# Blood Vessel Mechanics

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Department of Bioengineering

BIOEN 326

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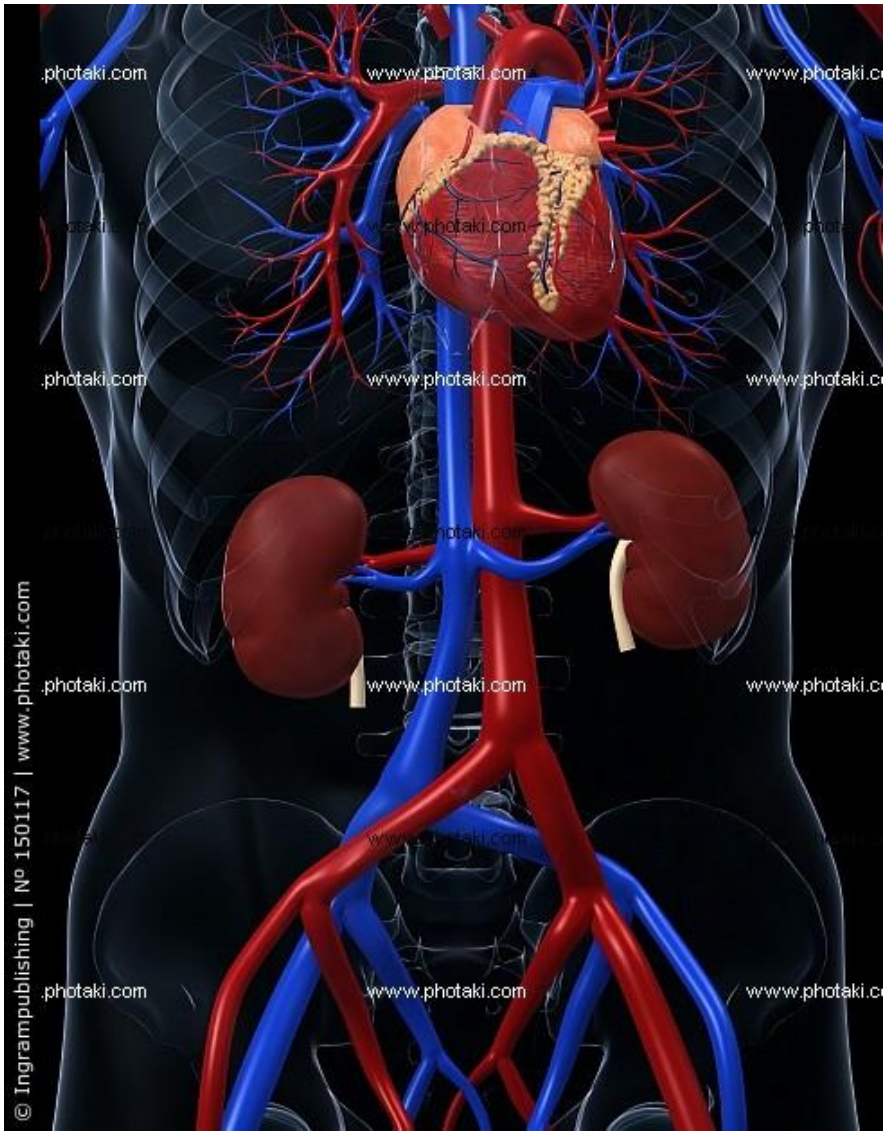
# Vasculature in our body

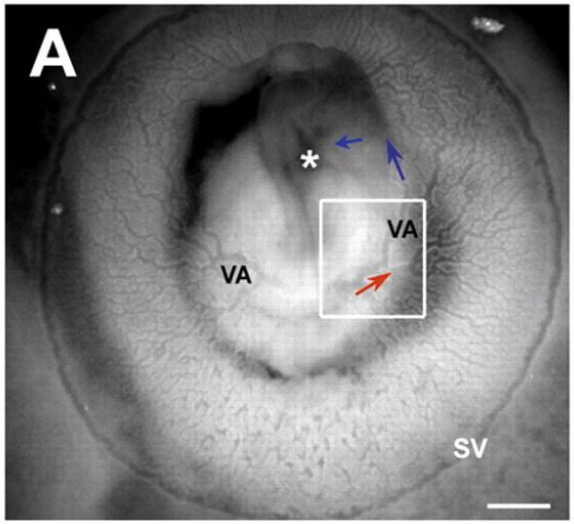


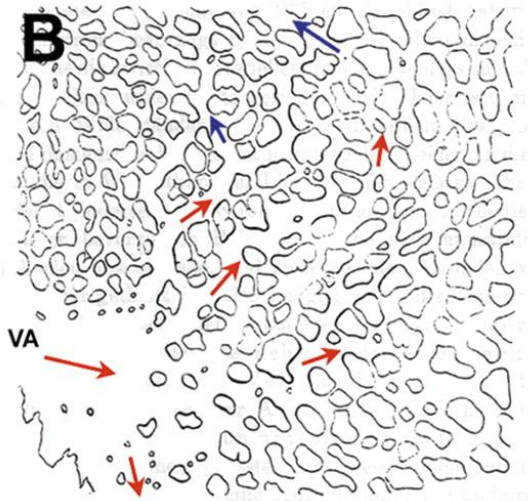

A. structure:
- 100,000 km of pipes!
- total surface area 800–1000 $m^2$
- 60,000 miles of capillaries
- diameters from 10 μm to 2 cm
- double network connected at smallest scale (anastomosed)

B. function:
- provide nutrients, oxygen to tissues and remove waste
- self-regulation/homeostasis, tissue remodeling and healing
- cellular, molecular trafficking

C. mechanics:
- Pressure: 5 – 120 mmHg
- Flow: 0.03 – 40 cm/s

# Development of the Vasculature

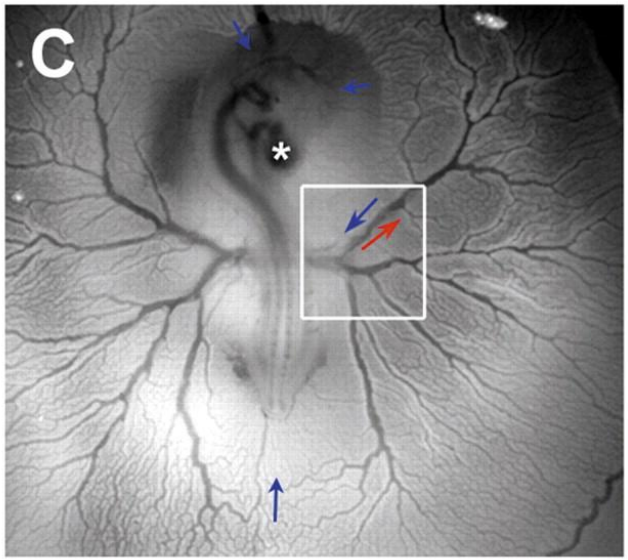


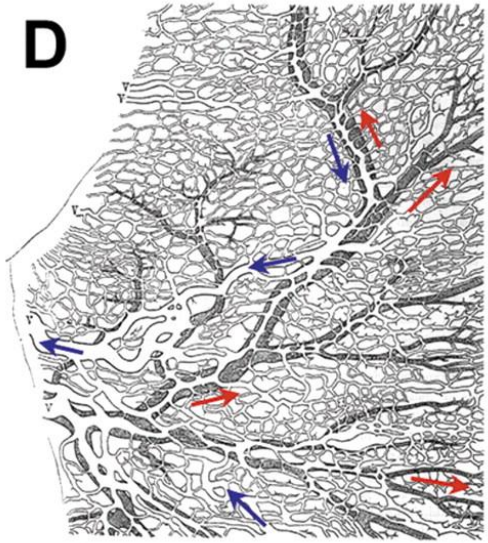




Chicken embryos

Yolk sac vessels just after the onset of perfusion.

Connected tube formed.




Embryo 26 hours later than in A

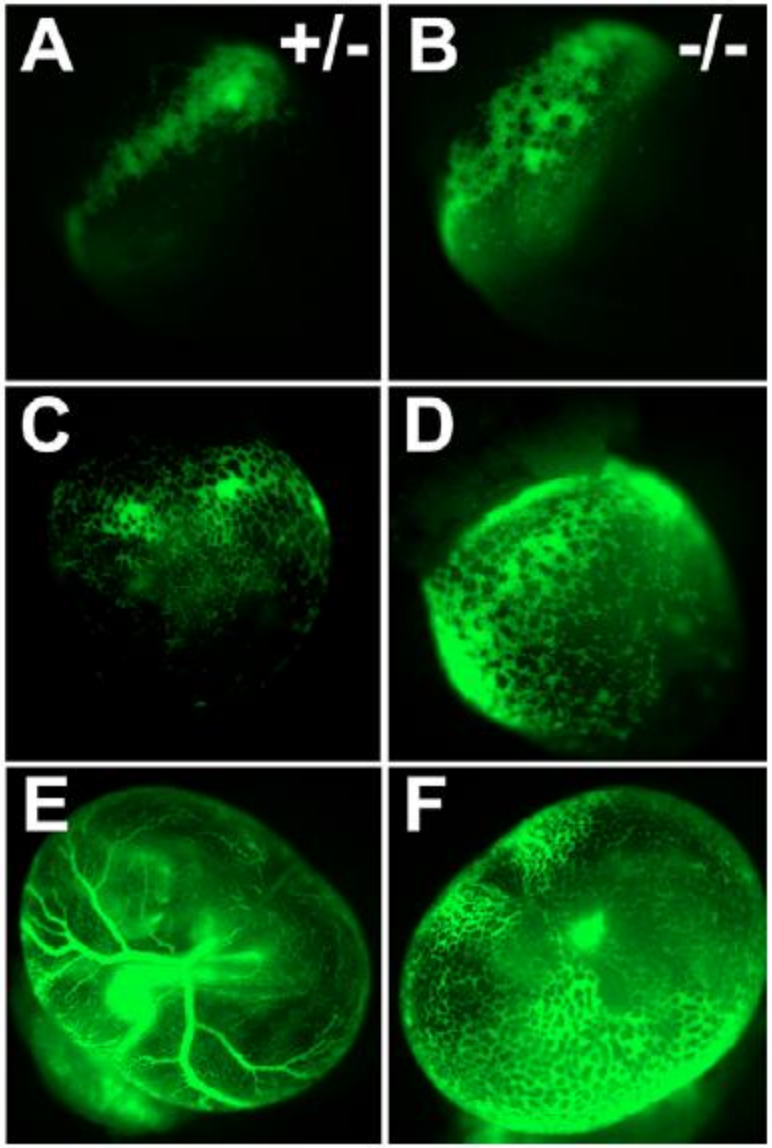
Hierarchical structure formed.

*(le Noble, Development 2004)*

# Development of the Vasculature

Mouse embryos:

Normal impaired heart function (impaired contractility *Mlc2a*$^{-/-}$).

