719.001 - Mechanics of biological tissues (2 SSt VO, WS 2021-2022)

Lecturers:

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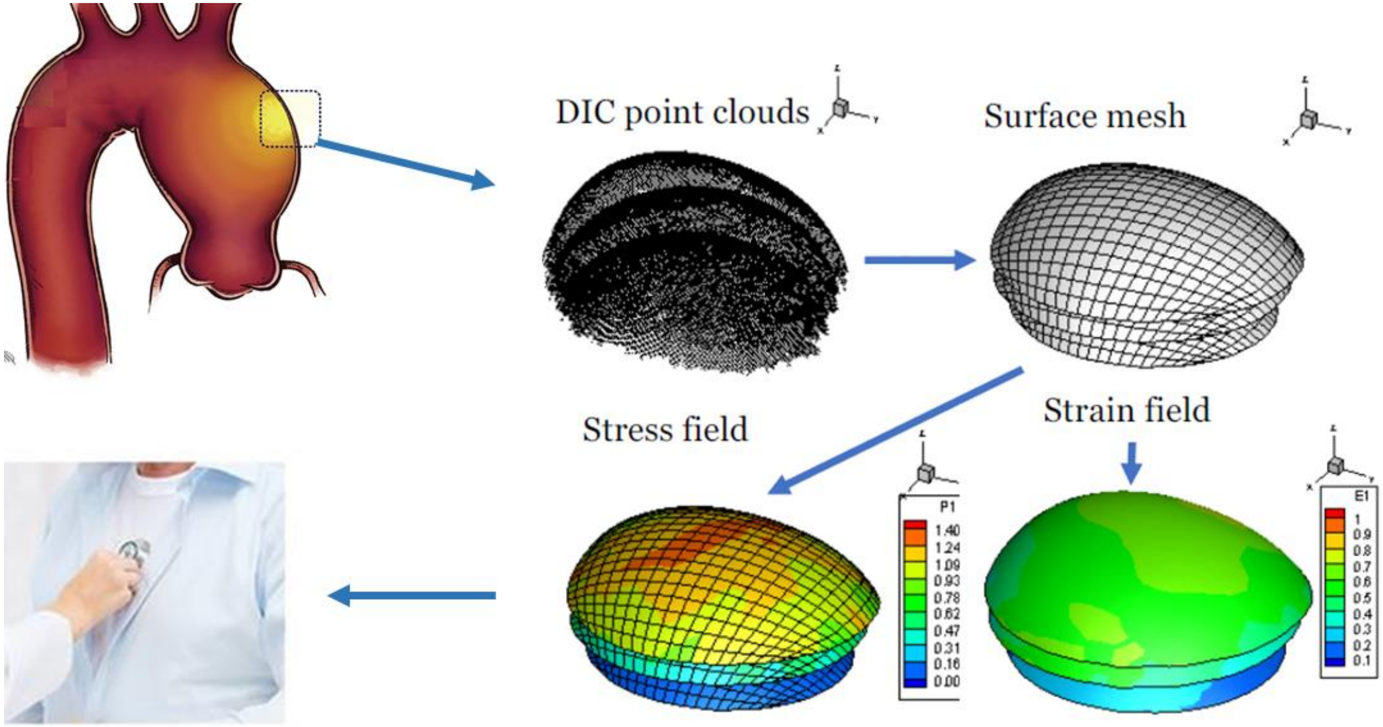
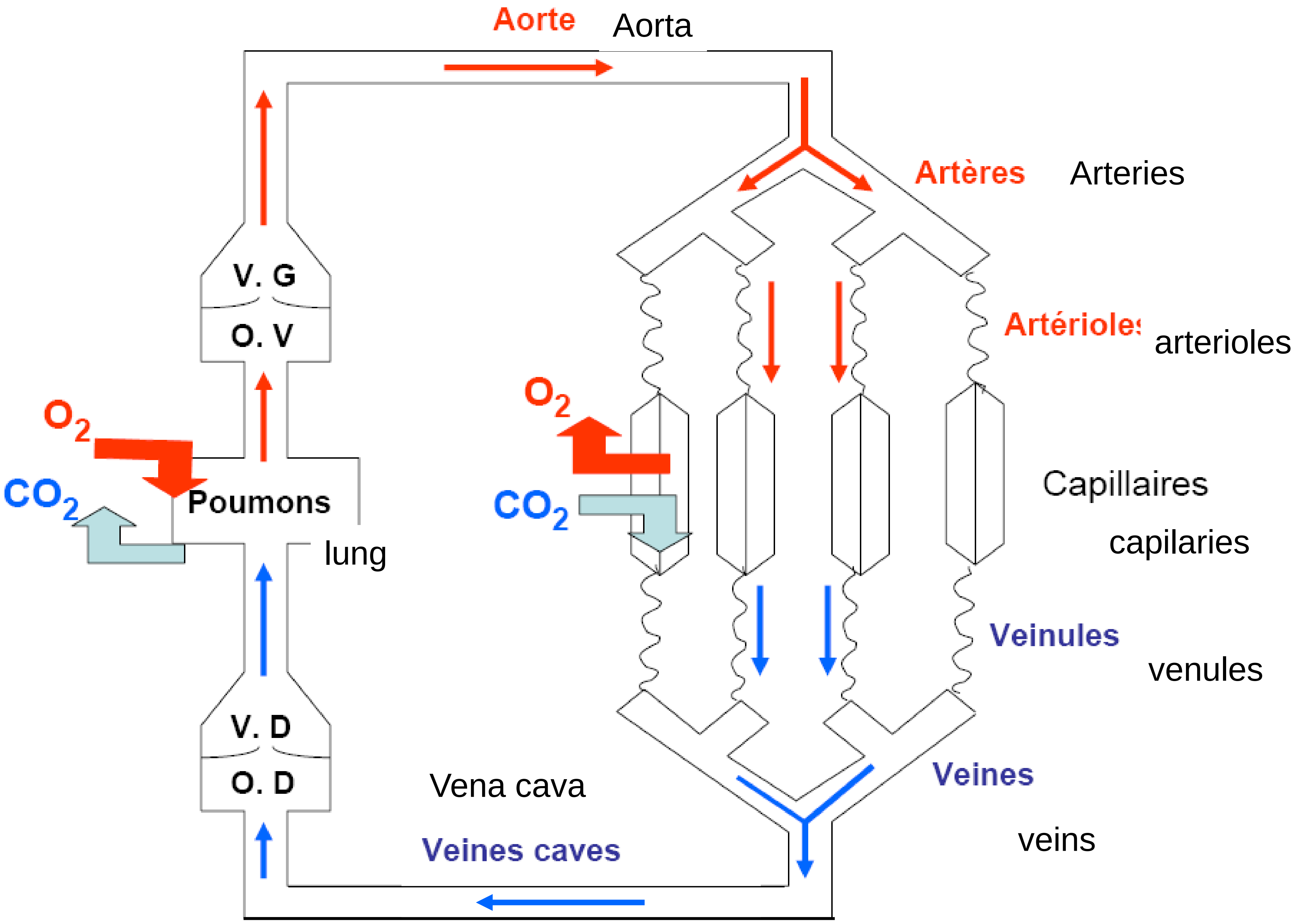


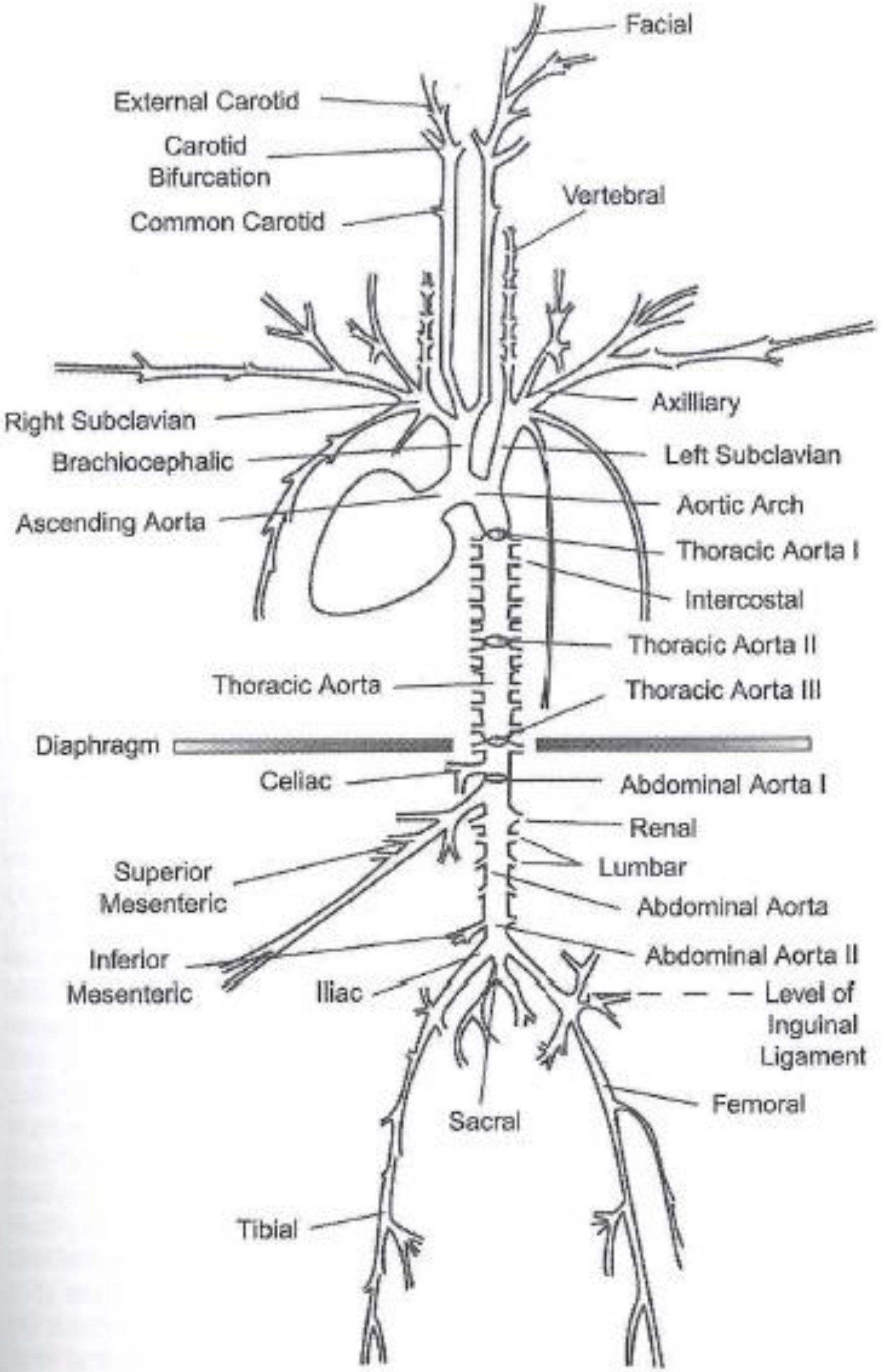
Contents:

