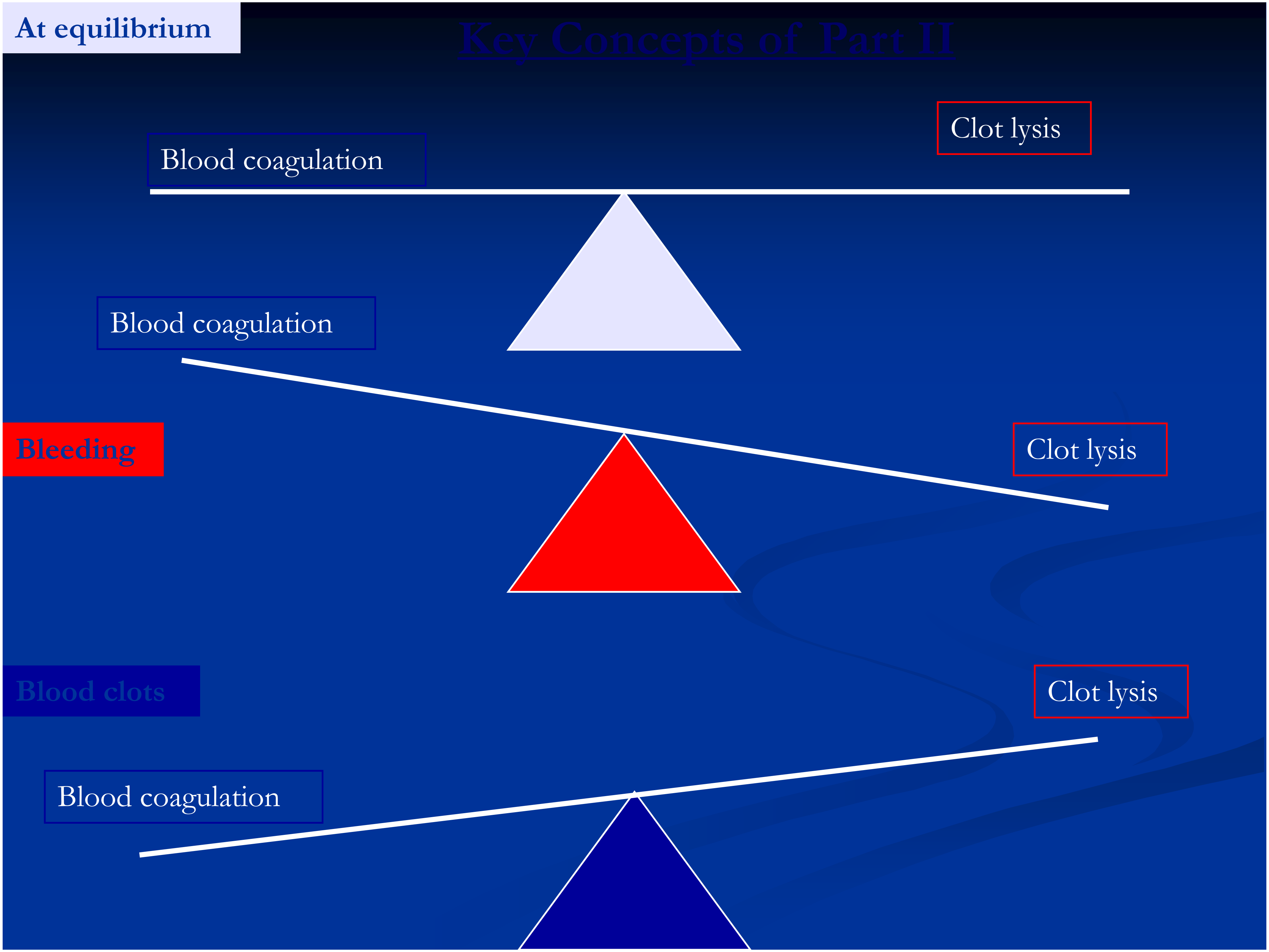
Intrinsic activation (plasma based) initiated through Factor XIIa and allikrien. Thus, the contact system of coagulation serves as an intrinsic activator.

Extrinsic activation (cellular based) initiated by way of stimuli such as vascular injury, ischemia, exercise, stress and pyrogens.

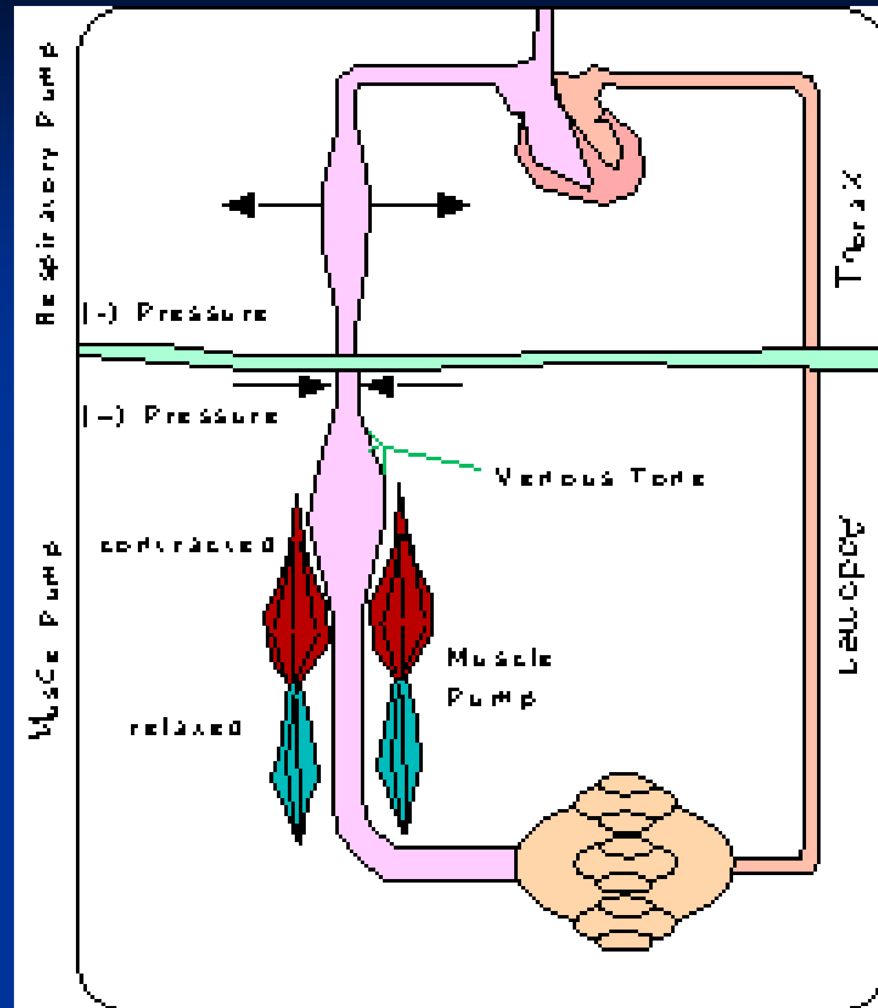
Exogenous
(Therapeutic) activation (drug based) includes streptokinase, urokinase and tPA tissue plasminogen activator).

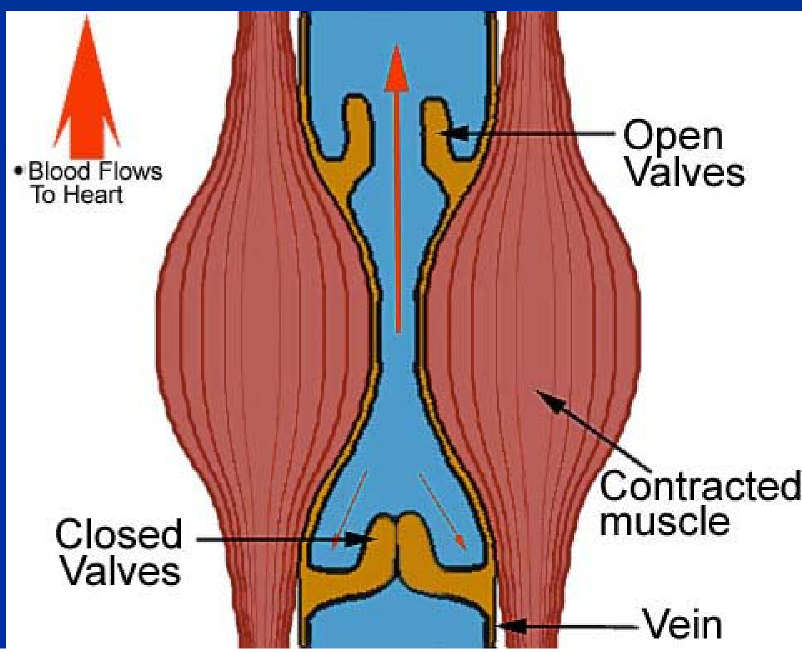
Summary


a
Anti-thrombotic endothelium
RBC
t-PA
PAI-1
Plasminogen
Plasmin
Fibrinogen
↓ Thrombin
Platelet
WBC
Fibrin
b
Inflammatory cytokine release
WBC
Fibrinogen
Prothrombotic endothelium
t-P
Plasminogen
Plasmin
↑↑ Thrombin
Fibrin
PAI-1
Selectins
Fibrin/platelet thrombus


Key Concepts of Part II
At equilibrium
Blood coagulation
Clot lysis
Bleeding
Blood coagulation
Clot lysis
Blood clots
Blood coagulation
Clot lysis

Deep Venous Thrombosis





Contraction of muscles helps the blood to be pushed up the vein.

1998 Nobel Prize to cardiovascular system: NO (nitric oxide)

ROBERT F. FURCHGOTT (State University of New York, Downstate)

LOUIS J. IGNARRO (UCLA)

FERID MURAD (U Texas, Huston)

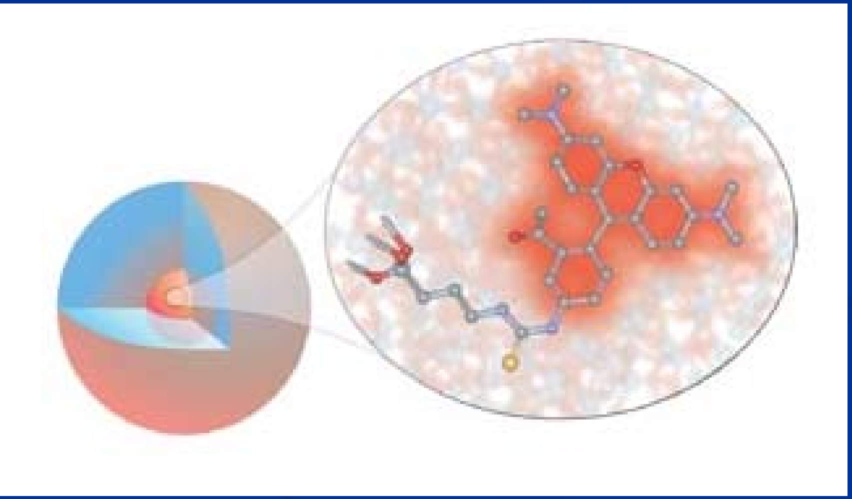
for their discoveries concerning nitric oxide as a signaling molecule in the cardiovascular system.