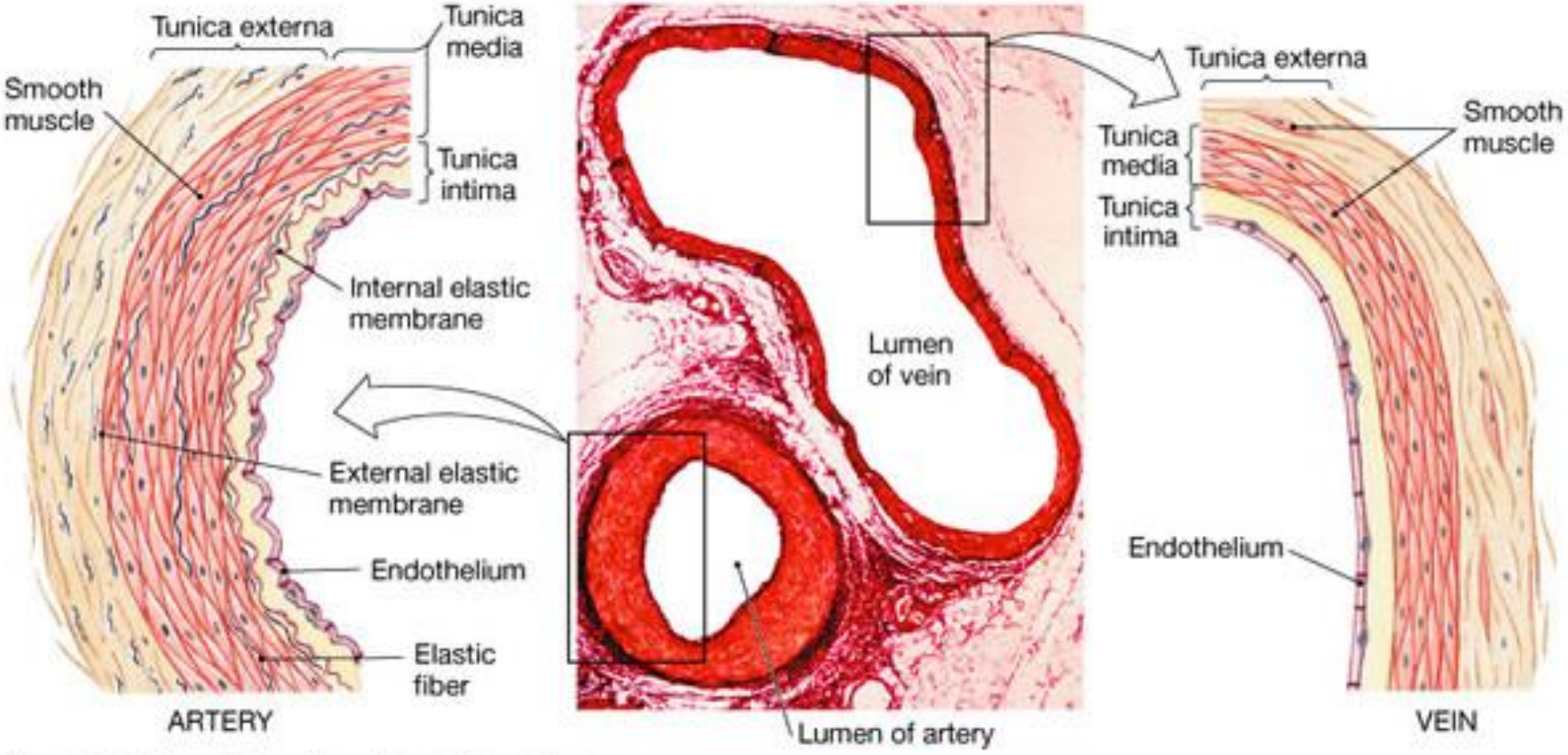



When heart function is impaired, hierarchical branching does not develop

Flow and hydraulic pressure control vascular structure

*(Lucitti, Development 2007)*

# A Typical Artery and a Typical Vein

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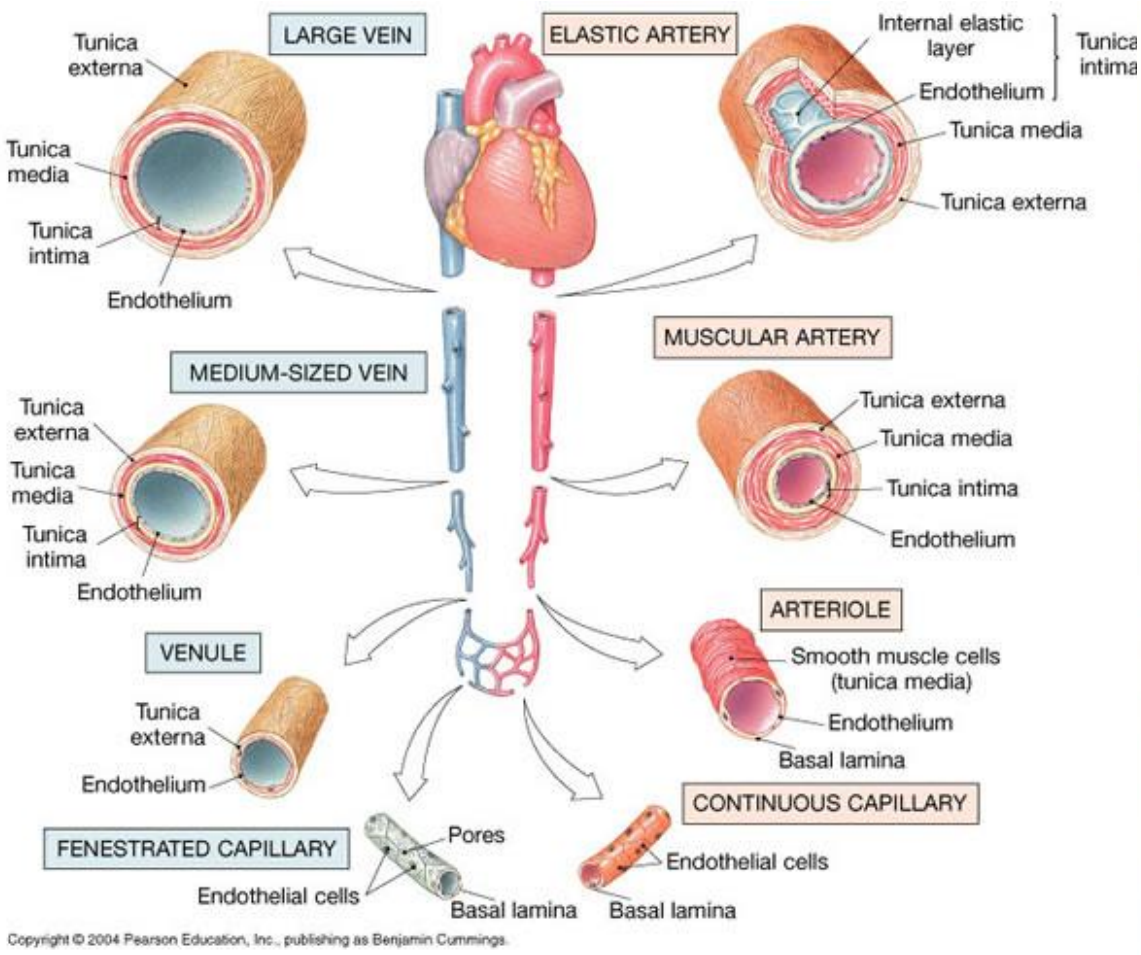
# Blood Vessel Structure



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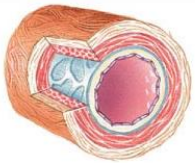
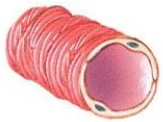
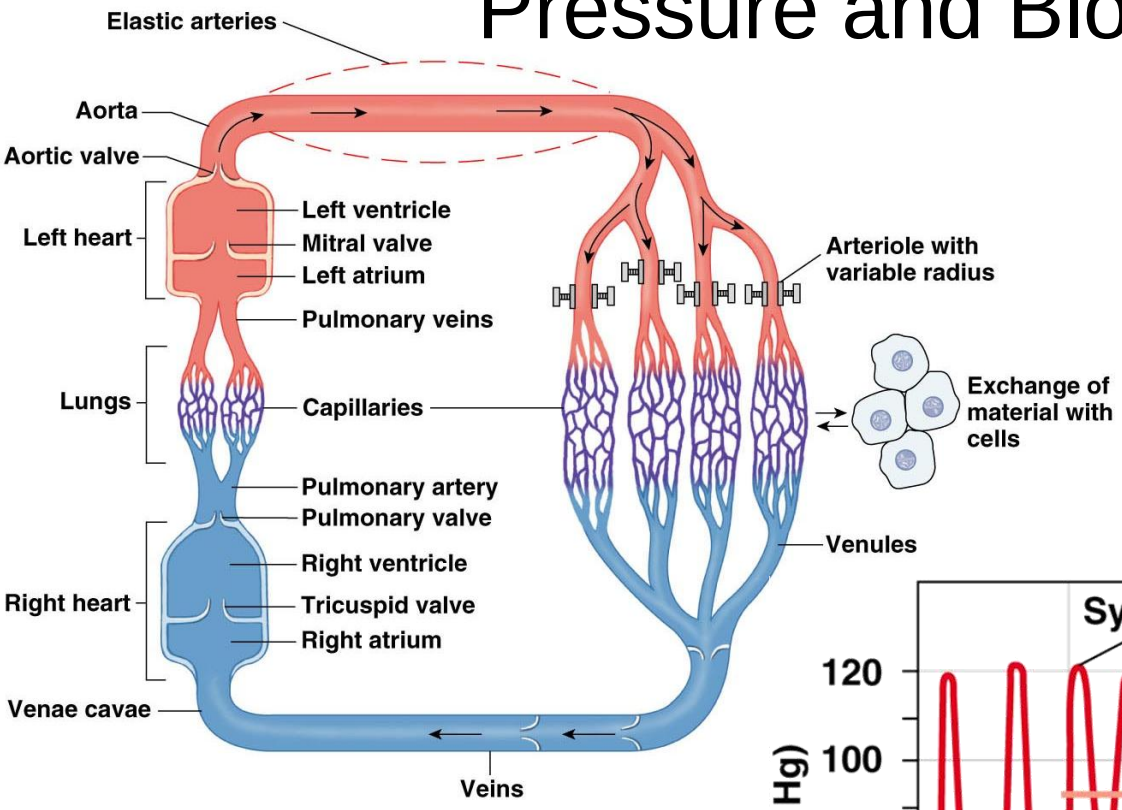
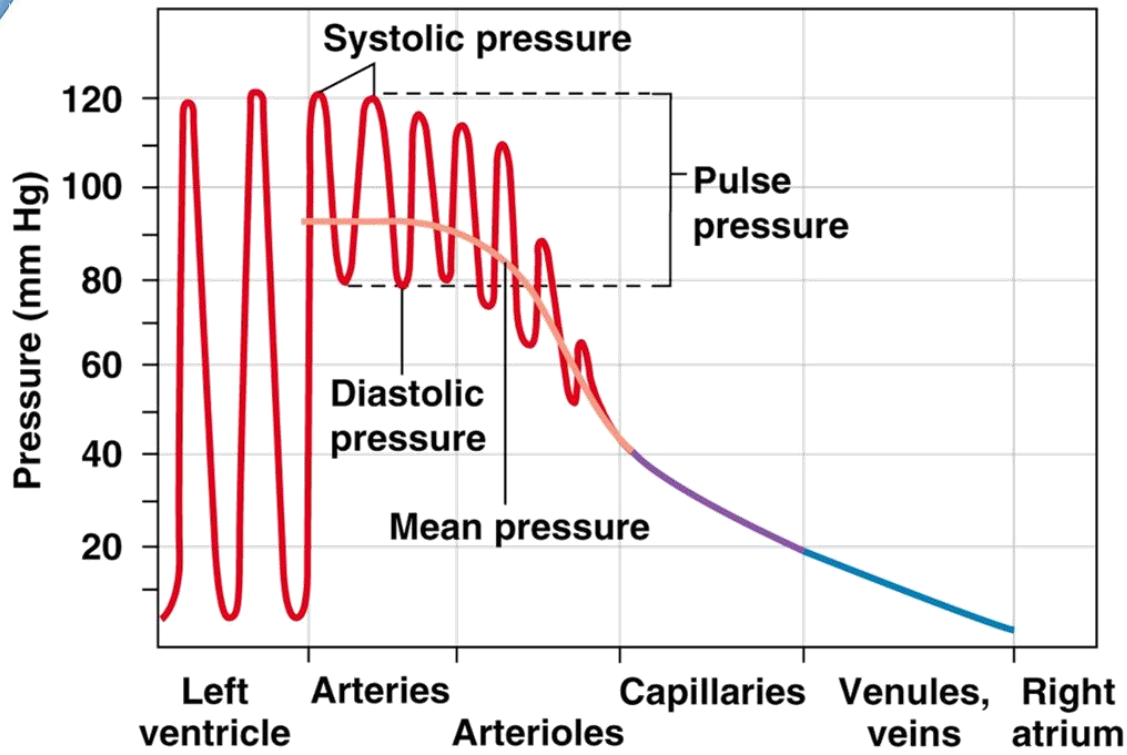
| | Mean diameter | Mean wall thickness | Endothelium / Elastic tissue / Smooth muscle / Fibrous tissue | |
|---|---|---|---|---|
| Artery | 4.0 mm | 1.0 mm | |  |
| Arteriole | 30.0 μm | 6.0 μm | |  |
| Capillary | 8.0 μm | 0.5 μm | |  |
| Venule | 20.0 μm | 1.0 μm | |  |
| Vein | 5.0 mm | 0.5 mm | |  |