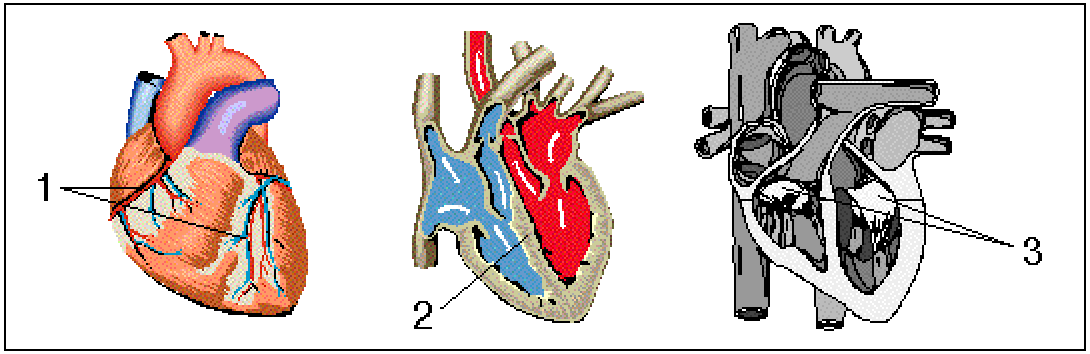
- Tissue biology basics. Link between microstructure and macroscale properties, and experimental characterization techniques. Structure, function and mechanical behaviour of tissues and organs (bone, cartilage, ligament, tendon, intervertebral disc, skin, nerve, skeletal muscle, heart, lung, artery, vein). Composition, function and mechanics of biological fluids.
- Cardiovascular biomechanics. Cardiovascular system. Biodynamic biological fluids. Biomechanics of the blood circulation. Ability to model specific problems such as the pulse wave in arteries, the effect of compression on the veins for the venous blood return
- Modeling approaches for continuum biomechanics of soft tissues: reminders of the basics in finite deformation mechanics and hyperelasticity, poroelasticity, chemoelasticty, other constitutive equations, relationships between the constitutive equations and the microstructure of tissues.
- Characterization of damage and failure mechanics of soft tissues, local analysis of rupture modes in soft tissues, experimental characterization and numerical implementation
- Advanced experimental approaches for soft tissue mechanics: full-field measurement techniques, imaging techniques, link between experiments and modeling
- Introduction to inverse problems, Identification of material parameters from full-field measurements, Characterization of maps of material parameters at different scales

Blood circulation

Arteries and veins


Aorte
Aorta
Artères
Arteries
Artérioles
arterioles
V. G
O. V
O_2
CO_2
Poumons
lung
O_2
CO_2
Capillaires
capilaries
Veinules
venules
Veines
veins
V. D
O. D
Vena cava
Veines caves


Facial
External Carotid
Carotid Bifurcation
Vertebral
Common Carotid
Axilliary
Right Subclavian
Left Subclavian
Brachiocephalic
Aortic Arch
Ascending Aorta
Thoracic Aorta I
Intercostal
Thoracic Aorta II
Thoracic Aorta
Thoracic Aorta III
Diaphragm
Celiac
Abdominal Aorta I
Renal
Lumbar
Superior Mesenteric
Abdominal Aorta
Inferior Mesenteric
Abdominal Aorta II
Iliac
Level of Inguinal Ligament
Femoral
Sacral
Tibial

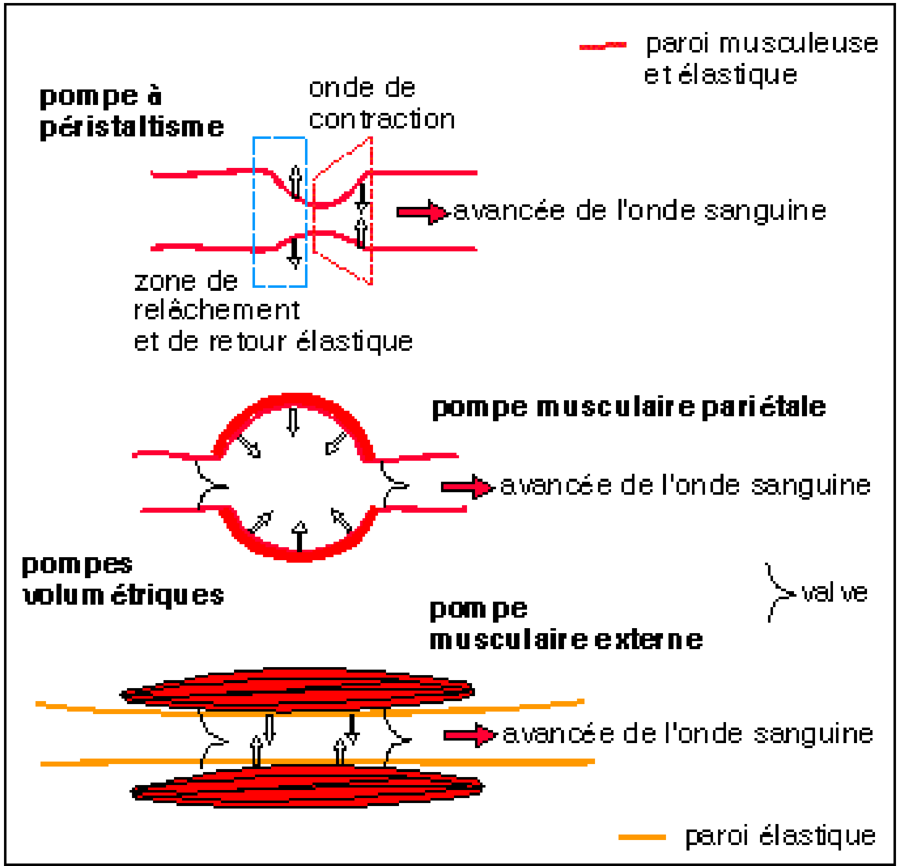


Pomping = 2 states:

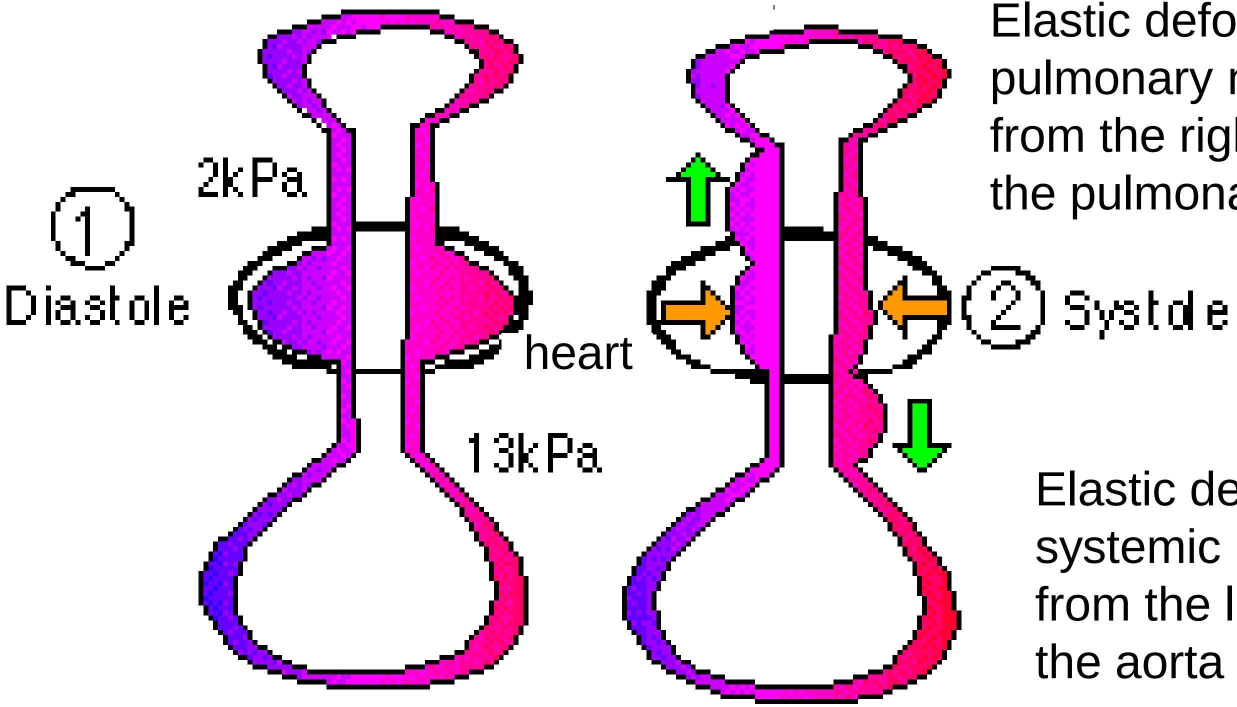
-Relaxed state (**diastole**), in which the heart is filled due to venous return,

-Contracted state (**systole**) or systolic ejection in which a certain volume of blood is projected into the aorta.

The cardiac pump is not the only pump in the circulary system.