Objectives

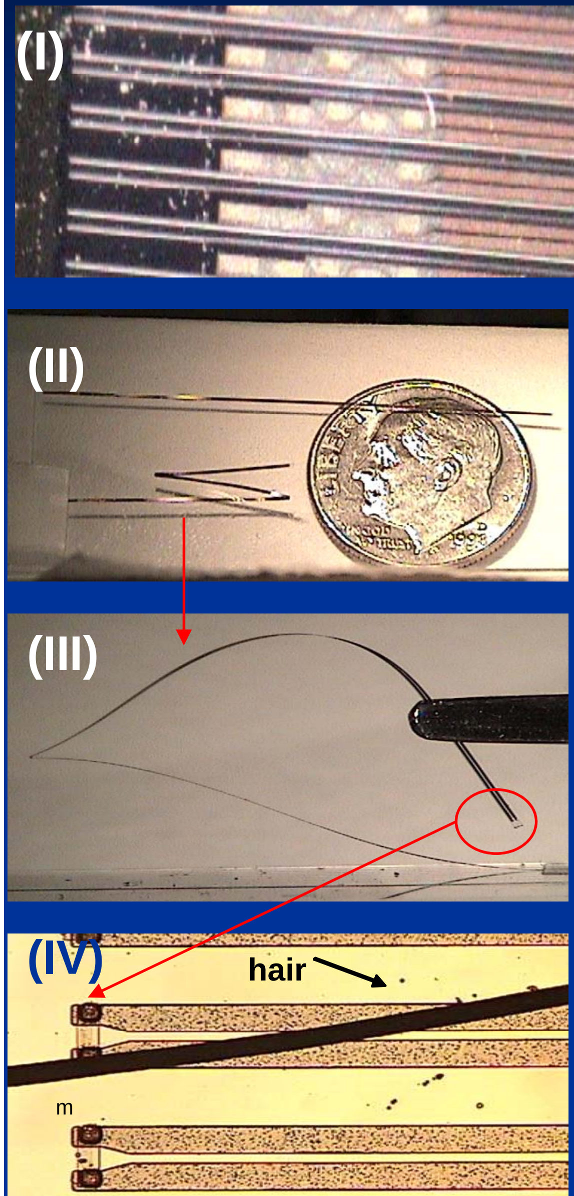
- **Introduce vascular systems**
  - Inertia vs. viscous force
- **Interface vascular dynamics with vascular biology**
  - Hemodynamics and vascular oxidative stress
  - Balance between thrombosis and thrombolysis
- **Translate vascular dynamics to an *in vivo* model**
- Bridge bioengineering, industry and medicine

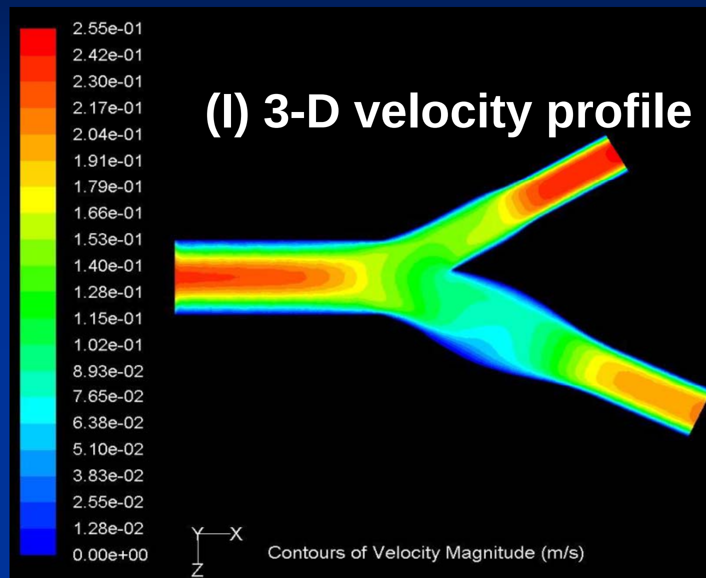
Cardiovasculature: A Dynamic Sensing and Actuating System

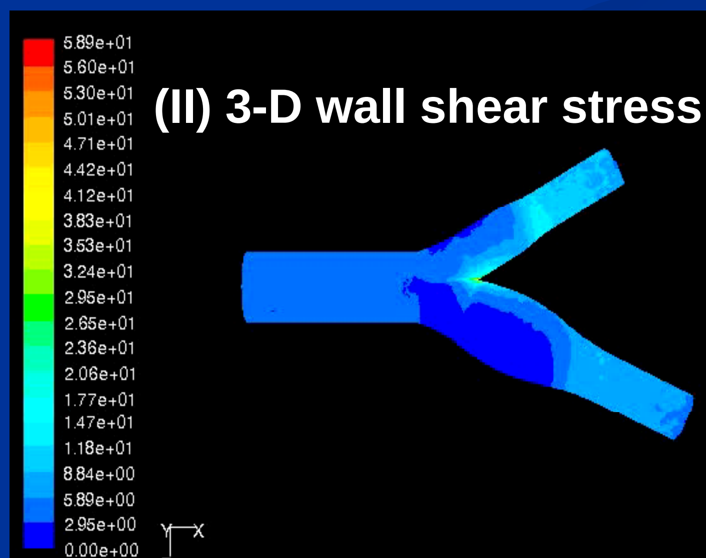
- Too monotonous
- Too easy
- Too biological
- Too clinical
- Too little MEMS
- Too little class interactions
- Too little engineering
- Too much basic sciences
- Too little depth
- Too little breadth



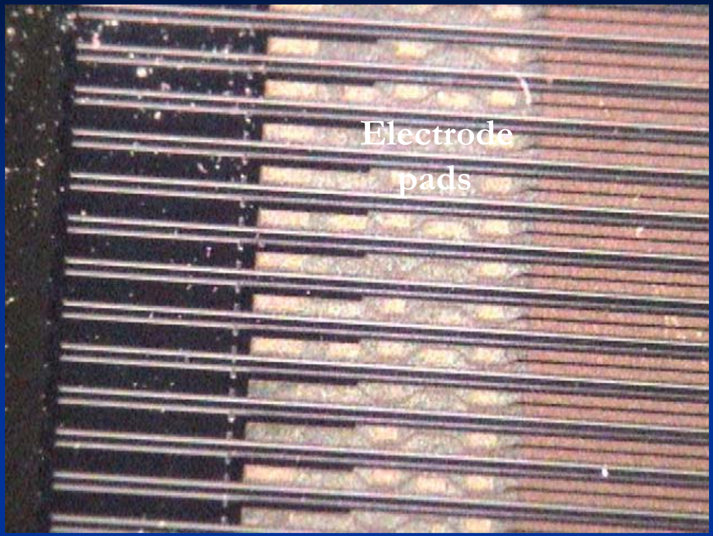
Translating MEMS to Assess Pathophysiology of Atherosclerosis



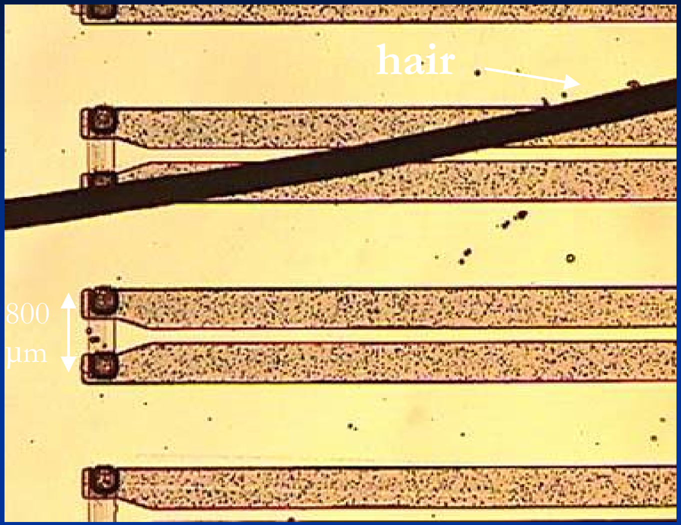




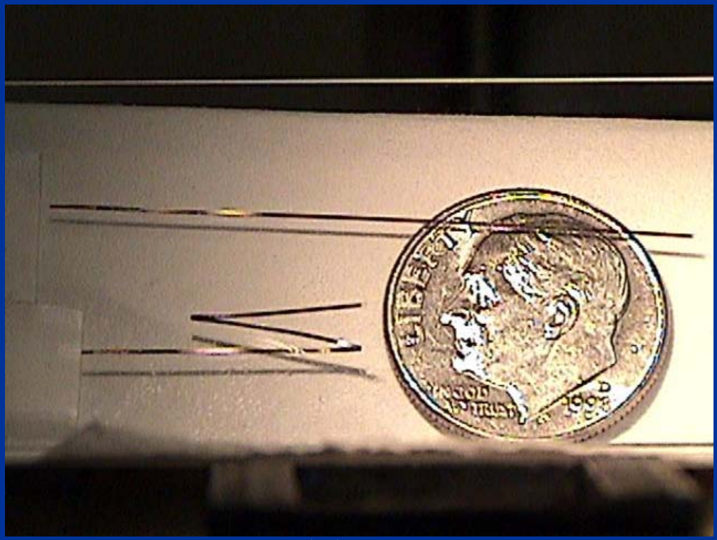
Flexible Polymer MEMS Sensors



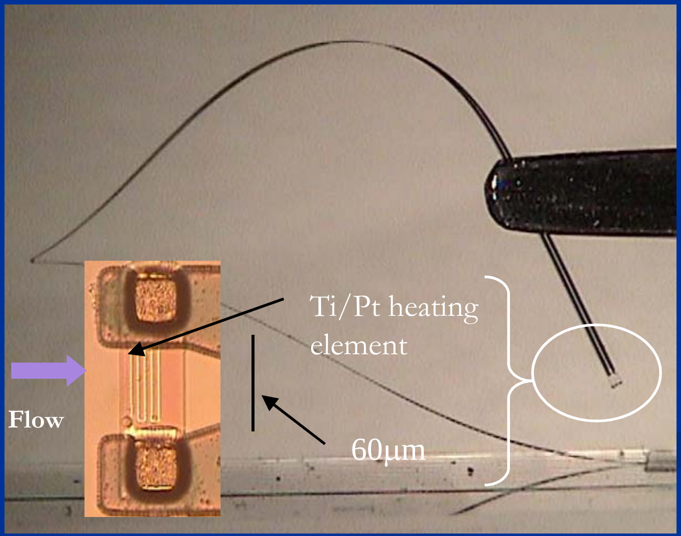
(a)



(b)



(c)

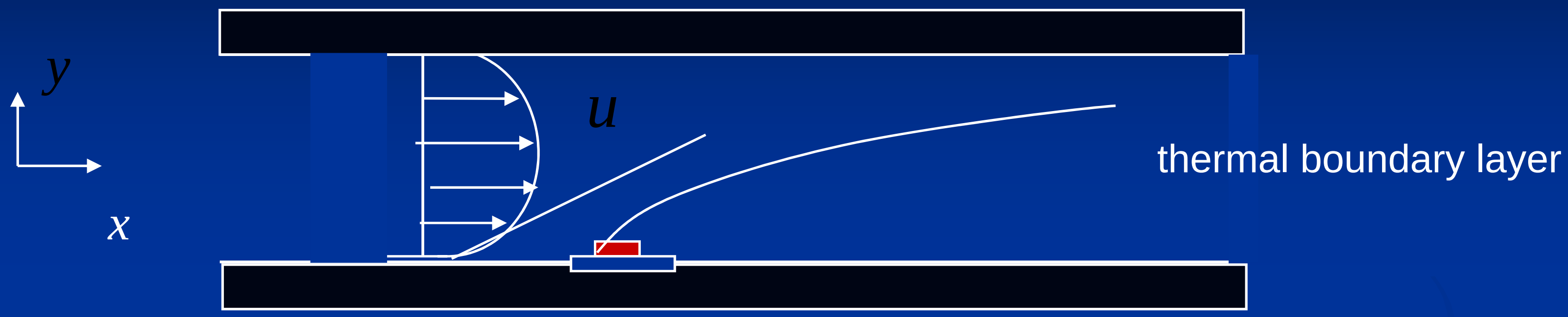


(d)

Yu , Li, Kim, Hsiai, IEEE ASME J MEMS, 2008

Operating Principle of Shear Stress Sensors:

Relation between convective heat transfer and shear stress



$$\tau_w = \mu \frac{\partial u}{\partial y}\bigg|_{y=0}$$

Indirectly measured by heat convection:

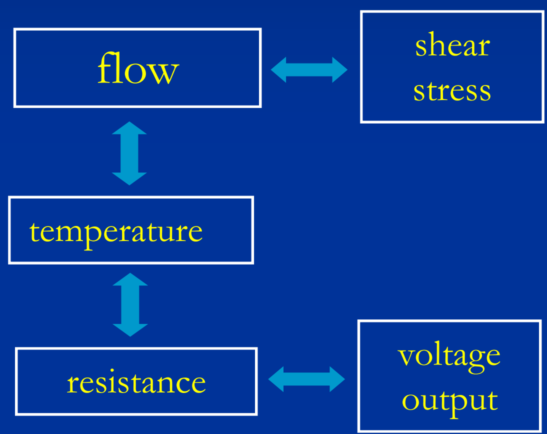
$$V_o^2 / R_s \approx Q_{conv} \propto \tau_w^{1/3}$$