# Pressure and Blood Flow

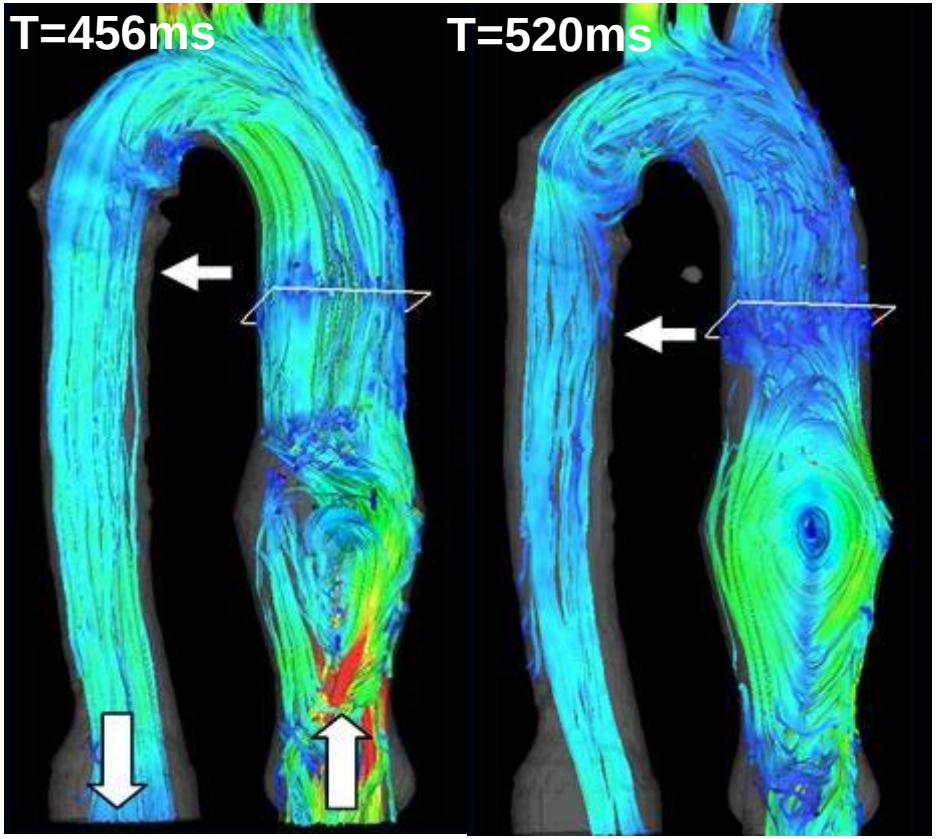


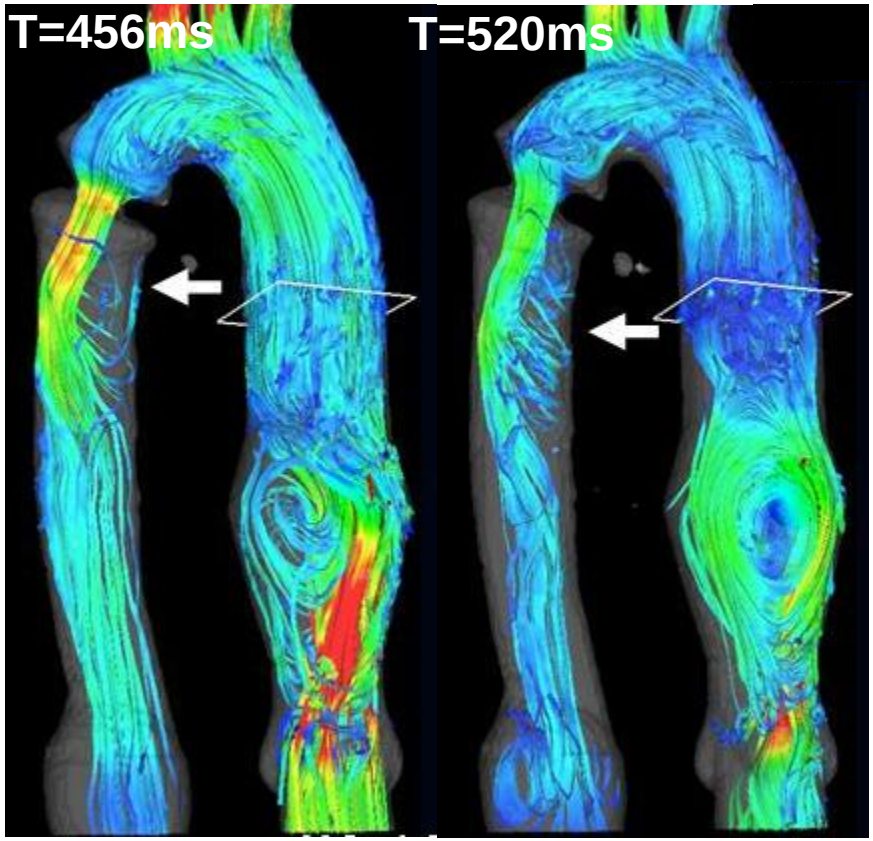
# Pressure and blood flow

Poiseuille's relationship: $\Delta P = \frac{8\mu l Q}{\pi r^4}$ (steady, laminar, pipe flow)

**MRI, velocity mapping in thoracic aorta**



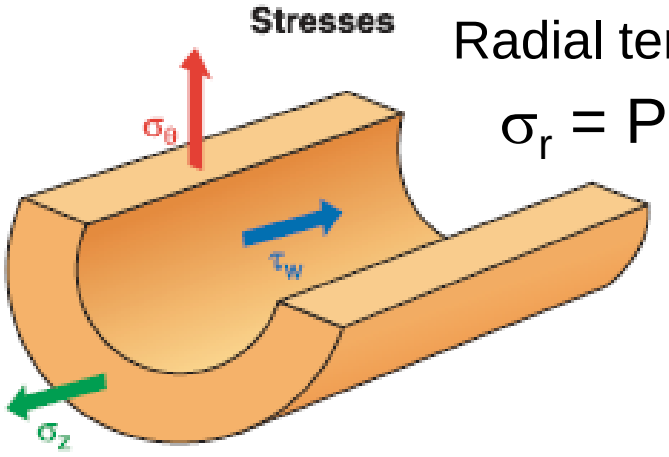

Stenosis, w/o




Stenosis, 54%

*(Canstein , MRM, 2006, 2007)*

# Mechanics: vessel wall




Radial tension:

$\sigma_r = P$

Longitudinal stress:

$\sigma_z = F/A$

$= Pd^2 / ((d+2t)^2 - d^2)$

Hoop stress:

$\sigma_\theta = PD_m / 2t$

# Vessel Wall Associated Pathologies

## 1. Atherosclerosis

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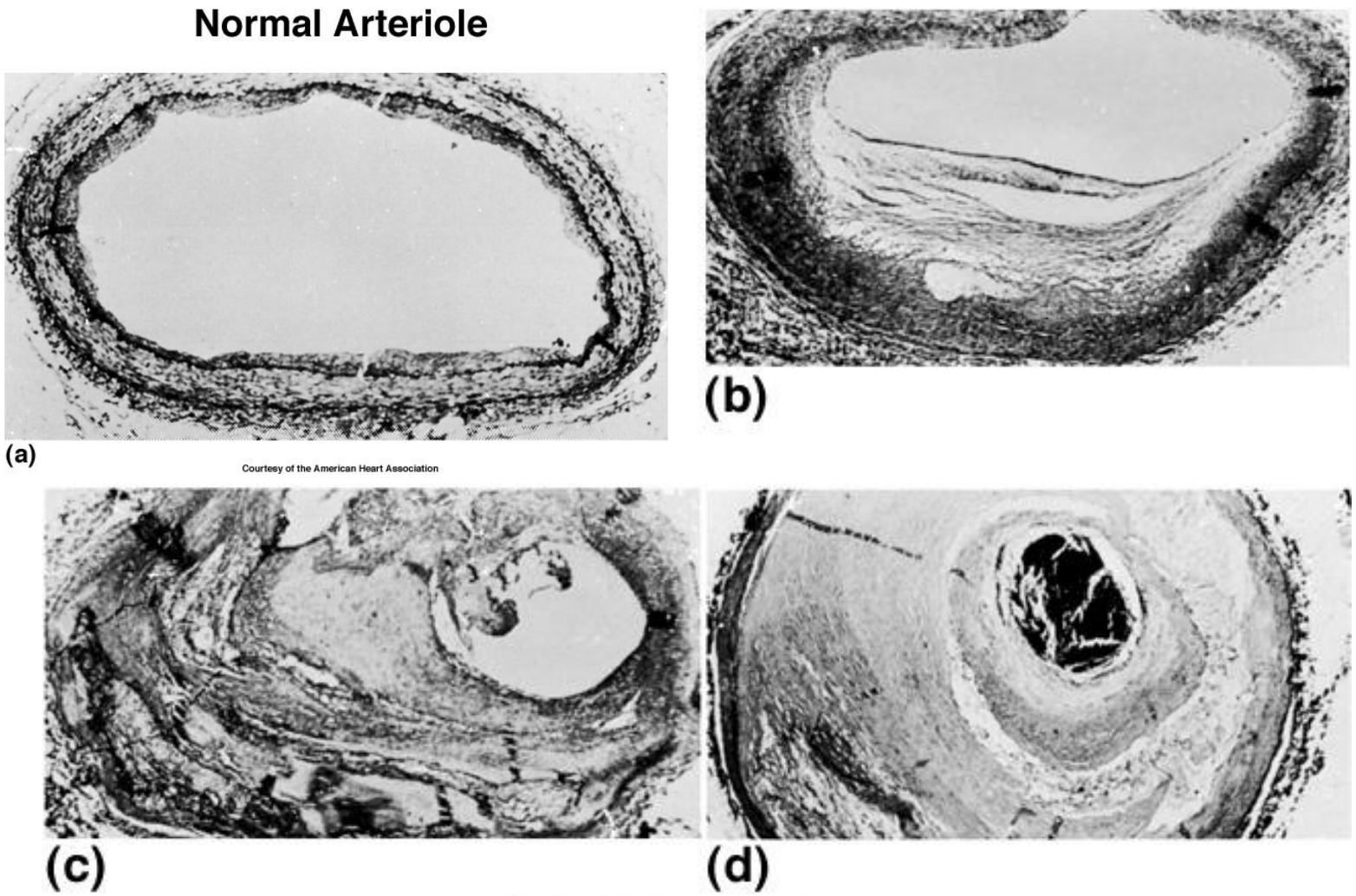
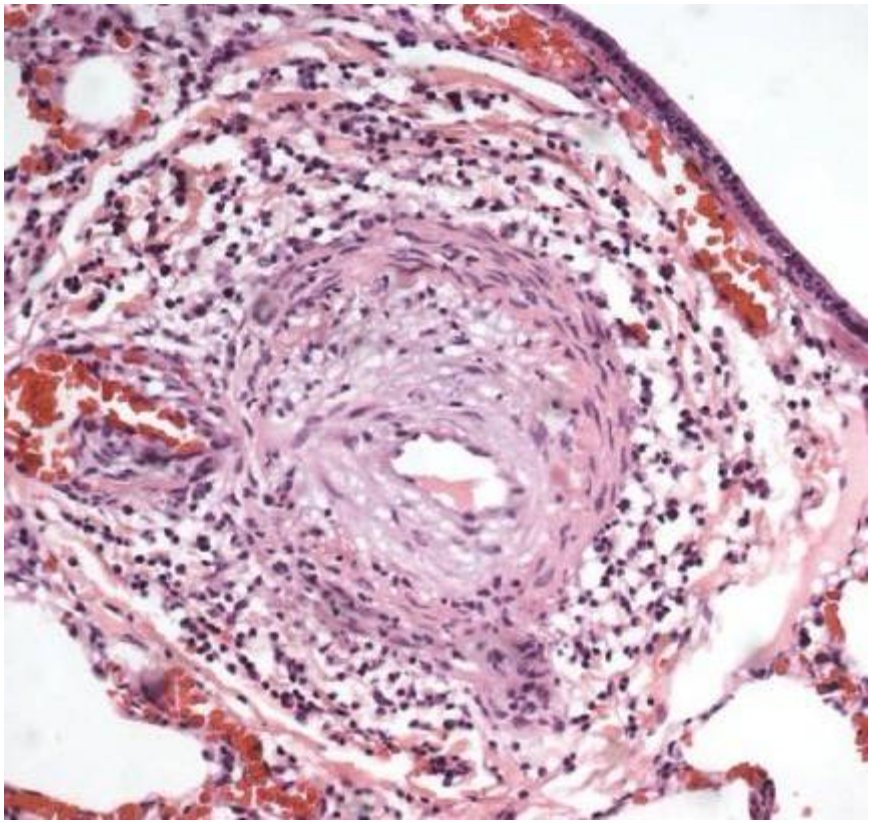
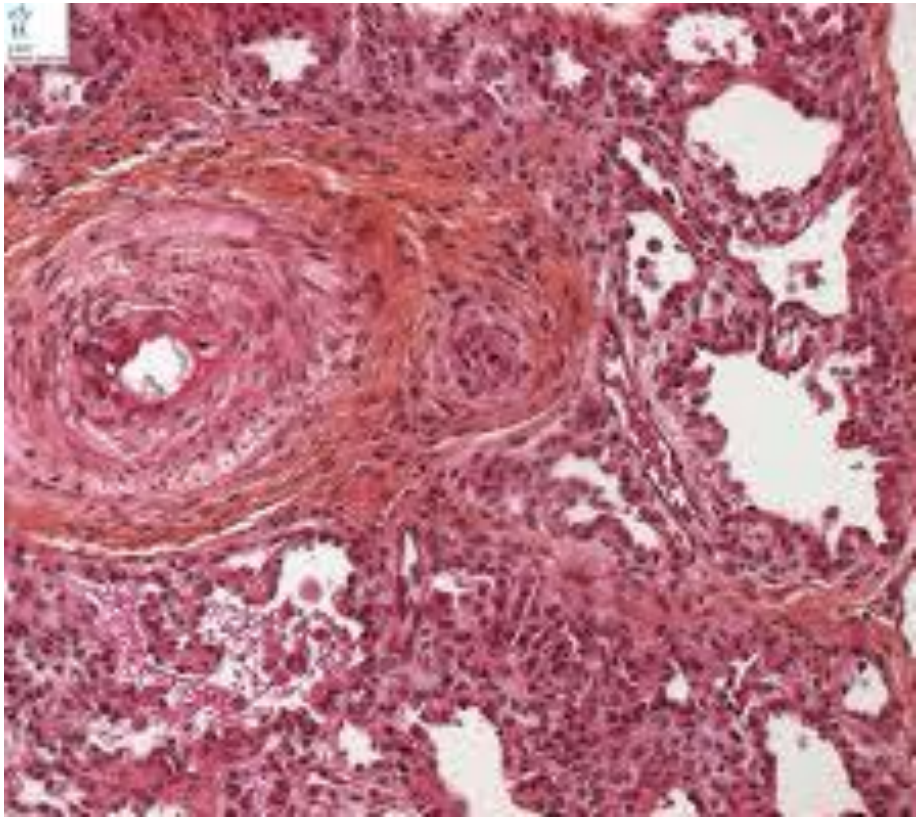


