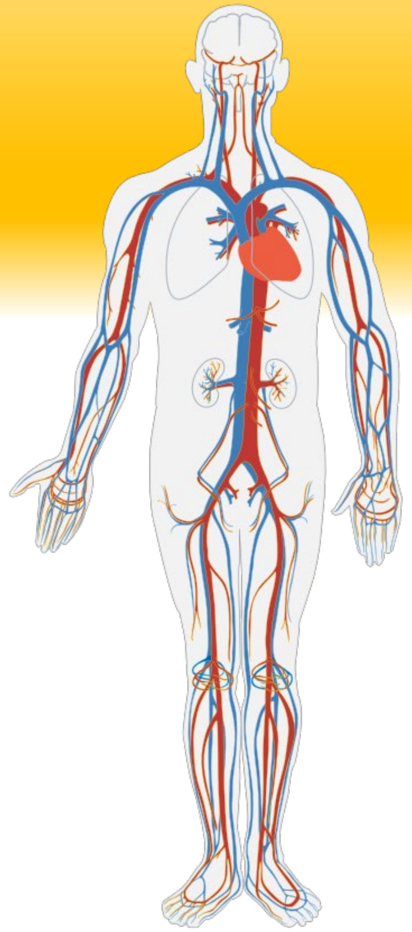
Introduction to Cardiovascular Biomechanics



Lukáš Horný

Department of Mechanics, Biomechanics and Mechatronics
Faculty of Mechanical Engineering
Czech Technical University in Prague

Last modified December 2023
http://users.fs.cvut.cz/~hornyluk/home

Circulatory System: Introductory notes

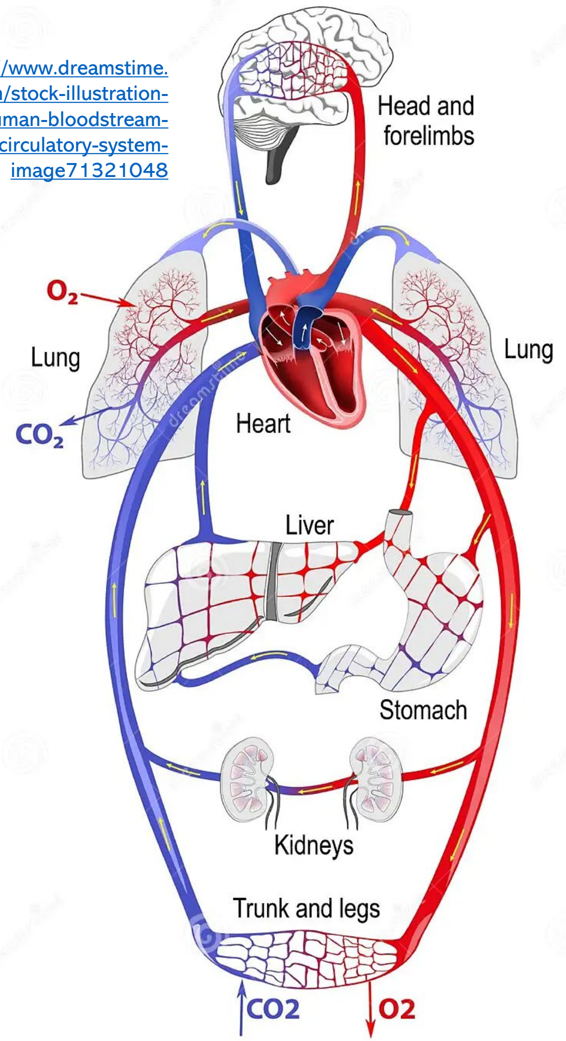
Circulatory system

- Purpose → Blood supply throughout the body

- Parts → Heart
  Blood vessels
  Blood

- Principle → The heart pressurizes the blood
  The blood flows in the vessels
  and circulates from the heart through organs to the heart

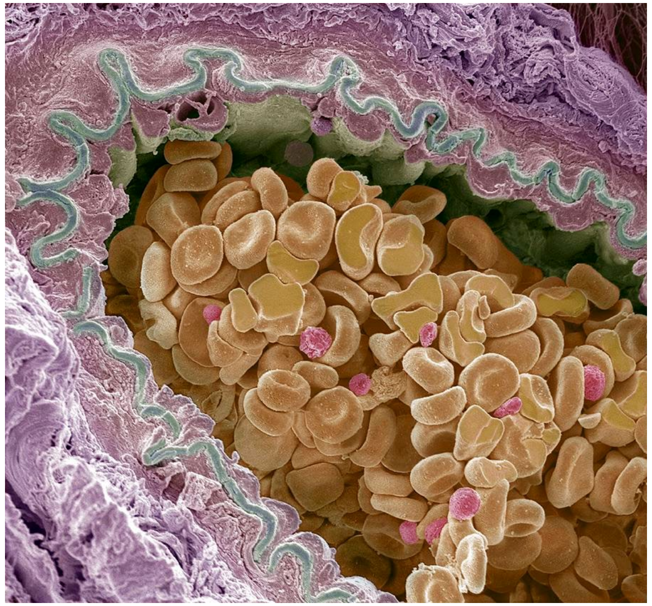
https://www.dreamstime.com/stock-illustration-human-bloodstream-circulatory-system-image71321048



Circulatory system

- Purpose → Blood supply throughout the body

- Blood is a transport medium for

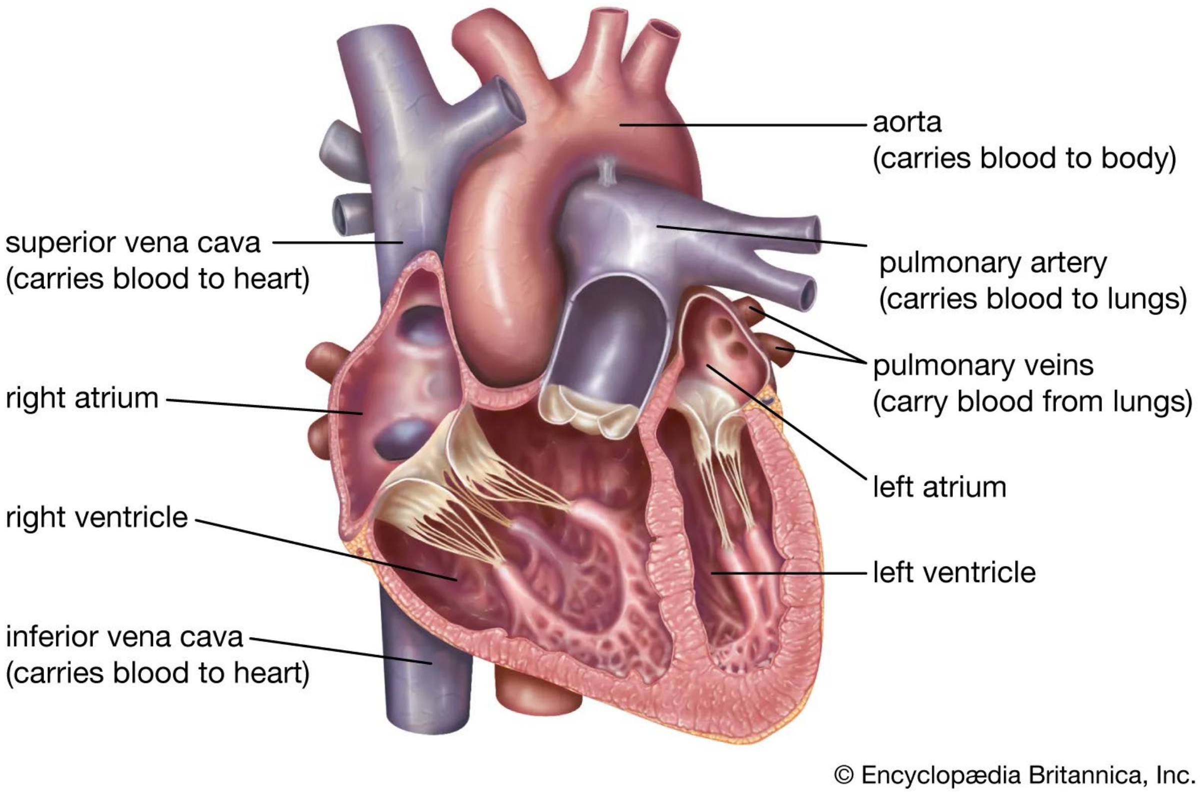


O_2
Nutrients and metabolic waste
Immune system reaction
Regulatory molecules
Heat

Red blood cells and platelets in the lumen of the arteriole. Colored SEM.
https://fineartamerica.com/featured/elastic-artery-cross-section-sem-steve-gschmeissner.html

Circulatory system

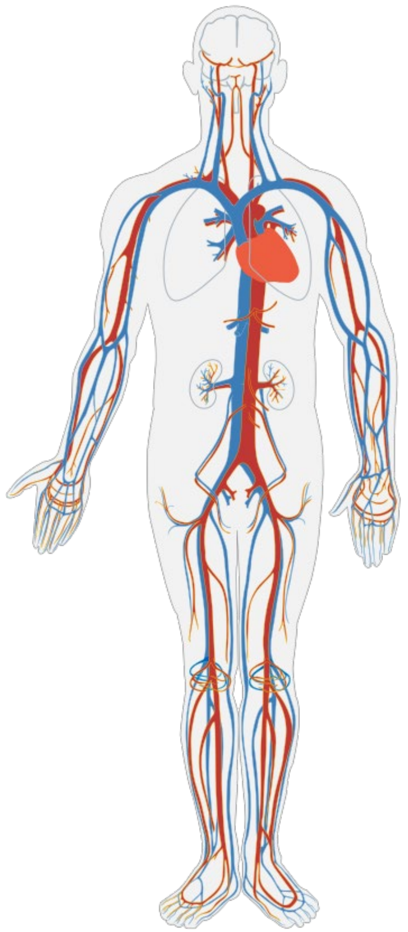
- Parts → Heart



https://www.britannica.com/science/heart

Blood vessels

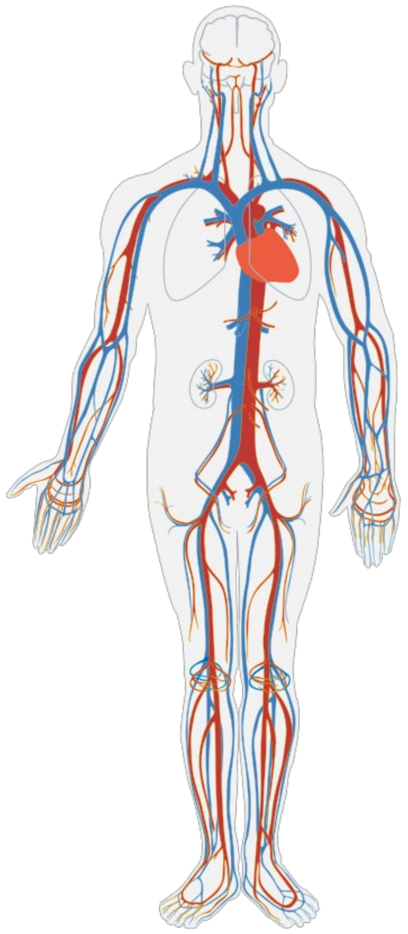
Blood

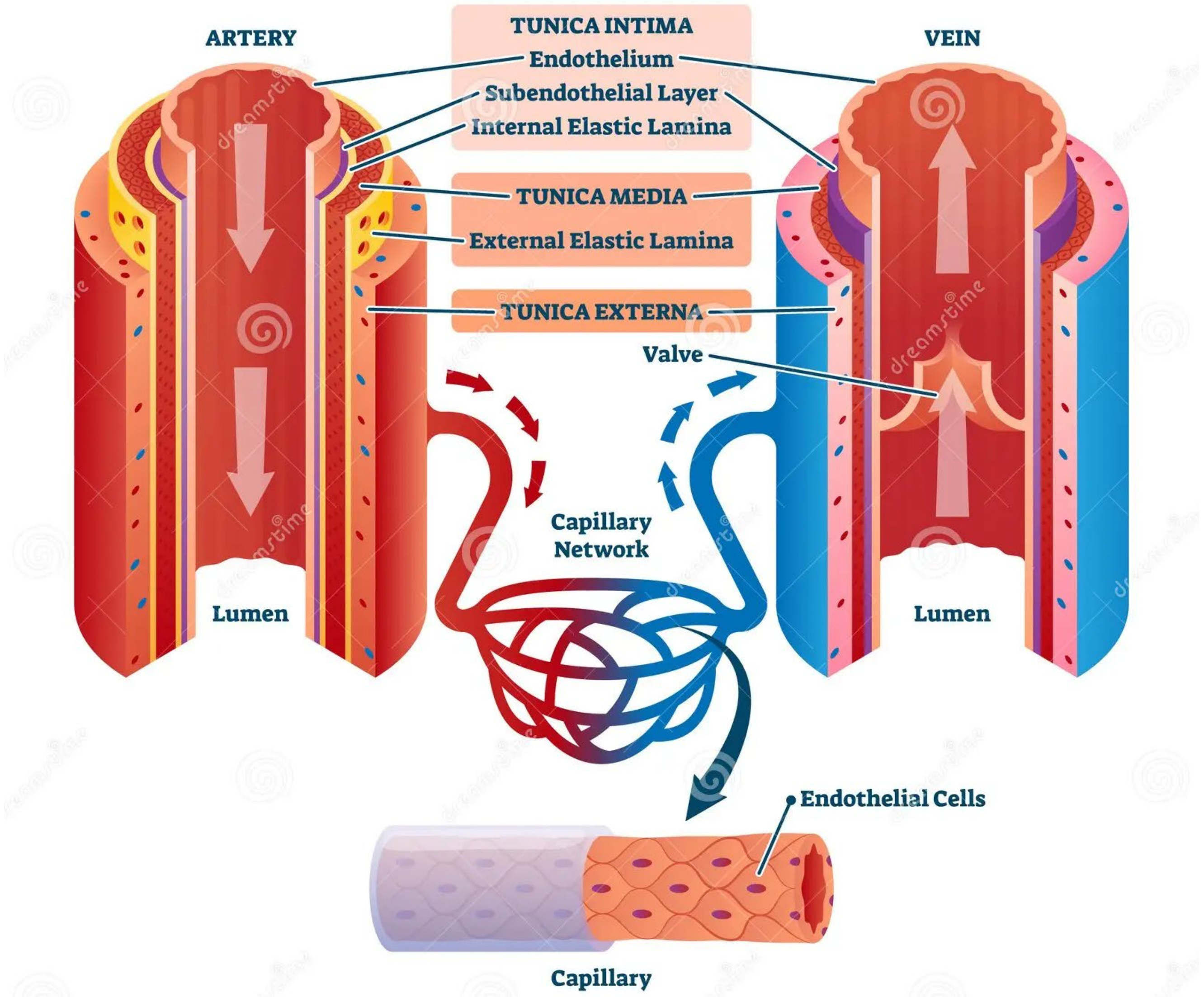


https://pressbooks.bccampus.ca/nutr1100/chapter/the-cardiovascular-system/

Circulatory system

- Parts → Heart
  Blood vessels



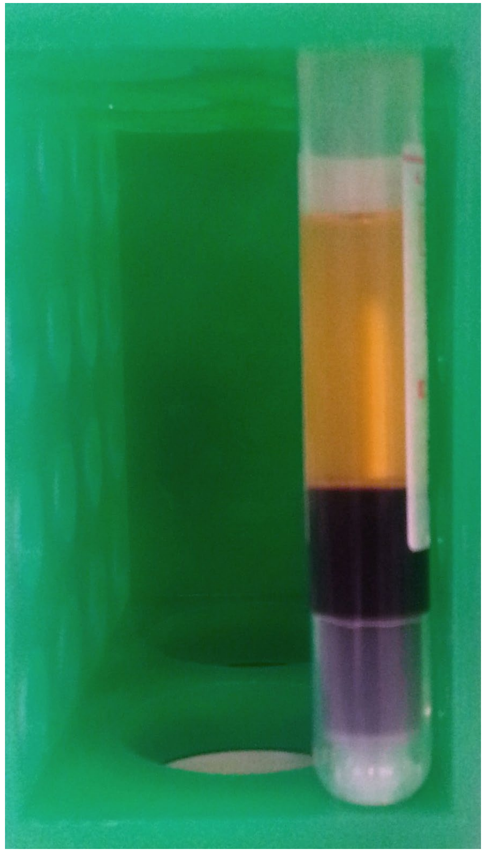


Blood

https://www.dreamstime.com/blood-vessels-artery-vein-internal-structure-vector-illustration-blood-vessels-artery-vein-internal-structure-image190053683

Circulatory system

- Parts → Heart
  Blood vessels
  Blood



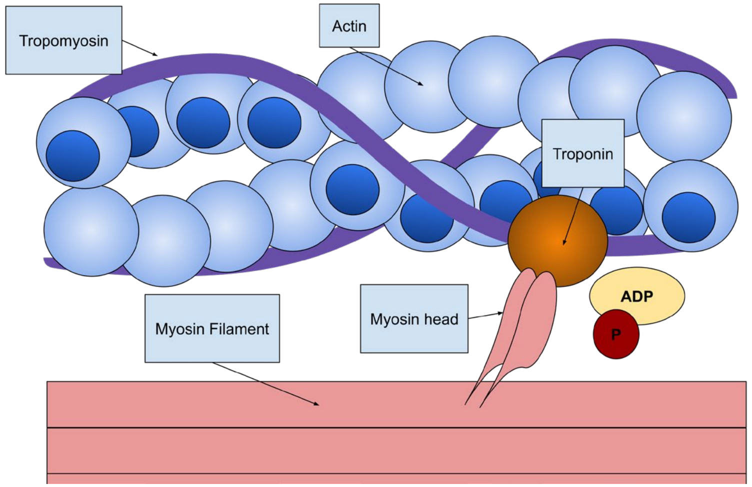
https://commons.wikimedia.org/wiki/File:Krew_Frakcjonowana.jpg

- Suspension of solid particles and blood plasma
- Liquid phase (≈55%): water (≈90%) + plasma proteins (≈7%) + hormones (≈2%) + enzymes + glucose + minerals
- Solid particles: red and white blood cells and platelets

Circulatory system

Forces and interactions ⟵ Blood supply throughout the body

- Transportation phenomena → Mechanics
- Contraction → Chemo-mechanical
- Control of contraction → Electro-mechanical



https://en.wikipedia.org/wiki/Sliding_filament_theory#/media/File:Sliding_Filament_Theory.svg

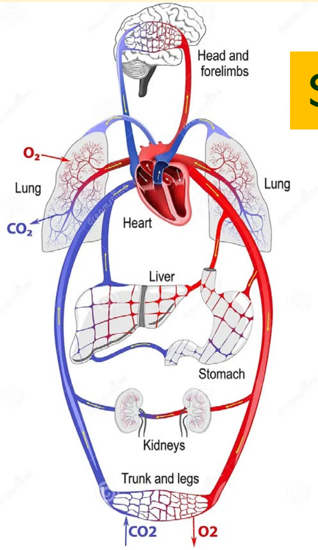
Outline of content

- Basic anatomy of the blood circulation
- Physiology
- Experiments and simulations
- Diseases and treatment from an engineer's perspective

Basic Anatomy of the Blood Circulation

Anatomy of the circulation

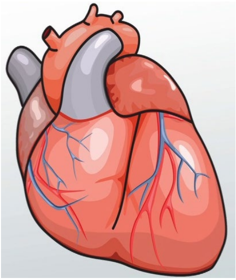
- System
- Organs
- Tissues
- Cells and extracellular matrix and interstitial liquid
- (Macro)molecular structure of a matter