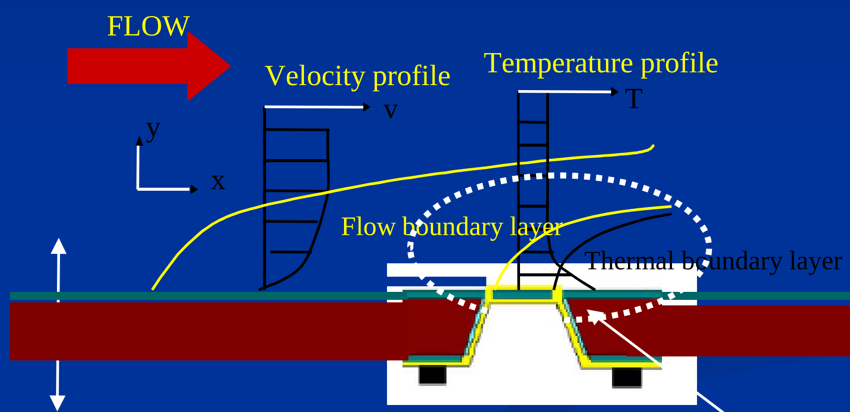
The heat convection from a resistively heated element to the flowing fluid is measured, from which a value for shear stress is inferred

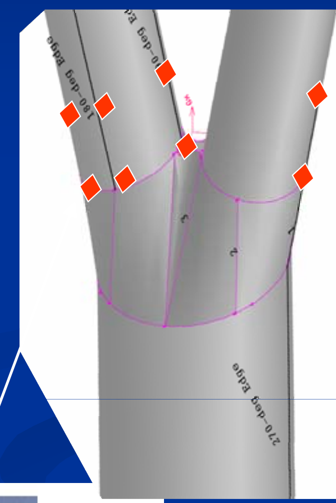
Liu et al, J MEMS 2000
Huang et al, 1995

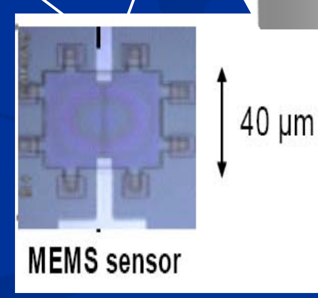
MEMS Shear Stress Sensors

- MicroElectroMechanical Systems (MEMS) for high temporal and spatial resolution





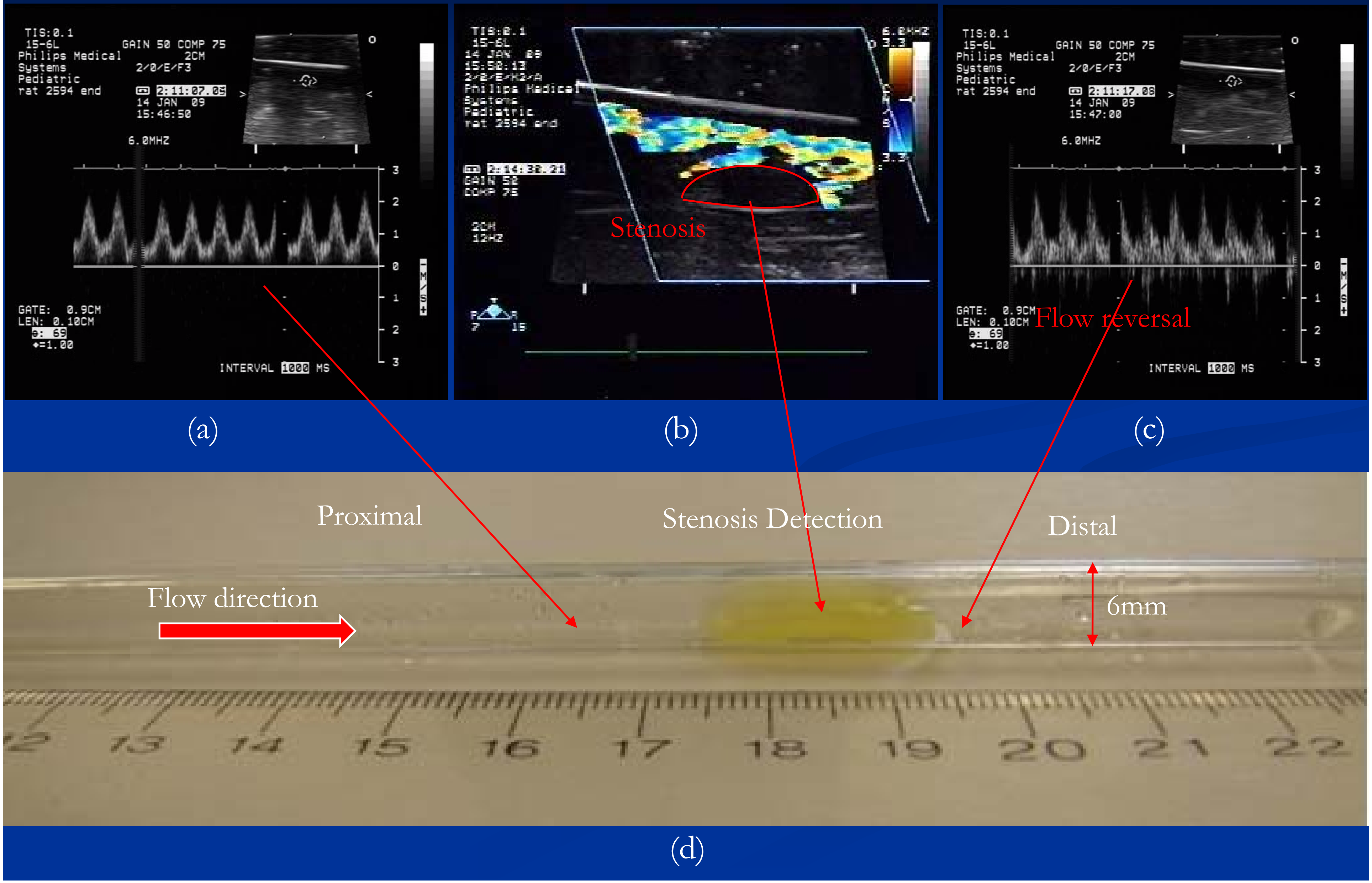




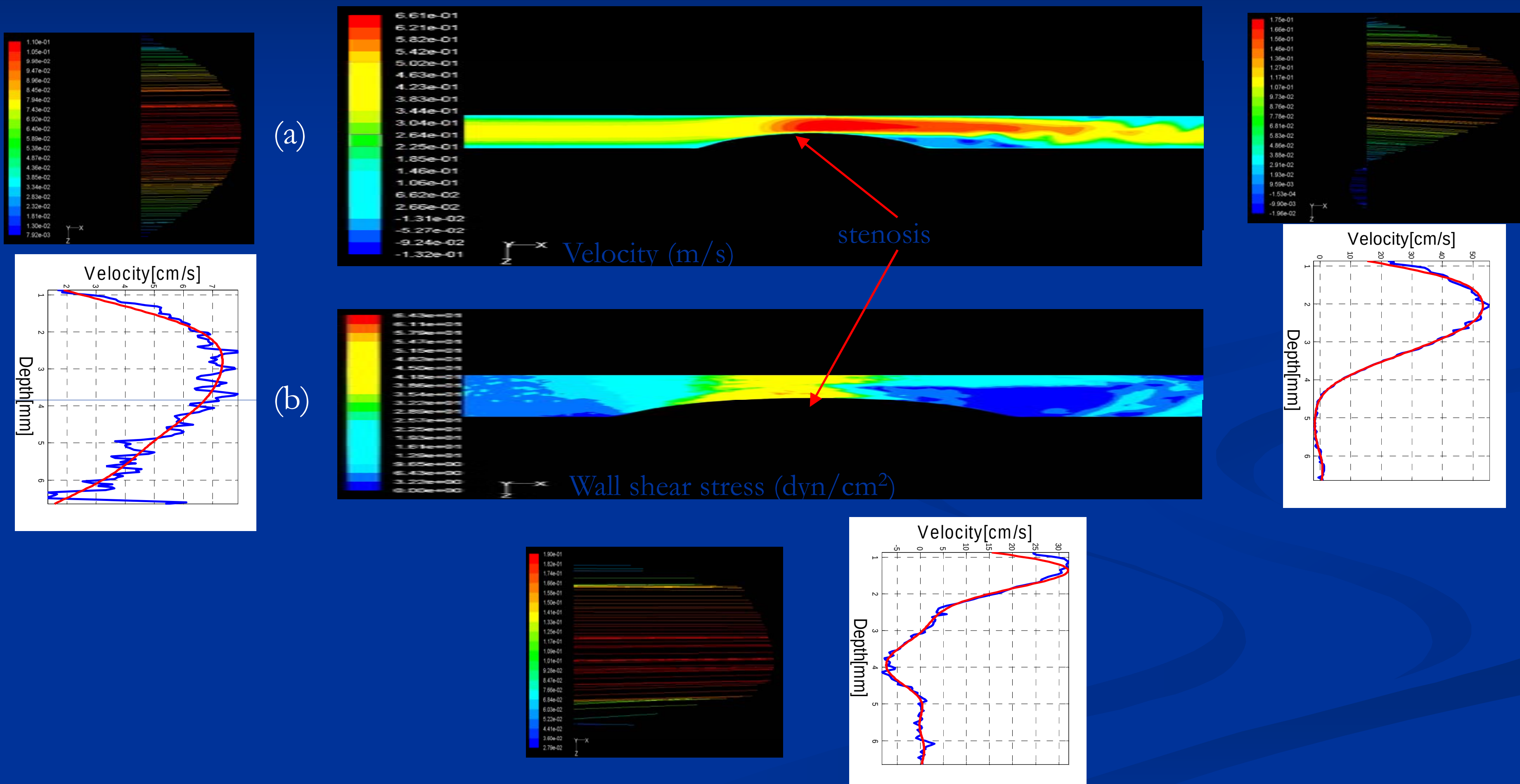
- The operational principle: Convective heat transfer
  - Sensing element: an electrical resistor
  - Resistance varies with temperature
  - An electrical current is heating up the sensing element
  - Flow past the sensing element changes the temperature and resistance

Soundararajan, G., Rouhinizadeh, M., Yu, H. Kim, E. S., Hsiai, T., MEMS shear stress sensors for microcirculation, *Sensors and Actuators: A. Physical*. 2005.

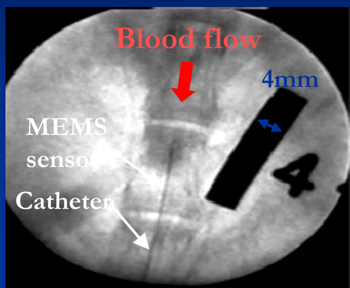
In Vitro Stenotic model: Combining Doppler, CFD, and MEMS sensors

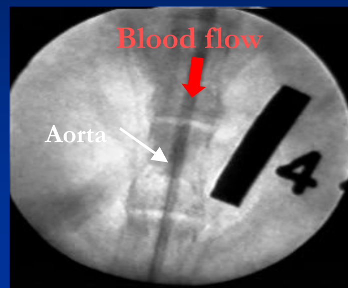


Flow Separation and Flow Reversal post stenotic region



Translating *In Vitro* to *In Vivo* Models





The angiogram delineated the diameter of the rabbit aorta after contrast dye injection.

The angiogram revealed the aortic arch, descending aorta, and left carotid arteries.