# Vessel Wall Induced Pathologies

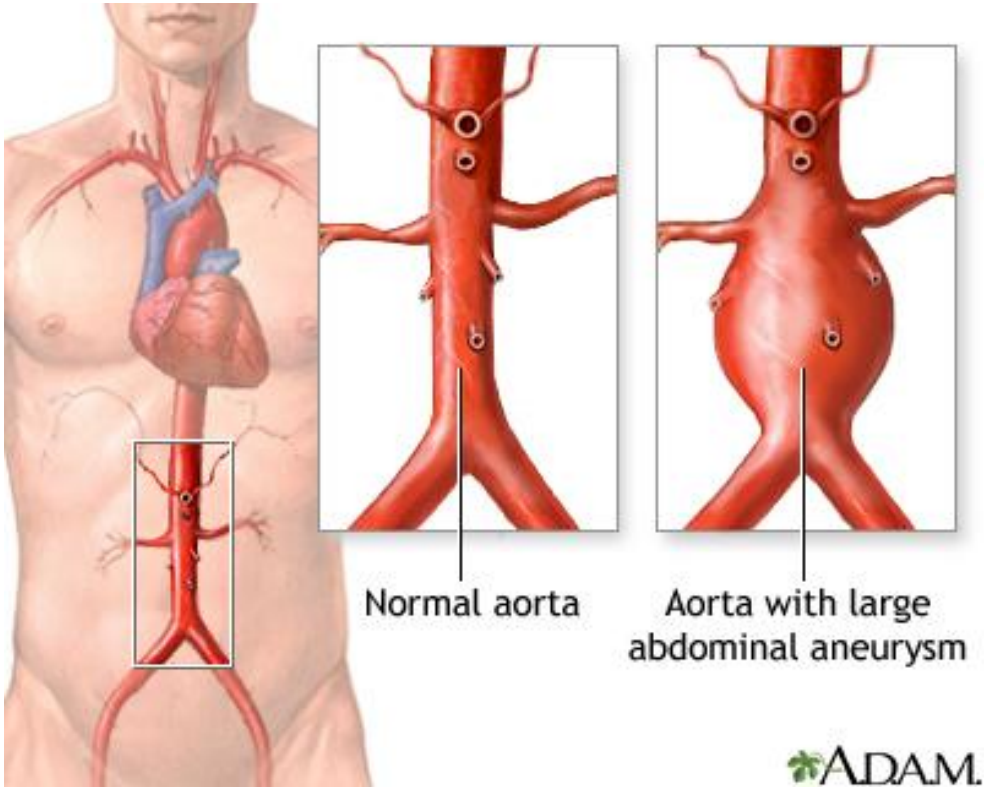
2. Hypertensive Vascular Disease





# Vessel Wall Induced Pathologies

3. Aneurysms



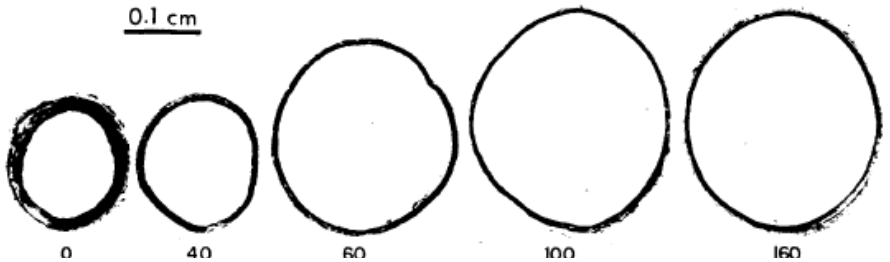

High risk of rupture and bleeding

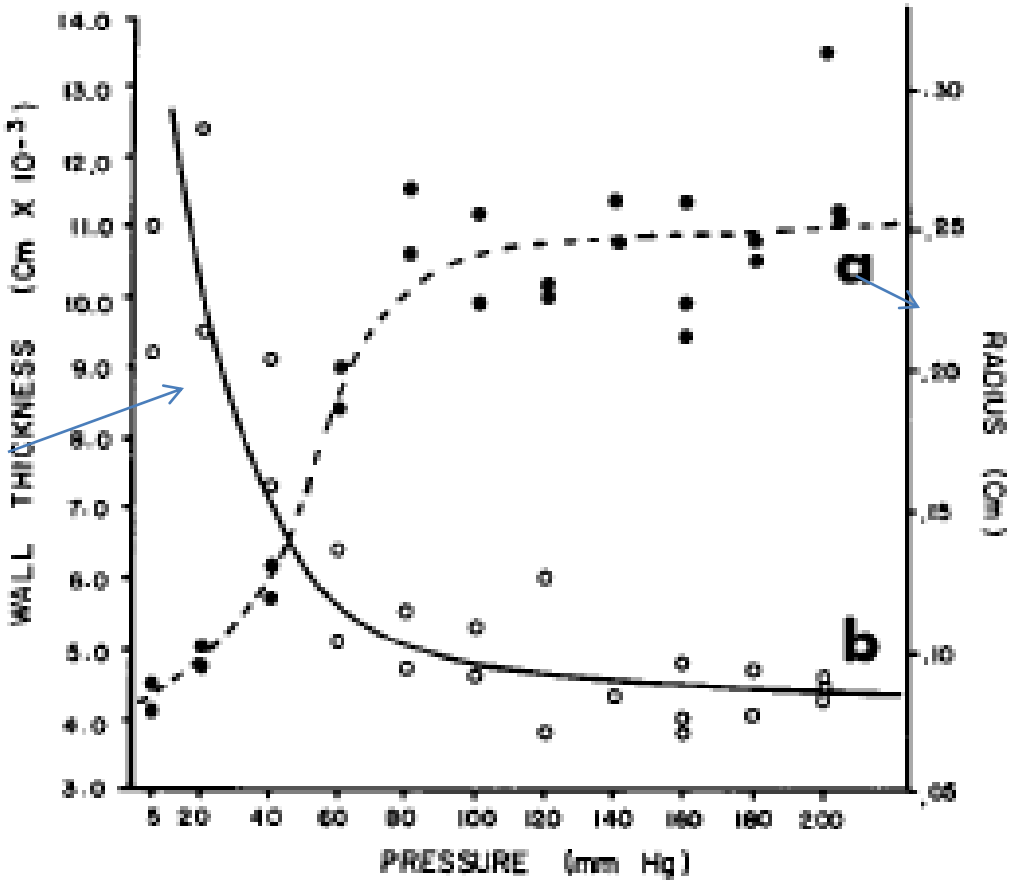
# What are the structural components?

| ARTERY/VEIN | % $H_2O$ | % COLLAGEN | % ELASTIN | C:E RATIO |
|---|---|---|---|---|
| Aorta | 70.4 ± 0.4 | 45.5 ± 1.7 | 30.1 ± 1.7 | 1.58 ± 0.15 |
| Carotid | 71.1 ± 0.1 | 50.7 ± 2.1 | 20.1 ± 1.0 | 2.55 ± 0.13 |
| Coronary | 63.2 ± 1.0 | 47.9 ± 2.6 | 15.6 ± 0.7 | 3.12 ± 0.12 |
| Femoral | 68.0 ± 0.3 | 44.5 ± 1.4 | 24.5 ± 1.6 | 1.89 ± 0.14 |
| Mesentary | 70.8 ± 0.5 | 38.1 ± 1.7 | 26.5 ± 1.7 | 1.51 ± 0.15 |
| Renal | 70.4 ± 0.7 | 42.6 ± 1.6 | 18.7 ± 1.8 | 2.46 ± 0.27 |
| Vena cava | | 35.07 ± 2.1 | 21.0 ± 3.7 | 1.67 ± 0.18 |
| Jugular vein | | 41.8 ± 2.8 | 47.1 ± 3.1 | 0.89 ± 0.09 |
| Femoral vein | | 47.0 ± 4.7 | 45.3 ± 2.6 | 1.04 ± 0.11 |

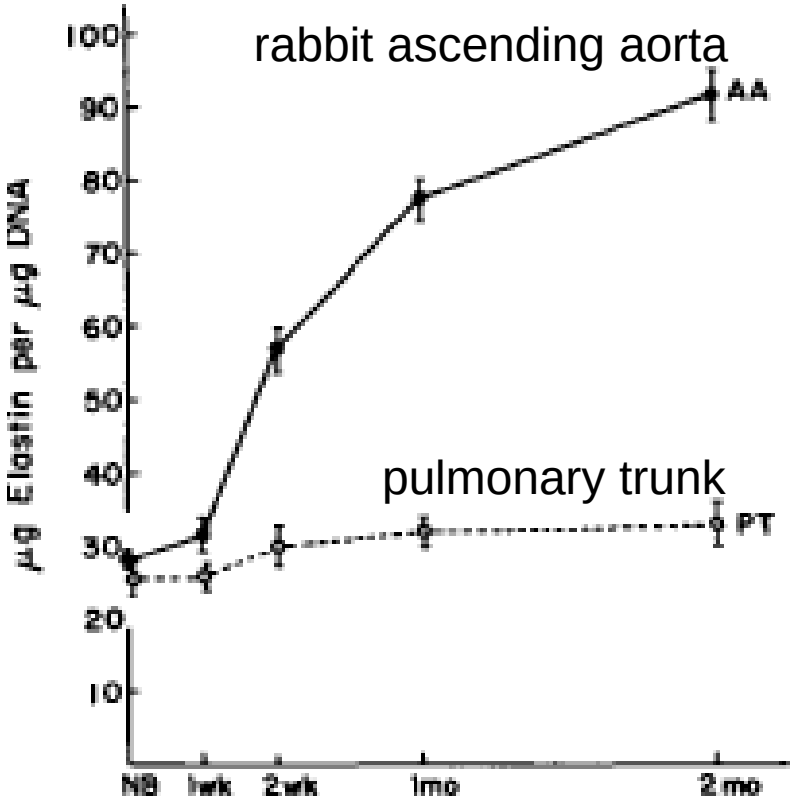
*(Fischer GM & Llaurado JG, 1966; Zocalo, ISRN Physiology, 2013)*