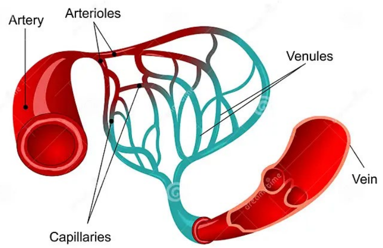


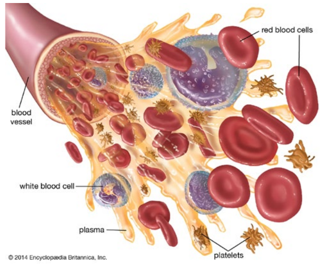
System

https://thumbs.dreamstime.com/z/capillary-blood-medical-illusration-works-35491042.jpg?w=768

https://www.britannica.com/science/blood-biochemistry



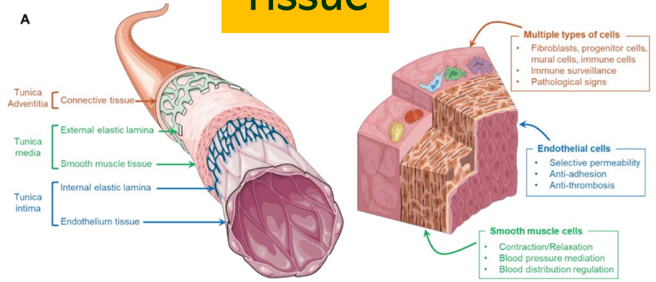




https://study.com/learn/lesson/myocardium-function-location-parts.html

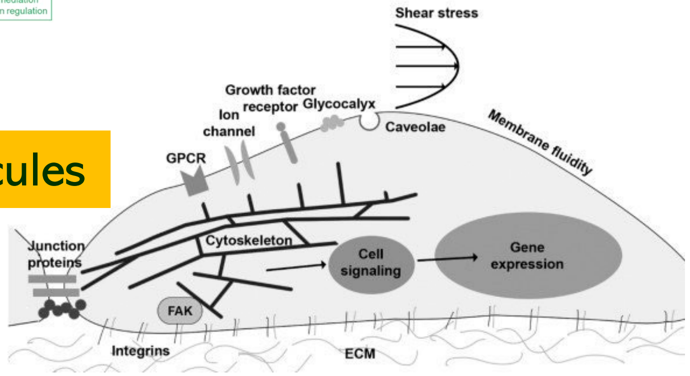
Organs

Tissue



https://www.mdpi.com/2072-666X/13/2/326

Cells and macromolecules



https://jbiomedsci.biomedcentral.com/articles/10.1186/1423-0127-21-3

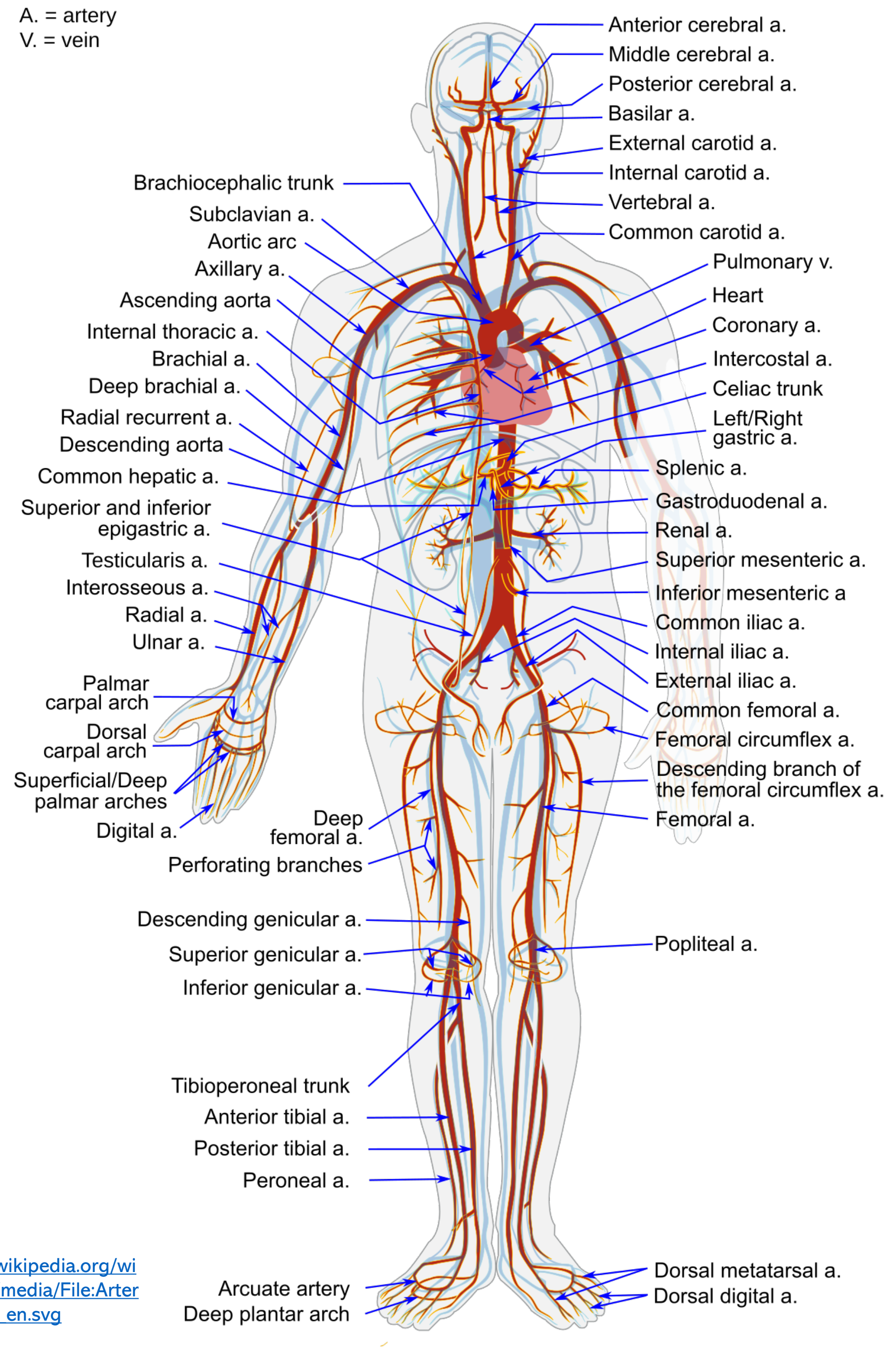
Anatomy

- System

Circulation: Heart - organs – heart

Arteries conduct blood from the heart to the organs

Higher blood pressure and thicker wall than veins

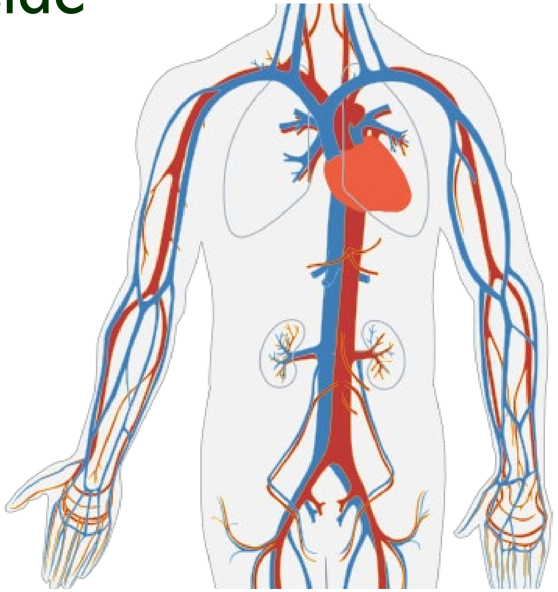


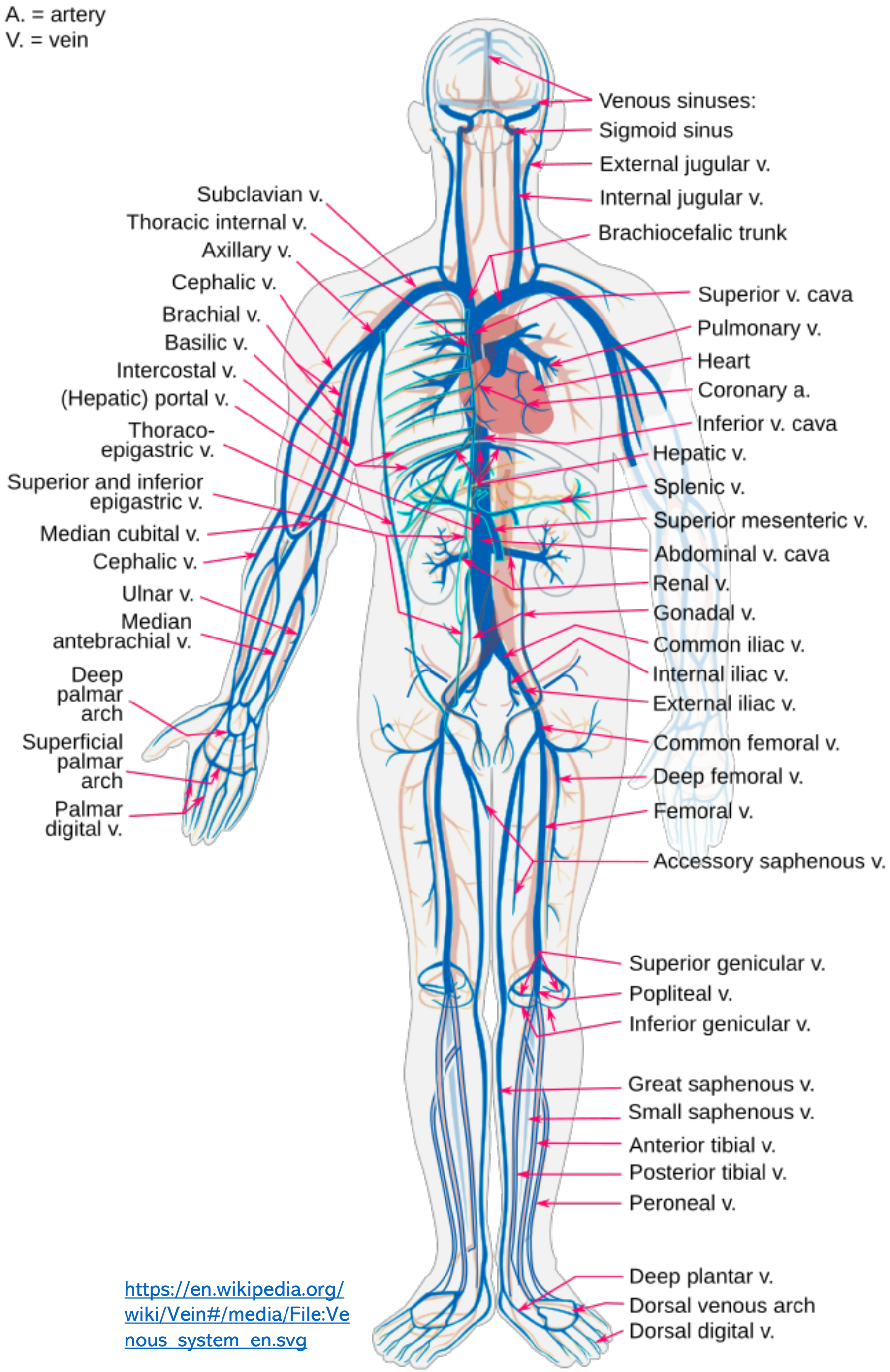
https://en.wikipedia.org/wiki/Artery#/media/File:Arterial_System_en.svg

Anatomy

- System

Veins and arteries usually form pairs
This means that inflow channels
and outflow channels usually run
side by side



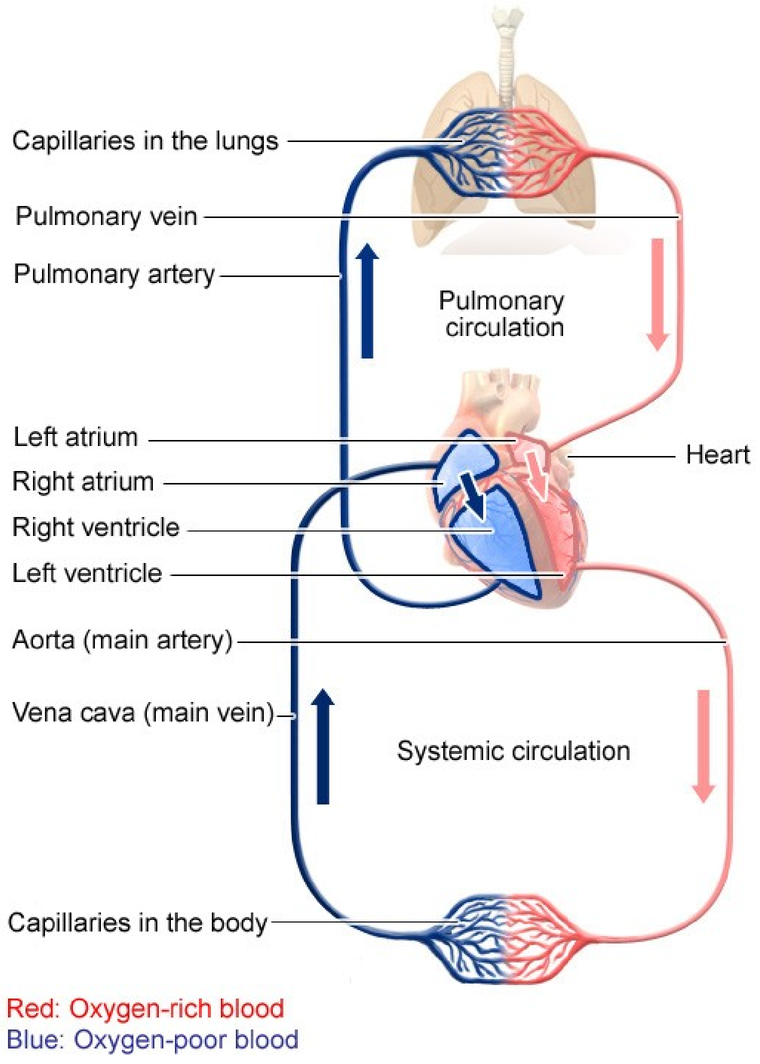


https://en.wikipedia.org/wiki/Vein#/media/File:Venous_system_en.svg

Anatomy of the circulation

- The system consists of two circulations

- Systemic circulation (body, major)
- Pulmonary circulation (minor)



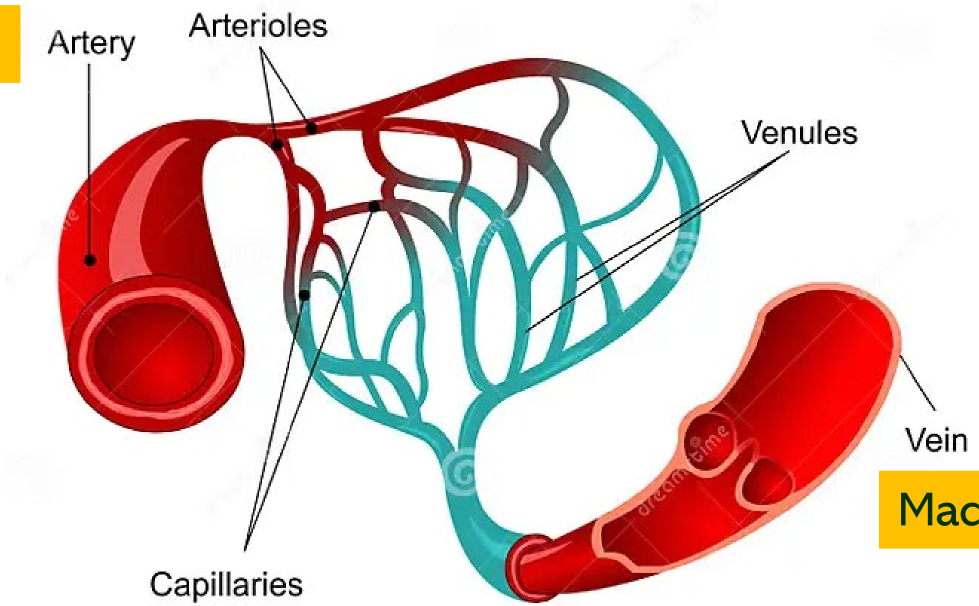
https://www.informedhealth.org/how-does-the-blood-circulatory-system-work.html

Anatomy of the circulation

- Microcirculation

The systemic circulation is often described as consisting of macrocirculation and microcirculation

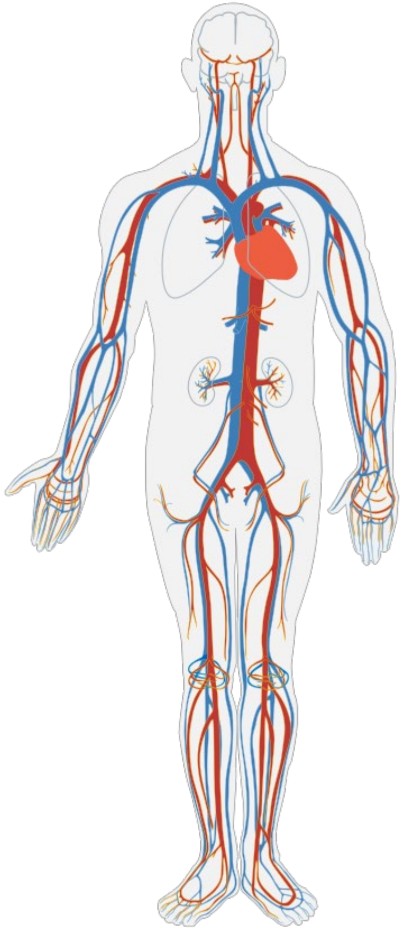
Macrocirculation



Macrocirculation

Microcirculation

Macrocirculation

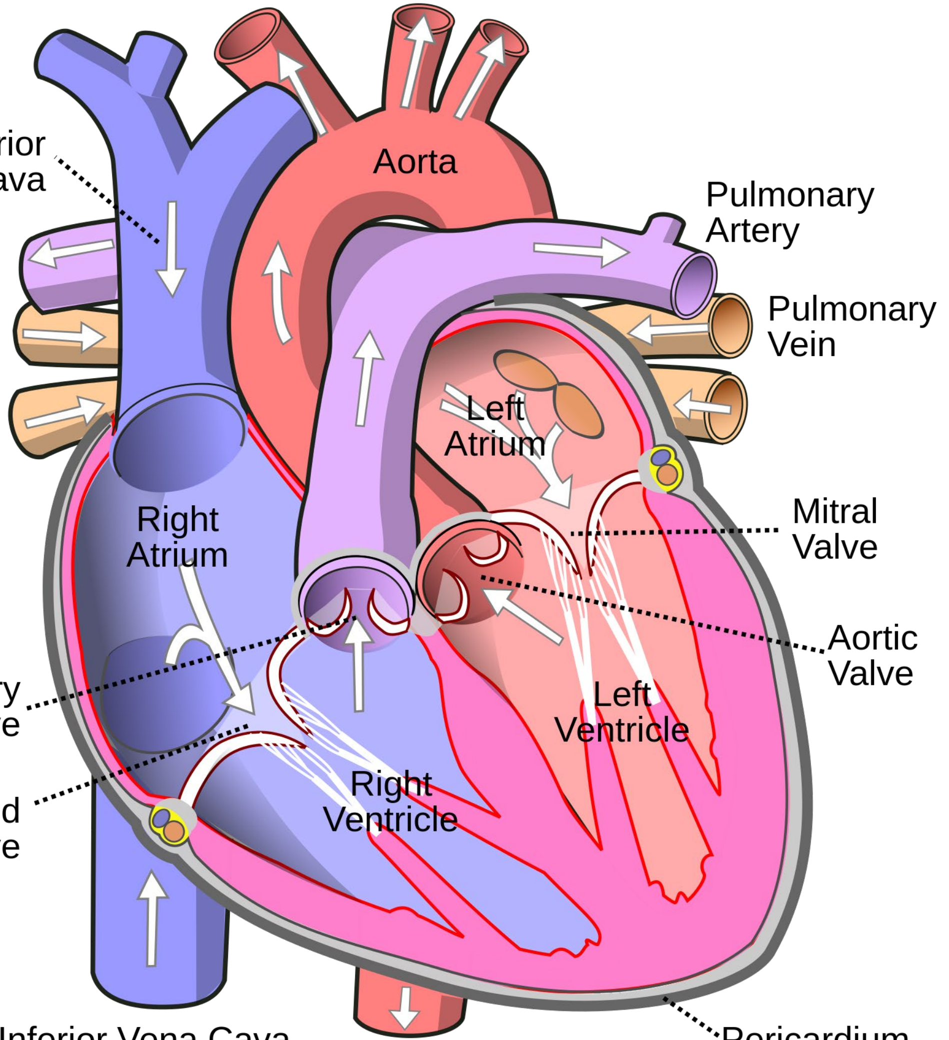


Anatomy of the heart

- Left (systemic) and
  Right (pulmonary) heart

- Four chambers =
  L&R atrium + ventricle

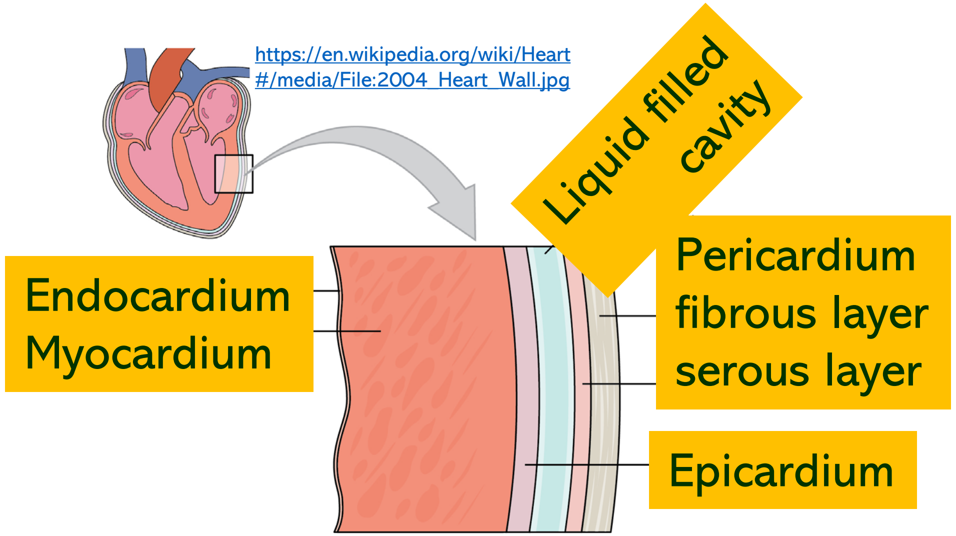
- Valves for one way flow



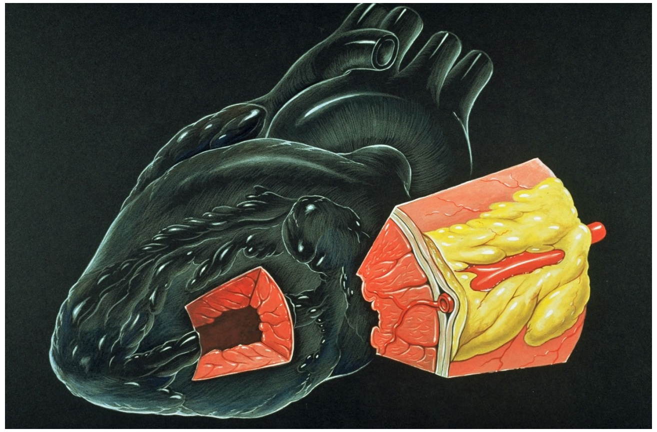
https://en.wikipedia.org/wiki/Heart#/media/File:Diagram_of_the_human_heart_(cropped).svg