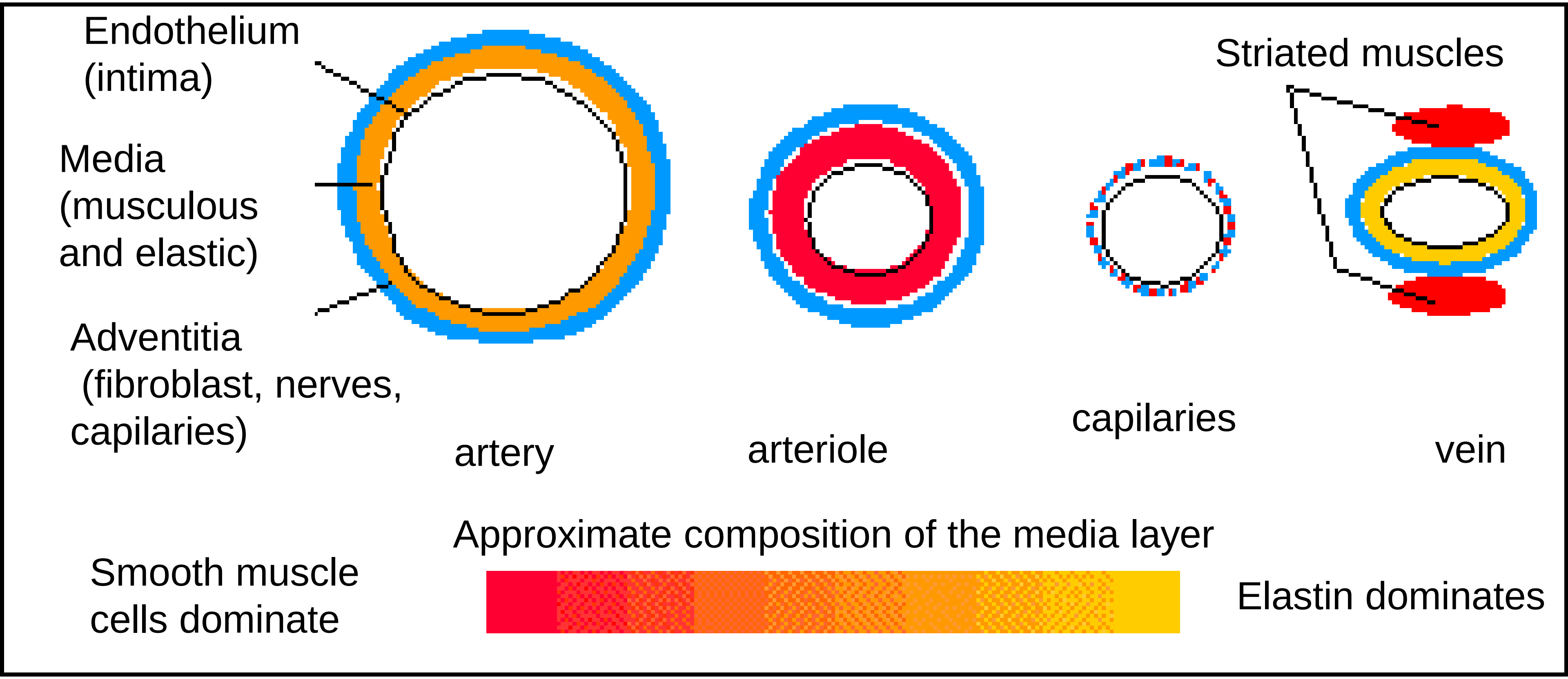
Pulmonary circulation

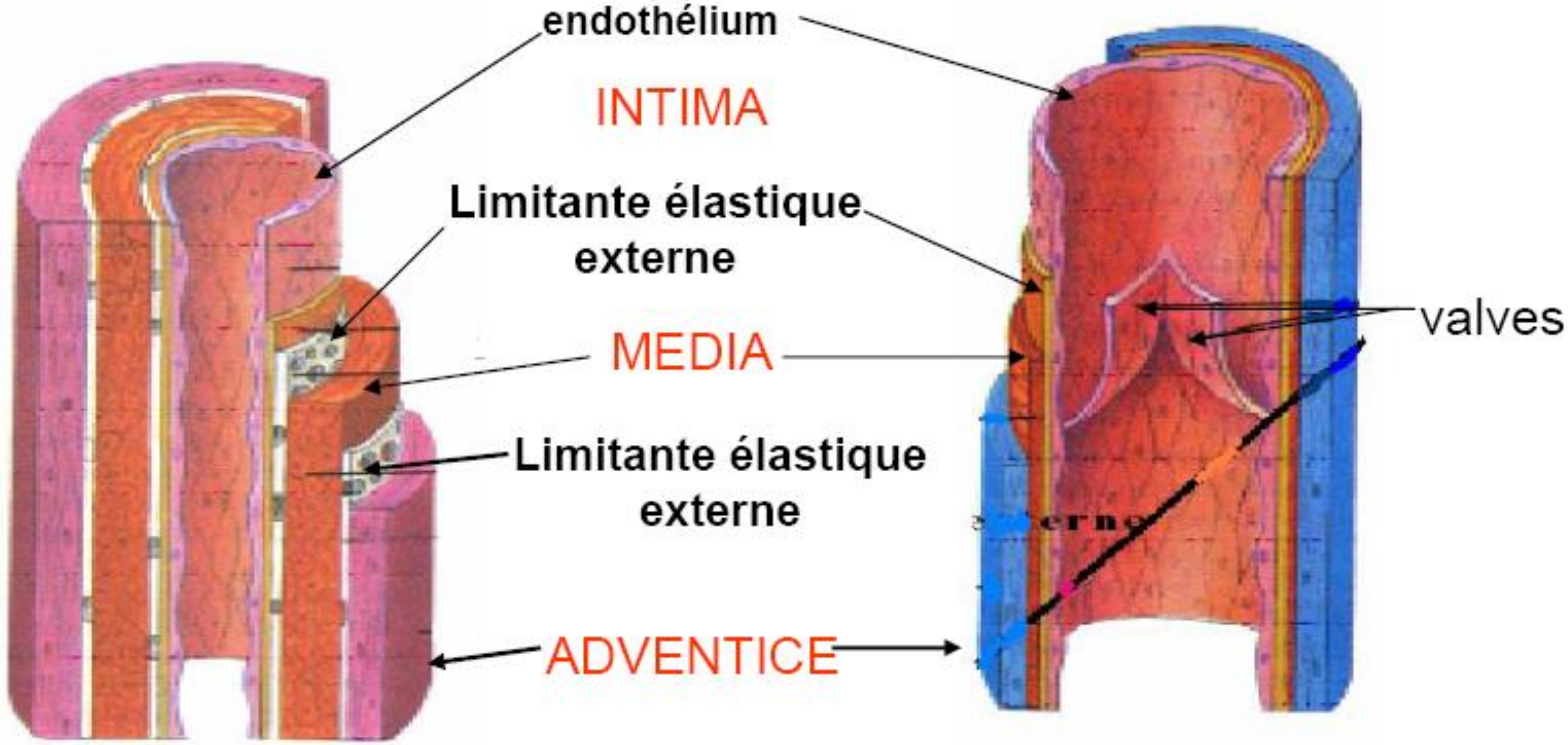


Elastic deformation of the pulmonary network: ejection from the right ventricle into the pulmonary artery

Elastic deformation of the systemic network: ejection from the left ventricle into the aorta

Systemic circulation


Endothelium (intima)
Media (musculous and elastic)
Adventitia (fibroblast, nerves, capilaries)
artery
arteriole
capilaries
vein
Striated muscles
Approximate composition of the media layer
Smooth muscle cells dominate
Elastin dominates