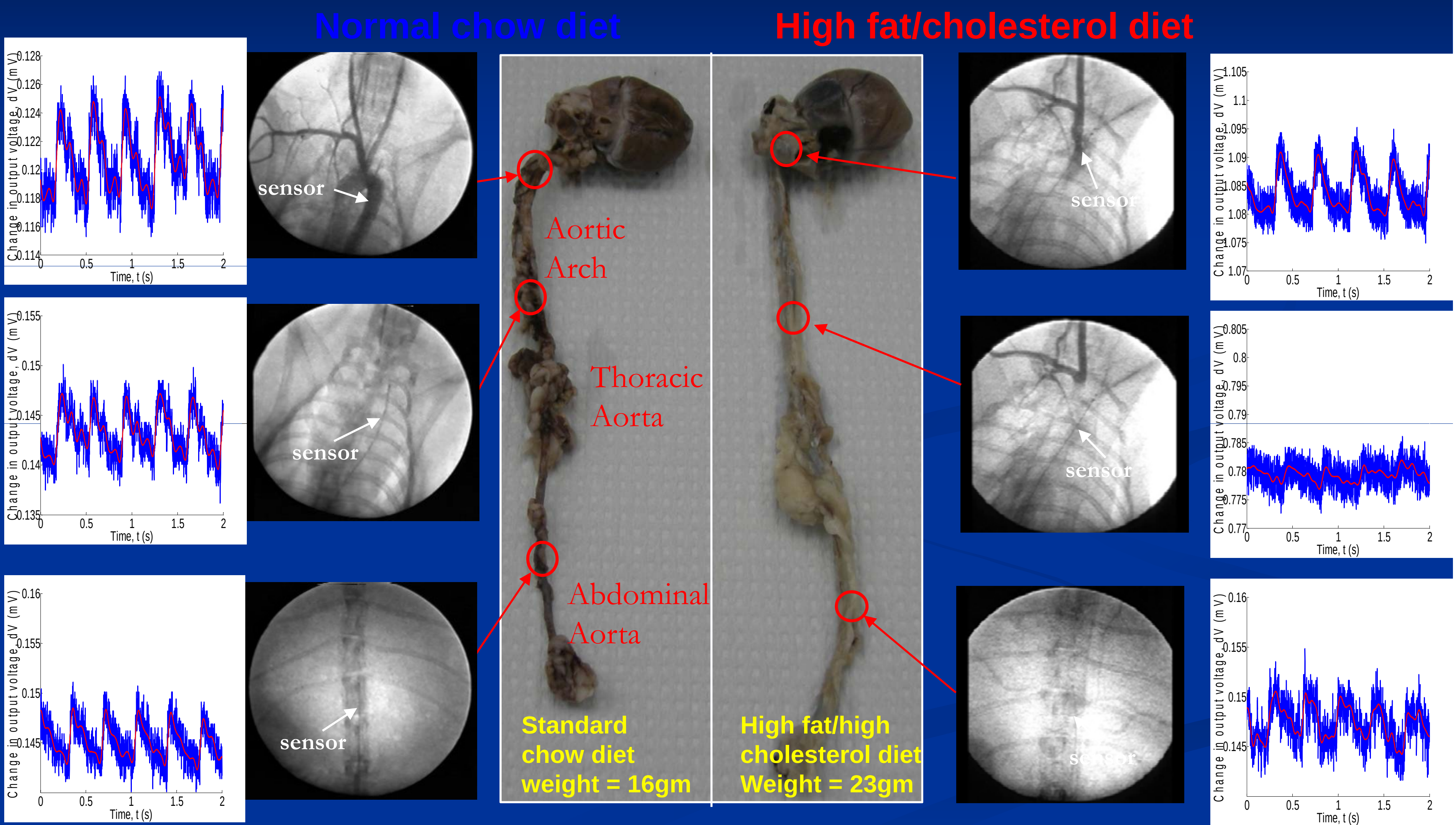
New Zealand White (NZW) rabbit

A physician was deploying the sensor via the femoral-cut-down approach.

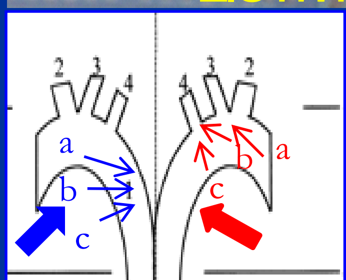
MEMS sensor in the rabbit arterial system

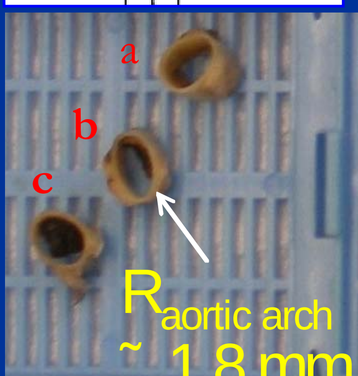
Yu, H., Ai, L., Hsiai, T. K., et al. Flexible Polymer Sensors for In Vivo Intravascular Shear Stress Analysis, *IEEE/ASME J MEMS*, 2008