Anatomy of the heart

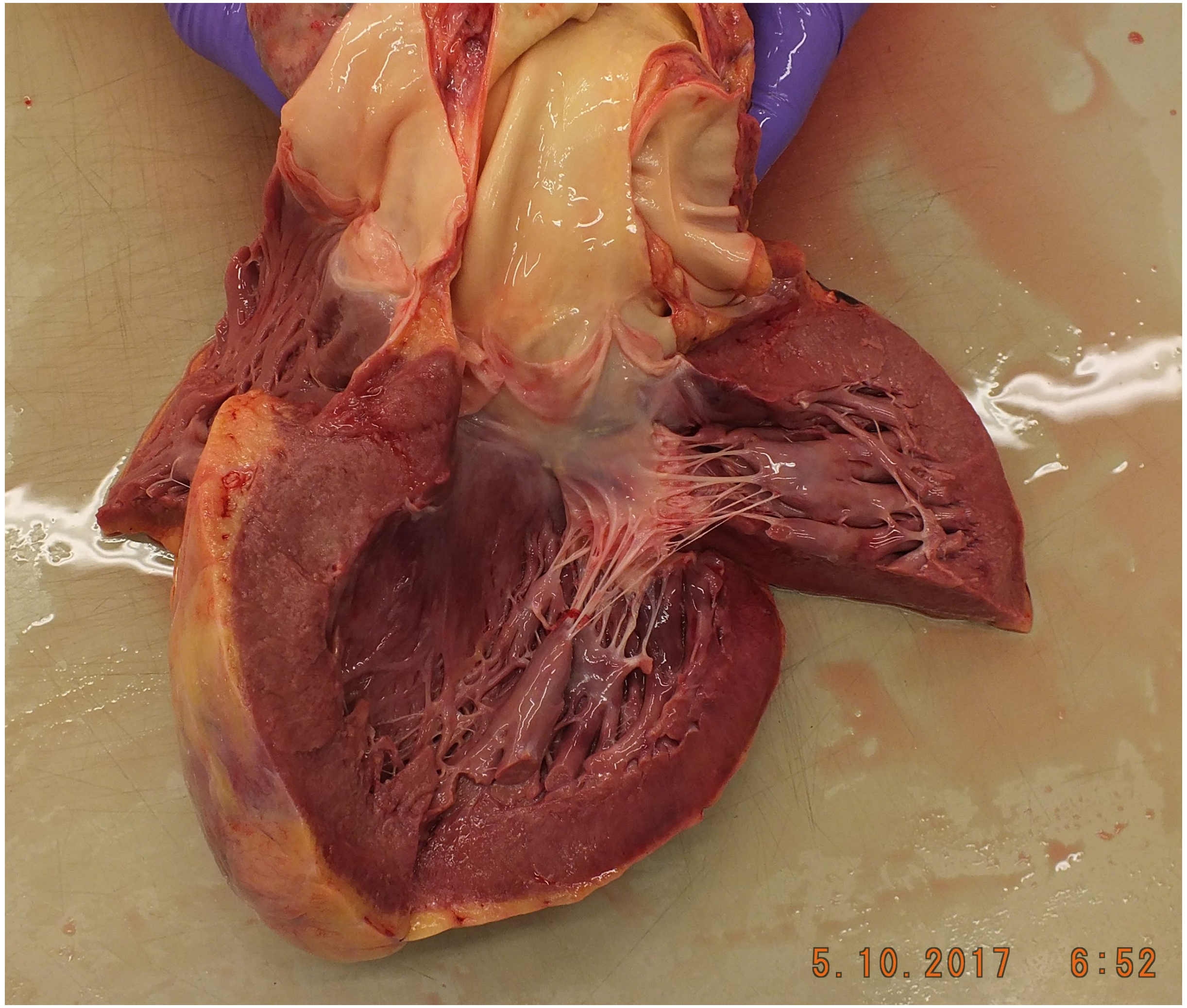
- Structure of the heart muscle



https://en.wikipedia.org/wiki/Heart#/media/File:2004_Heart_Wall.jpg

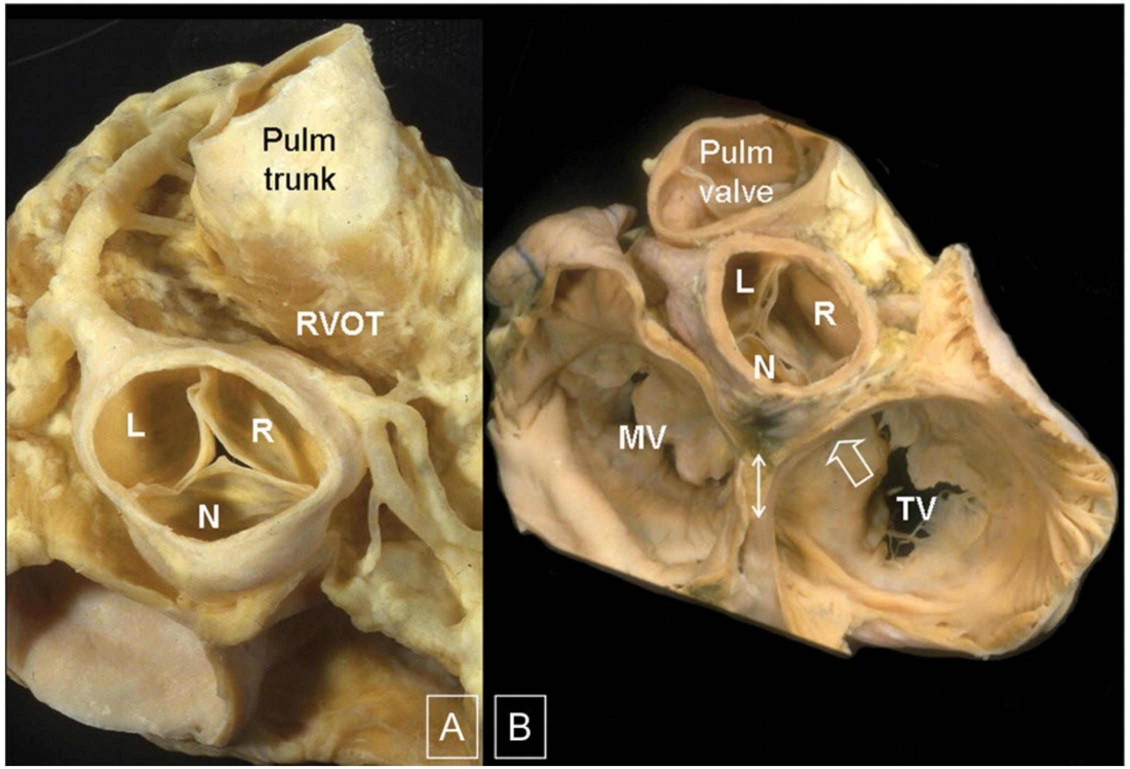


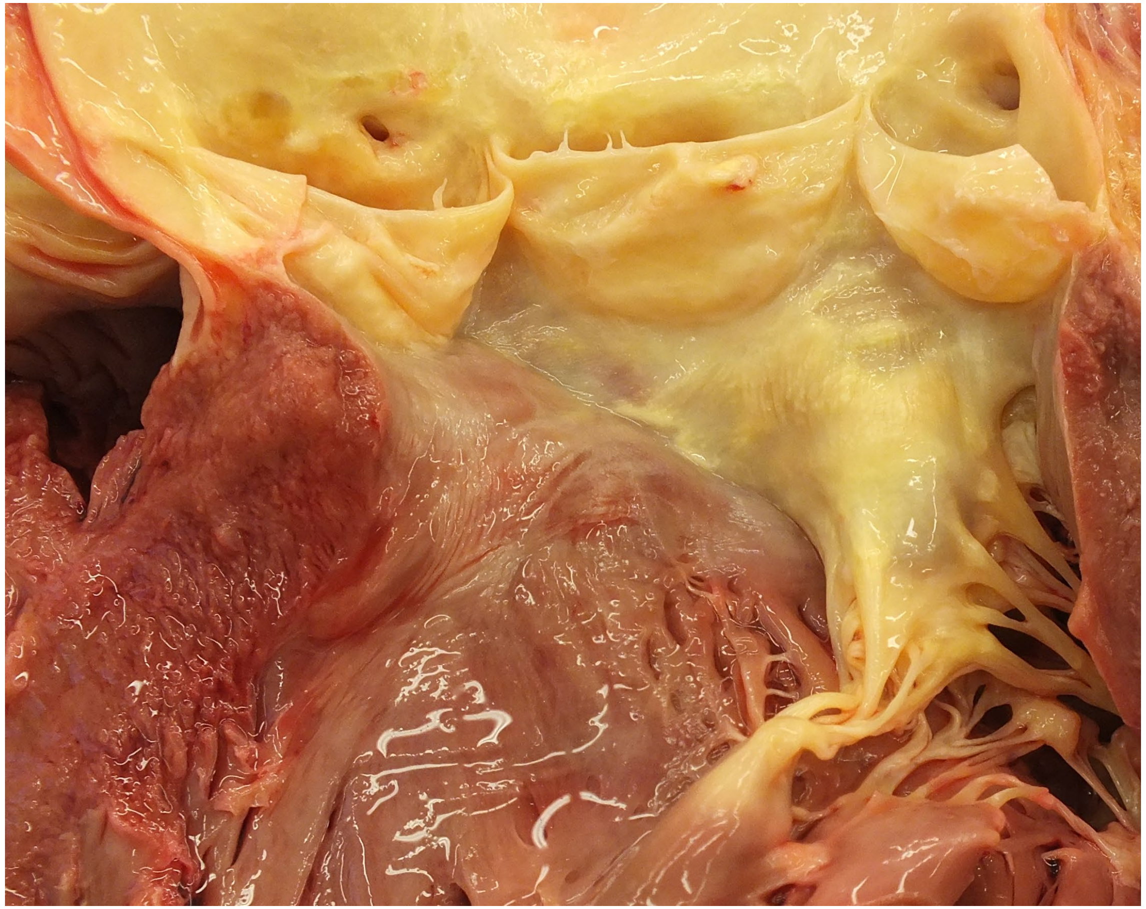
https://www.wikiskripta.eu/w/Srdce#/media/Soubor:Heart_myocardium_diagram.jpg



Anatomy of the heart

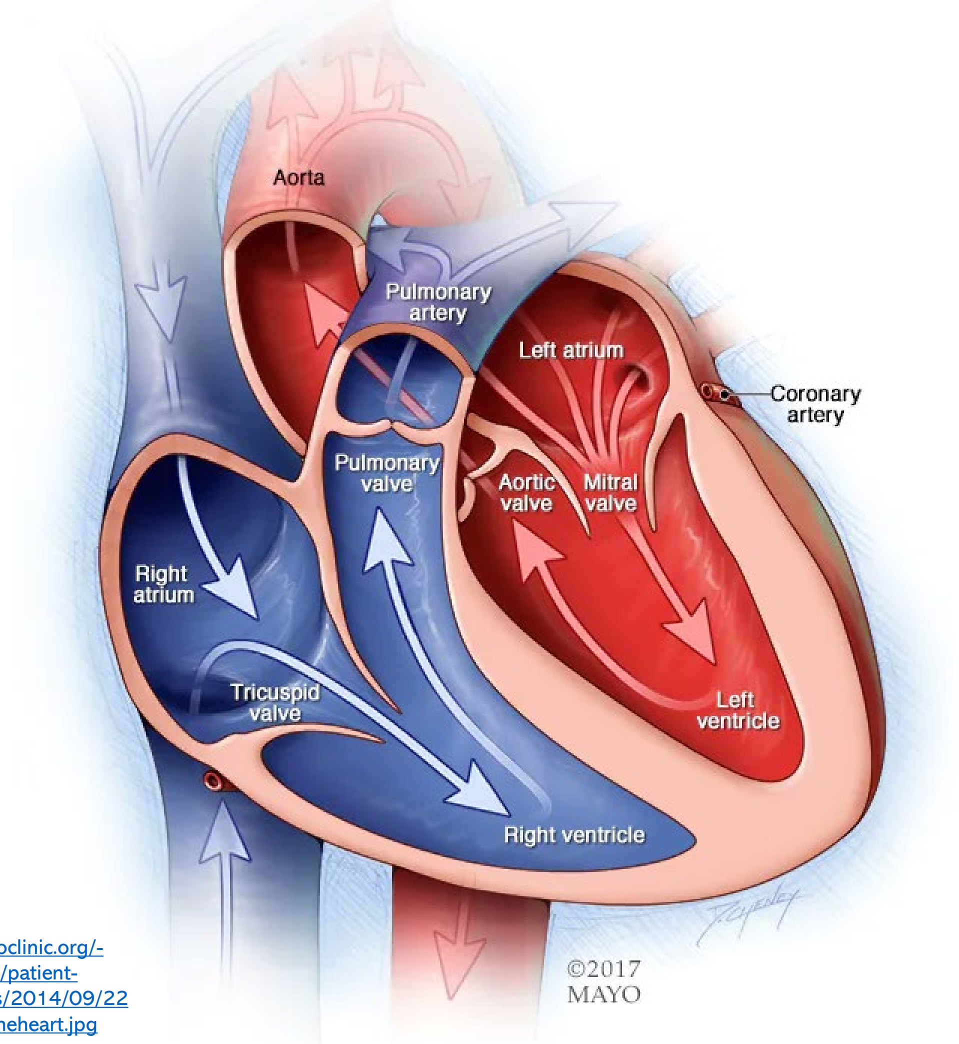
- Structure of the heart muscle



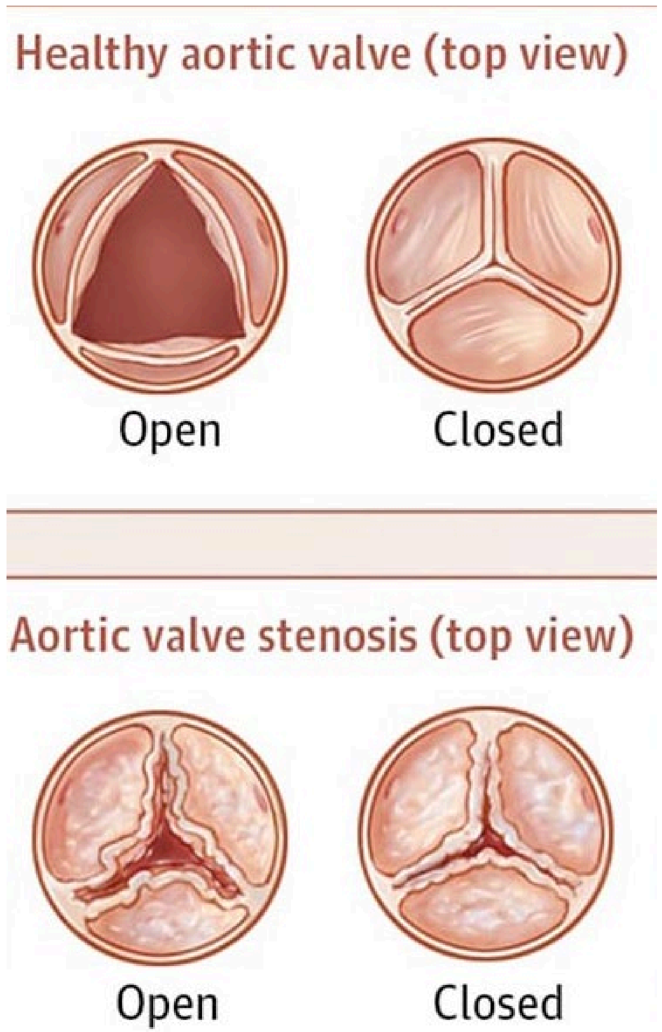


Anatomy of the heart

- Structure of the heart muscle



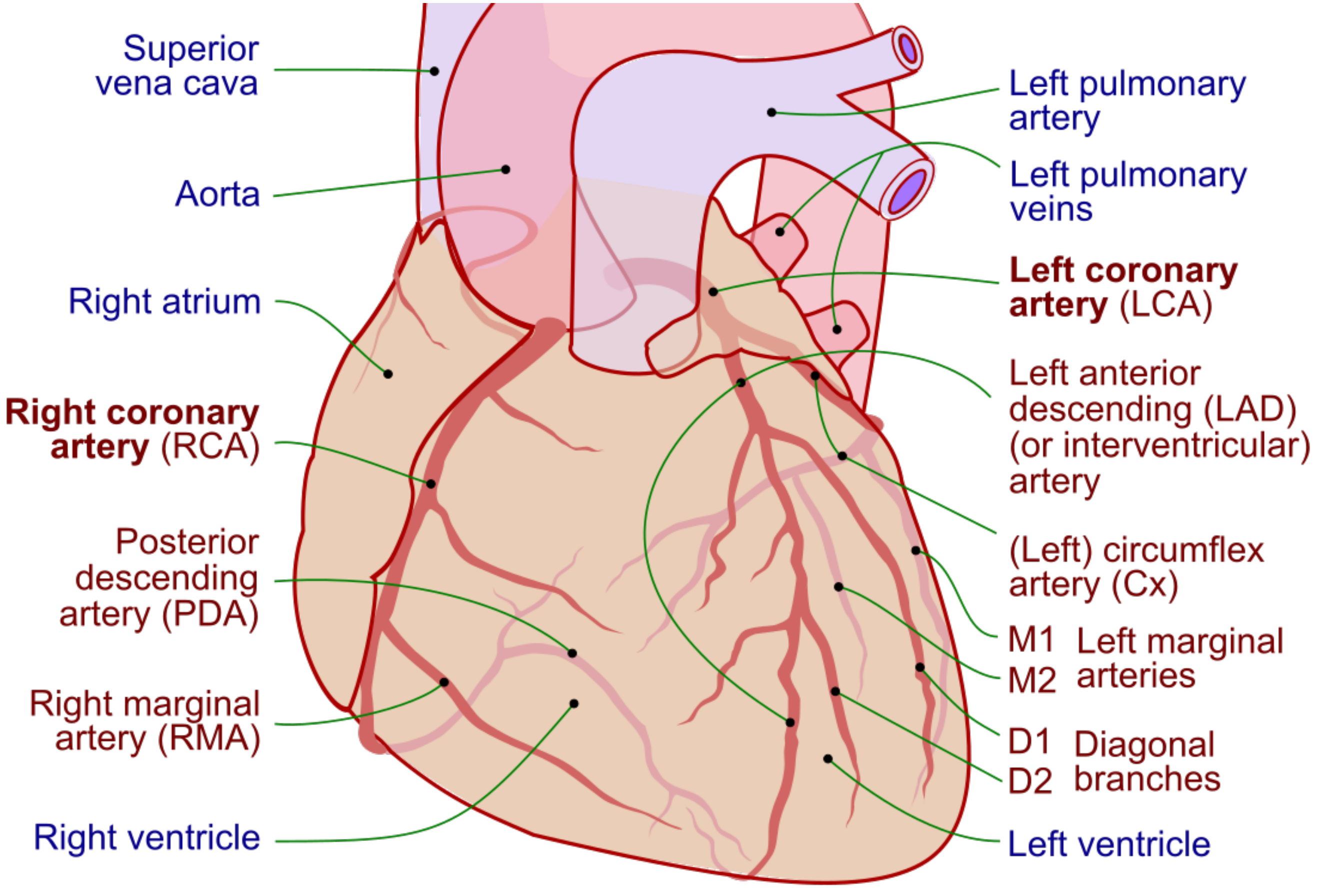
https://www.mayoclinic.org/-/media/kcms/gbs/patient-consumer/images/2014/09/22/12/43/mcdc7_theheart.jpg



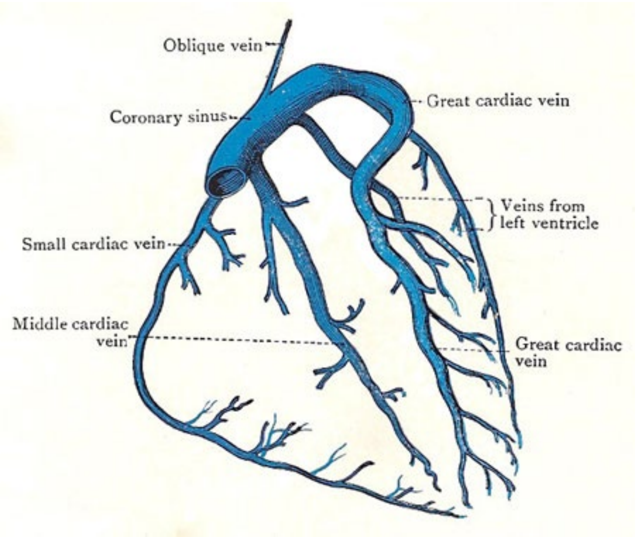
https://www.heartvascularcentre.com/wp-content/uploads/2018/12/aortic-valve-stenosis.jpg