endothélium

INTIMA

Limitante élastique
externe

MEDIA

Limitante élastique
externe

ADVENTICE

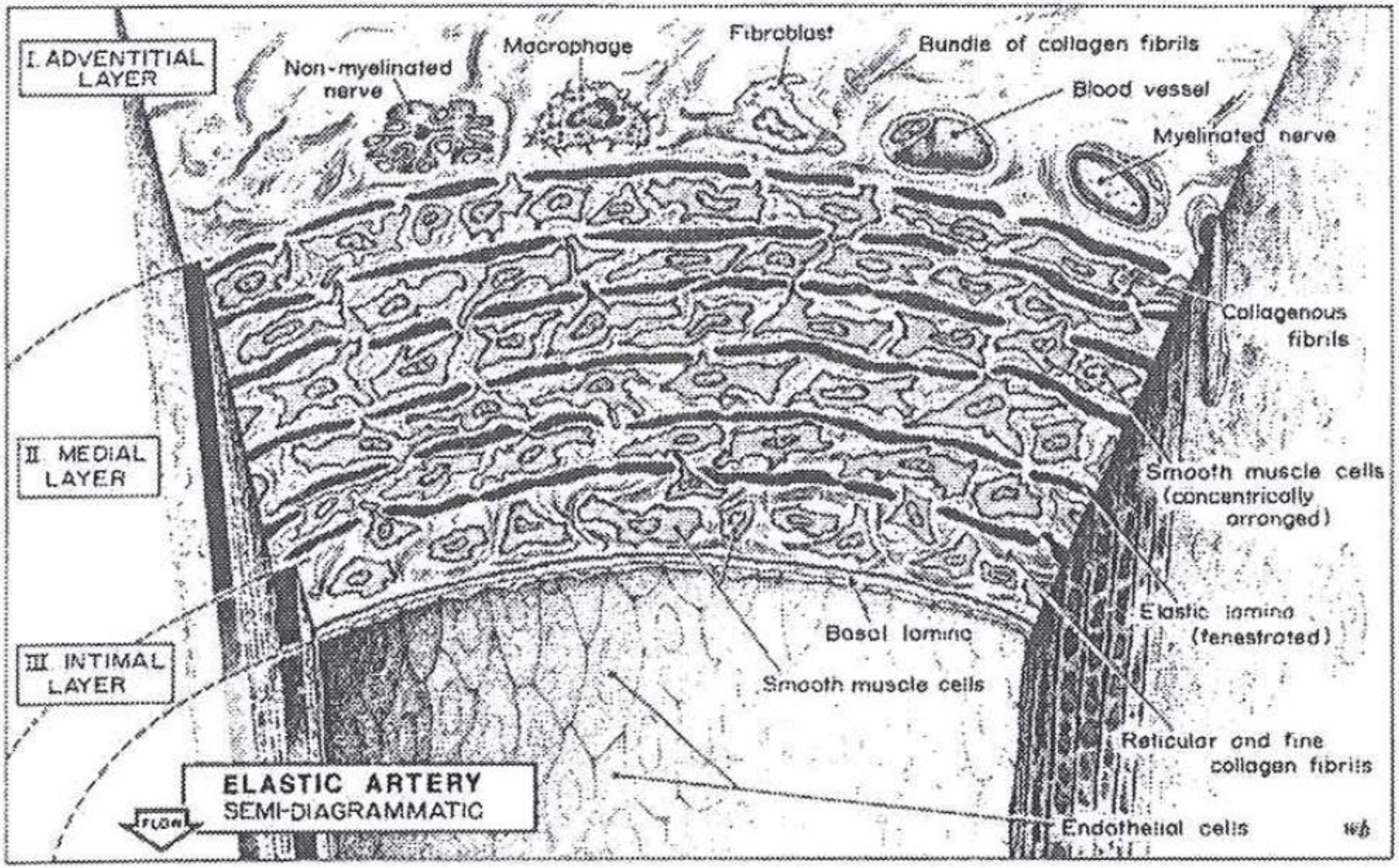
valves

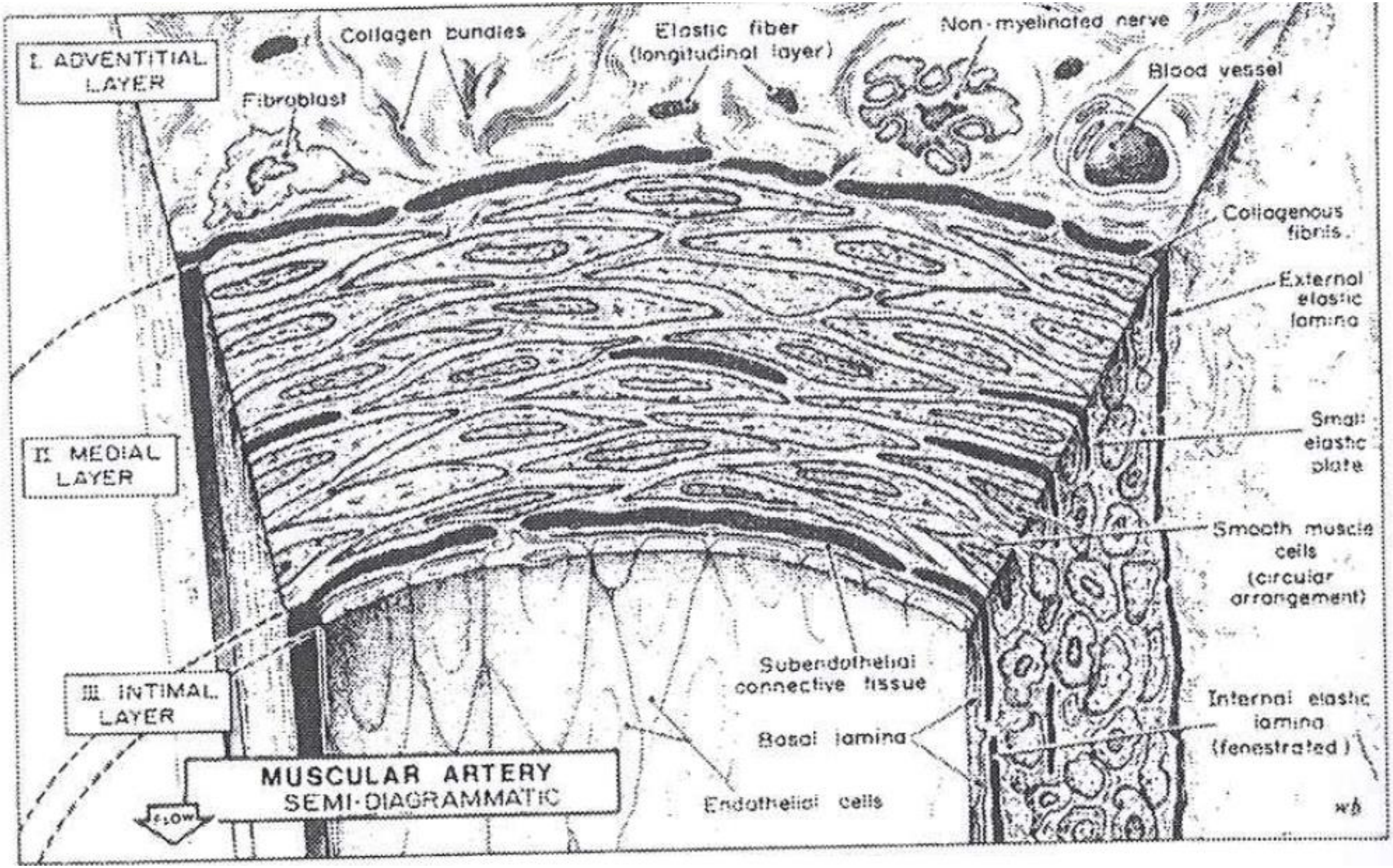
ARTERE

artery

VEINE

vein

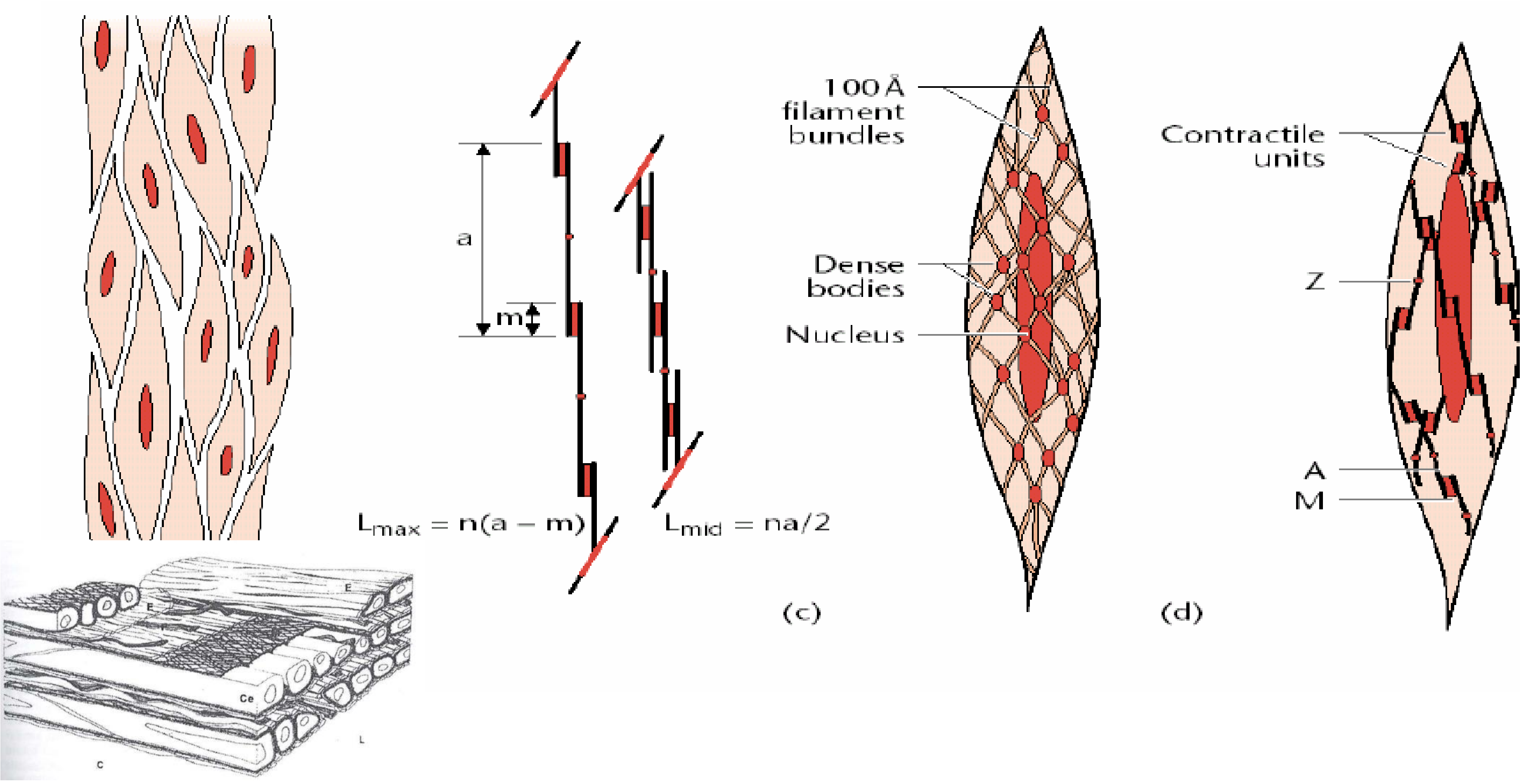

I. ADVENTITIAL LAYER
Non-myelinated nerve
Macrophage
Fibroblast
Bundle of collagen fibrils
Blood vessel
Myelinated nerve
Collagenous fibrils
II. MEDIAL LAYER
Smooth muscle cells (concentrically arranged)
Elastic lamina (fenestrated)
Basal lamina
Smooth muscle cells
III. INTIMAL LAYER
Reticular and fine collagen fibrils
ELASTIC ARTERY
SEMI-DIAGRAMMATIC
FLOW
Endothelial cells
wb


I. ADVENTITIAL LAYER
Collagen bundles
Elastic fiber (longitudinal layer)
Non-myelinated nerve
Blood vessel
Fibroblast
Collagenous fibrils.
External elastic lamina
Small elastic plate
II. MEDIAL LAYER
Smooth muscle cells (circular arrangement)
III. INTIMAL LAYER
Subendothelial connective tissue
Internal elastic lamina (fenestrated)
Basal lamina
MUSCULAR ARTERY
SEMI-DIAGRAMMATIC
FLOW
Endothelial cells
wb