# Structure of aorta



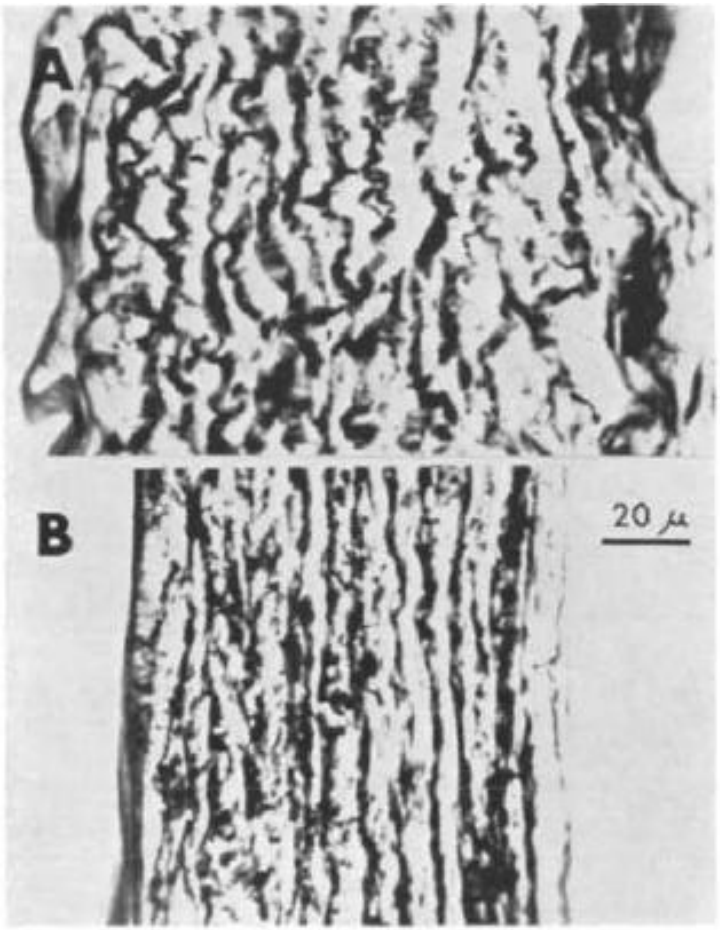

*(Wolinsky, Cir Res, 1964)*



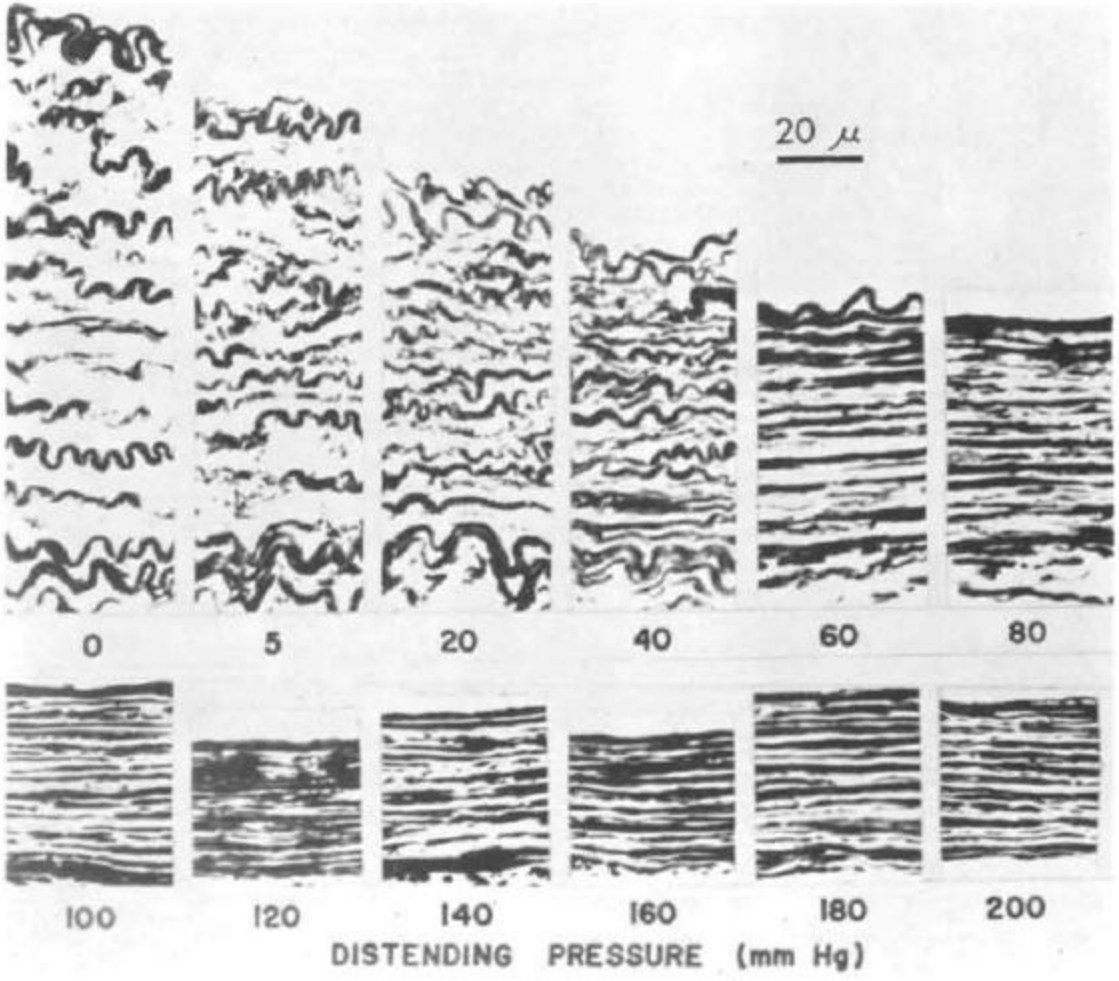

$T_{AA} = T_{PT}$ **Medial tension** $T_{AA} = 6T_{PT}$

*(Leung, Circ Res, 1977)*

# Vessel wall composition – aortic elastin



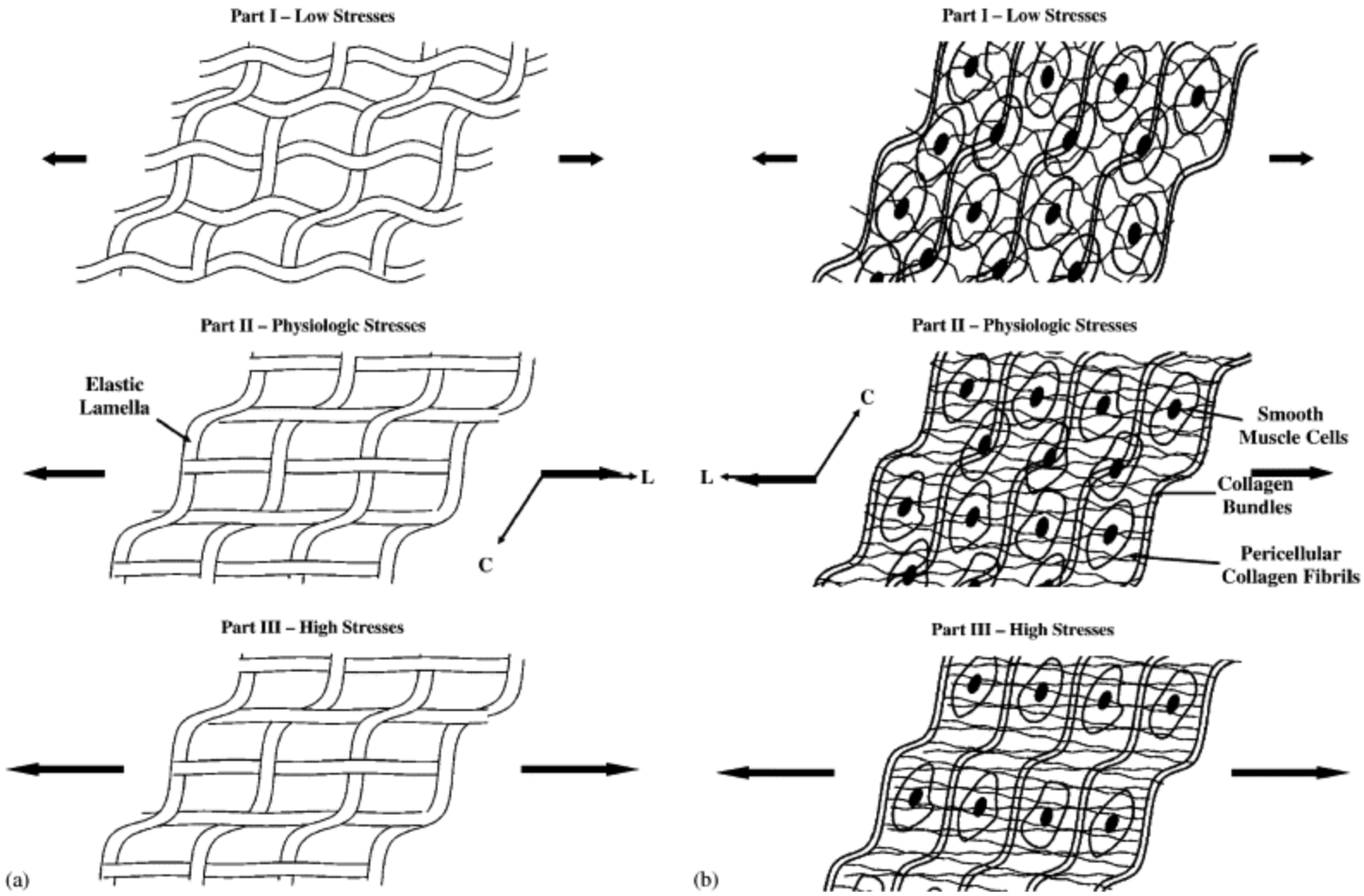

Longitudinal section




Cross-sectional section

*(Wolinsky, Cir Res, 1964)*

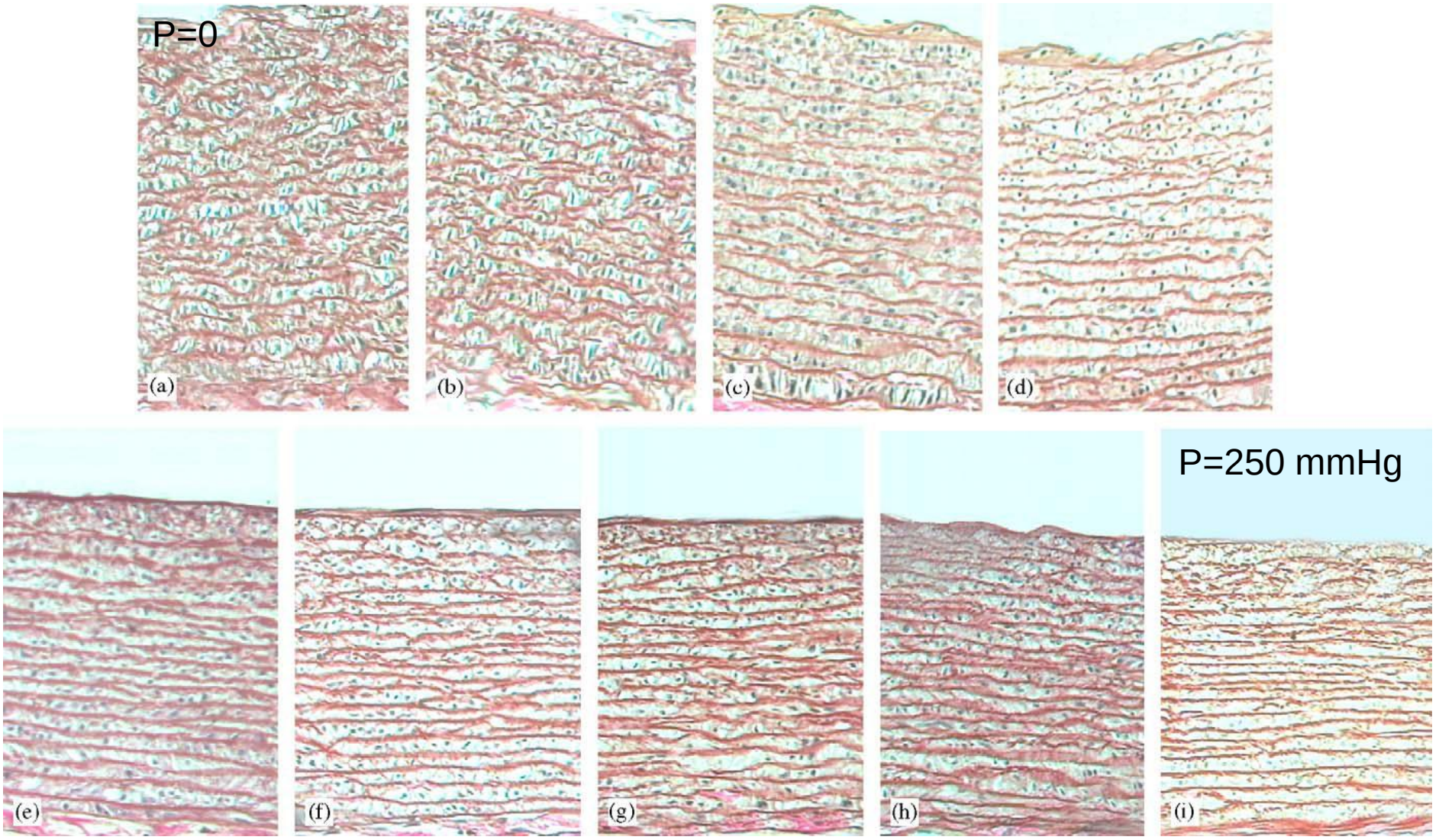
# Vessel wall composition – aortic elastin