Descending aorta

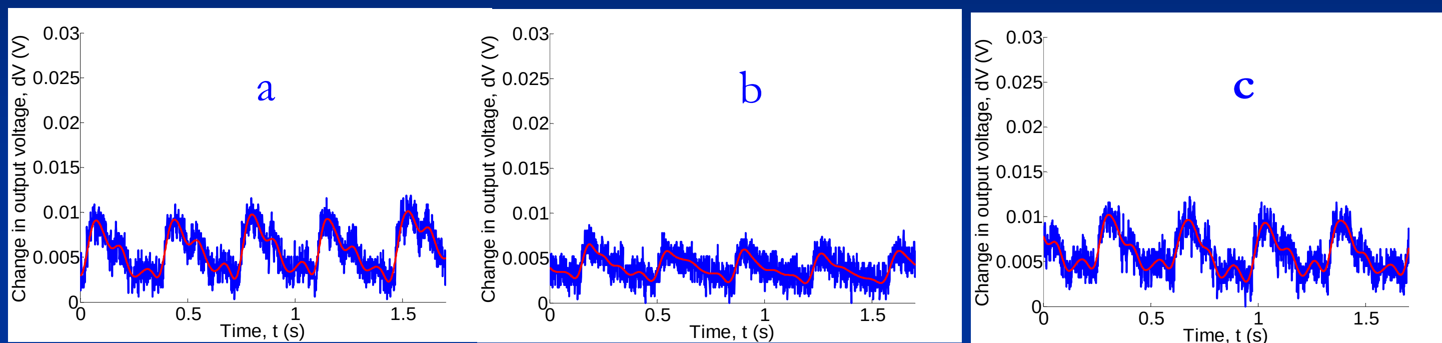


Aortic arch

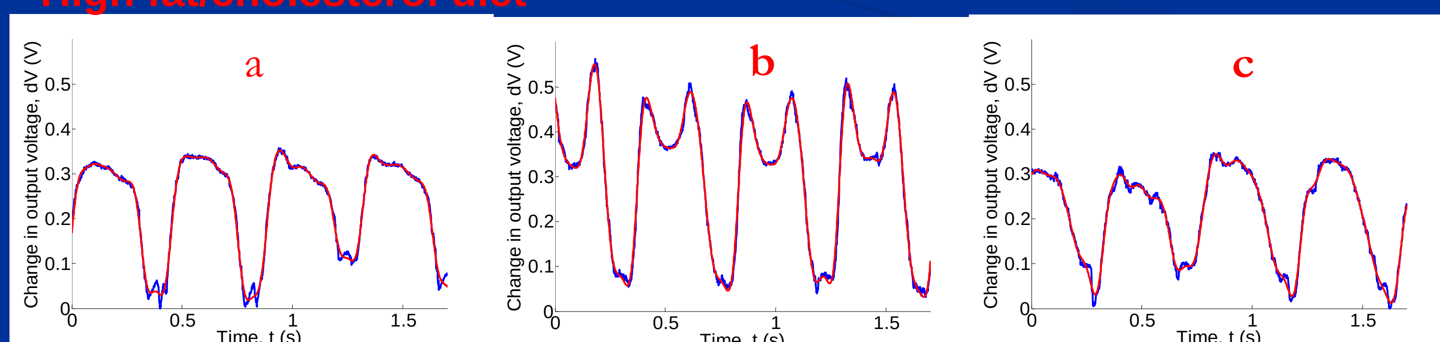




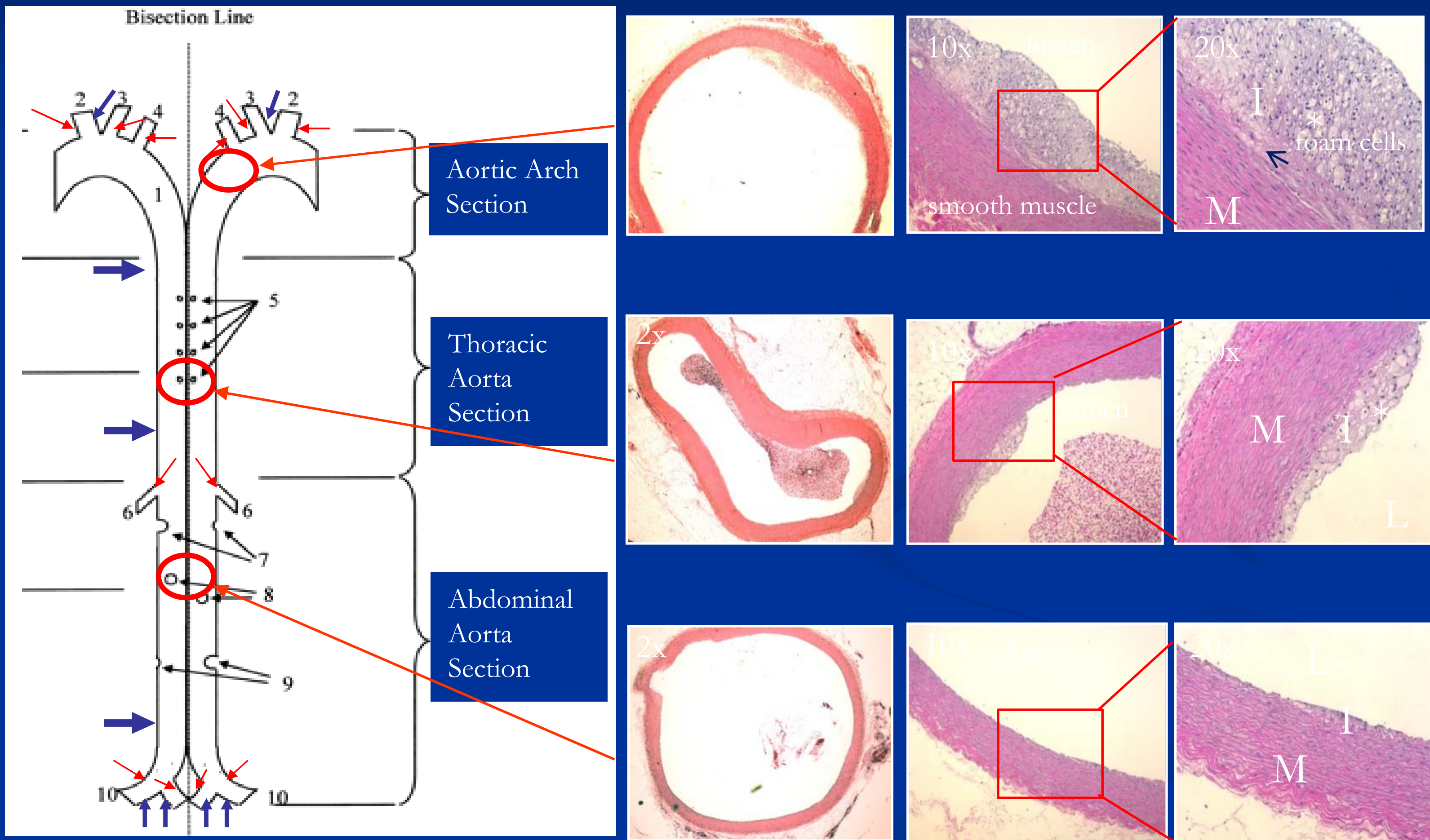
Normal chow diet



High fat/cholesterol diet

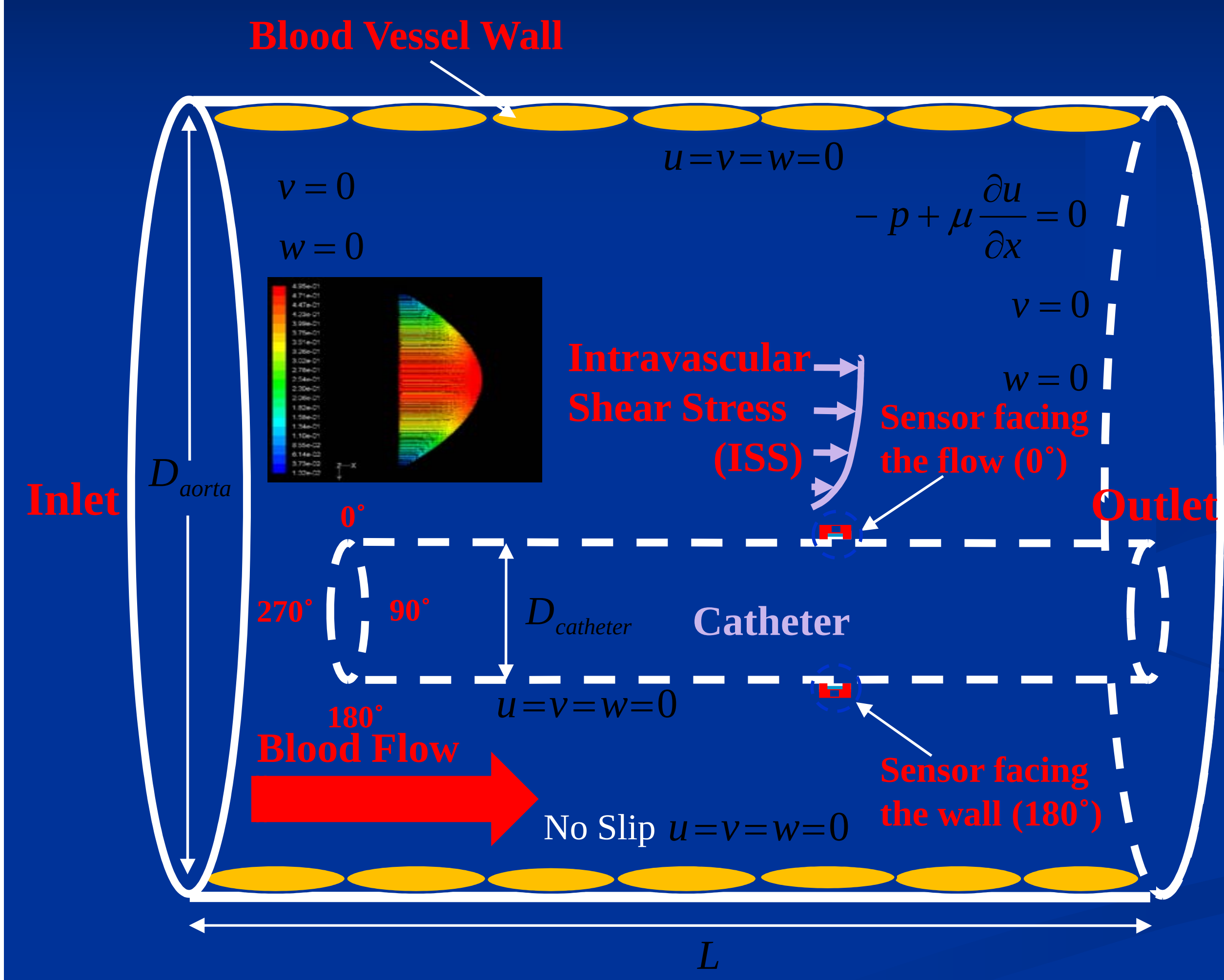


Immunohistochemistry

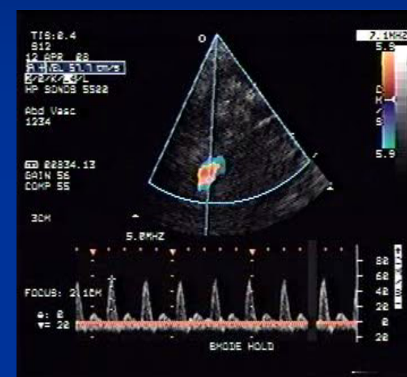


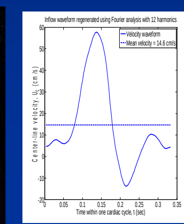
Heart rate at 200 beats/minute; Respiratory rate at 30 times/minute

Geometry and Boundary Conditions

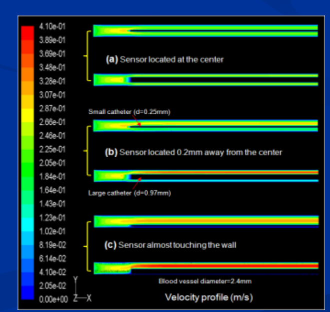


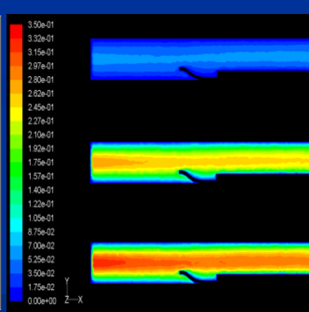
Measured and regenerated waveforms





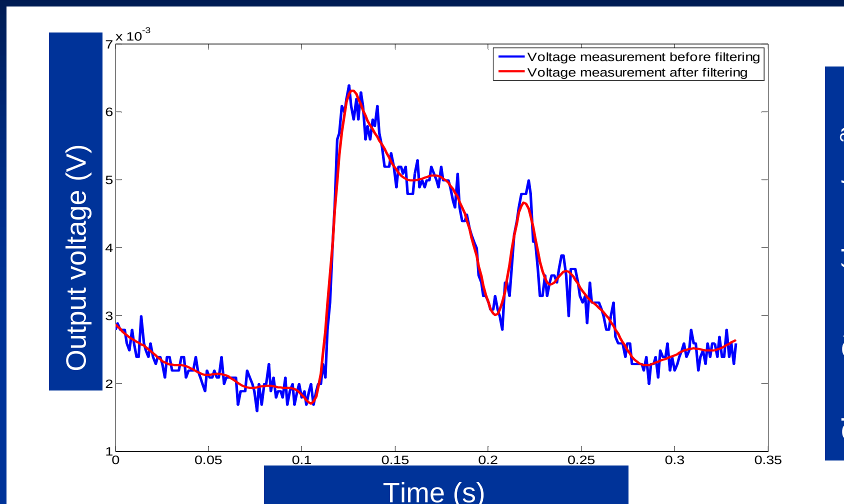
Effects of catheter and flow rates



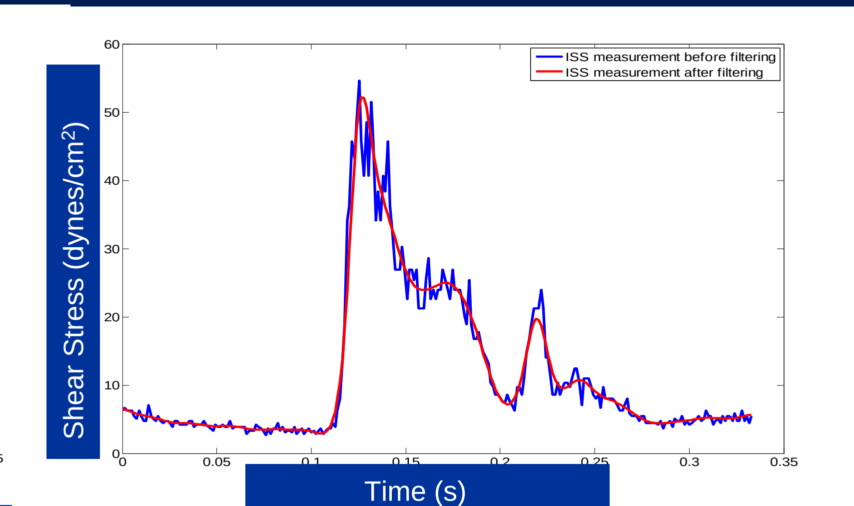


Ai, L., Yu, H., Hsiai, T. K., et al. Optimization of intravascular shear stress assessment in vivo, *J Biomech*, 2009.

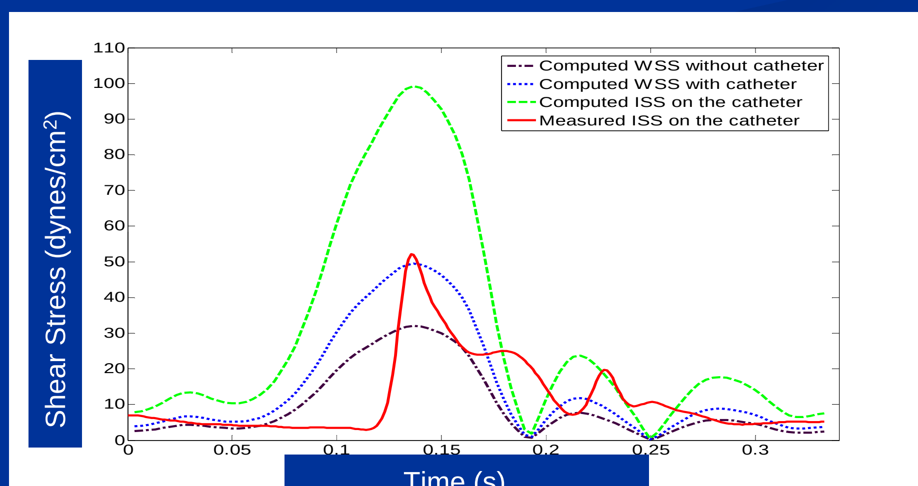
Conversion of output voltage to shear stress



(a) Real-time voltage signals

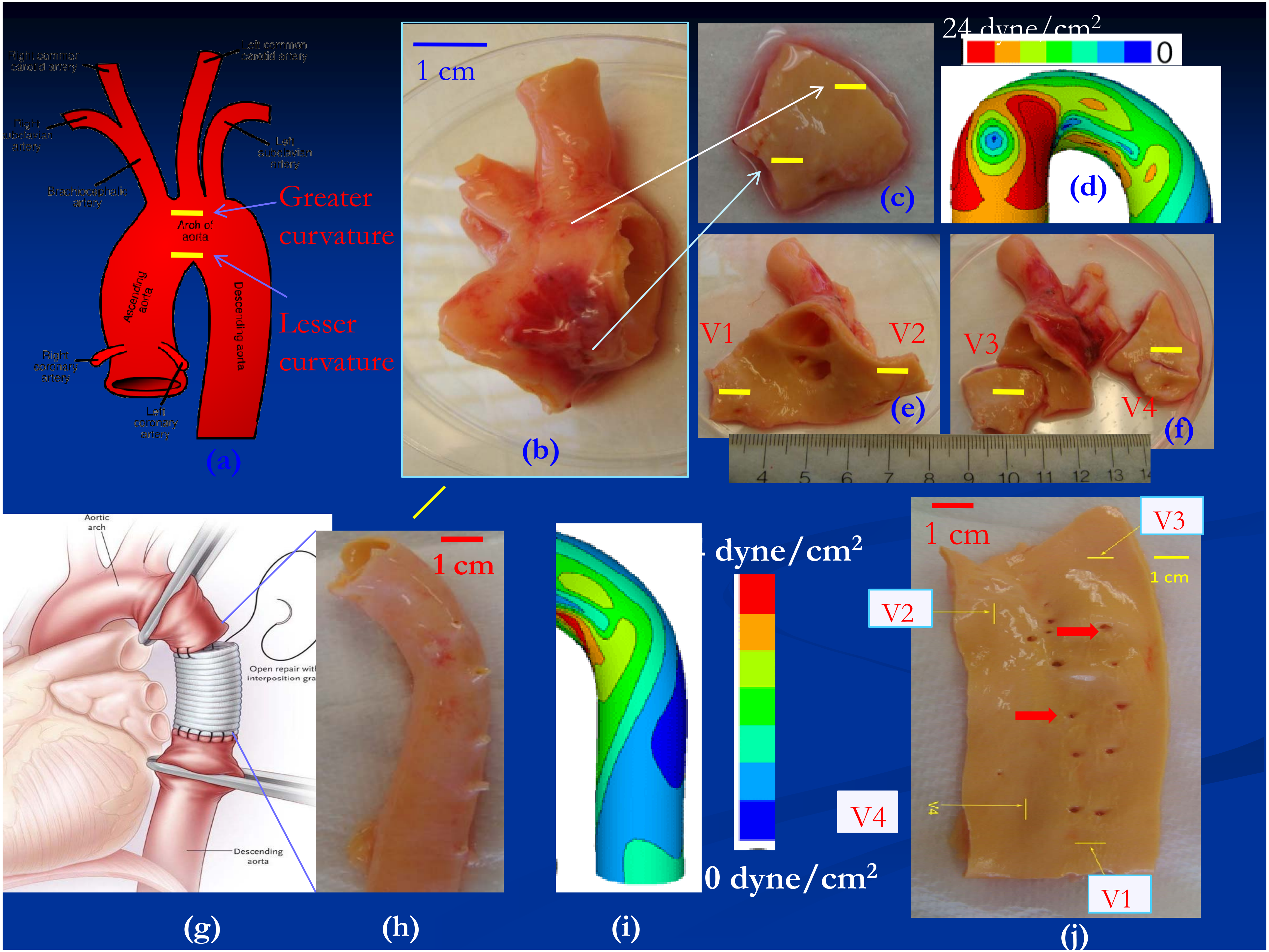


(b) Shear stress converted from voltage signals.