Anatomy of the heart

- Heart vasculature



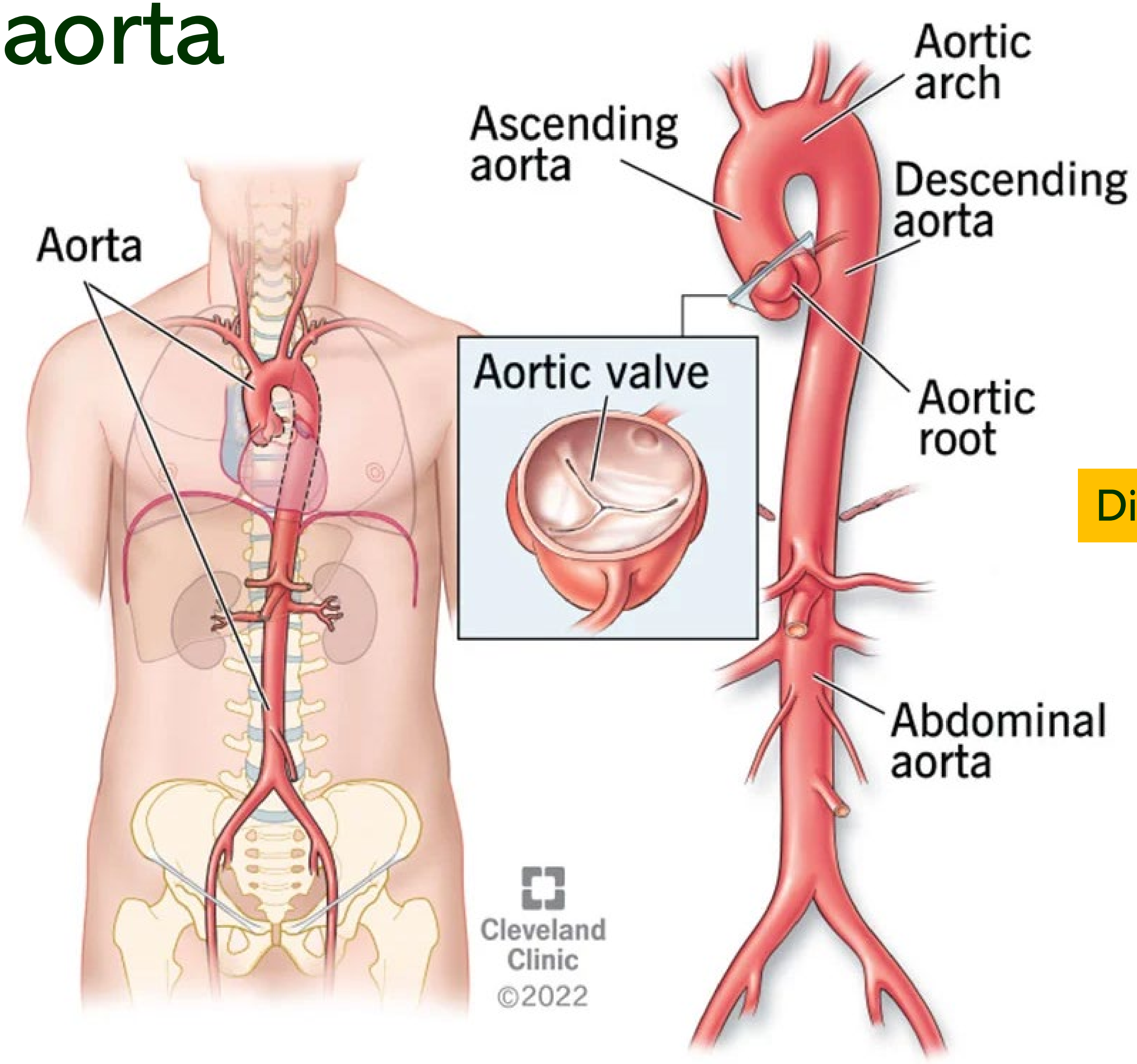
https://en.wikipedia.org/wiki/File:Coronary_arteries.svg



https://www.google.com/url?sa=i&url=https%3A%2F%2Fwww.daviddarling.info%2Fencyclopedia%2FC%2Fcoronary_vein.html&psig=AOvVaw2cMjH6eYx7PgjR5ccZvYAu&ust=1697275027764000&source=images&cd=vfe&opi=89978449&ved=0CBEQjRxqFwoTCJjT-qrY8oEDFQAAAAAdAAAAABB1

Blood vessels

- The aorta



https://my.clevelandclinic.org/-/scassets/images/org/health/articles/17058-aorta-anatomy

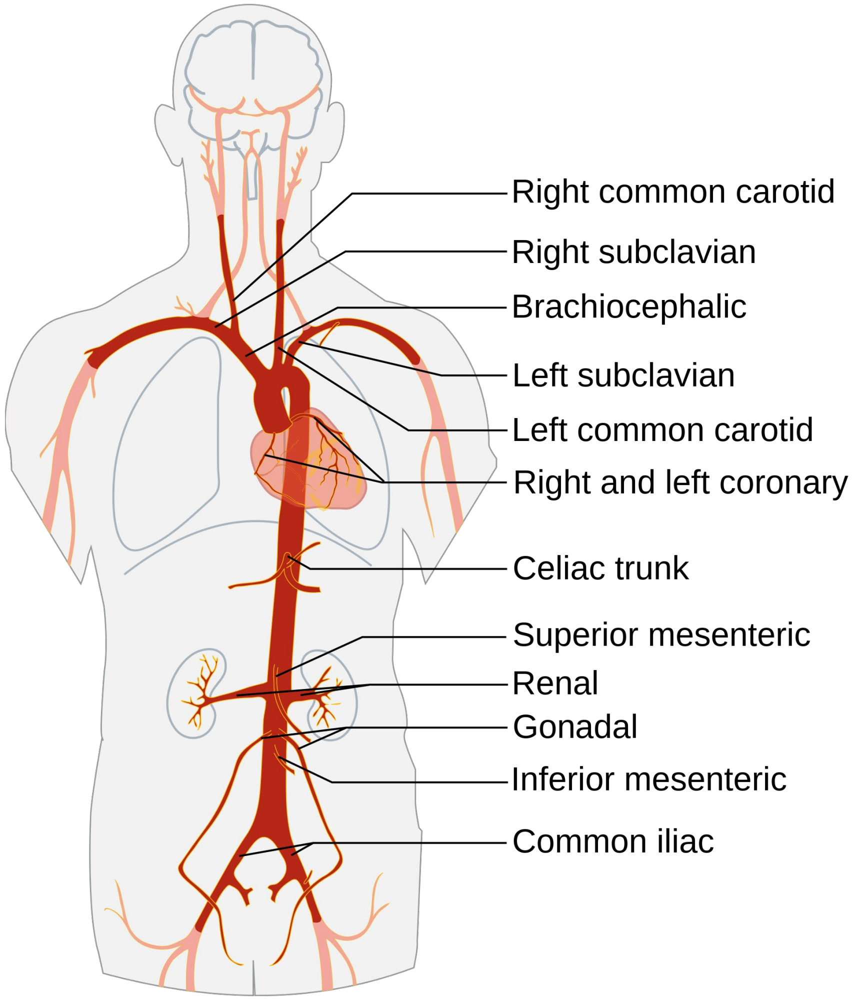
Thoracic segment

Diaphragma

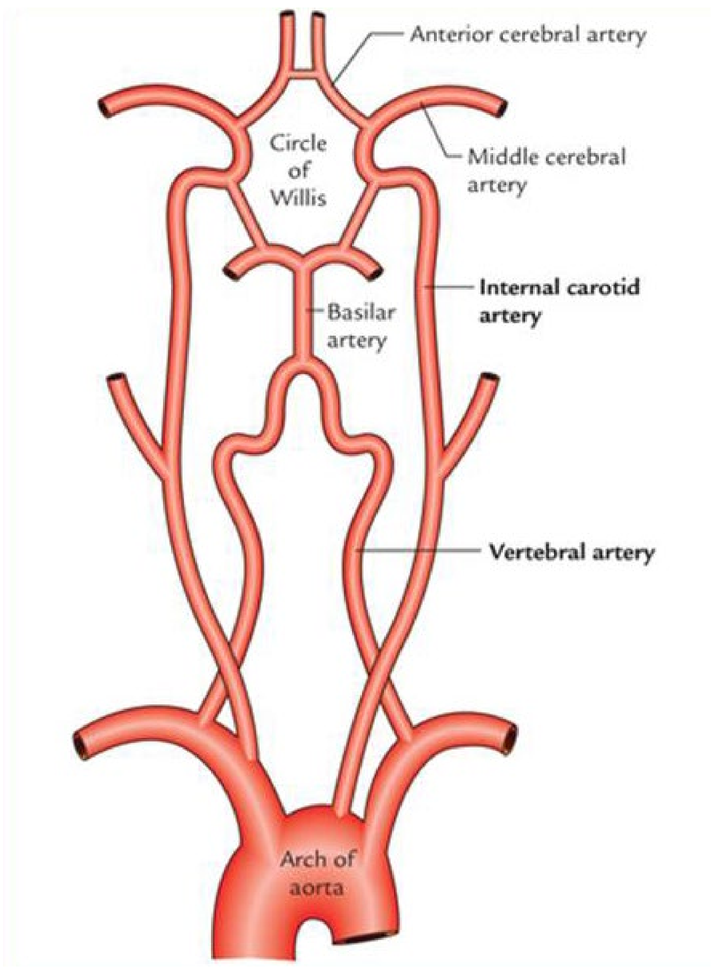
Abdominal segment

Blood vessels

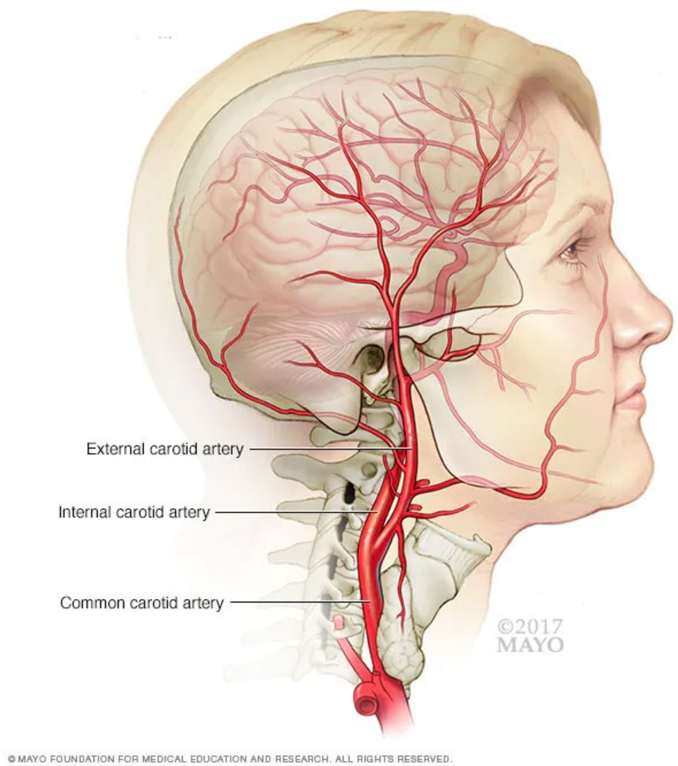
- Blood supply to the brain



https://commons.wikimedia.org/wiki/File:Aorta_branches.jpg



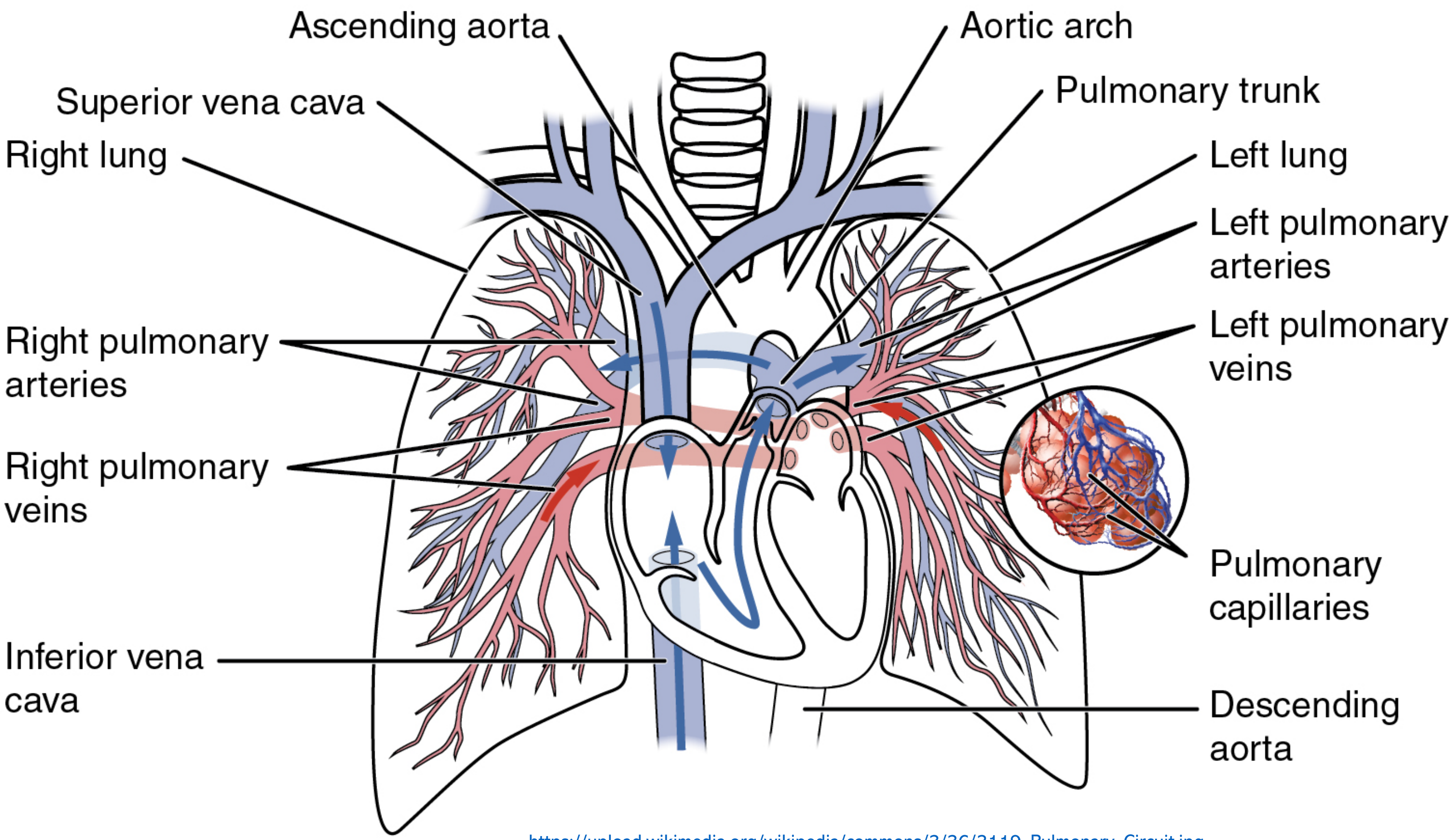
https://doctorlib.info/anatomy/textbook-clinical-neuroanatomy/15.html



https://www.mayoclinic.org/-/media/kcms/gbs/patient-consumer/images/2017/11/07/19/55/mcdc7_carotidartery-8col.jpg

Blood vessels

- Pulmonary circulation

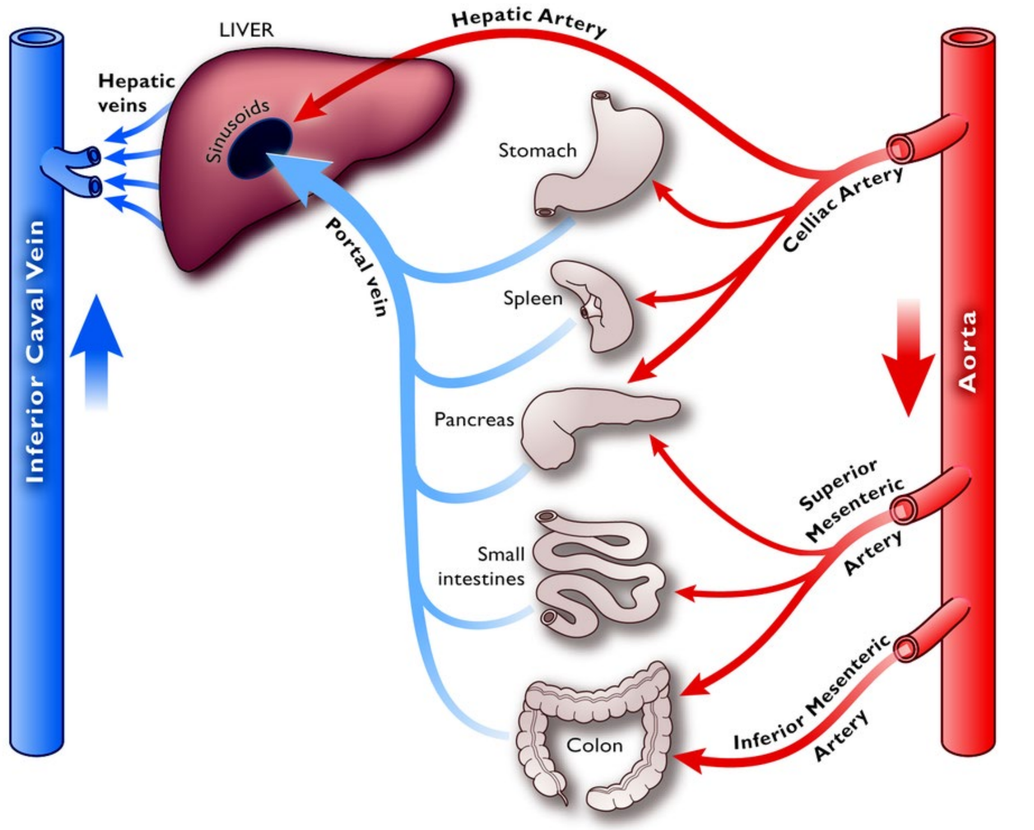


https://upload.wikimedia.org/wikipedia/commons/3/36/2119_Pulmonary_Circuit.jpg

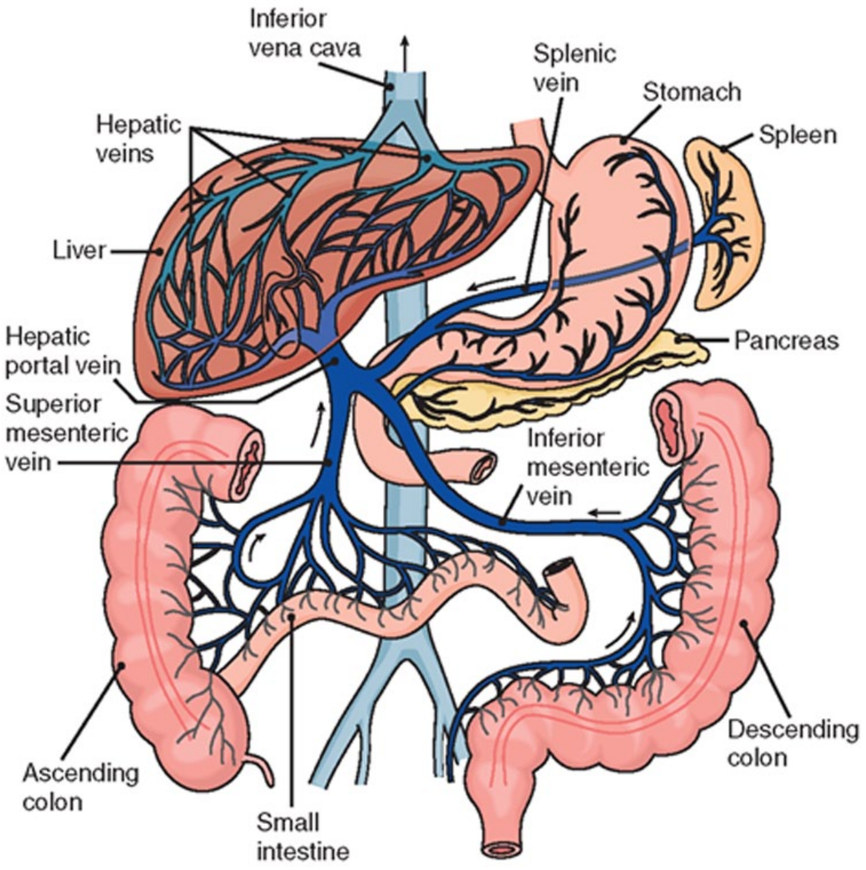
Blood vessels

- (Hepatic) Portal circulation

  The portal vein does not carry blood from the organs towards the heart but to the next organ, which is the liver.



https://pubs.asahq.org/anesthesiology/article/100/2/434/7011/Catecholamine-induced-Changes-in-the-Splanchnic