SMOOTH MUSCLE CELLS

fascicle

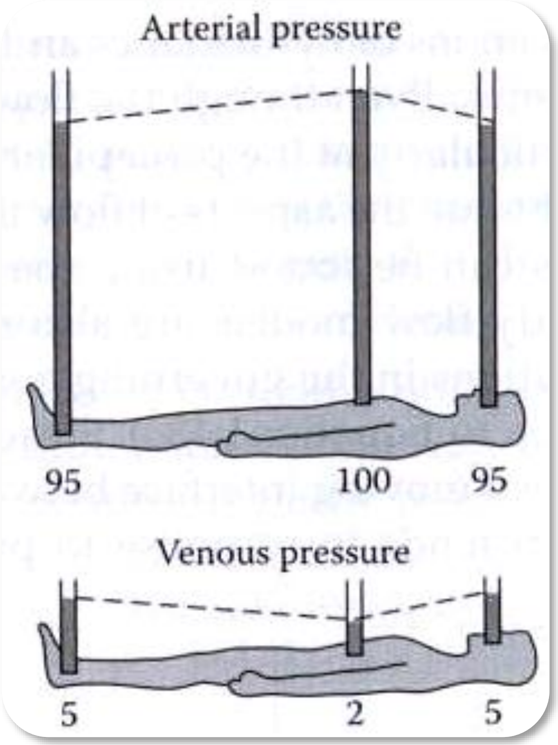
Single cell



Hydrostatics in the Circulation

- Blood pressure in the "lying down" position
  - Arterial: 100 mmHg
  - Venous: 2 mmHg

- Distal pressure is lower

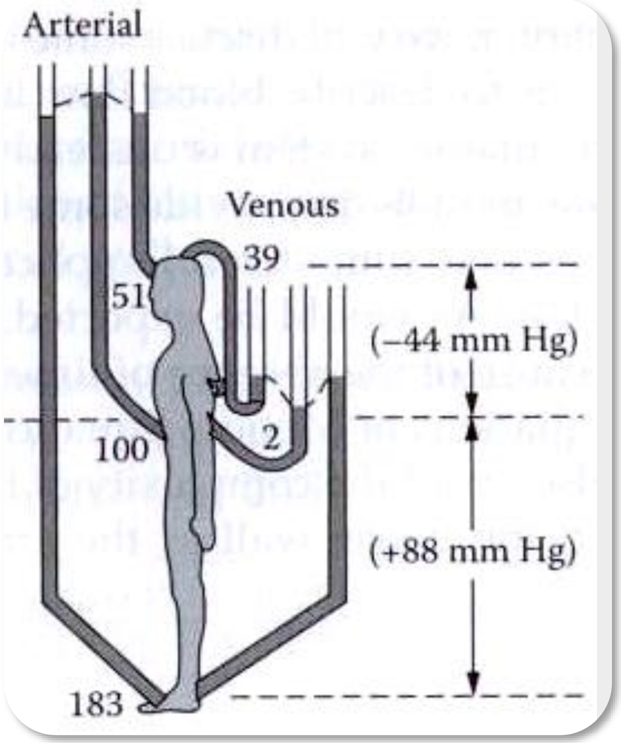


Hydrostatic pressure differences in the circulation "lying down" position

Hydrostatics in the Circulation

- Blood pressure in the "standing up" position
  - Head artery: 50 mmHg
  - Leg artery: 180 mmHg
  - Head vein: -40 mmHg
  - Leg vein: 90 mmHg

- Pressure differences due to gravitational effects



Hydrostatic pressure differences in the circulation "standing up" position

Hydrostatics in the Circulation

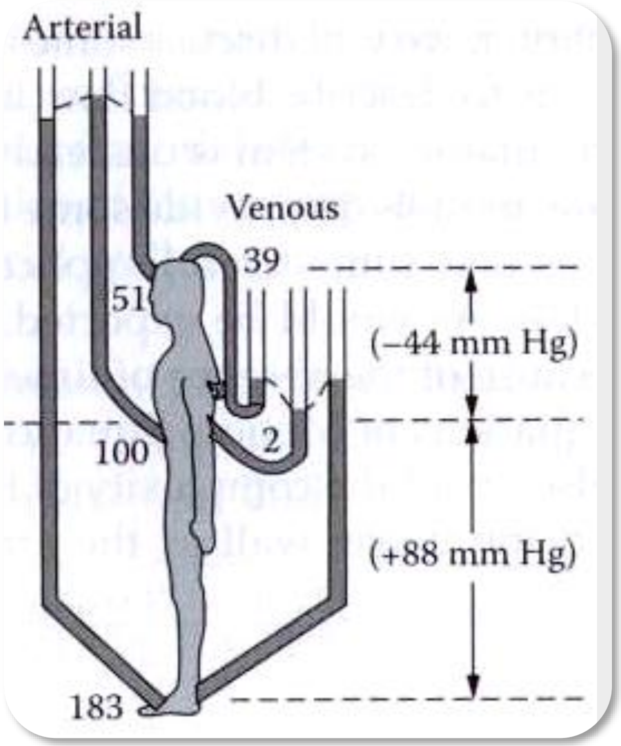
- Bernoulli equation:

$$\frac{V^2}{2g} + \frac{p}{\rho g} + z = const$$

- Tube of constant cross section:

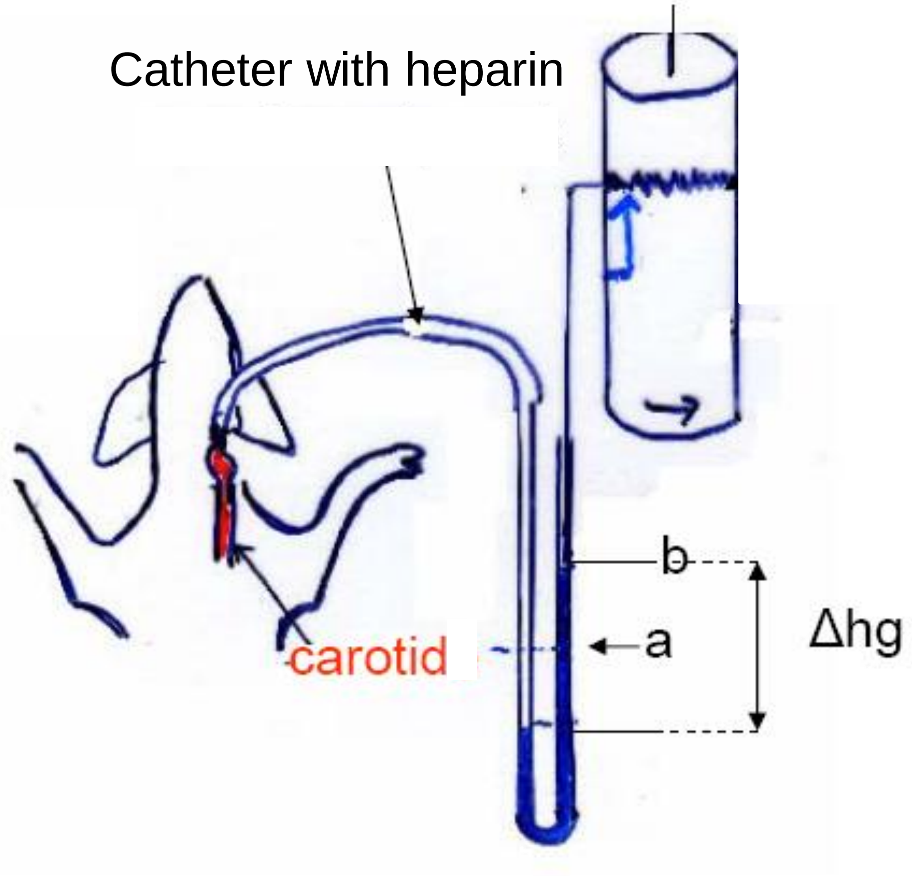
$$\Delta p = \rho g \Delta z$$

- Effects of pressure on vessels:
  - Arteries are stiff: pressure does not affect volume
  - Veins are distensible: pressure causes expansion