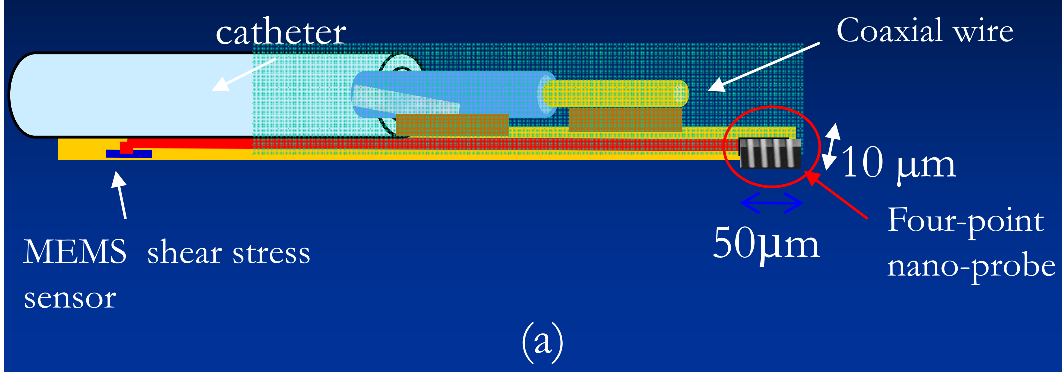
(c) Experimental shear stress curve (in red) compared with computational results

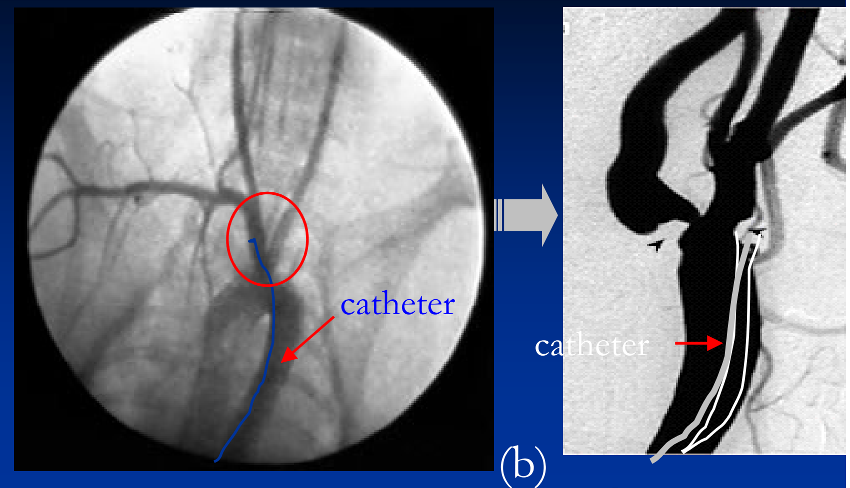
Ai, L., Yu, H., Hsiai, T. K., et al. Real-time Intravascular Shear Stress in the Rabbit Abdominal Aorta , *IEEE Trans. Biomed. Eng.*, 2009.

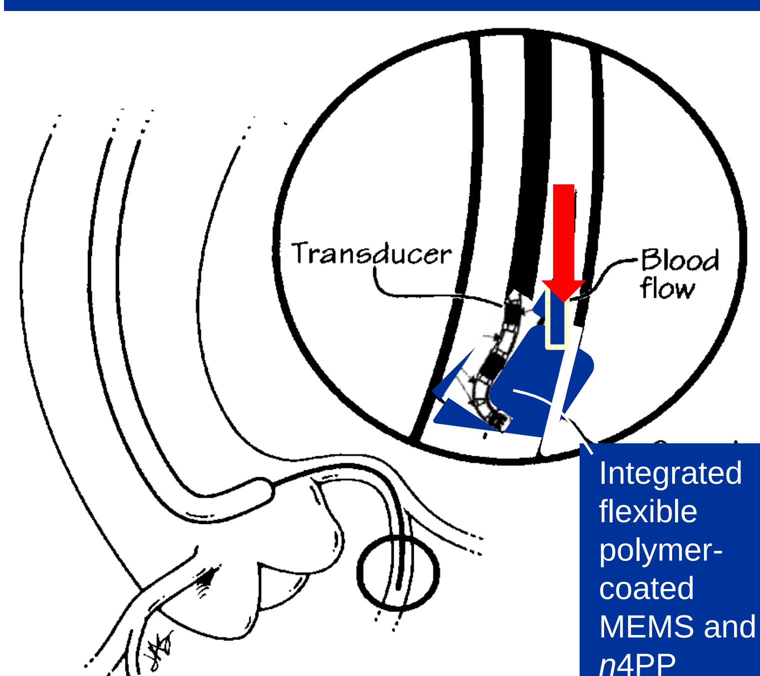


Arch of aorta
Greater curvature
Ascending aorta
Descending aorta
Lesser curvature
(a)
1 cm
(b)
(c)
24 dyne/cm^2
0
(d)
V1
V2
(e)
V3
V4
(f)
Aortic arch
Open repair wit
interposition gra
Descending aorta
1 cm
dyne/cm^2
0 dyne/cm^2
1 cm
V3
1 cm
V2
V4
V1
(g)
(h)
(i)
(j)

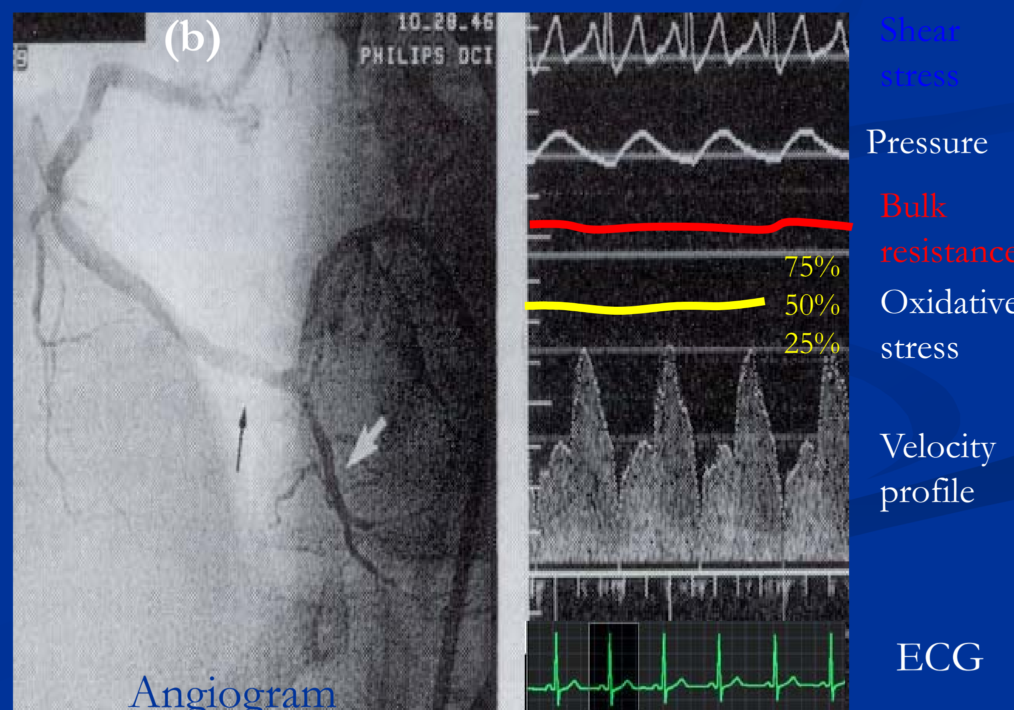
Early detection of Mechanically Unstable Plaque for Selective Intervention







Integrated flexible polymer-coated MEMS and *n*4PP



Objectives

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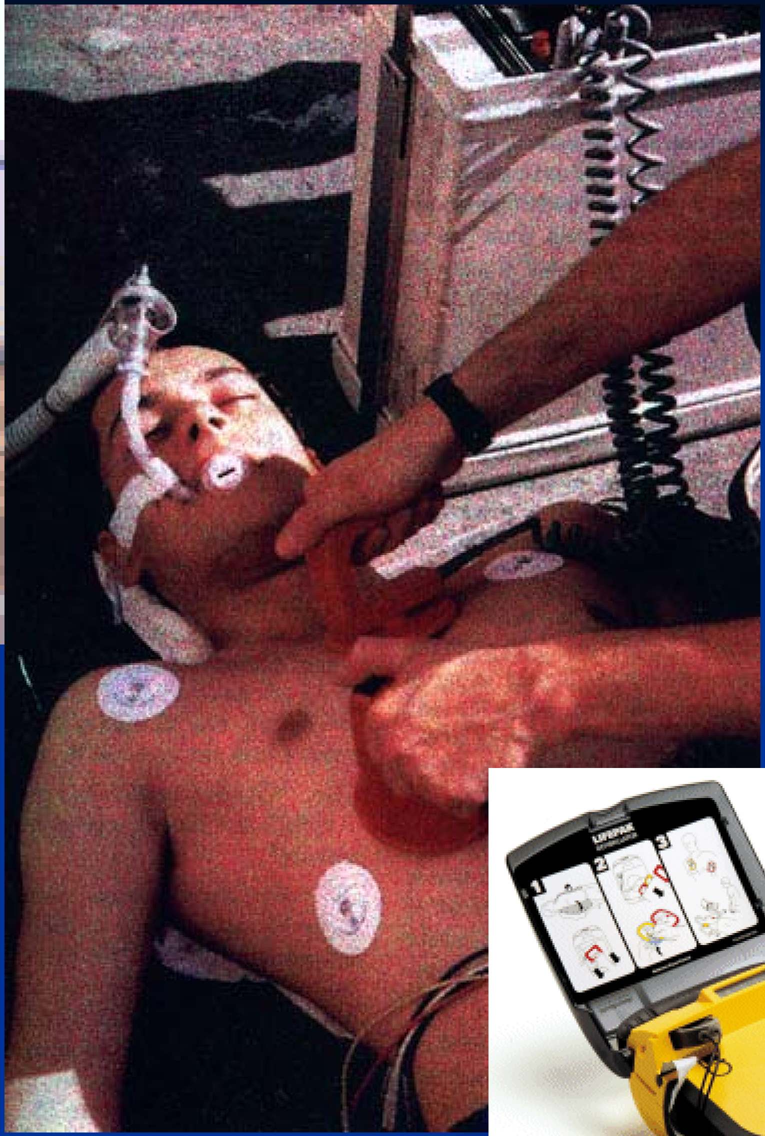
- **Bridge bioengineering, industry and medicine**