*(Sokolis, J Biomechanics, 2006)*

# Aortic wall composition – elastin

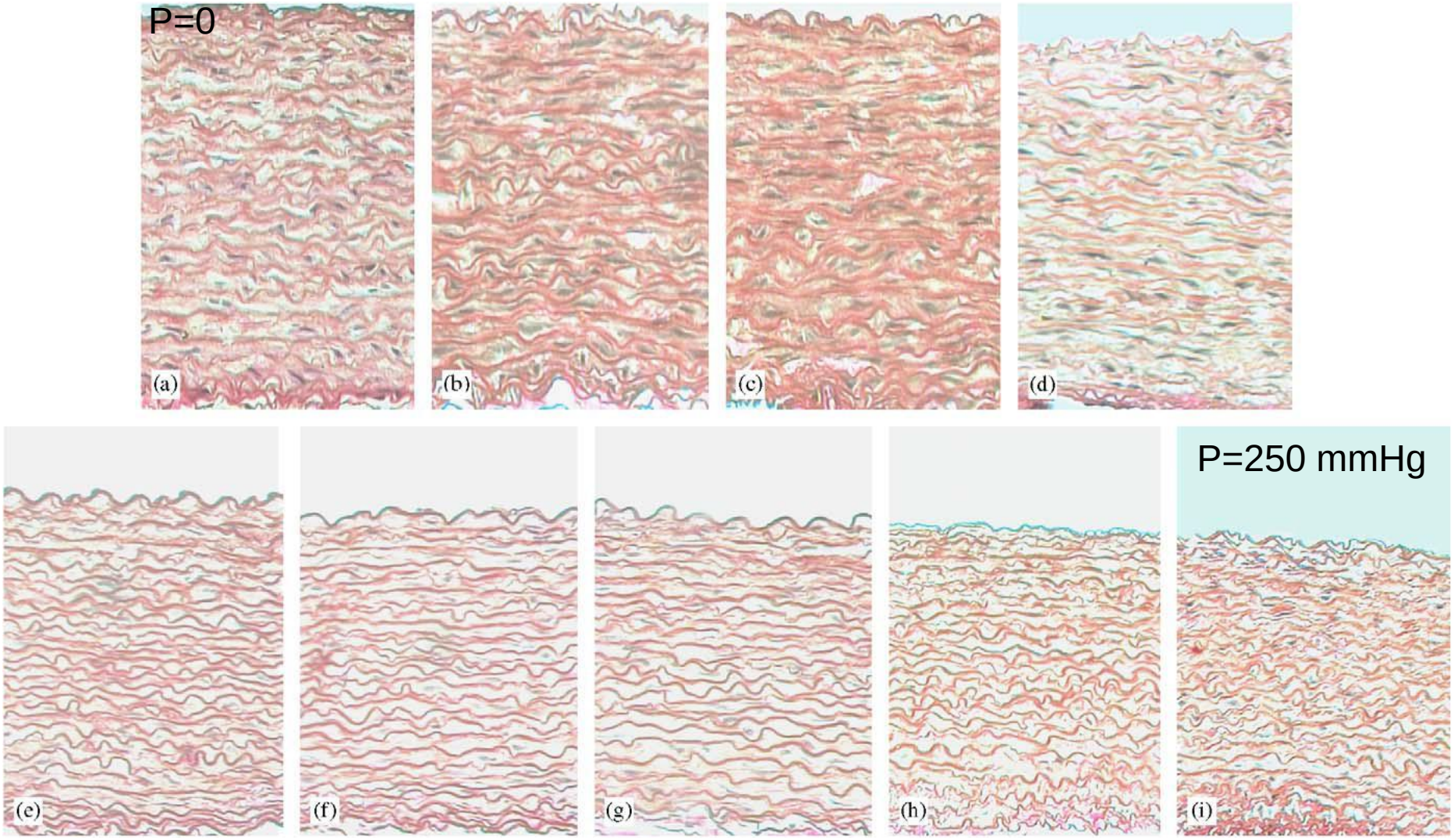
Longitudinal section




*(Sokolis, J Biomechanics, 2006)*

# Aortic wall composition – elastin

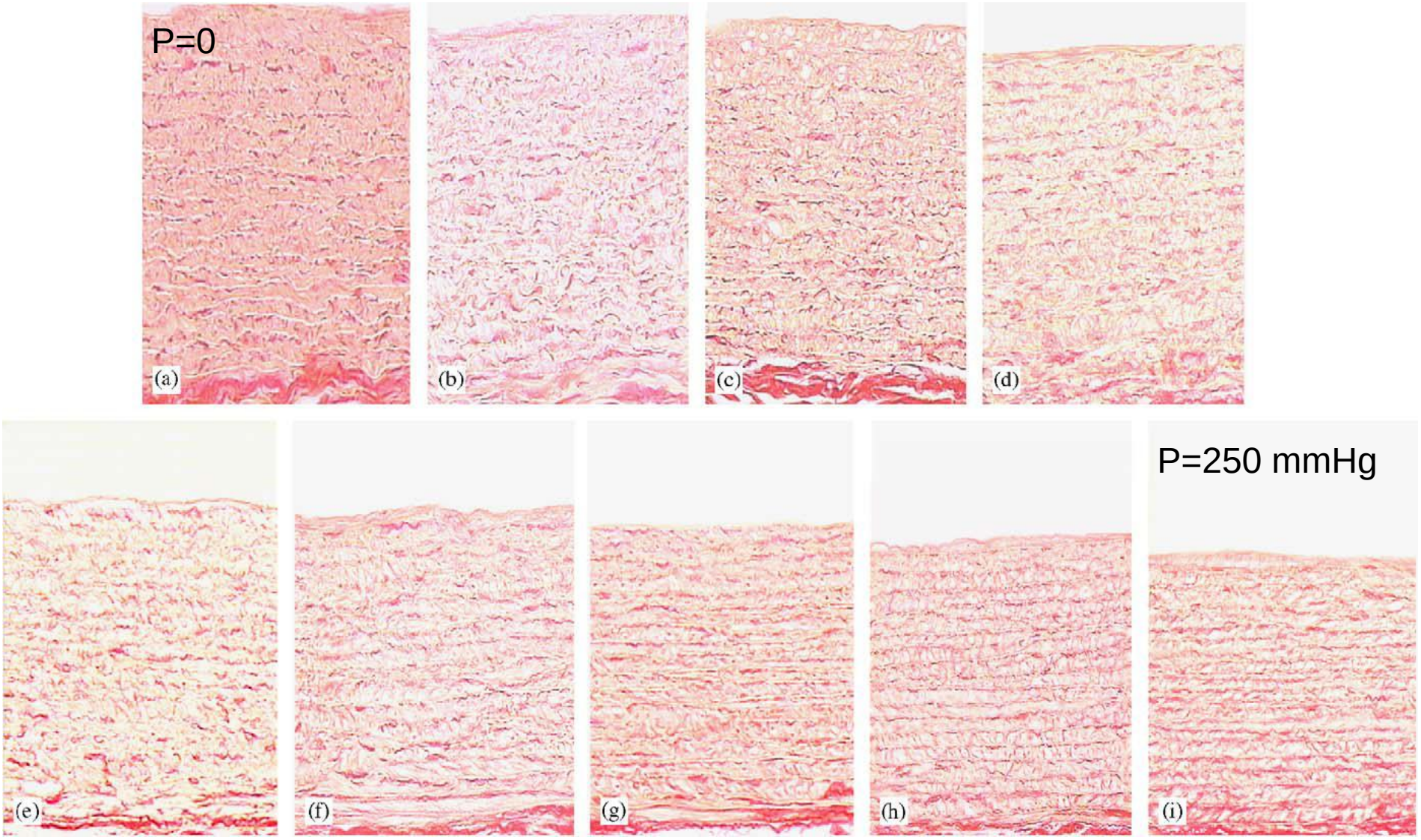
circumferential section




*(Sokolis, J Biomechanics, 2006)*

# Aortic wall composition – collagen

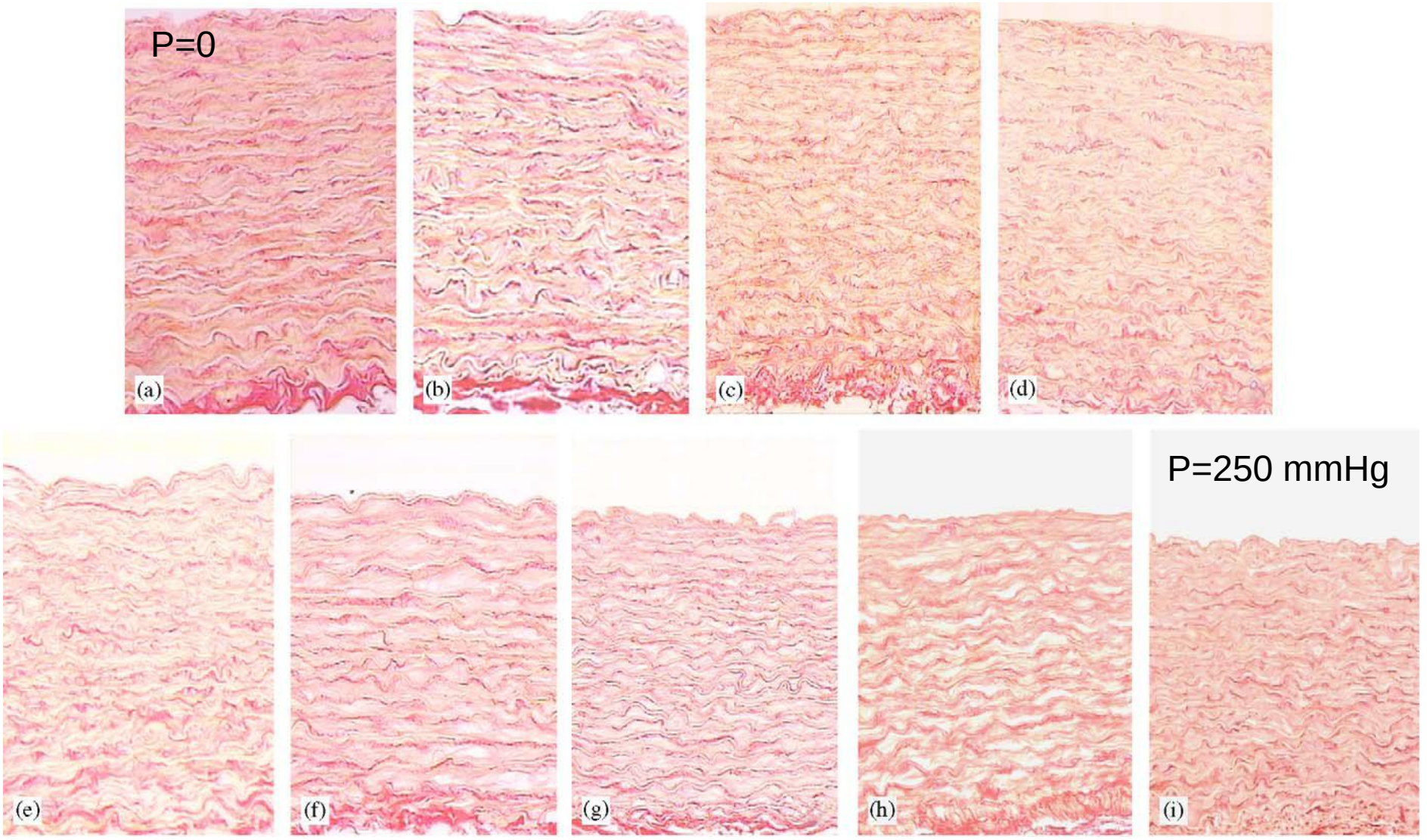
Longitudinal section




*(Sokolis, J Biomechanics, 2006)*

# Aortic wall composition –collagen

circumferential section



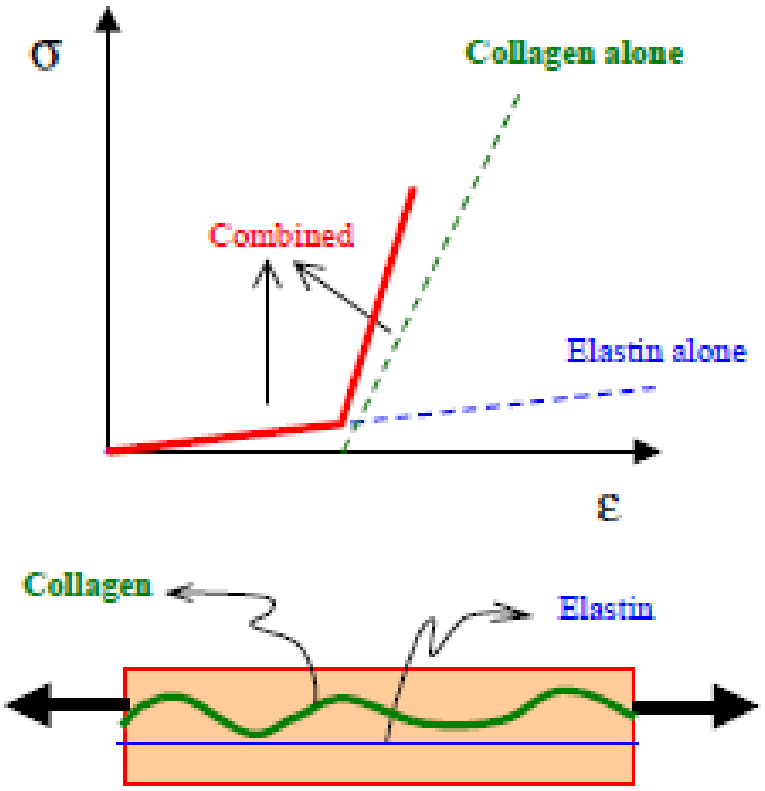

*(Sokolis, J Biomechanics, 2006)*

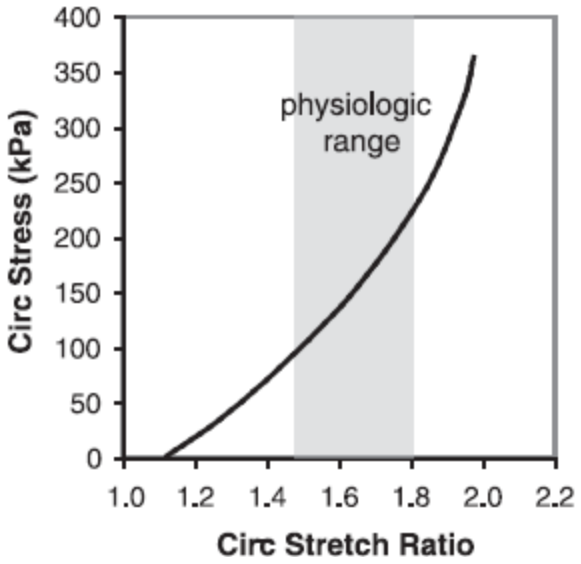