Hydrostatic pressure differences in the circulation "standing up" position

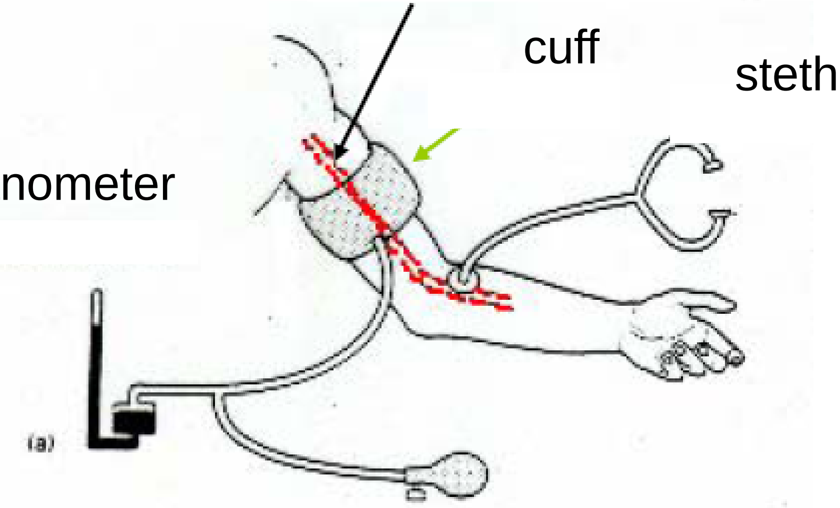
DIRECT PRESSURE MEASUREMENT


Catheter with heparin

carotid

Mercury manometer

CUFF MEASUREMENTS

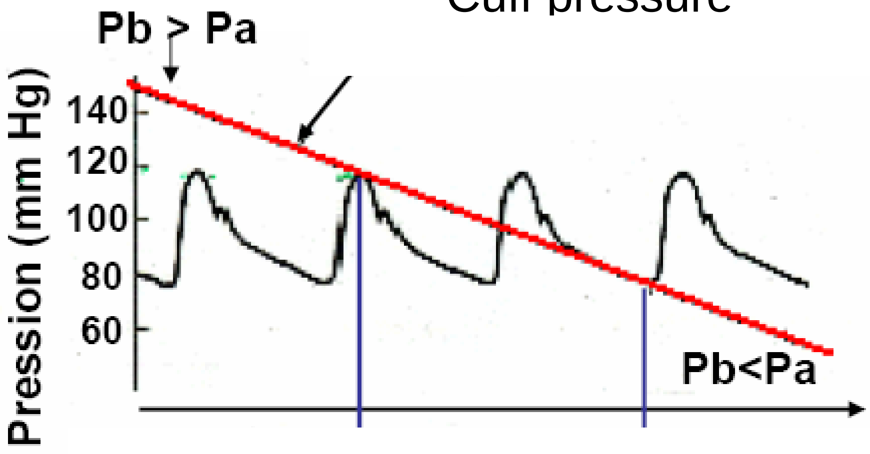


Humeral artery

cuff

stethoscop

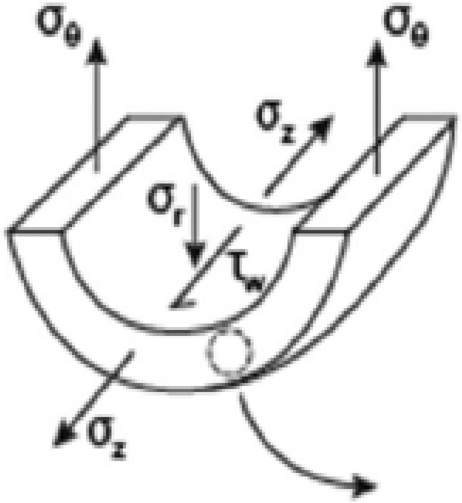
manometer



Cuff pressure

Korotkoff noises

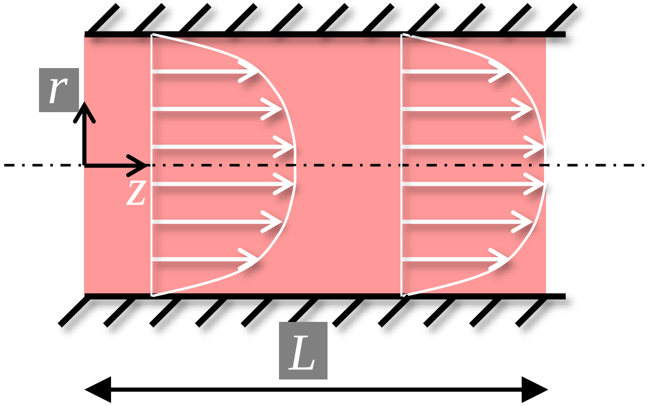
Basic equations of arterial mechanics



$$\tau_w = \frac{4\mu Q}{\pi a^3}, \qquad \sigma_\theta = \frac{P a}{h}$$

Hagen Poiseuille Model

- Assumptions:
  - incompressible
  - steady
  - laminar
  - circular cross section
- From exact analysis:

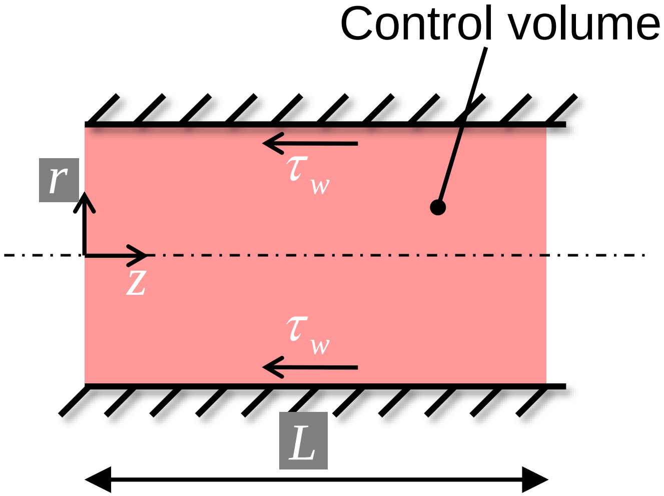


$$v_z\left(r\right) = \frac{\Delta p}{4\mu L}\left(r^2 - \frac{d^2}{4}\right)$$

$$Q = -\frac{\pi\,\Delta p\,d^4}{128\mu L}$$

Hagen Poiseuille Model

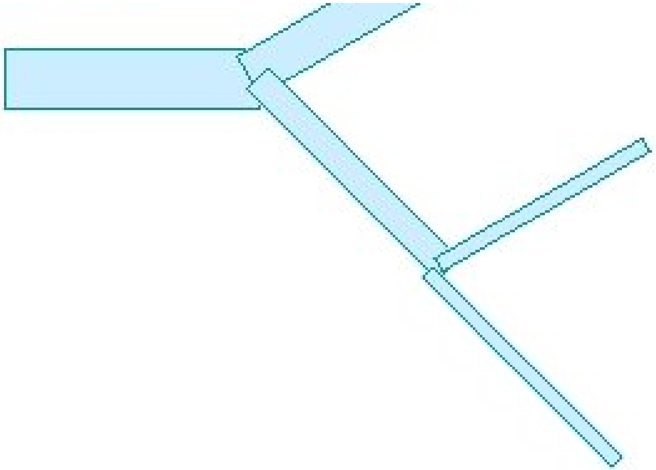
- Assumptions:
  - – incompressible
  - – steady
  - – laminar
  - – circular cross section



- From control volume analysis:

$$\Delta p = -\frac{4\tau_w L}{d}$$

Murray’s law



- Blood Flow in vessels
- Minimization of ‘work’

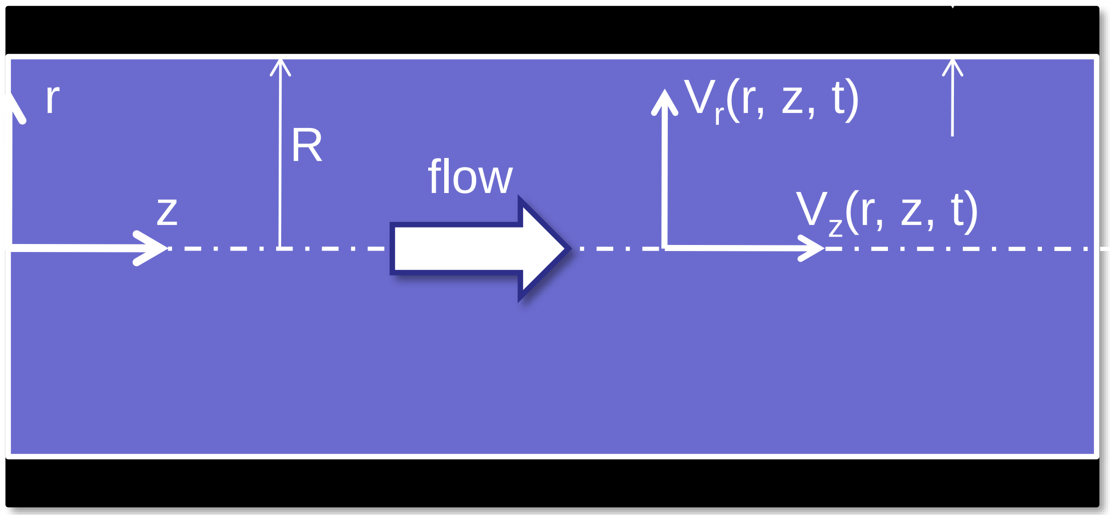
- Murray’s Law:

$$\sum r_{in}^3 = \sum r_{out}^3$$

- Laminar Flow, negligible friction loss (other than that due to viscous loss in laminar flow) , steady
- Turbulent, pulsating flow
- Assume

$$\Delta p = \frac{8\mu L Q}{\pi R^4} \qquad Work = Q\,\Delta p = \alpha \frac{Q^2}{r^4}$$

Moens Korteweg equation

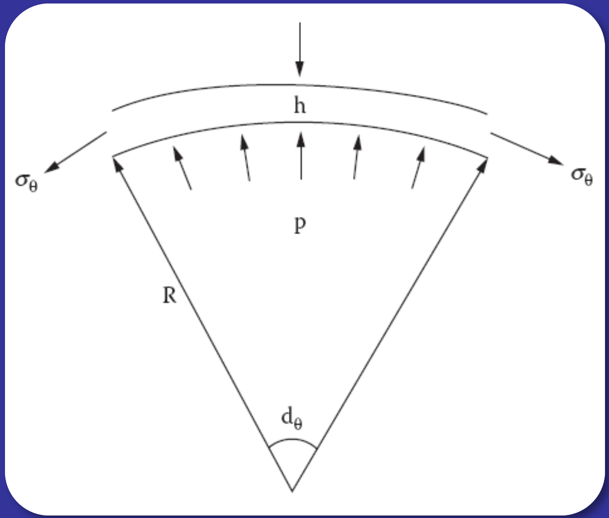


Infinitely long, thin-walled elastic tube of circular cross-section

Moens-Korteweg equation

- Tube equation of motion:

$$\rho_t h R d\theta \frac{d^2\eta}{dt^2} = Rpd\theta - \sigma_\theta h d\theta$$



- Coupling with fluid motion (with inertial effects):

$$\frac{\partial^2 p}{\partial z^2} = \frac{1}{c_0^2}\frac{\partial^2 p}{\partial t^2}$$

where

$$c_0^2(\omega) = \frac{hE}{2\rho R}\left(1-\frac{\omega^2 \rho_t R^2}{E}\right)$$