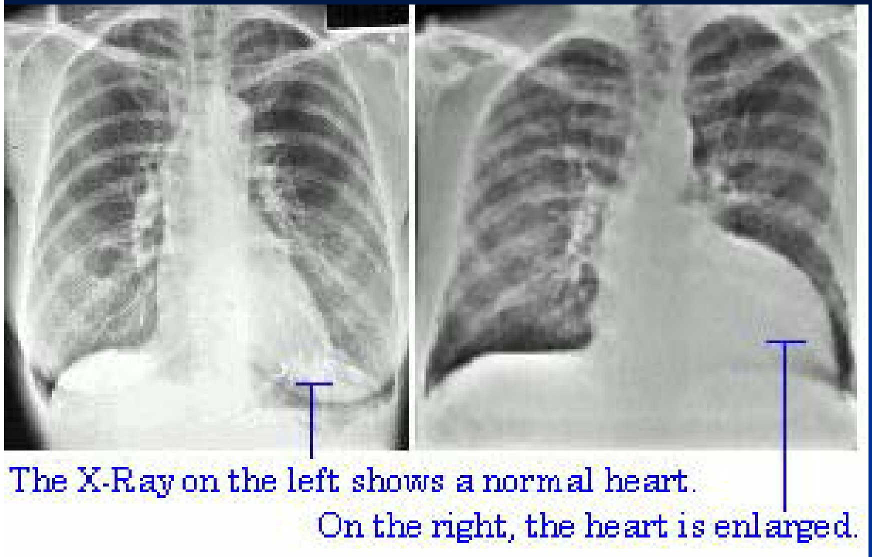
External Defibrillator

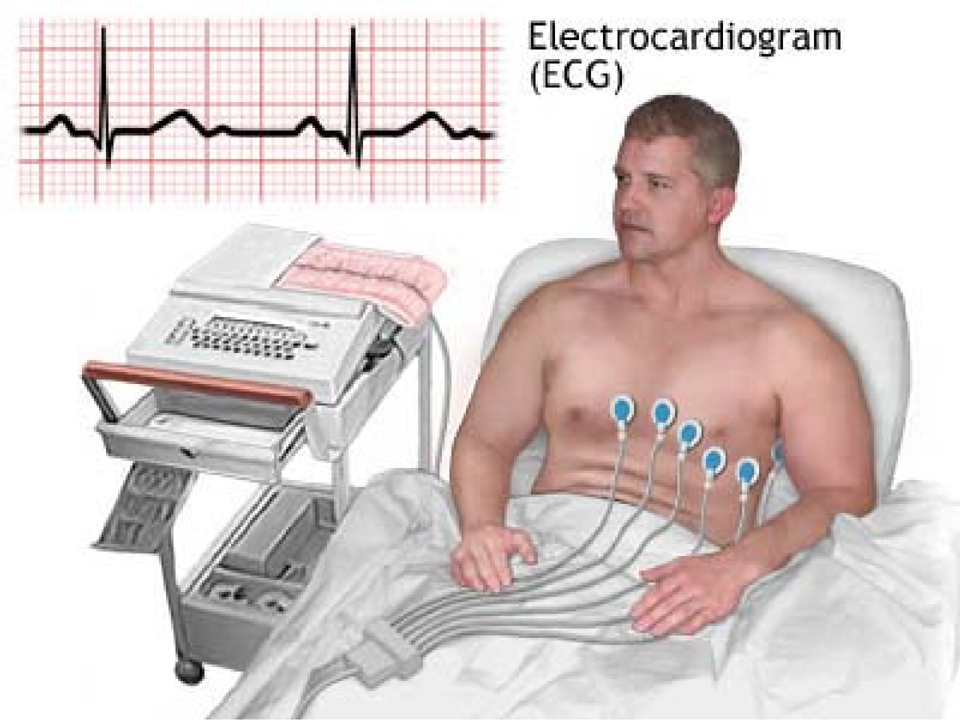


Emergency Room

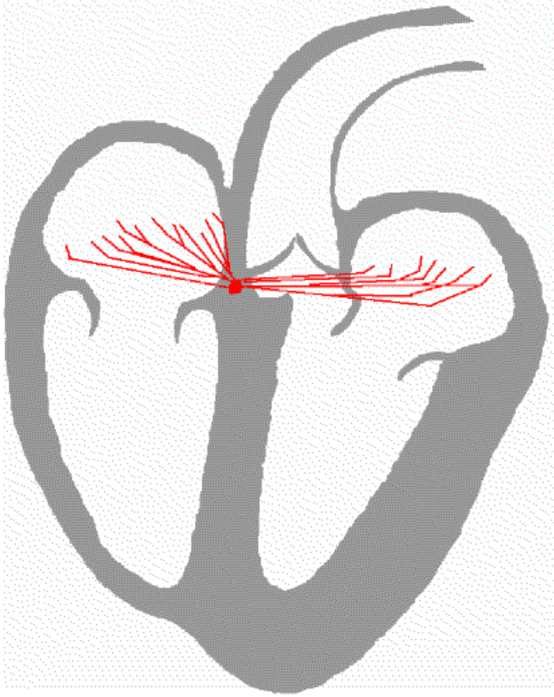
Diagnostic modalities

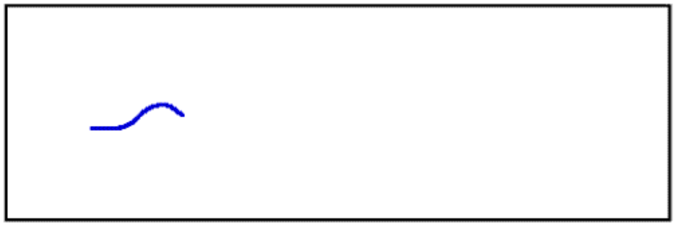
Chest X-Ray

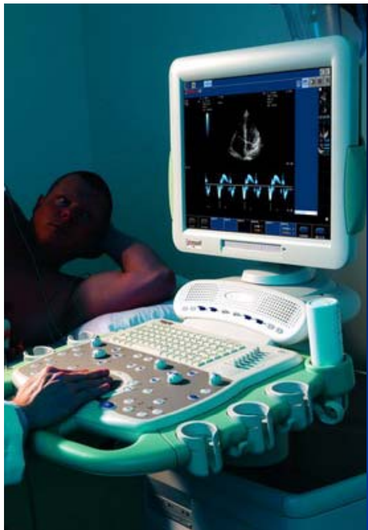


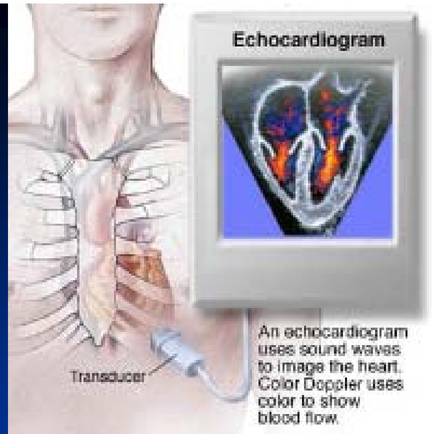


ECG/EKG (electrocardiogram)

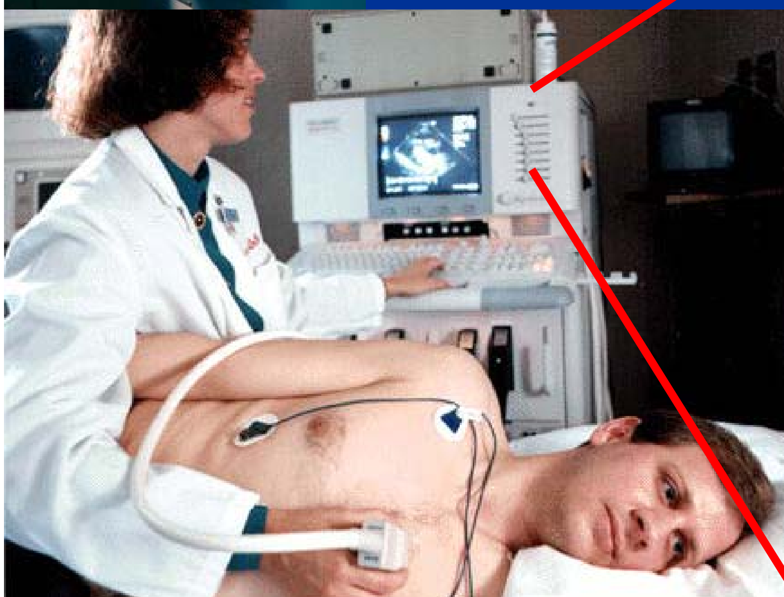


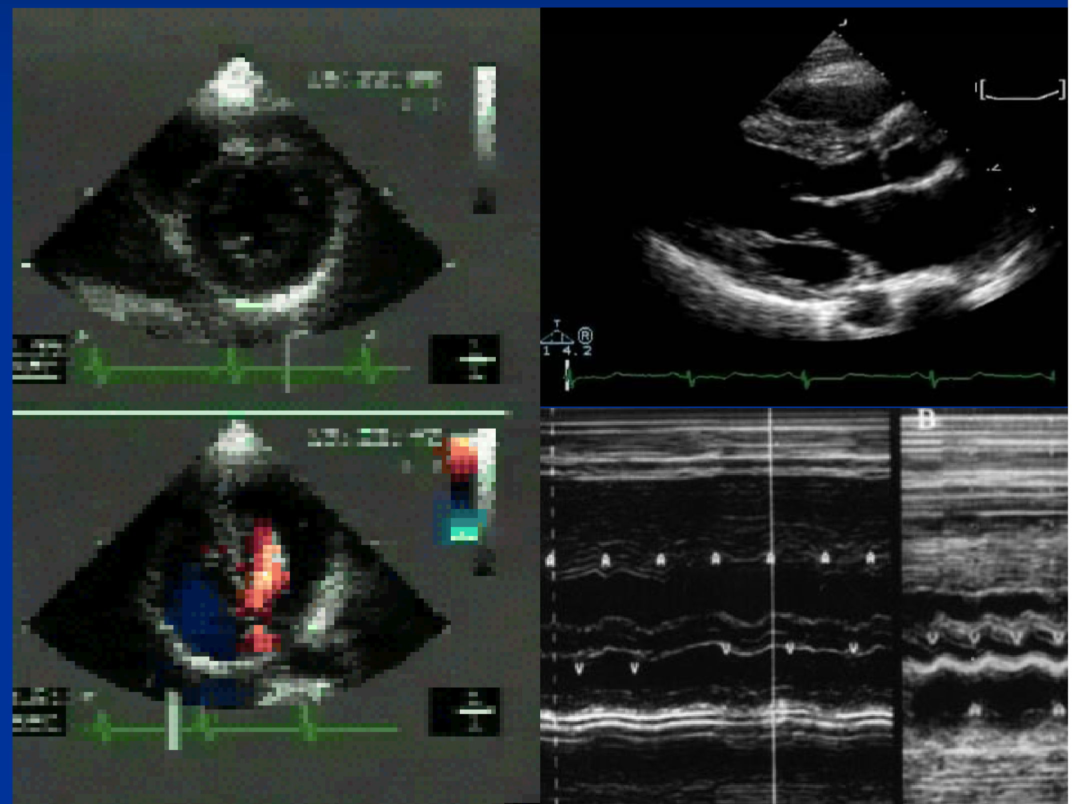






Echocardiogram





Echocardiography is the process of mapping the heart through echoes. The pulses are sent into the chest and the high-frequency sound waves bounce off of the heart's walls and valves. The returning echoes are electronically plotted to produce a picture of the heart called an echocardiogram.