# Vessel wall – Non-linear elasticity

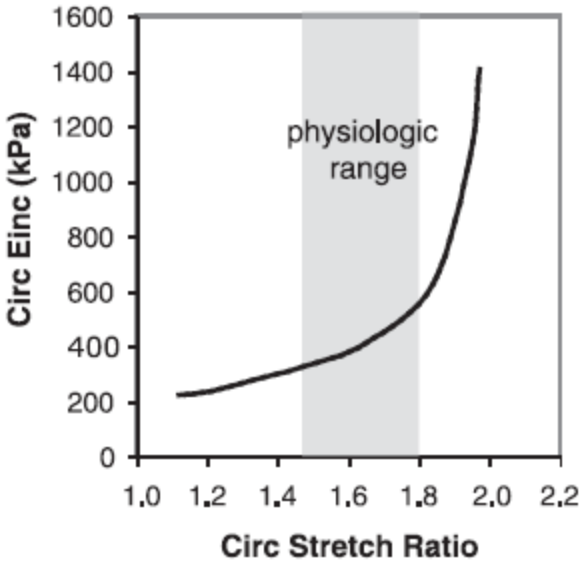
Heterogeneity: Two-phase materials

Collagen: $E = 10^9$ dynes/cm$^2$
Elastin: $E = 3 \times 10^6$ dynes/cm$^2$

$$\sigma = E\varepsilon$$



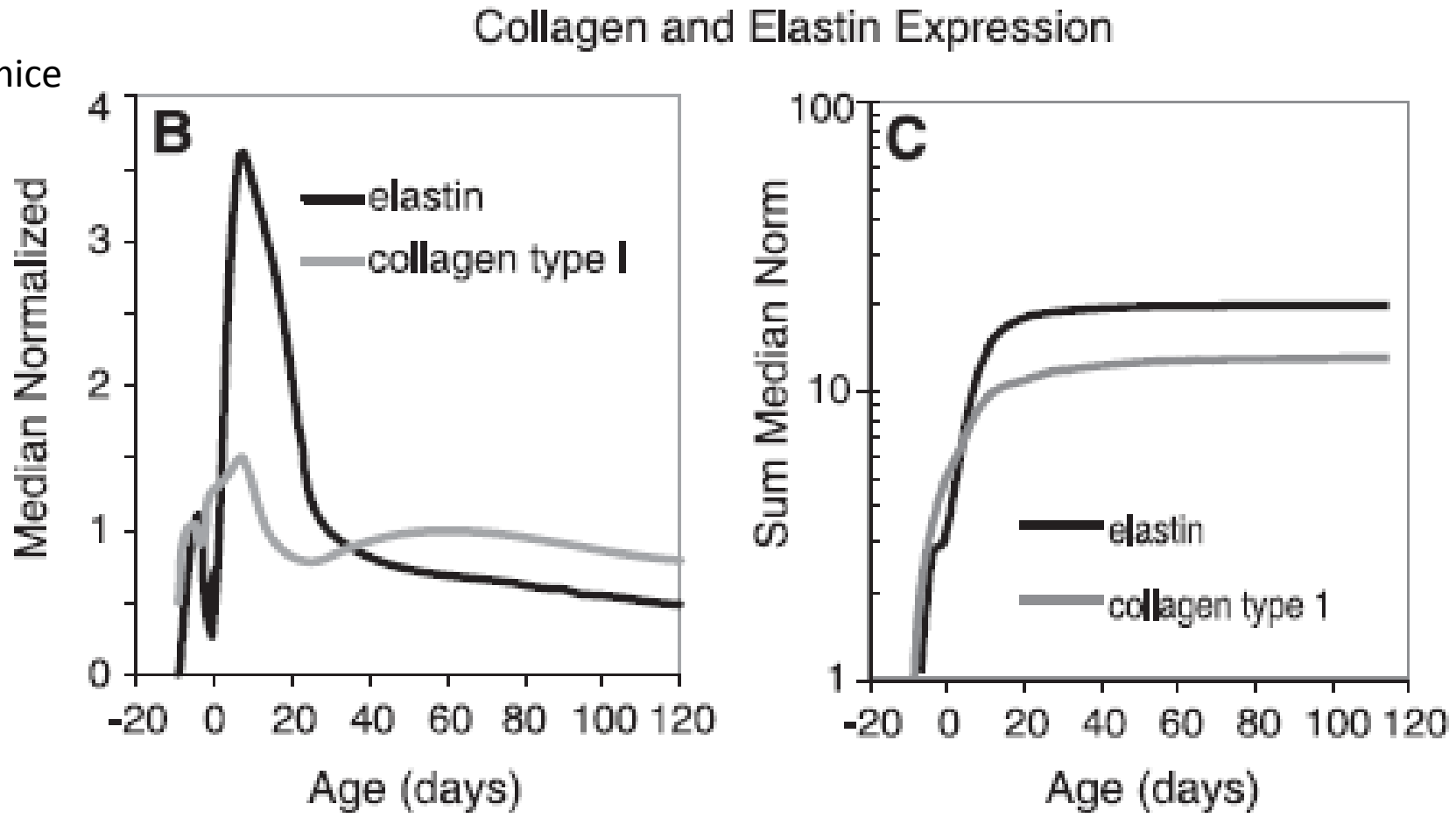




*(Wagenseil, Mecham, 2005)*

# Vessel wall composition - Aging

mice

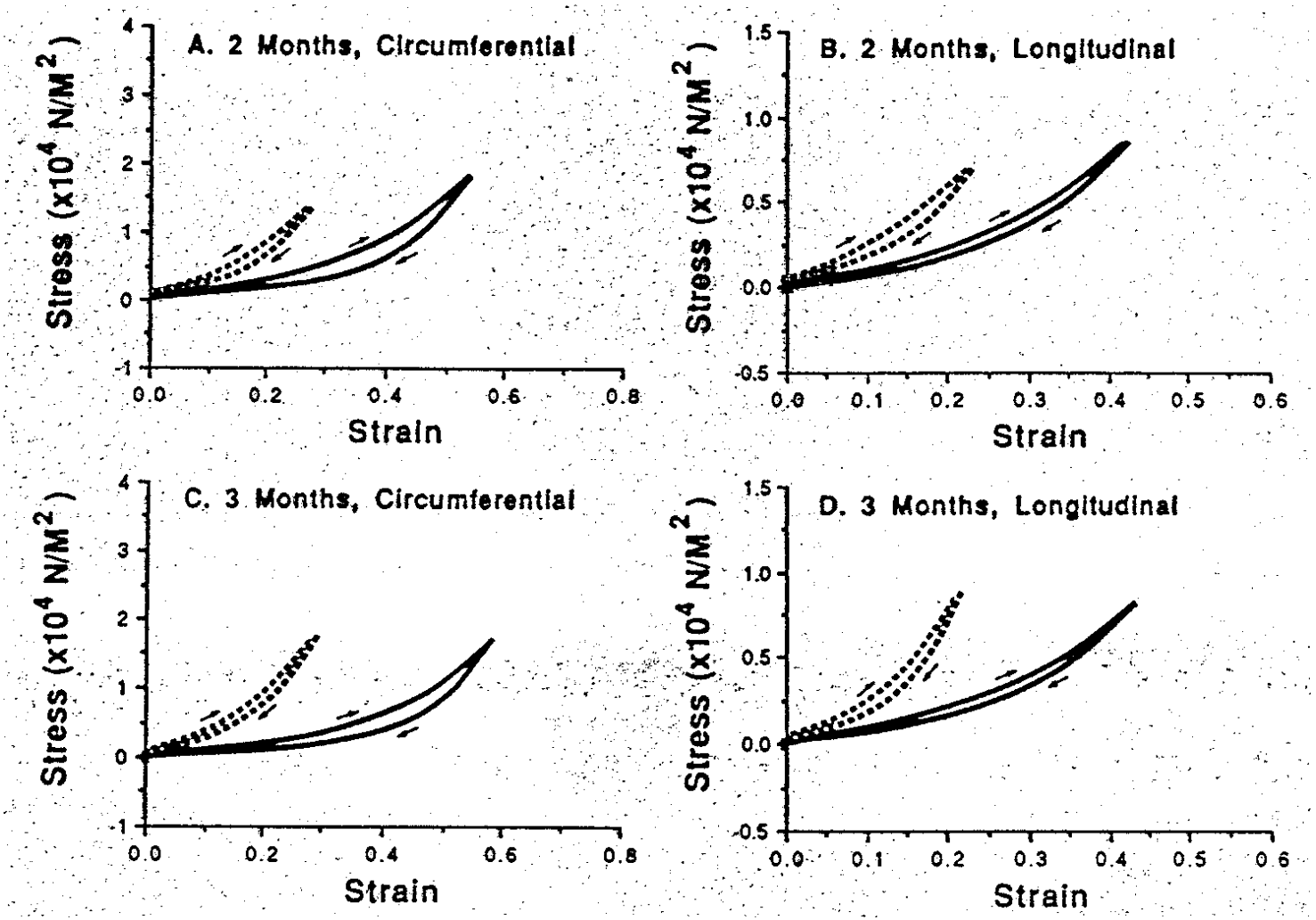



Diminished windkessel effect, hardening of the artery (fragmentation and loss of elastin)

*(Wagenseil and Mecham, Physiol Rev 2009)*

# Vessel wall function - disease

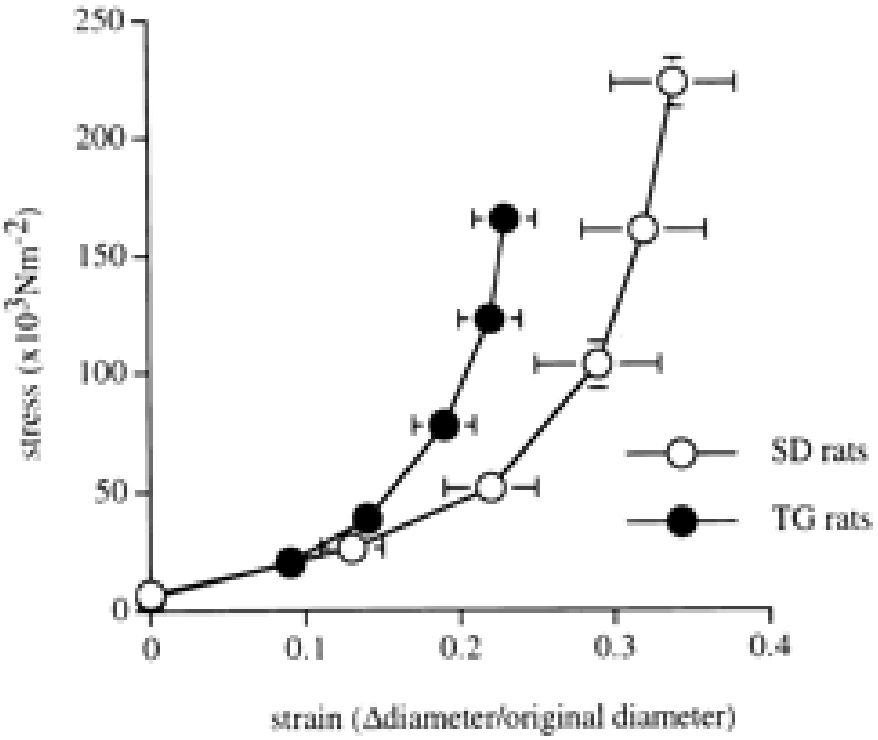
pulmonary arteries – rat smoking.