Experimental *vs.* Theoretical c_0

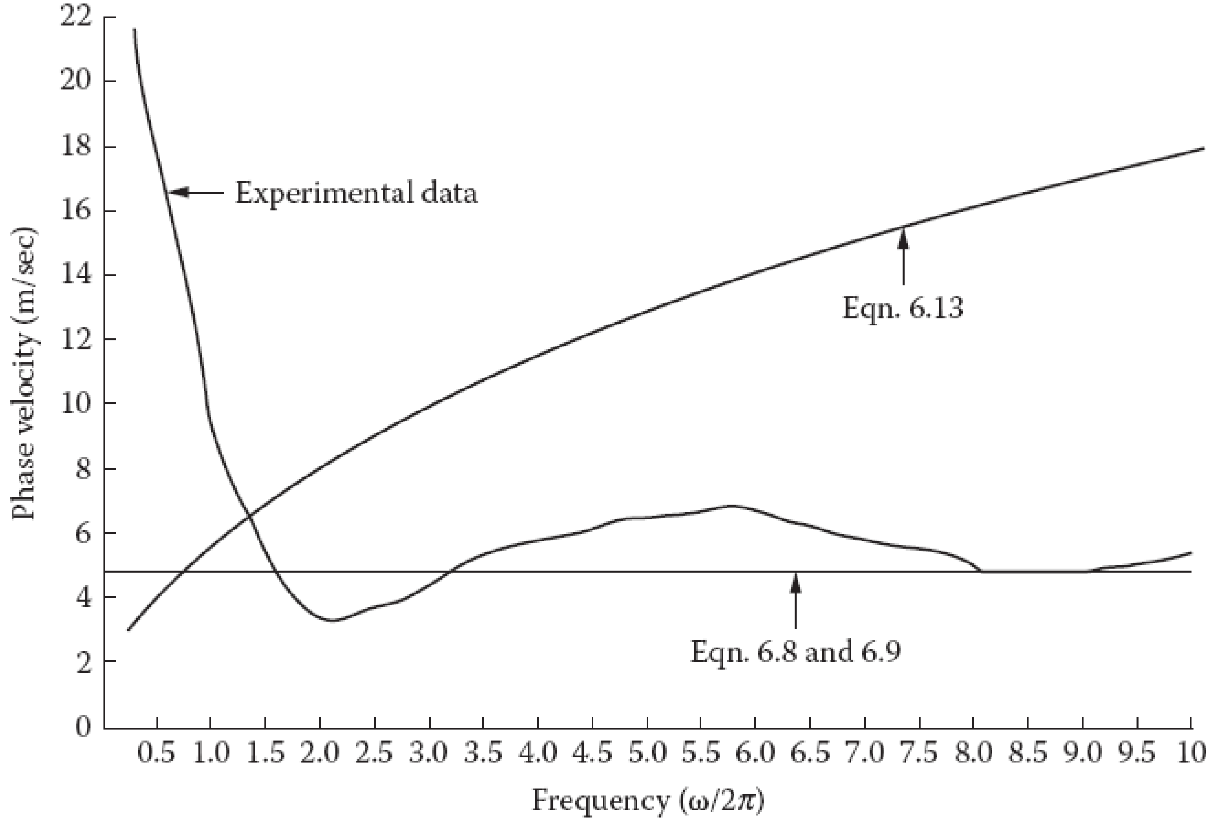
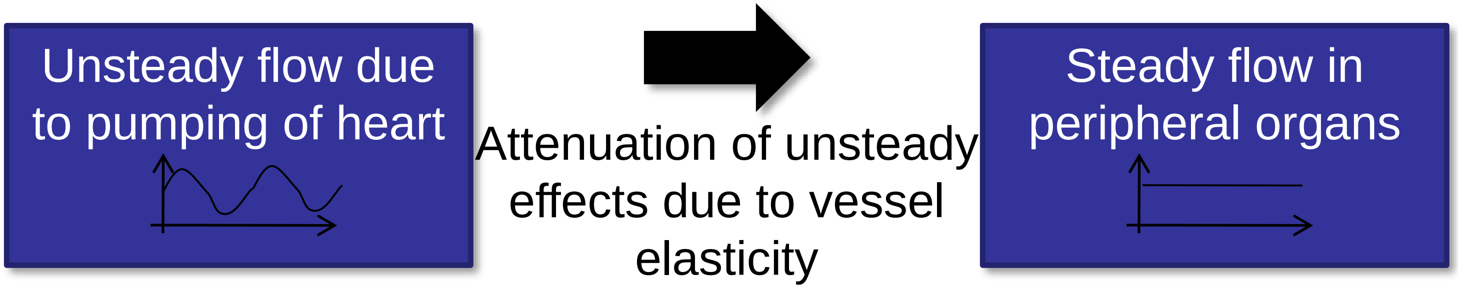


FIGURE 6.5
Pulse wave velocity plotted as a function of frequency from the theoretical models compared with experimental data. (Experimental curve redrawn from Noordergraaf, (1978) Elsevier, Philadelphia. With permission.)

Windkessel Theory

- Simplified model
- Arterial system modeled as elastic storage vessels



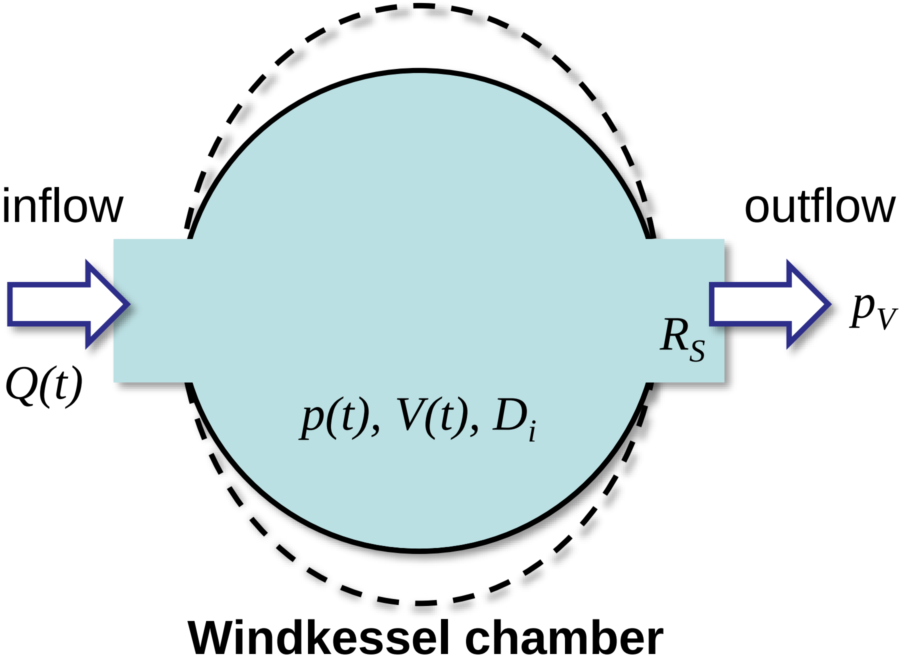
Unsteady flow due to pumping of heart

Attenuation of unsteady effects due to vessel elasticity

Steady flow in peripheral organs

- Arteries = interconnected tubes with storage capacity

Windkessel Theory



Variables	Definition
p	Windkessel chamber pressure
V	Windkessel chamber volume
D_i	Chamber distensibility
R_S	Peripheral resistance
Q	Ventricular ejection flow rate
p_V	Venous pressure

Definitions:

- Inflow: fluid pumped intermittently by ventricular ejection
- Outflow: calculated based on Poiseuille theory

Windkessel Solution

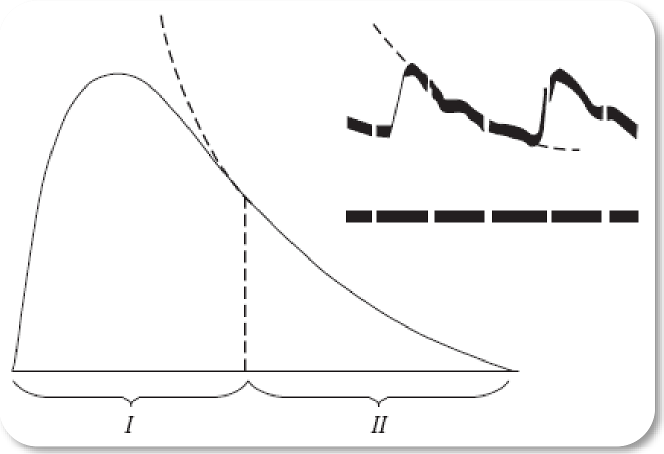
- Pressure pulse solution
  - Systole ($0 < t < t_s$):

$$p(t) = R_S Q_0 - \left(R_S Q_0 - p_0\right) e^{\frac{-t}{R_S D_i}}$$

  - Diastole ($t_s < t < T$):