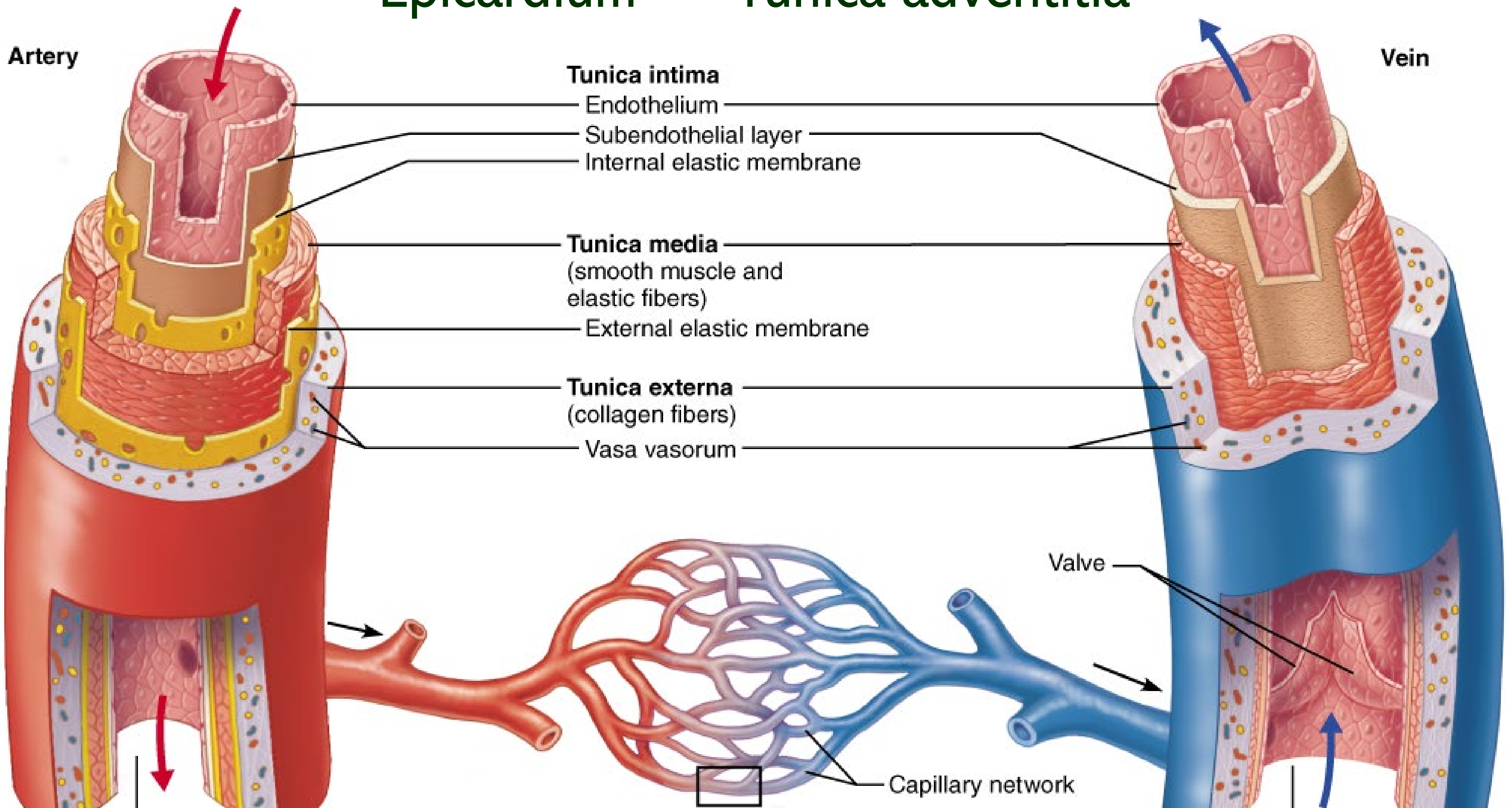


Blood vessels

- Internal structure

  3-layered design

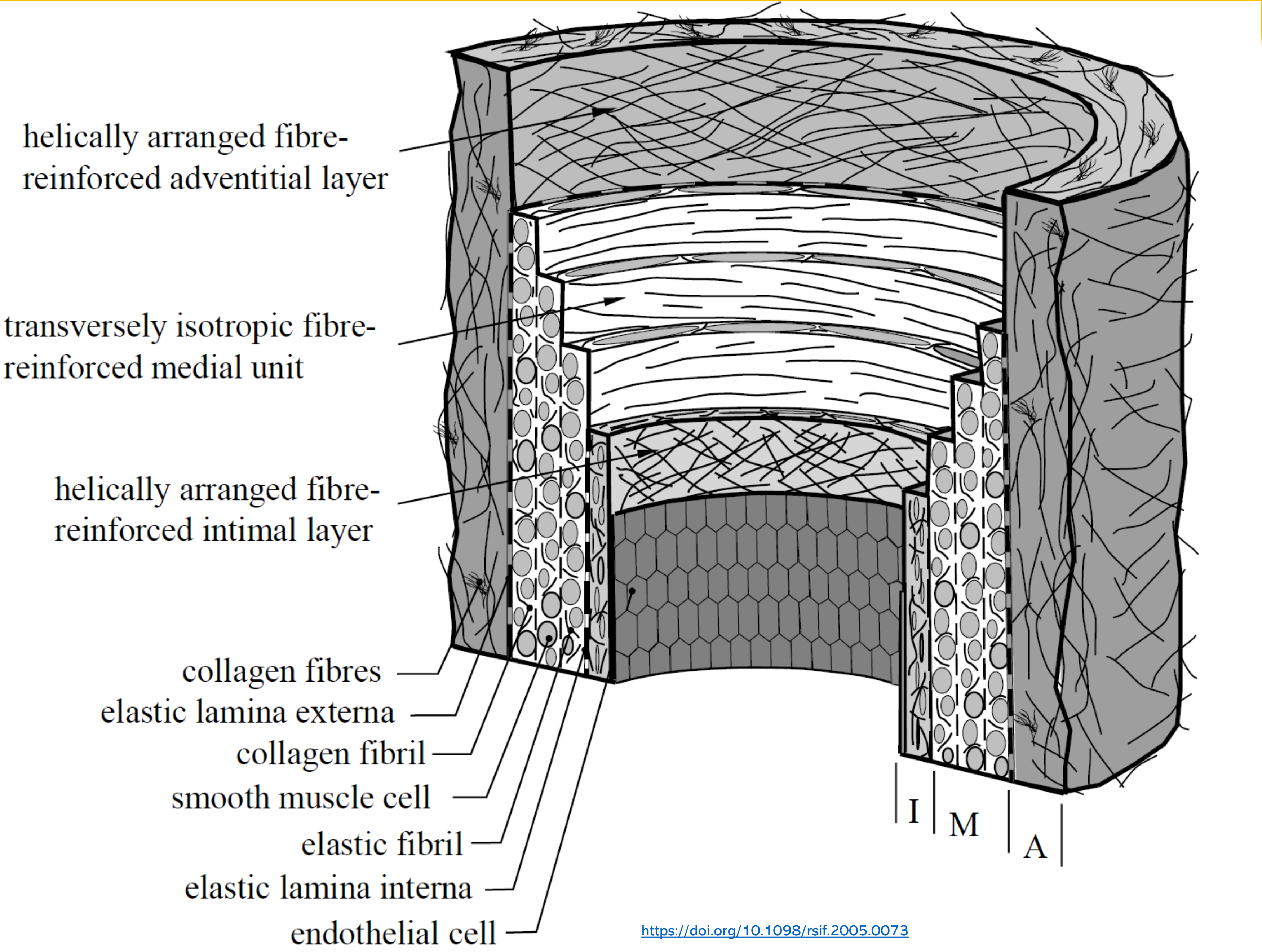
The Heart	Arteries/Veins
Endocardium	Tunica intima
Myocardium	Tunica media
Epicardium	Tunica adventitia



https://www.google.com/url?sa=i&url=https%3A%2F%2Fwww.vrogue.co%2Fpost%2Flabel-the-blood-vessel-human-bio-blood-vessels-biology-i-all&psig=AOvVaw1TAXDbH-YzsyEWpLSPKg4b&ust=1697368391985000&source=images&cd=vfe&opi=89978449&ved=0CBEQjRxqFwoTCND5uZK09YEDFQAAAAAdAAAAABAJ

Blood vessels

- Internal structure



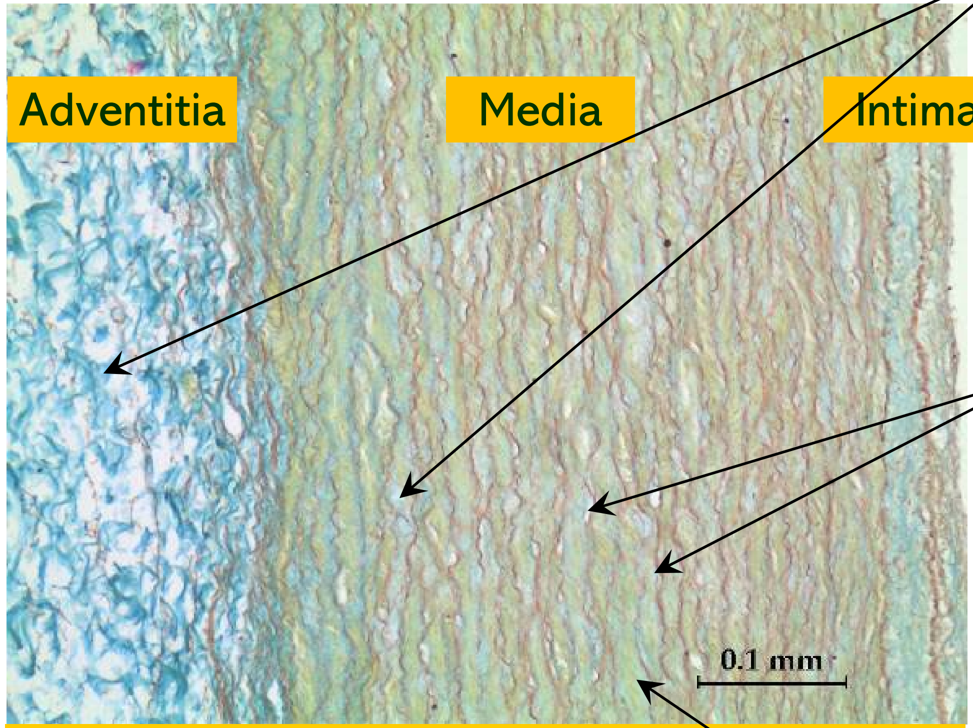
3-layered tube
-tunica intima
-tunica media
-tunica adventitia

https://doi.org/10.1098/rsif.2005.0073

Blood vessels

- Histology

section stained by orcein - elastica



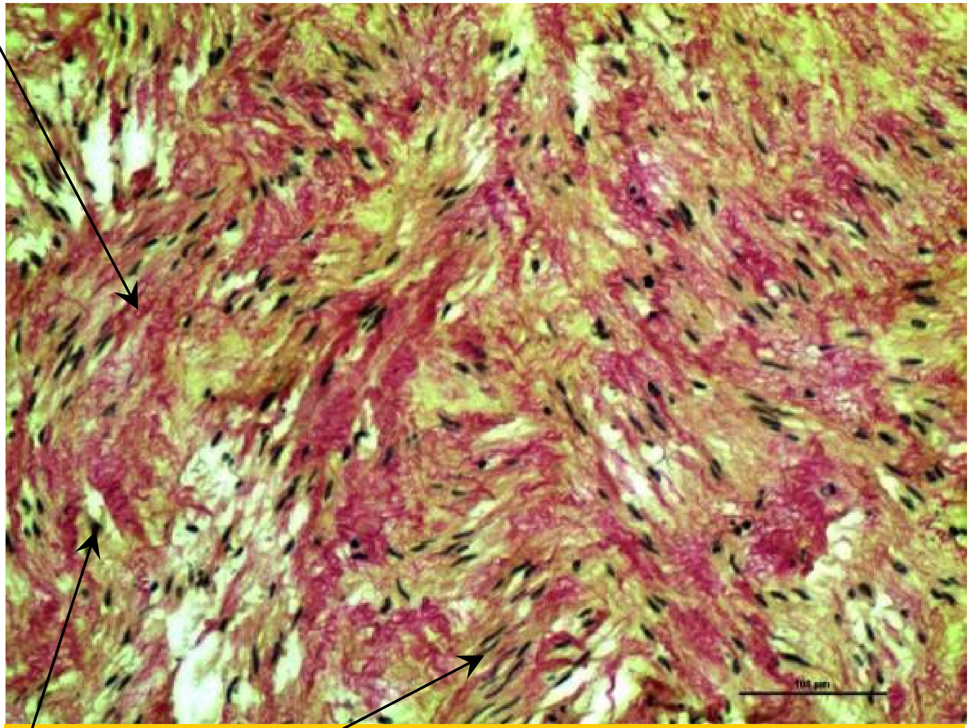
Section of the huma abdominal aorta
(out-of-plane dir = circumferential)

Approx. helically arranged bundles of collagen fibrils

(Fenestrated) Concentric elastic lamellas

Smooth muscle cells

and by Weigert - van Gieson

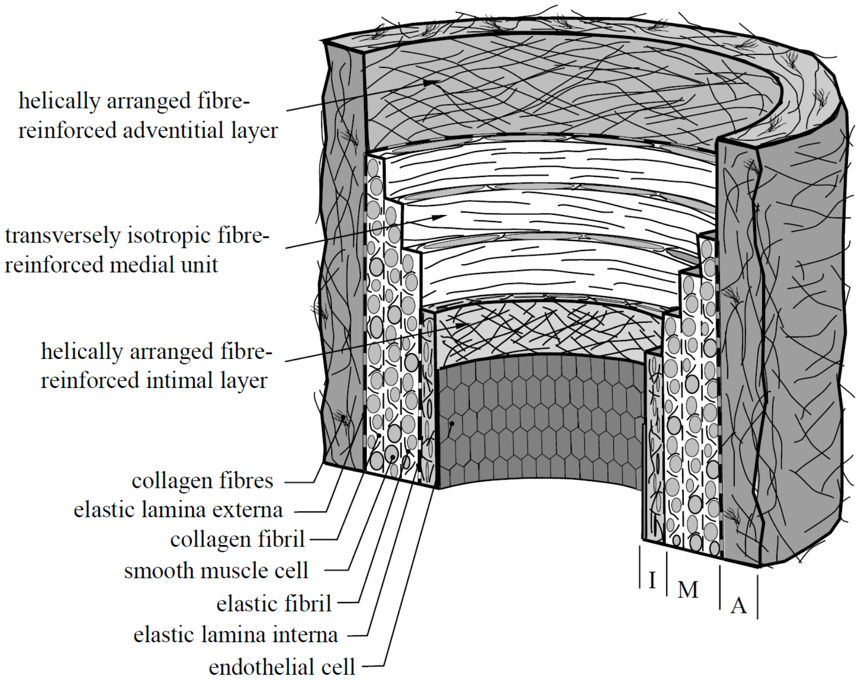


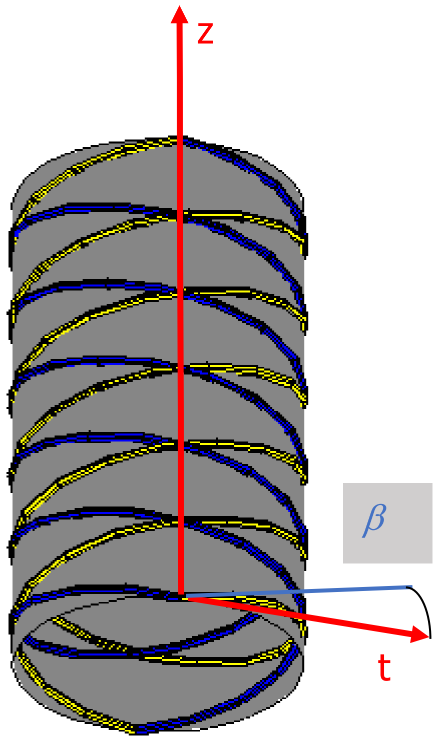
Section of the huma abdominal aorta
(out-of-plane dir = radial)

Blood vessels

- ## Internal architecture

theoretical model simplifies complex arrangement

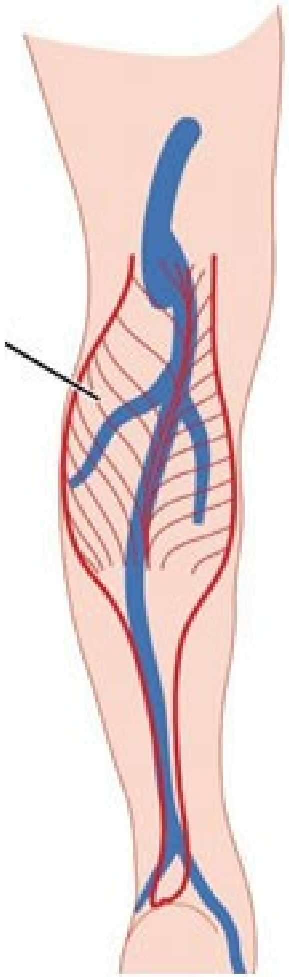




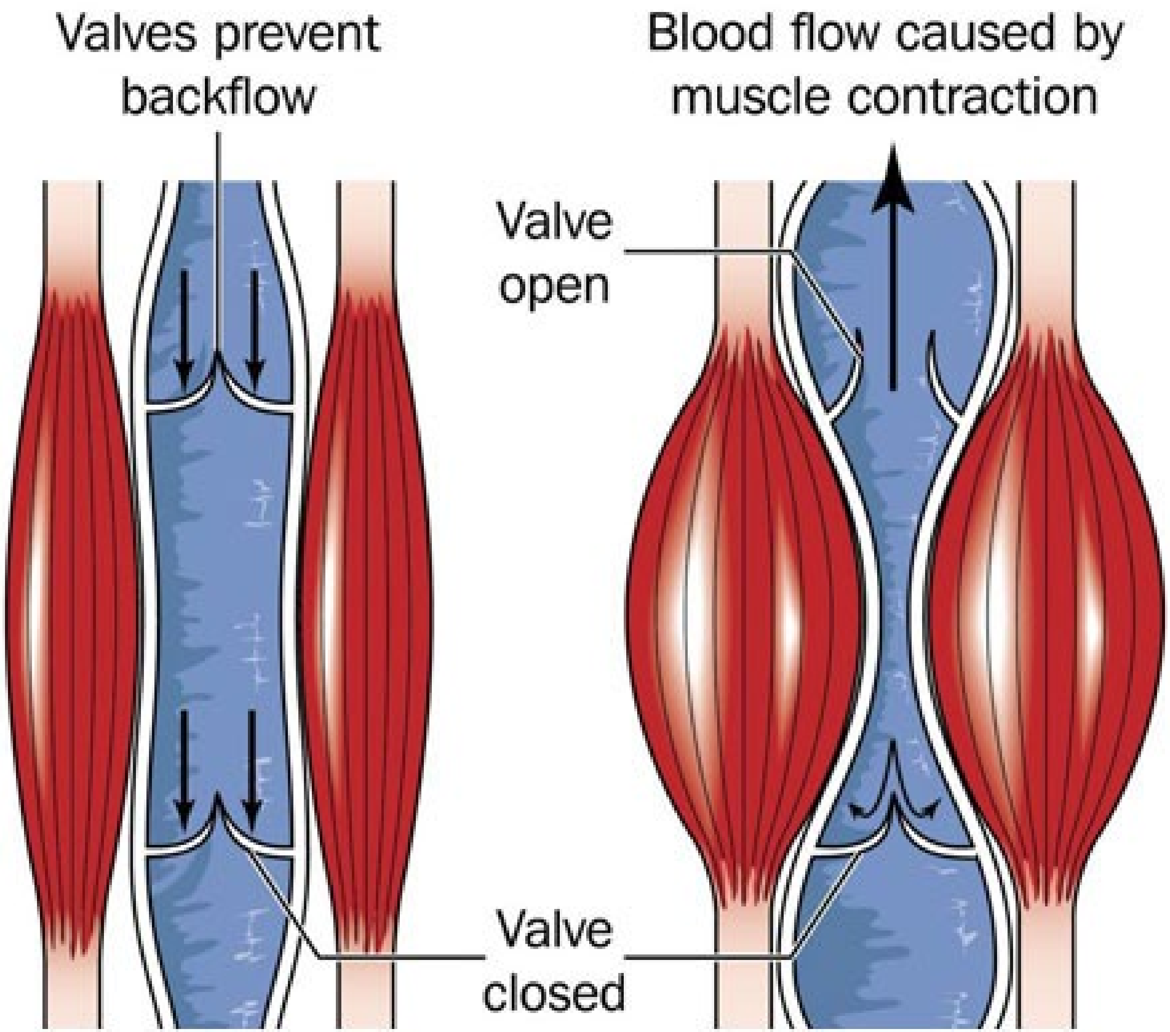
Blood vessels

- Vein valves

The veins are thin and highly compliant so that they can collapse under the external pressure of the muscles in the pump mechanism.



https://classnotes123.com/wp-content/uploads/2023/03/chronic-venous-insufficiency-.jpg