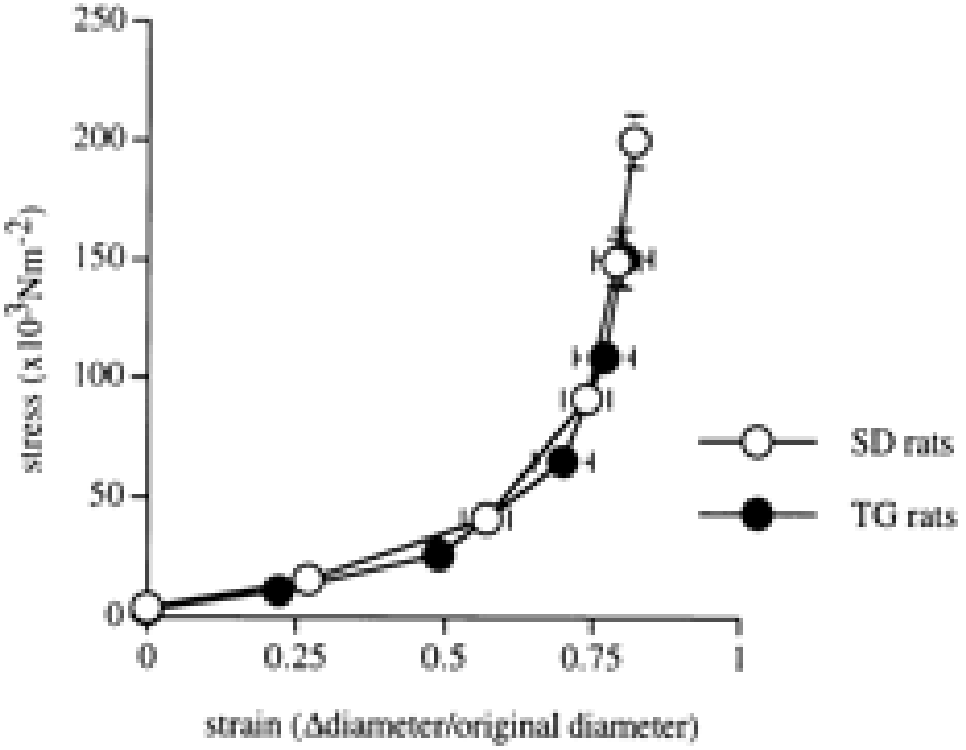

*(Liu and Fung, J Biomechanics, 1992)*

# Vessel wall function - hypertension

**Rat cerebral artery**

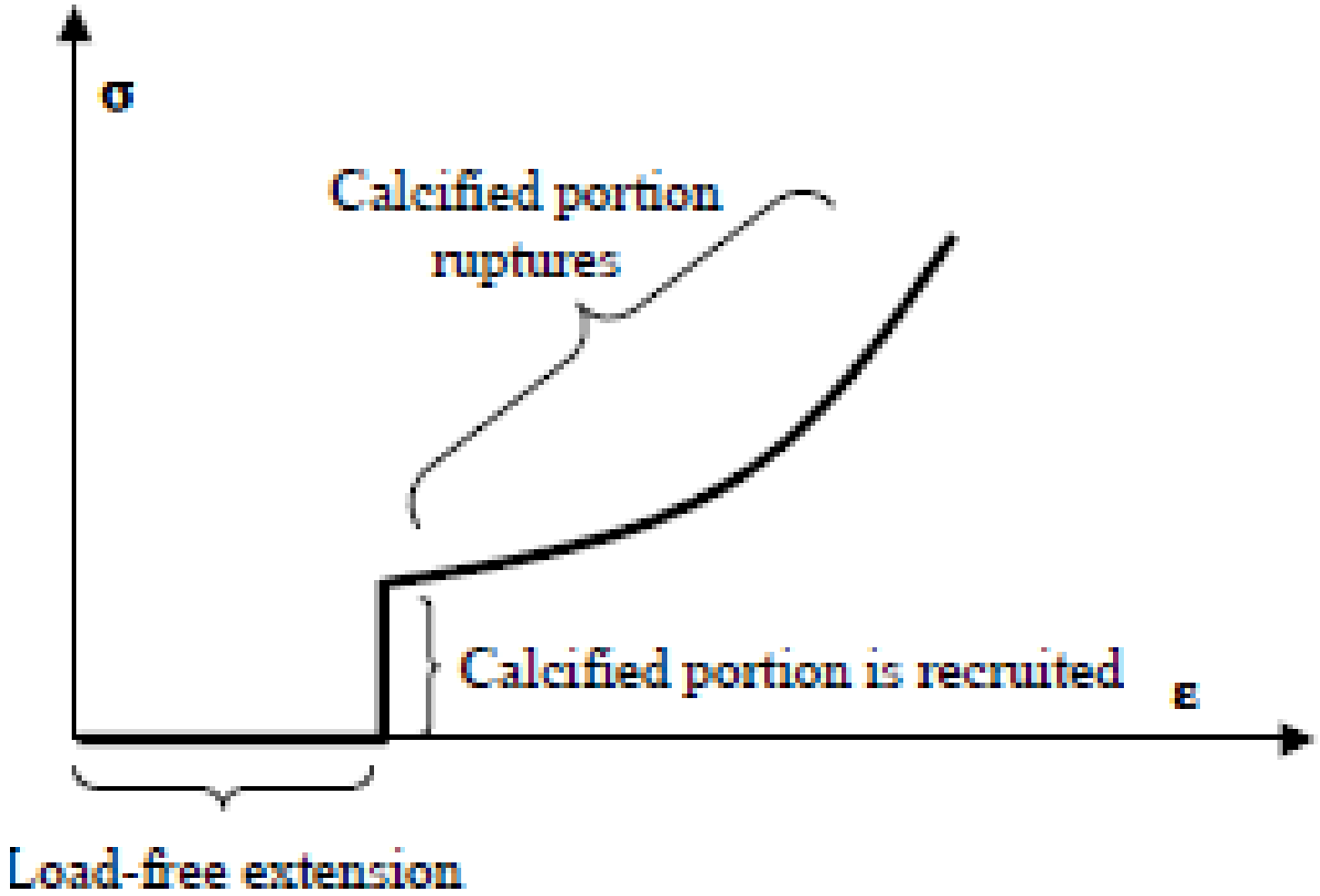



**3-order resistive vessel**




*(Dunn, Hypertension, 1997)*

# Vessel wall function - disease



# What causes the change of vessel structure and function?

Learn from the development:
In 1893, Thomas :

Vessel lumen size depends on blood flow

Vessel length depends on longitudinal force on connective tissues

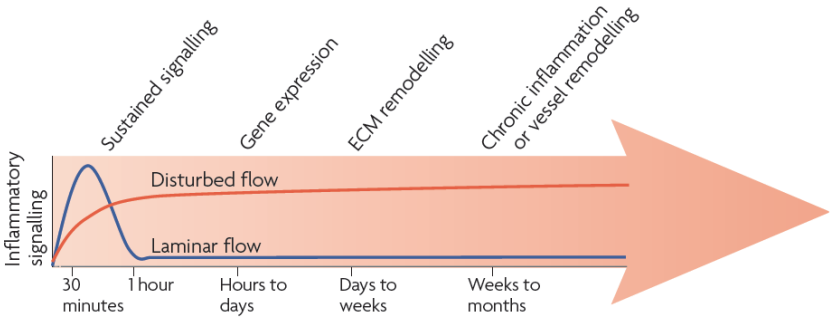
Vessel wall thickness depend on pressure

# Changes by the cells

ECs:

short term -> secrete vasoconstrictor or vasodilator to constrict or relax the smooth muscle cells

long term -> generate basement membrane



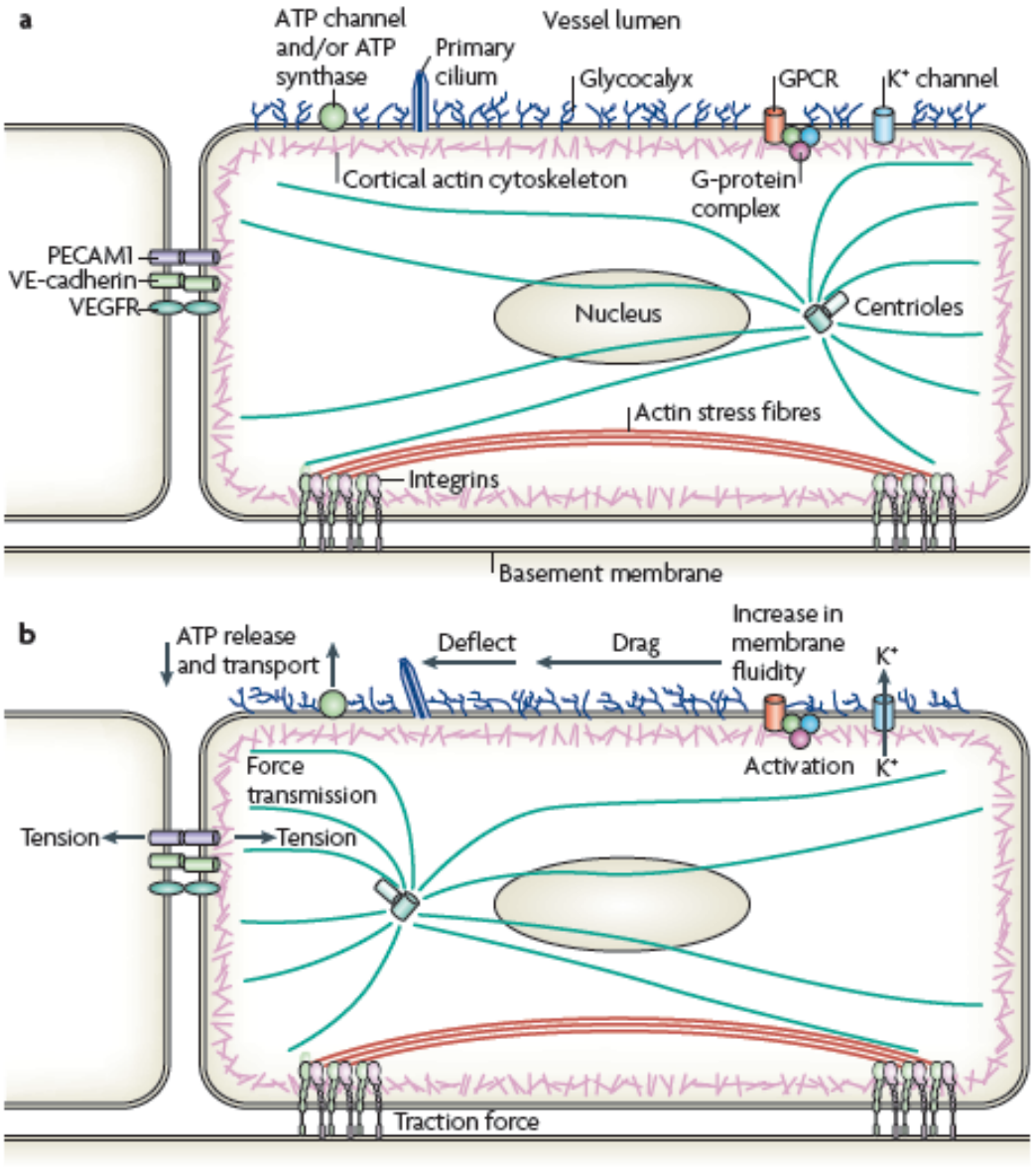

SMCs:

short term -> change diameter of artery wall in response to flow change.

long term -> change of elastin/collagen content (aneurysm), SMC replication

Collagen: I, III, V -> fibril-forming, responsible for vessel strength

# Mechanotransduction of ECs




Ion channels, integrins, receptor Tyr kinases, apical glycocalyx, primary cilia, heterotrimeric G proteins, PECAM1, VE cadherin

*(Hahn and Schwartz, Nat Rev Mol Cell Biology, 2009)*

# Mechanotransduction of SMCs

## What do they sense:

Transmural pressure (120/80mmHg in arteries, 30-40mmHg in capillaries)

Vascular wall strain by pulsative pressure (coronary artery, carotid artery)

Circumferential, axial wall tension; radial compression

Passive or active mechanics, myogenic tone

Shear stress from luminal flow

Results: thicken, stiffen, lengthen the vessel wall.

SMC replication

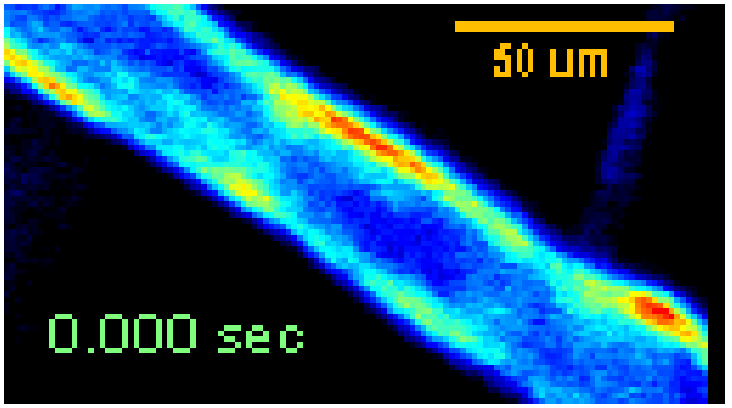
Elastin/collagen secretion

Vessel tortuosity

# Mechanotransduction of SMCs

How do they sense:

GCaMP2 Transgenic Mice, Ach stimulation




*(Tallini, Circ Res, 2007)*

Increased transmural pressure

↓

VSM membrane depolarization

↓

Activating calcium entry → Hyperpolarization,

↓ ↑

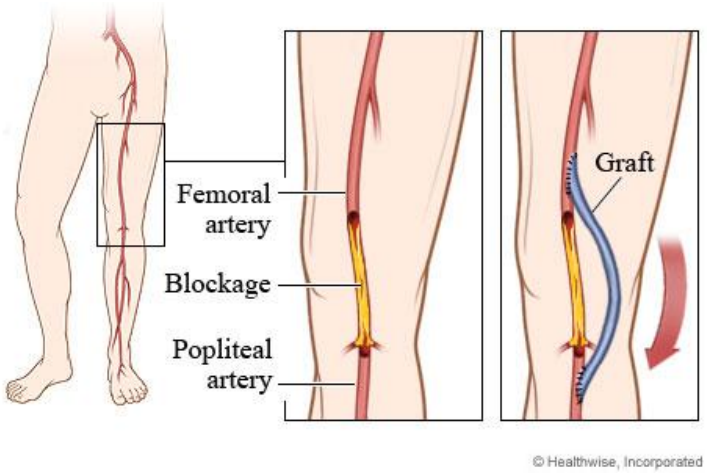
Vessel constriction → Activation of $K_{ca}$ channels

# Application and Vascular Engineering

Acute hypertension

Atherosclerosis – SMC proliferation, matrix calcification

Coronary bypass vein grafts – when veins becomes artery – VSM induced fibrosis (collagen deposition)




Engineered vessel grafts always lack of elastin