$$p(t) = p_T e^{\frac{T-t}{R_S D_i}}$$

p_0: pressure at $t=0$
p_T: pressure at $t=T$

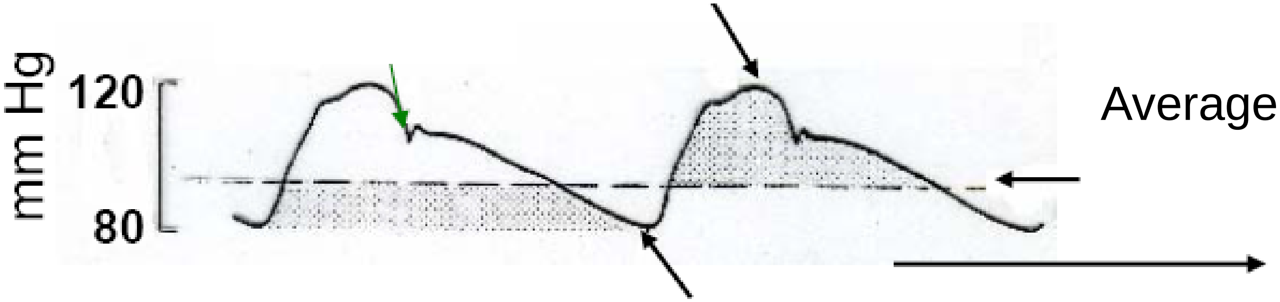


Windkessel (left) vs. actual (right) pressure pulse

- Stroke volume

$$V_S = \int_0^{t_S} Q(t)\, dt = Q_0 t_S$$

PULSE PRESSURE



Systolic pressure

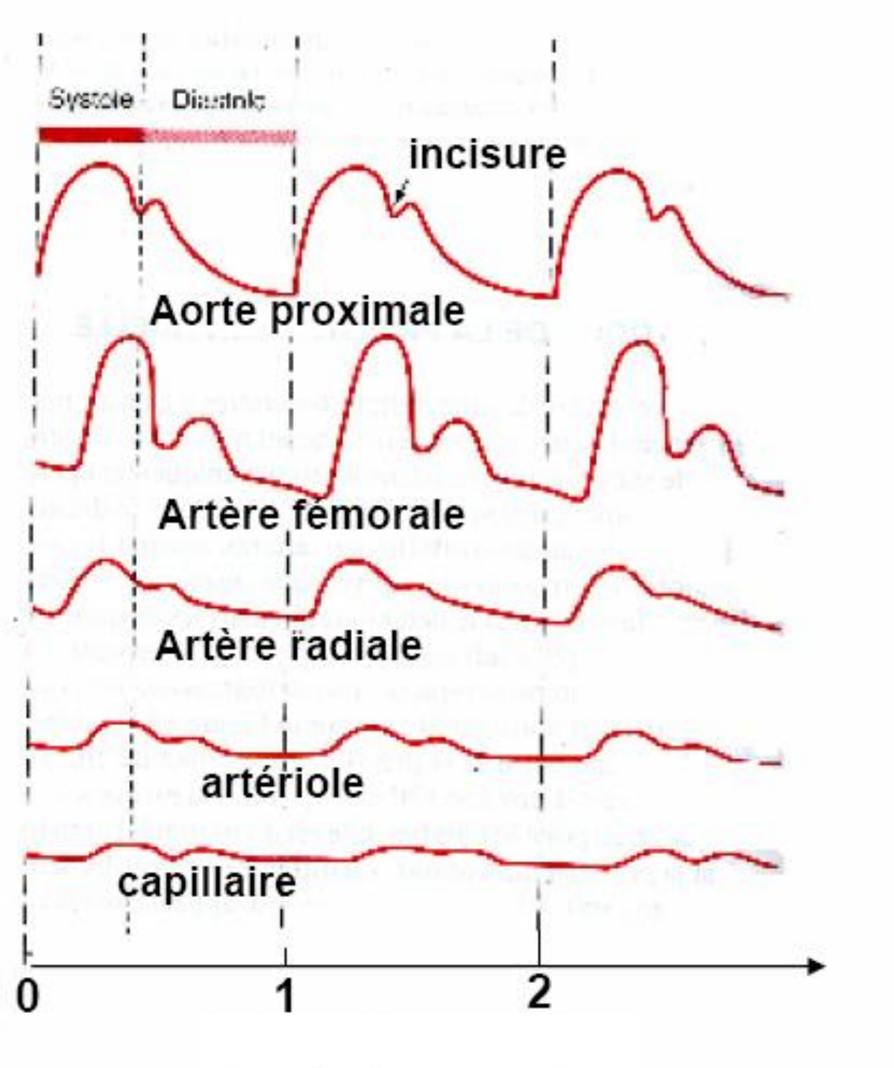
Average pressure

Diastolic pressure

Time

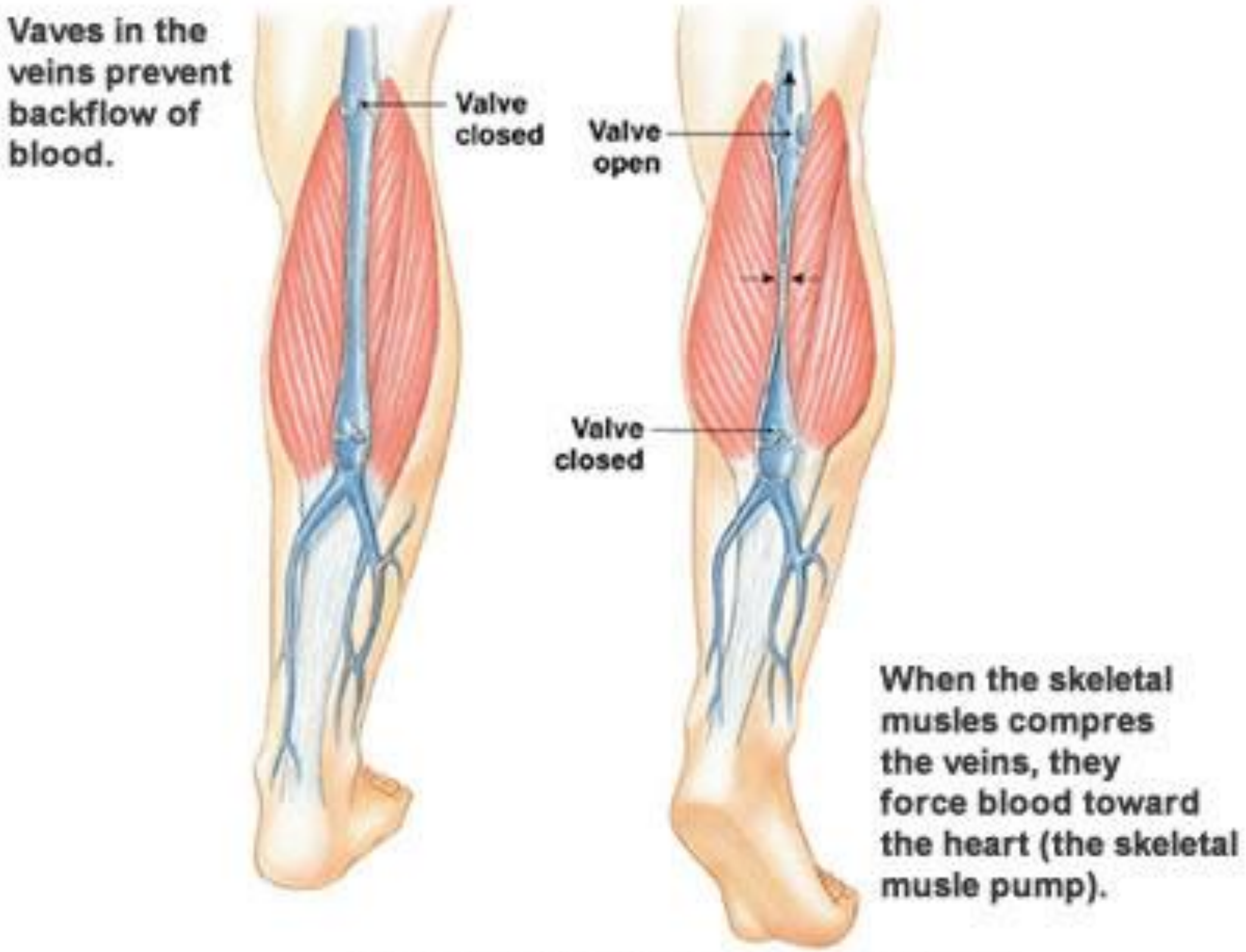
In the human, in average, the arterial pressure measured at the forearm is at 40 years:
Diastolic: 80mmHg, systolic: 140mmHg.
According to WHO, pathologic pressure is defined … (arterial hypertension)

Evolution of pressure oscillations throughout the vascular tree



Time (s)

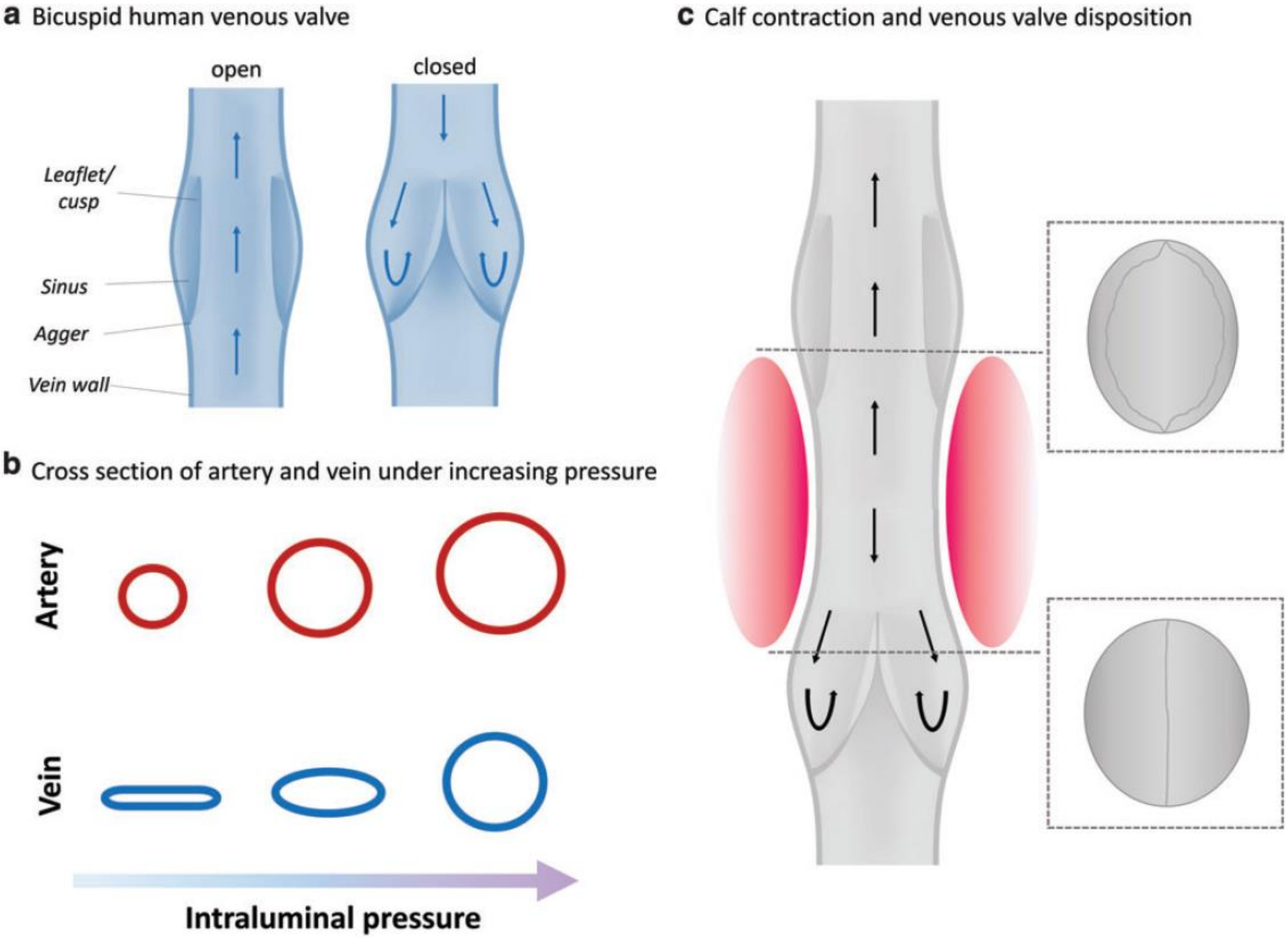
Vein biomechanics



Vaves in the veins prevent backflow of blood.

When the skeletal musles compres the veins, they force blood toward the heart (the skeletal musle pump).

Vein biomechanics



PROBLEM OF VEIN BIOMECHANICS

Considering the pressure distribution due to gravity and the mechanical behaviour of veins shown in the figure below, explain why we can feel dizzy when we stand up quicky from squatting or crouching.