Cells

- **Cardiomyocyte**
  - contractile cell
  mechanical work

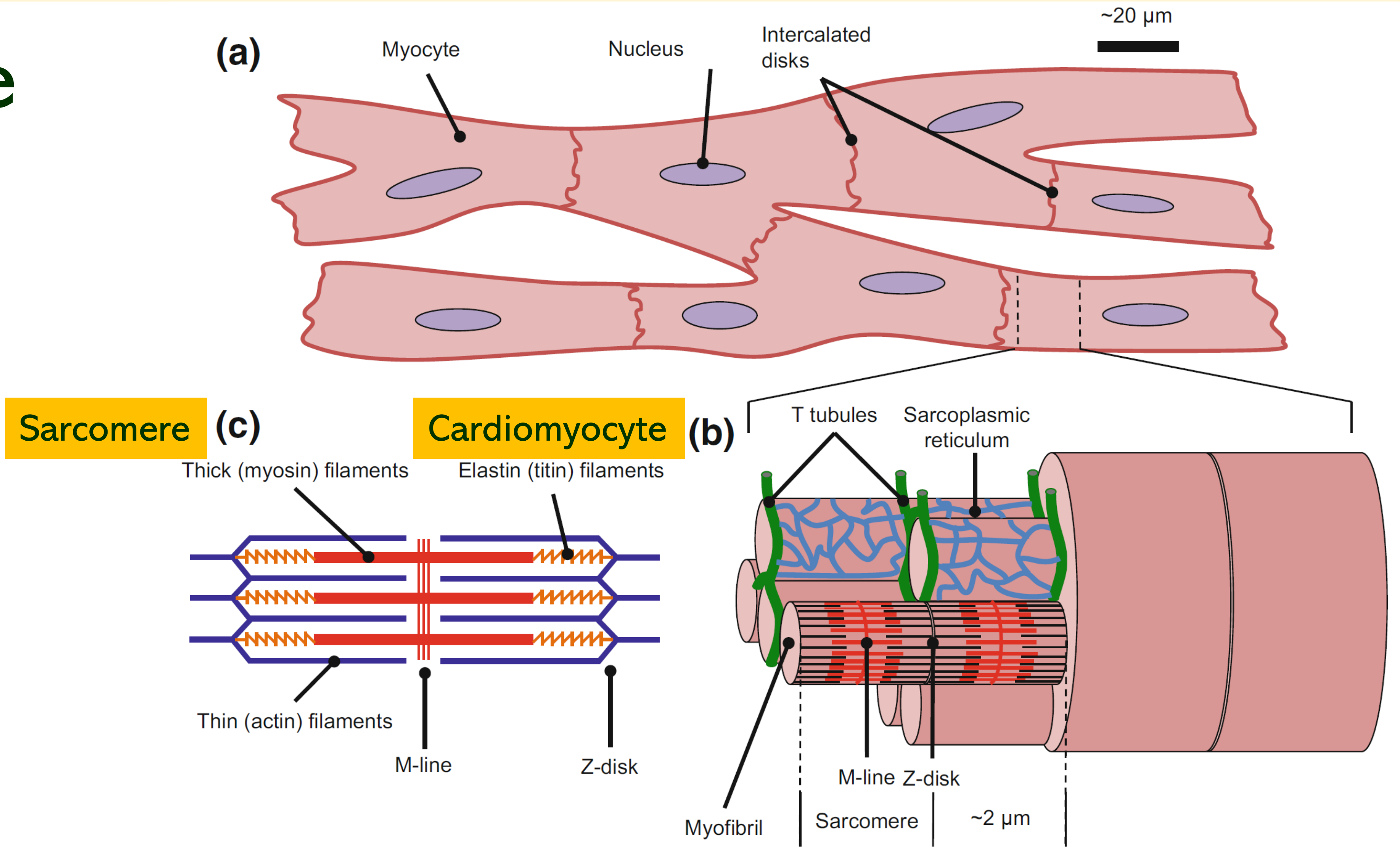
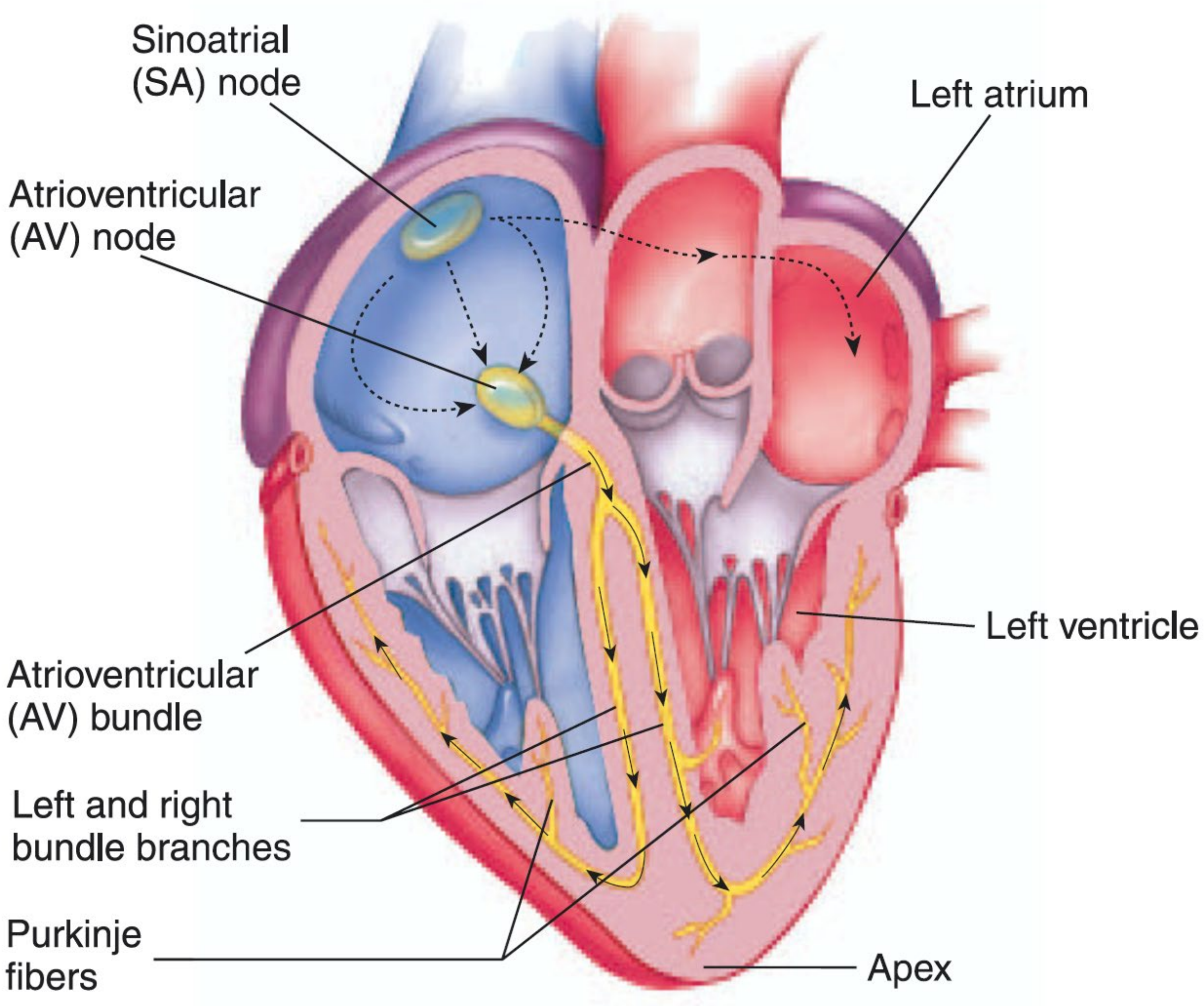


Fig. 6.3 Structure of cardiac tissue and myocytes. **a** Arrangement of cardiac myocytes and connections between them. **b** Internal structure of myocyte. **c** Diagram showing the contractile apparatus within a myofibril

https://link.springer.com/book/10.1007/978-3-319-46407-7

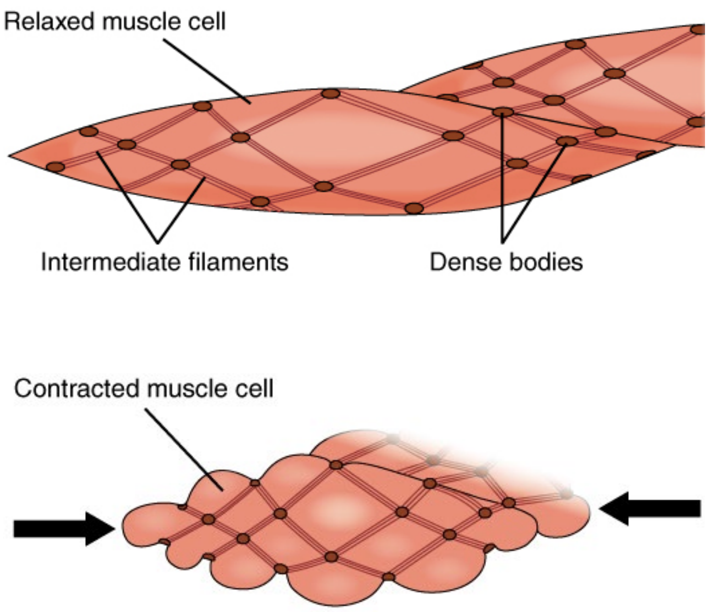
Cells

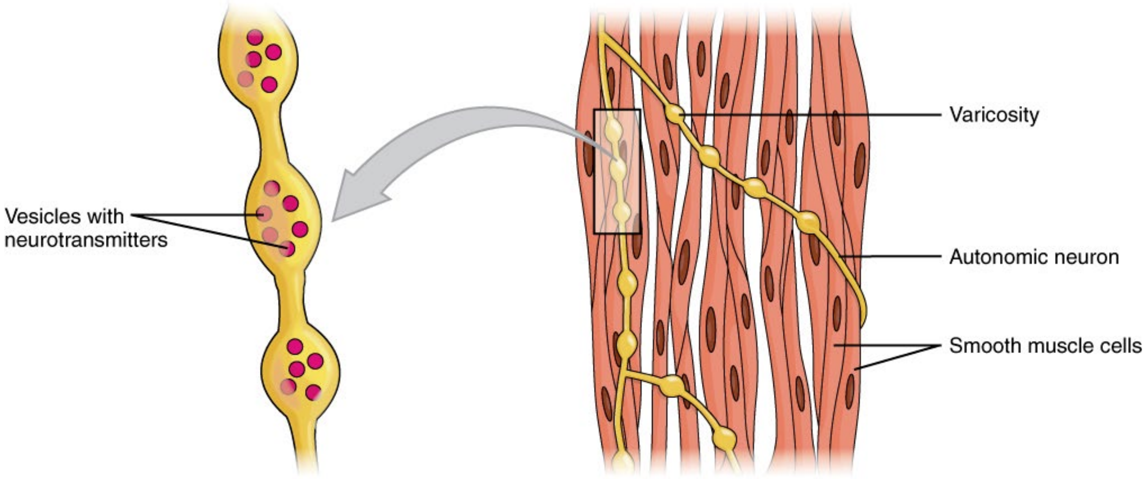
- Cardiomyocyte
  - pacemaker (conductor) cell
  signal transfer

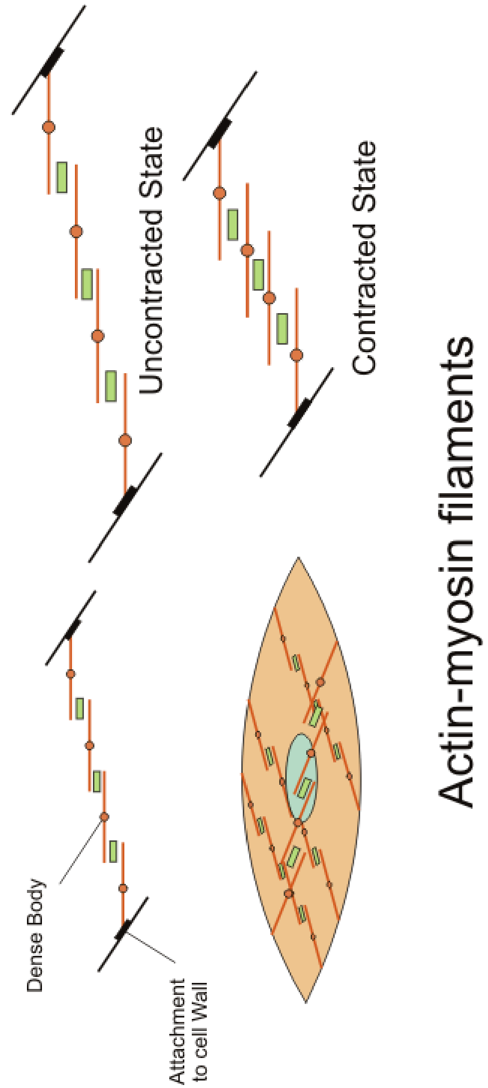


Cells

- Smooth muscle cell
  - in the tunica media
  - contractile
  - ECM synthesis



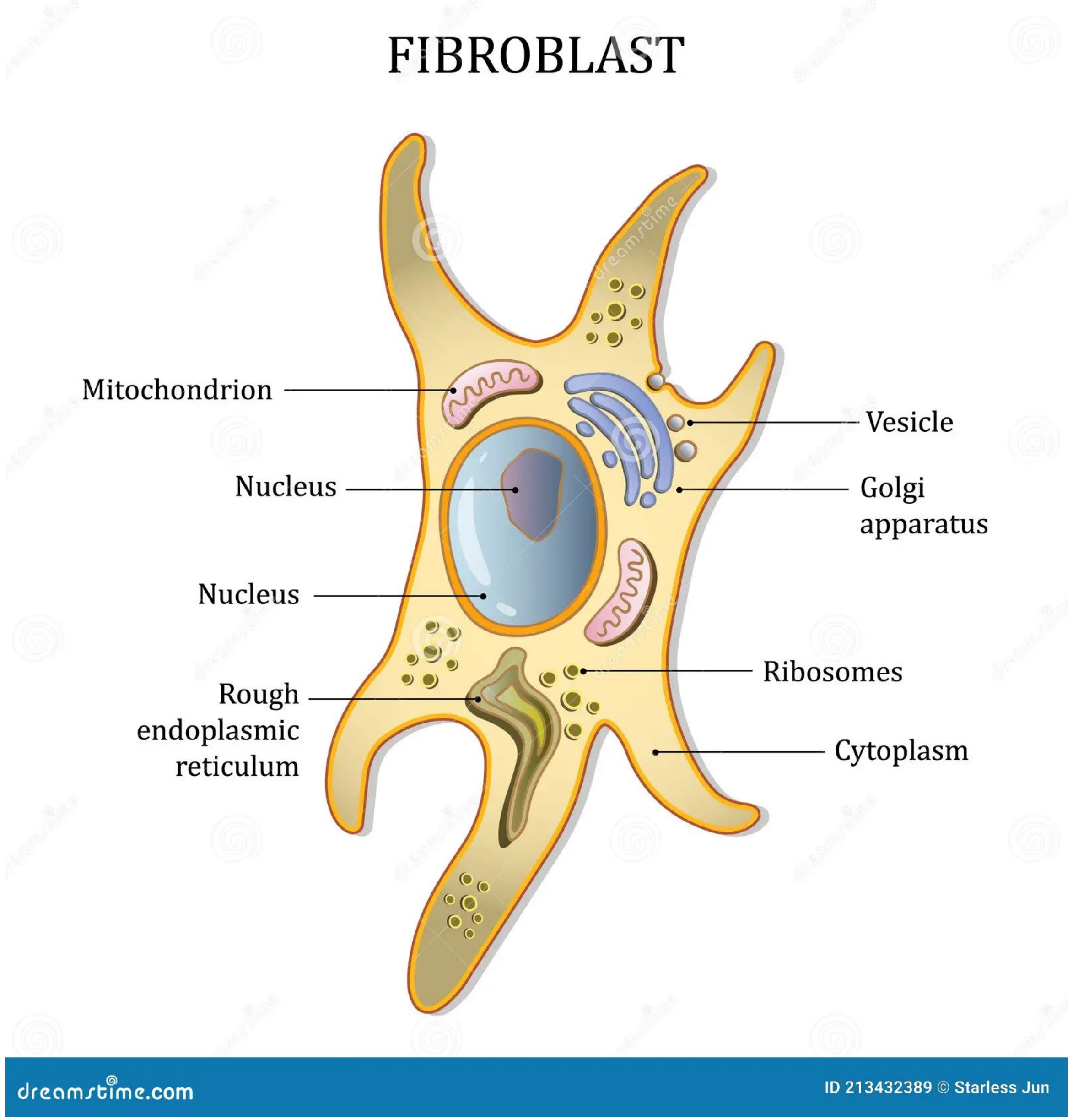




Cells

- Fibroblast
  - in the tunica adventitia
  - synthesis of extracellular matrix (building proteins)

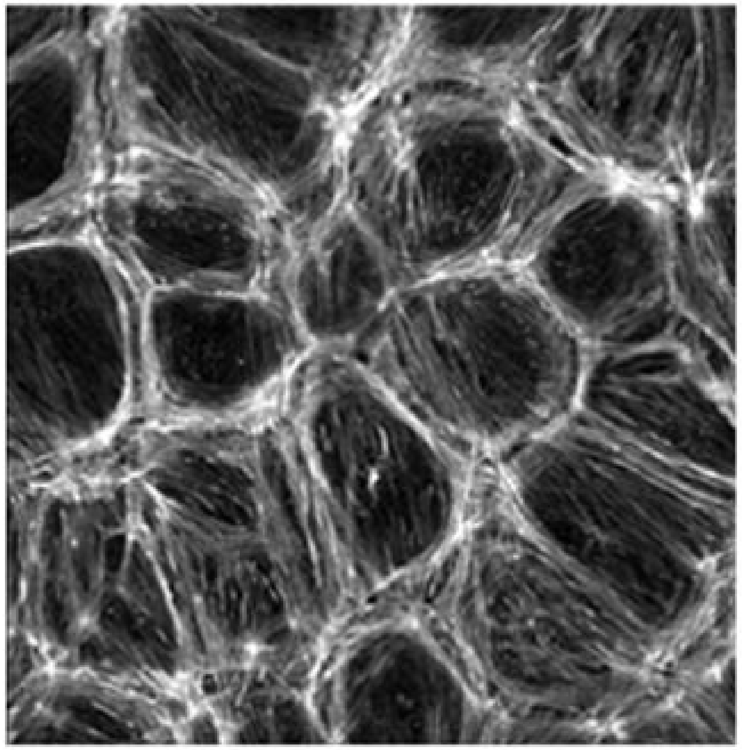
  collagens
  elastic fibers



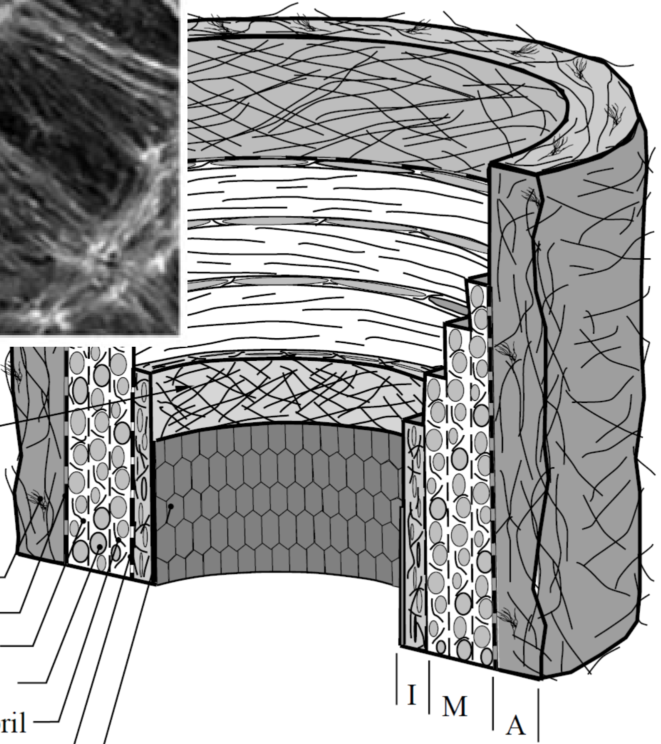
https://thumbs.dreamstime.com/z/structure-fibroblast-cells-cell-vital-to-skin-s-strength-elasticity-fibroblast-cell-structure-connective-213432389.jpg?w=768

Cells

- Endothelial cell
  - mechano-sensitive element
  converts mechanical signal to chemical signal
  - communication element
  controls passage of substances from bloodstream into the wall



https://www.sciencedirect.com/science/article/pii/S0002944010632099



Extracellular matrix

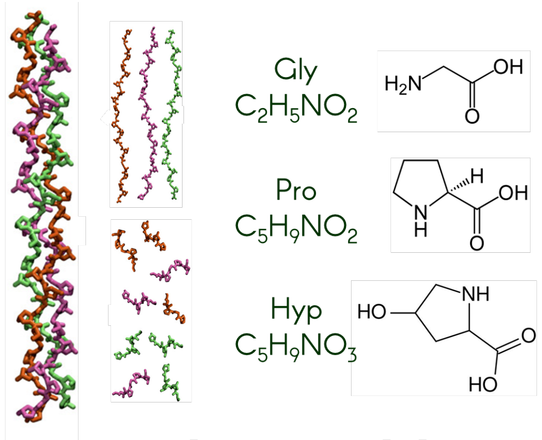
- Networks of collagen fibers
- Elastic fibers and membranes
- Laminins and integrins
- Ground substance

  gel-like mixture of various glycosaminoglycans, proteoglycans and glycoproteins
  + water