Ultra Fast Computed Tomography (CT)

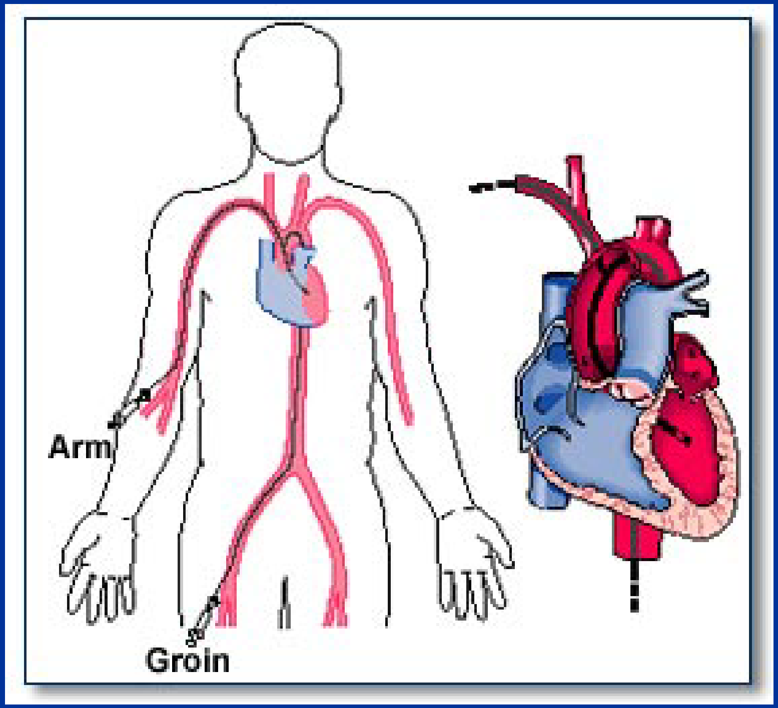
Computed tomography (CT or CAT scan) is a diagnostic imaging procedure that uses a combination of x-rays and computer technology to produce cross-sectional images (often called slices), both horizontally and vertically, of the body.

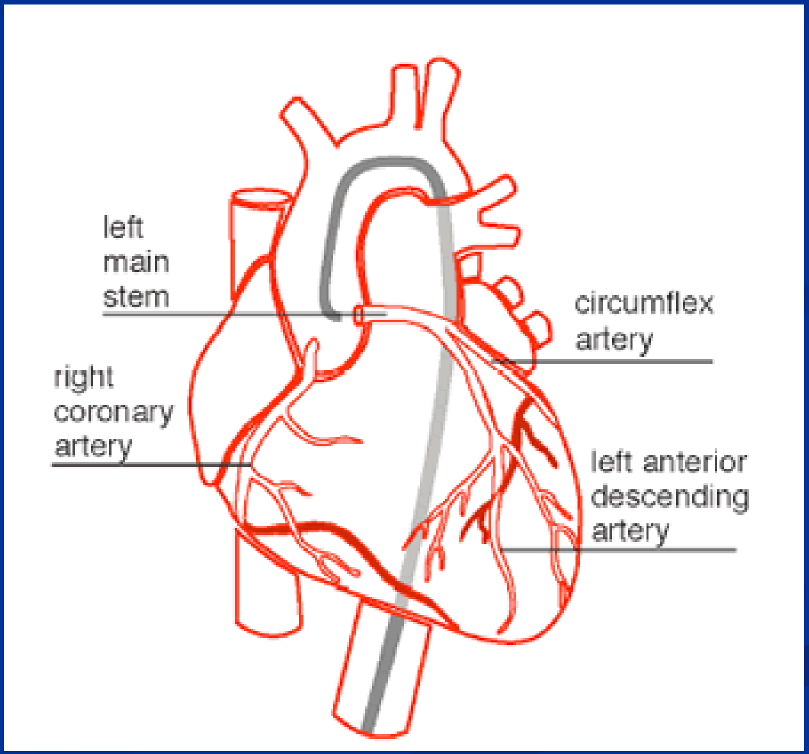
In standard x-rays, a beam of energy is aimed at the part of the body being studied. A plate behind the body part captures the variations of the energy beam after it passes through skin, bone, muscle, and other tissue.

Ultrafast CT scans can take multiple images of the heart within the time of a single heartbeat, thus providing much more detail about the heart's function and structures, and also greatly decreasing the amount of time required for a study.

Cardiac Cath Lab

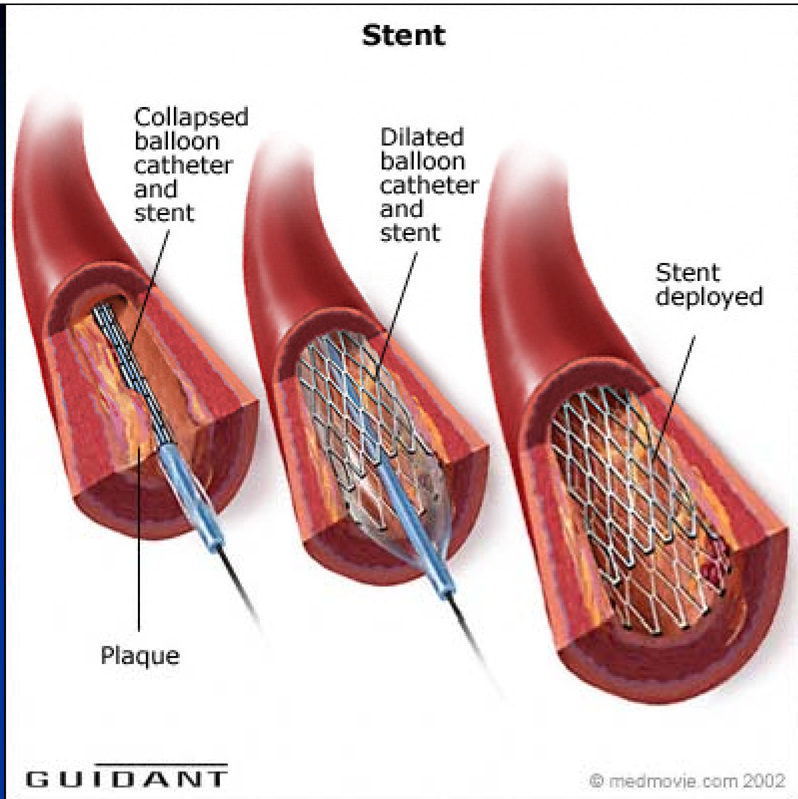
Coronary arteries

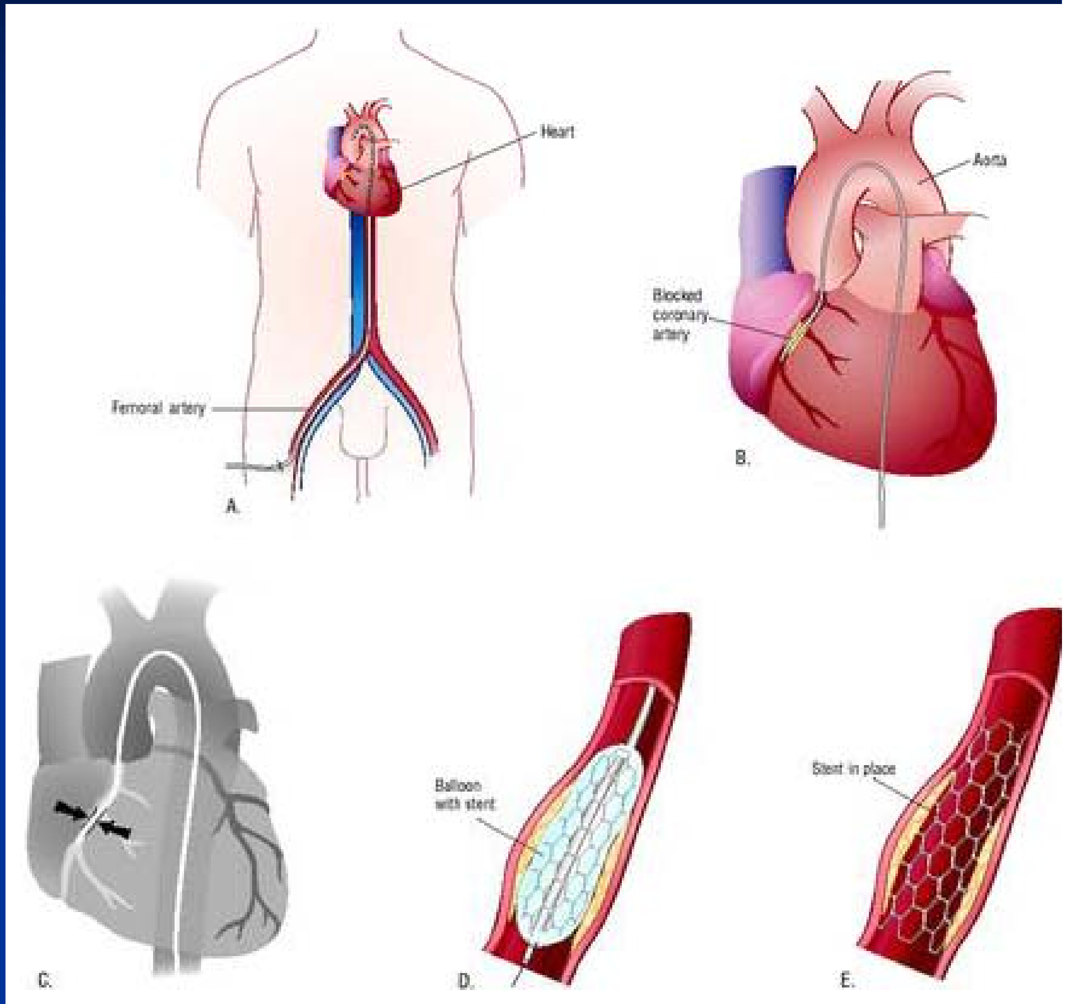




Angioplasty

Stents





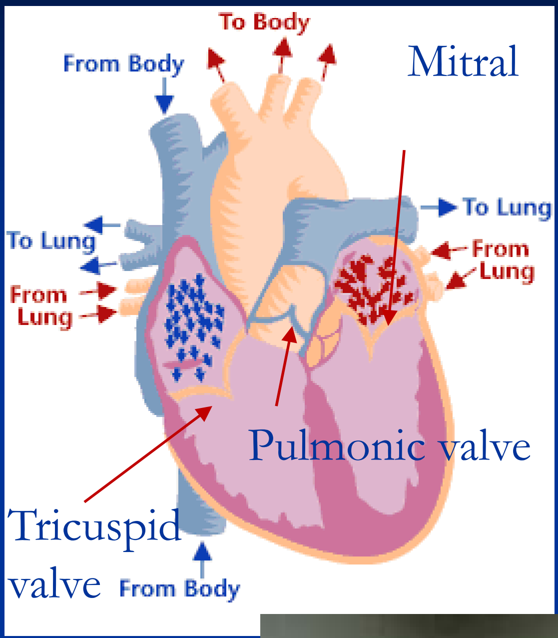
During angioplasty, a catheter is fed into the femoral artery of the upper leg (A). The catheter is fed up to coronary arteries to an area of blockage (B). A dye is released, allowing visualization of the blockage (C).
A stent is placed on the balloon-tipped catheter. The balloon is inflated, opening the artery (D). The stent holds the artery open after the catheter is removed (E).

Left Ventricular Assist Device (LVAD)

Because of the shortage of donor hearts, heart assist devices are often used to keep patients alive while they await **heart transplant**. Assist devices, which take over the majority of the heart's pumping function, allow the heart to rest, heal, and grow stronger.

As a result, patients often become healthier and stronger before they undergo transplant surgery.

Prosthetic Heart Valves



Heart valves have key roles in regulating blood flow the heart, opening and closing in sequence with each heartbeat.

These valves act like one-way doors, allowing blood to flow either forward into the next chamber, or out of the heart via one of two main blood vessels that carry blood away from the heart. The valves close to prevent back flow.

The two main prosthetic valve designs include mechanical and bioprosthetic (tissue) heart valves, some of which are shown below.

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Kathy Griendling	Emory U
Hanjoong Jo	Georgia Tech/Emory U
Stan Hazen	Cleveland Clinic

NIH NHLBI KO8 (HL068689)
NIH NHLBI RO1 (HL083015)
NIH R21 (HL091302)
AHA GIA (0655051Y)
AHA PDF (0425053Y)
AHA PDF (0615063Y)

The search for truth is one way hard another easy, for no one can master it fully nor miss it fully, each adds a little knowledge to our nature, and from all things assembled there arises a certain grandeur.

Aristotle

Thank You!