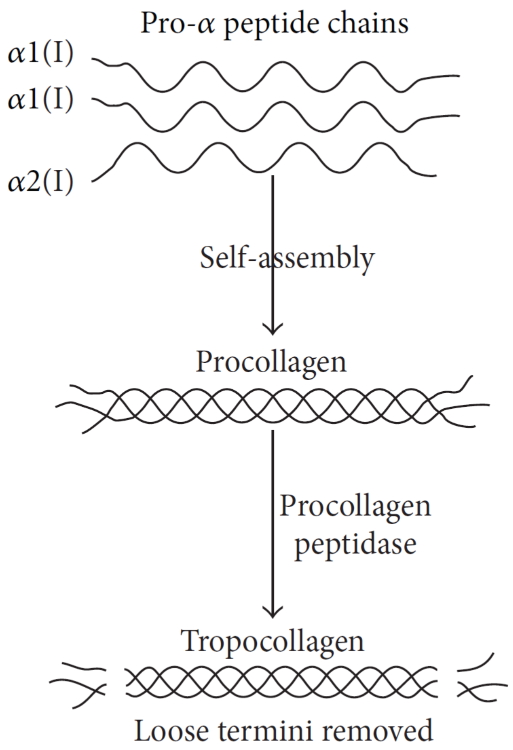
Collagen

- Forms Networks of fibers
- Collagen macromolecule = tropocollagen

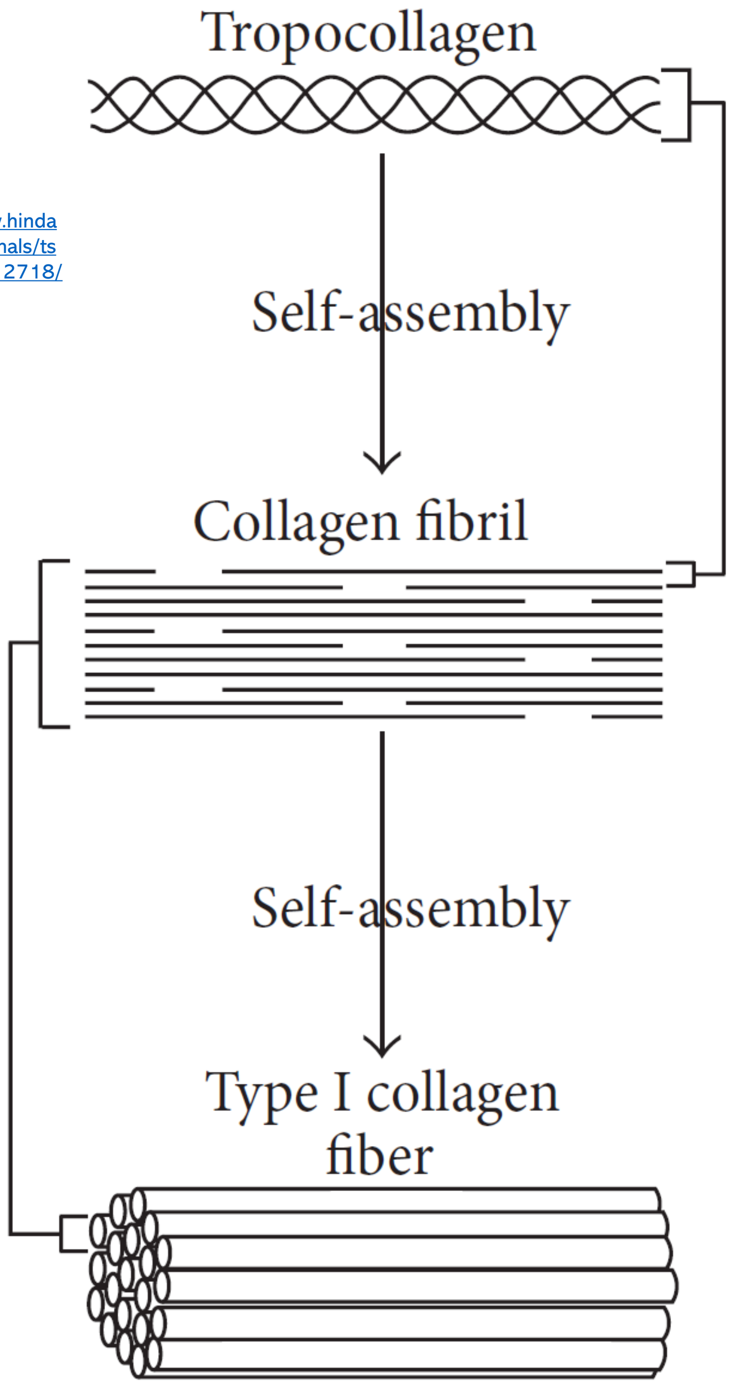
3-helix chain of amino acids



(tropo)collagen ≐ [Gly–Pro–X]$_n$ [Gly–Y–Hyp]$_m$



https://www.hindawi.com/journals/tswj/2013/812718/



Collagen

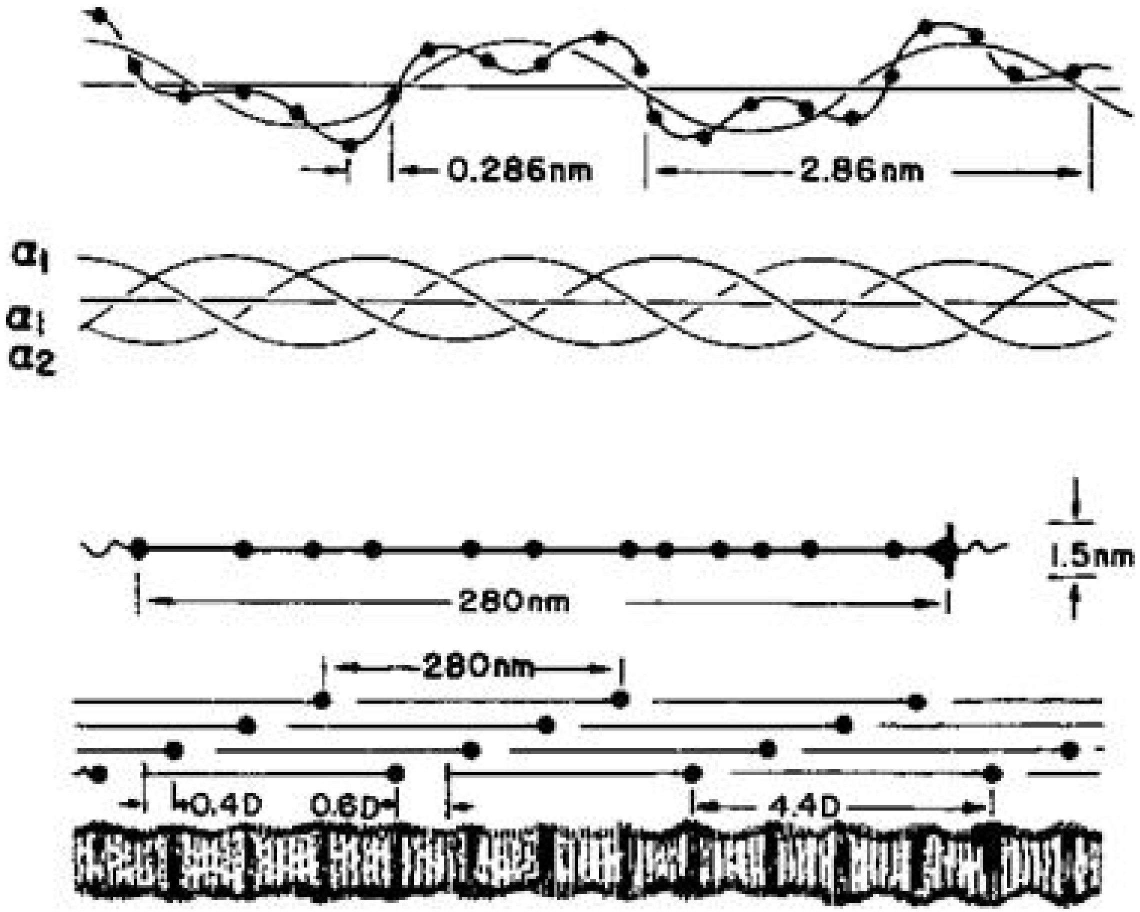
- Approx 30 isomers

Chained amino acids

Alpha chains forming (macro)molecule

collagen
molecular mass
≈300 000 g/mole

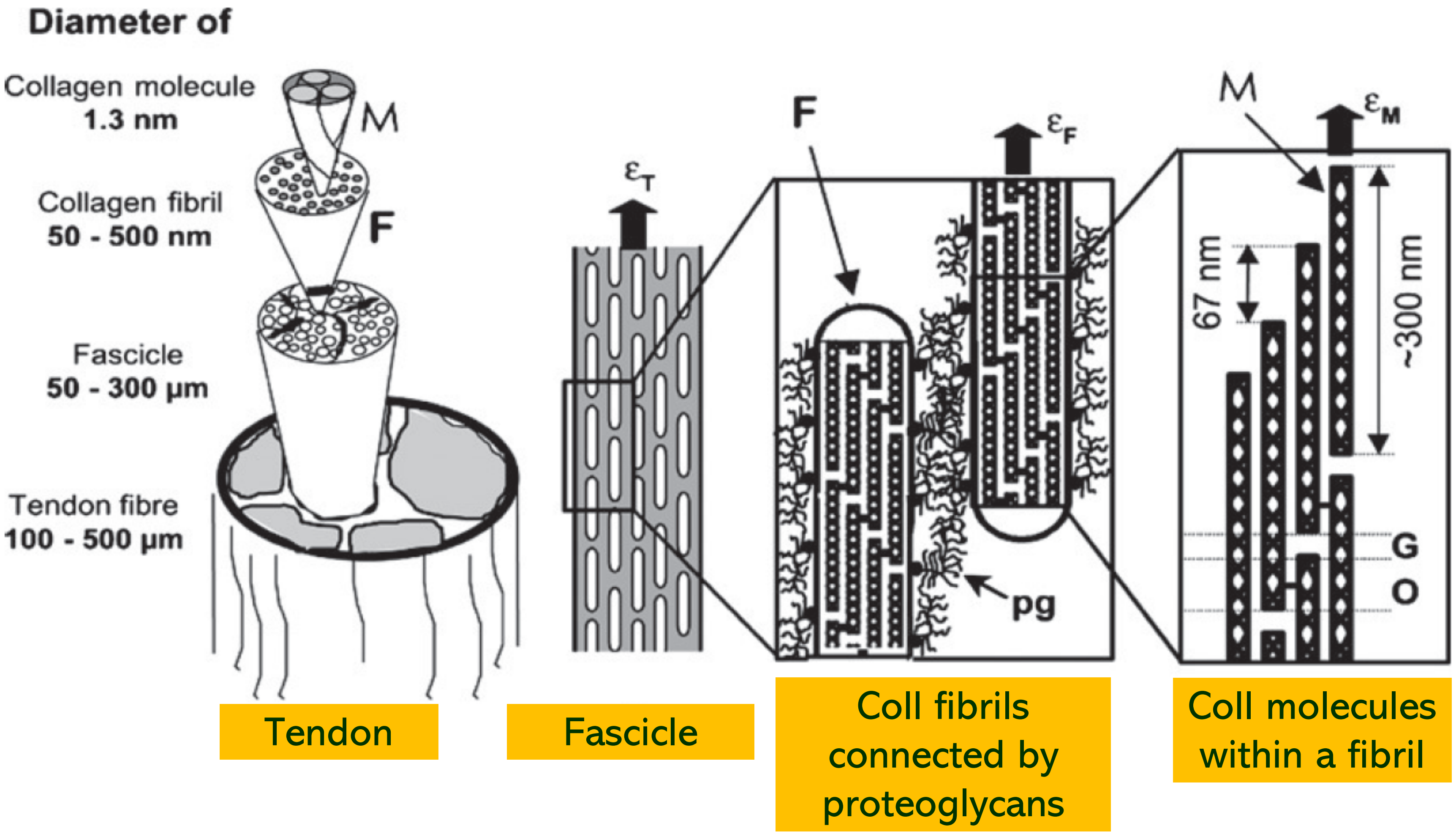
(Macro)Molecules forming a fibril



Collagen

- Complex hierarchical arrangement into fibril

tendon as
an example

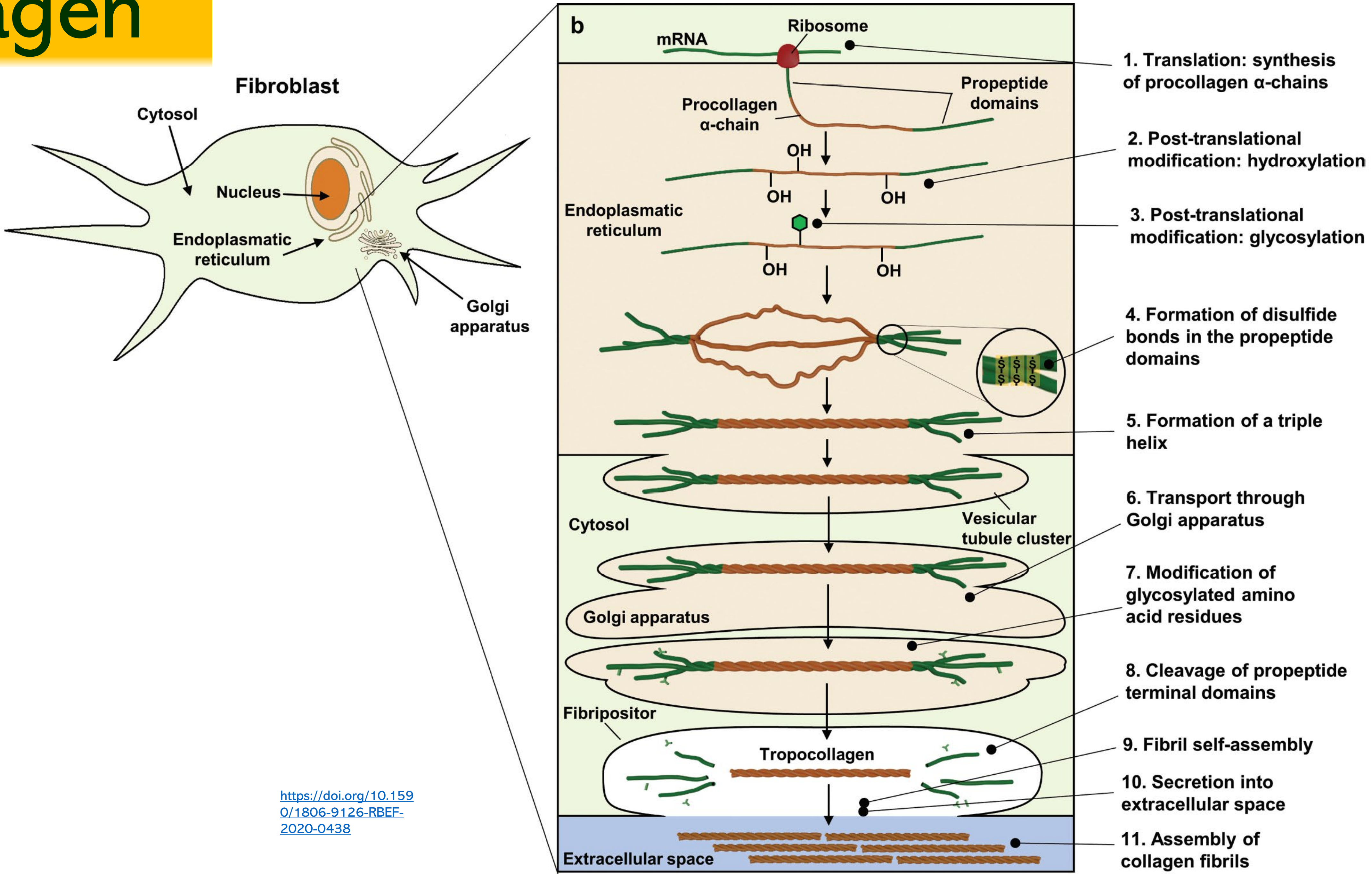


https://doi.org/10.1016/S1359-0294(03)00011-6

Collagen

Synthesis

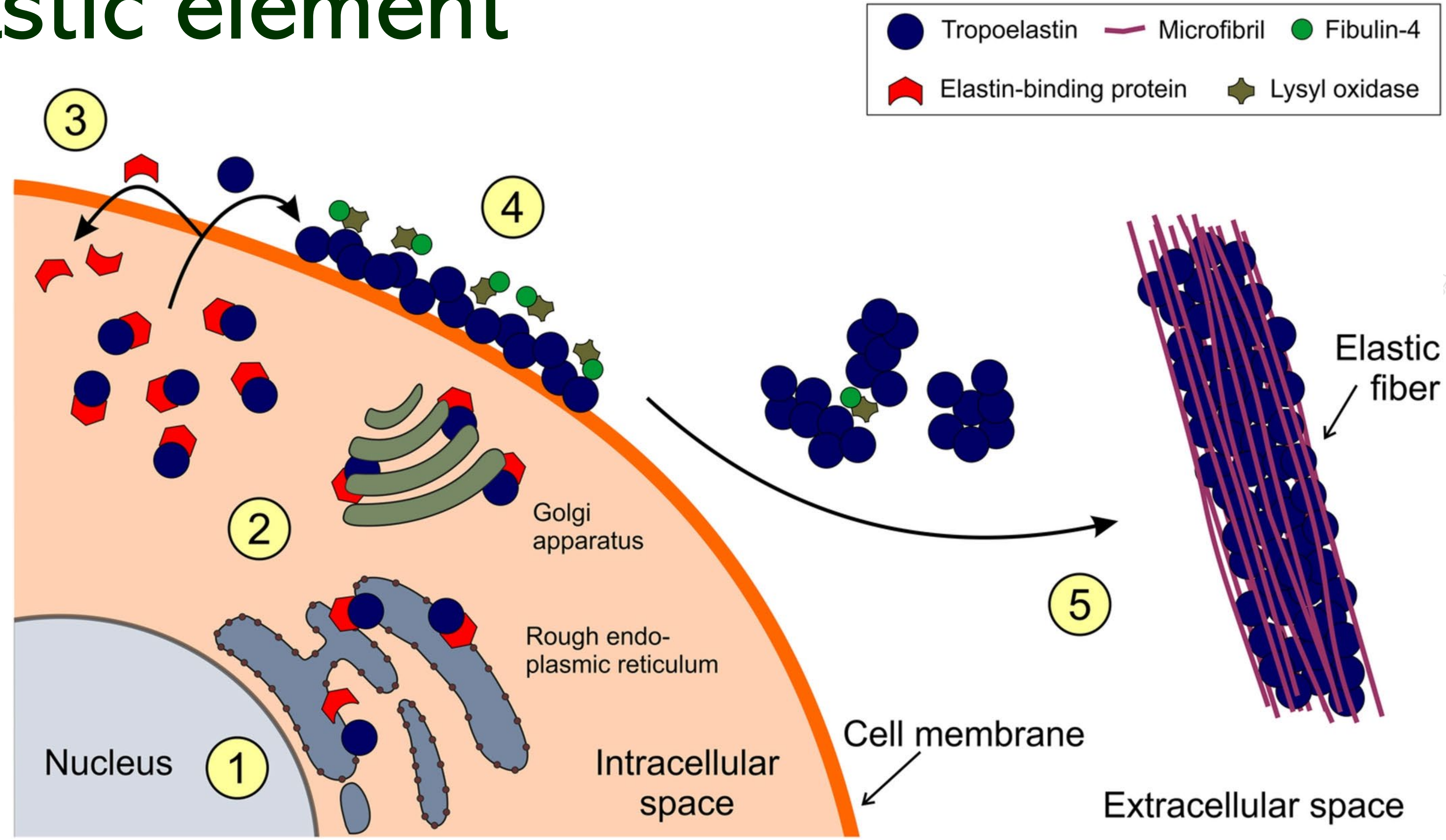
Cell nucleus: transcription of DNA to RNA

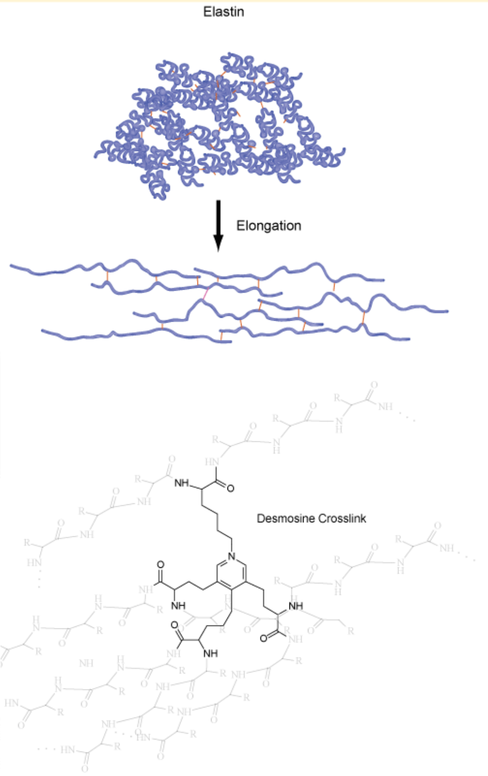


https://doi.org/10.1590/1806-9126-RBEF-2020-0438

Elastic fiber

- Fiber or membrane
- Elastin + microfibril
- Main elastic element
- β-sheet

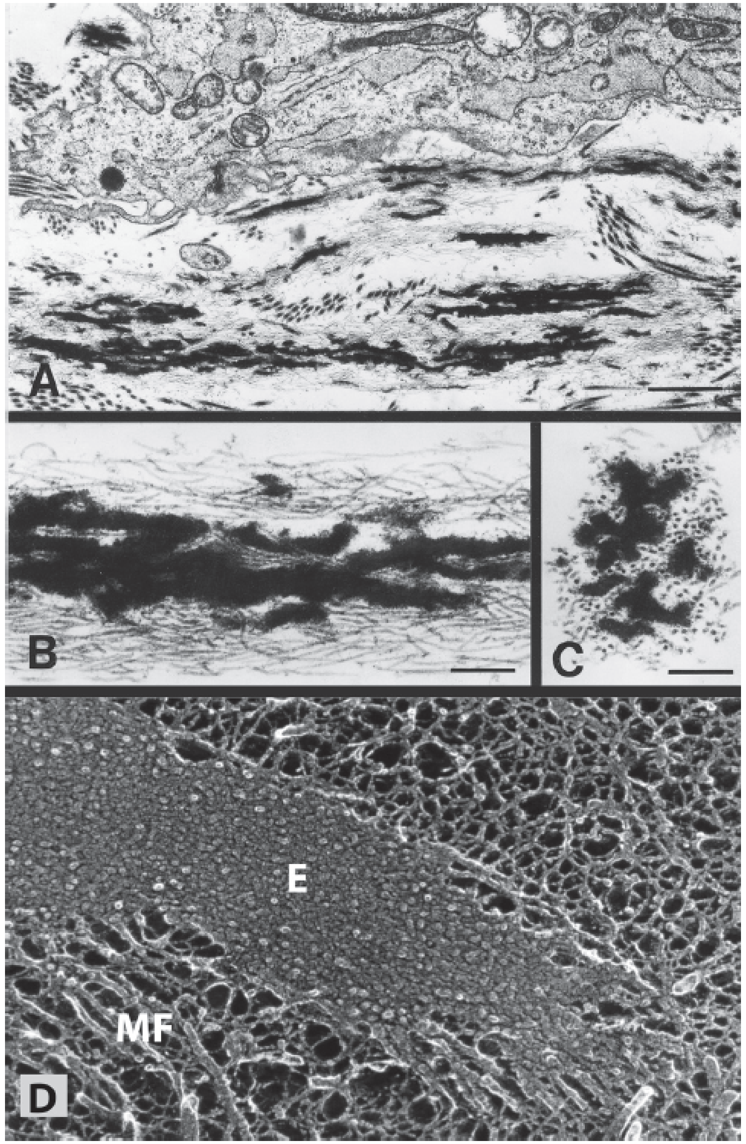




https://doi.org/10.1002/iub.2213

Extracellular matrix

Elastin
(β-sheet)

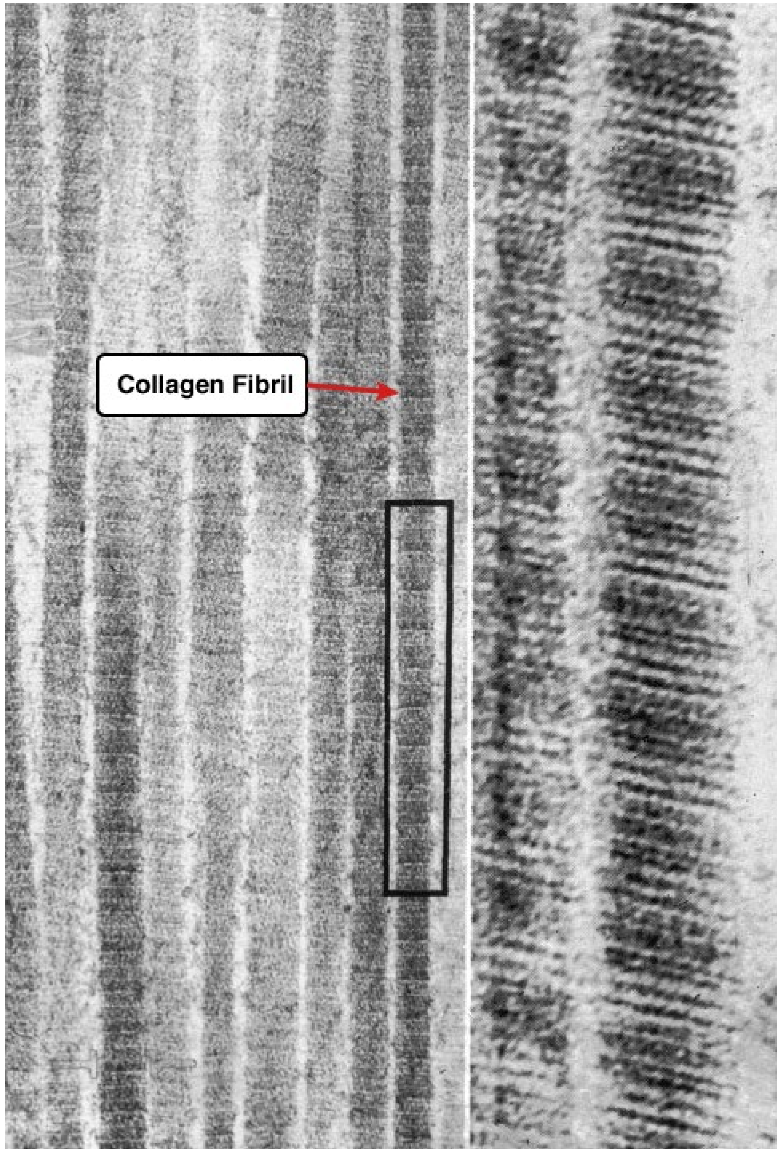


Collagen
(3 α-helix)

1 μm

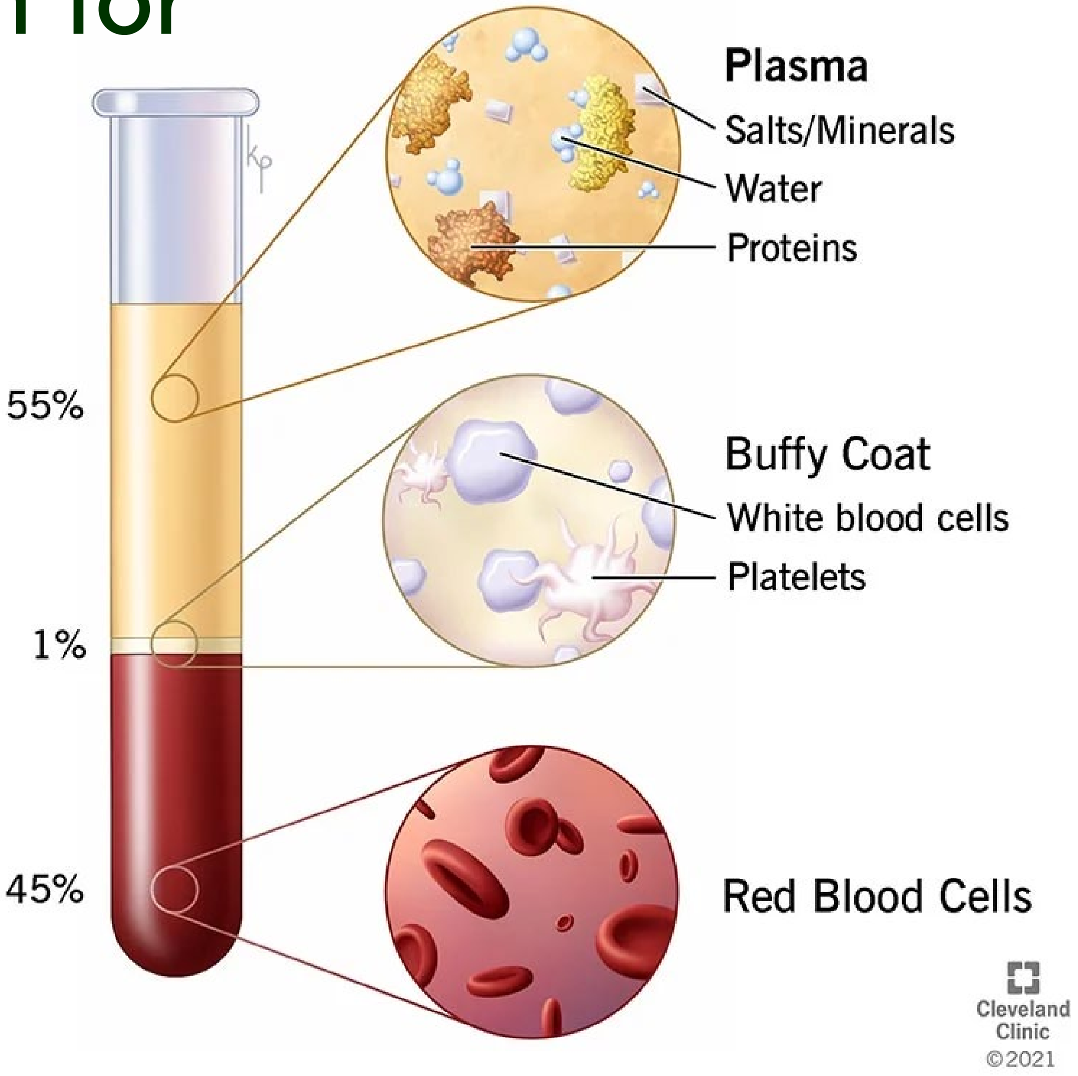
250 nm

≈ 10 nm



Blood

- Blood is transporting medium for
  - O2
  - Nutrients and metabolic waste
  - Immune system reaction
  - Regulatory molecules
  - Heat



https://my.clevelandclinic.org/health/body/22865-plasma

- The blood is a suspension of solid particles (approx. 45% vol.) and blood plasma (approx. 55% vol.) volume of 4.5 – 5.5 liters

Blood

- **Red blood cells**

  erythrocytes ~5 000 000 in mm^3

  oxygen, lack nucleus

- **Platelets**

  thrombocytes ~250 000 in mm^3

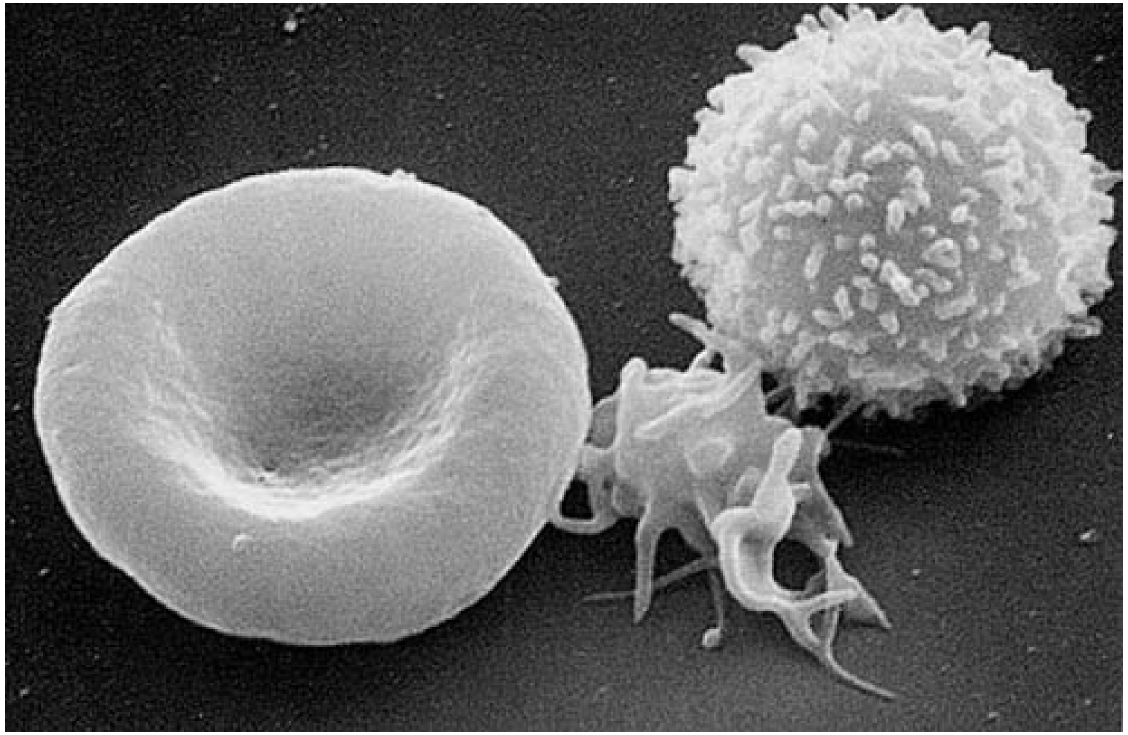
  ensure blood clotting (coagulation)

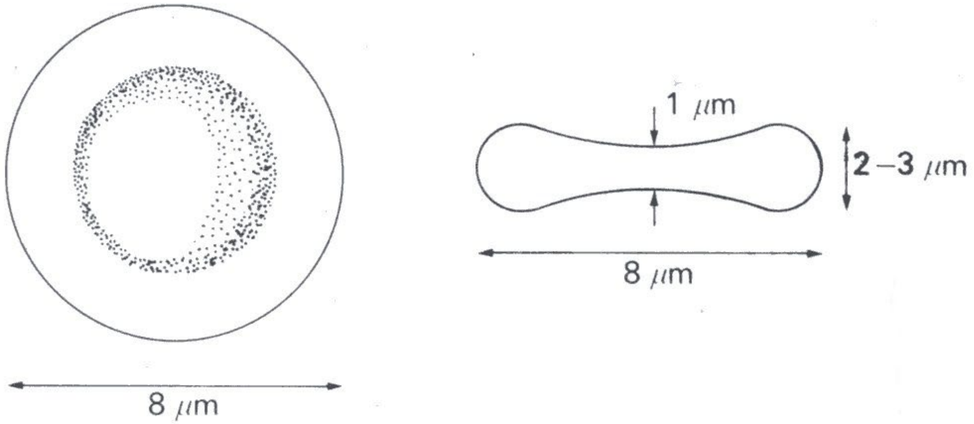
  also lack nucleus

- **White blood cells**

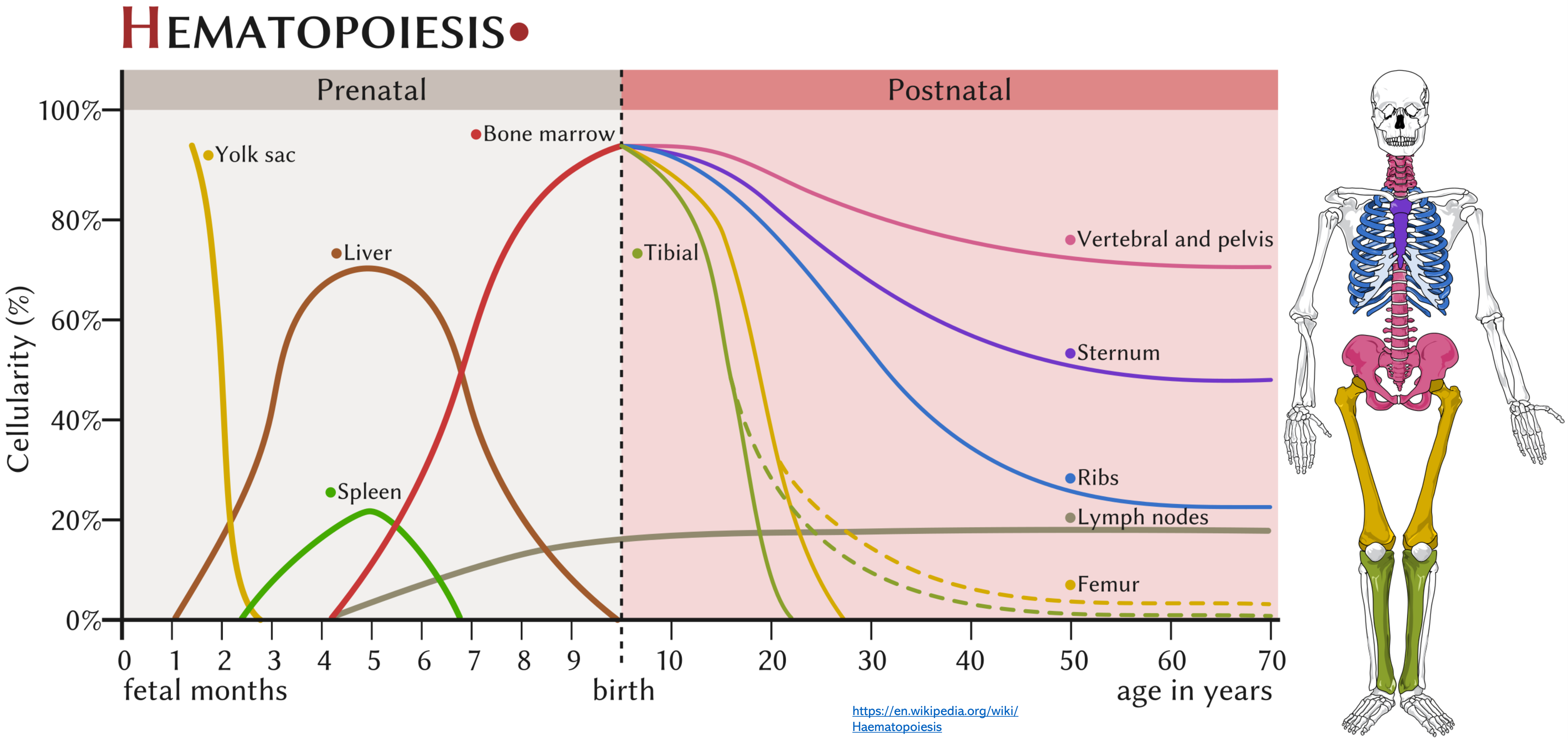
  leukocytes ~7000 in mm^3

  immune reaction





Blood



https://en.wikipedia.org/wiki/Haematopoiesis

Blood

- Blood plasma

  90% H_2O

  7% plasma proteins: serum albumin + globulins + fibrinogen + …

  2% hormones

  1% enzymes + glucose + minerals

Physiology of the Blood Circulation

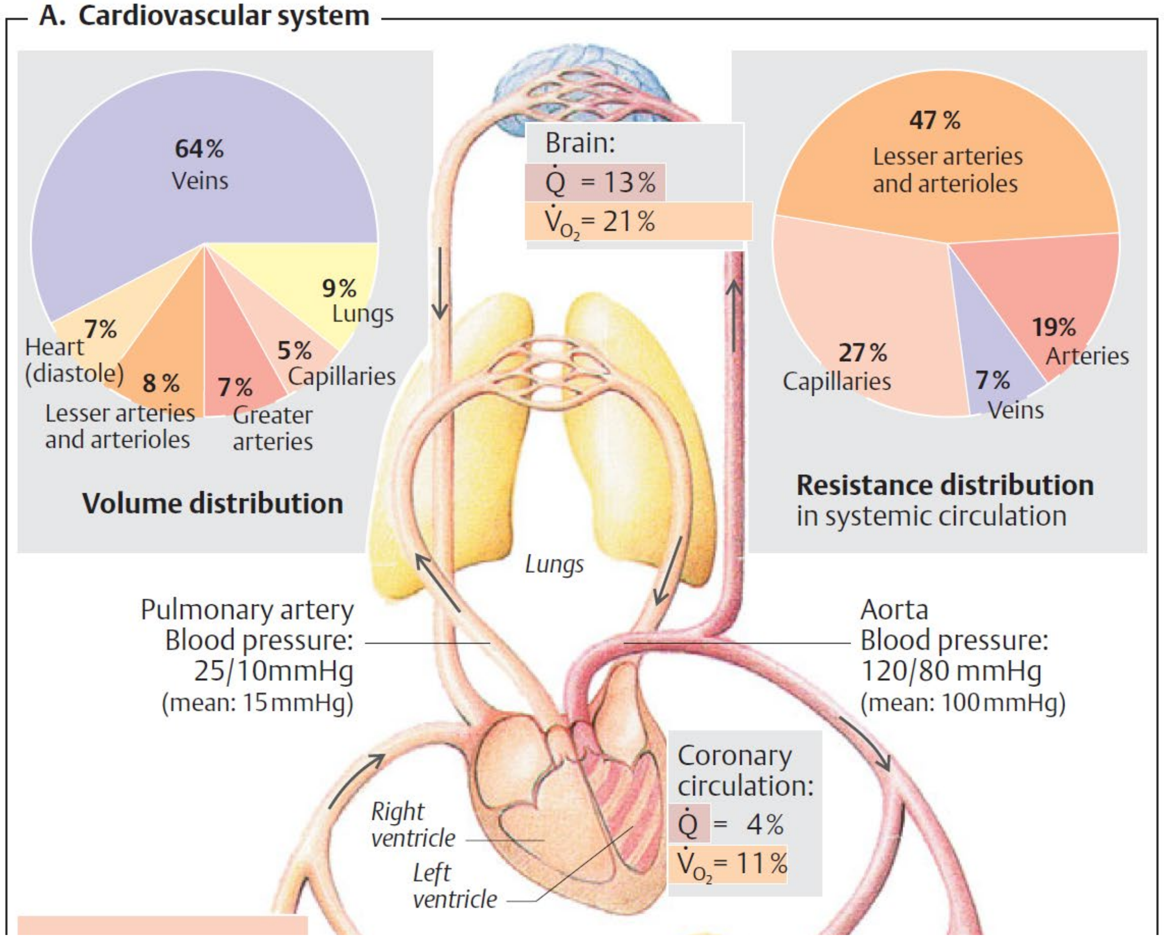
Physiology

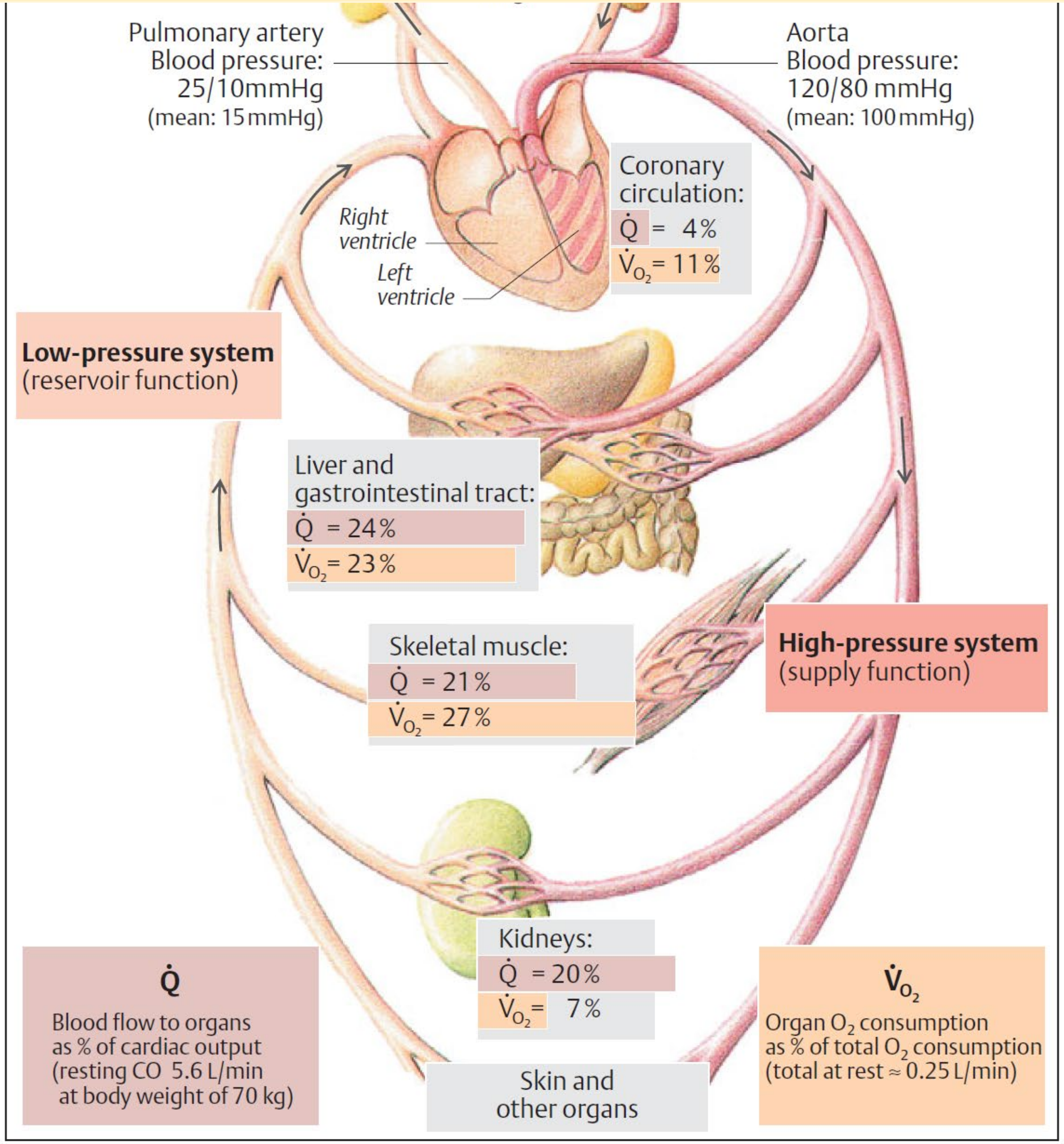
Physiology, as the name suggests, deals with the physics of life processes in the human organism.

Since the purpose of the cardiovascular system is to transport blood, the physiology of circulation is actually the essence of cardiovascular biomechanics.

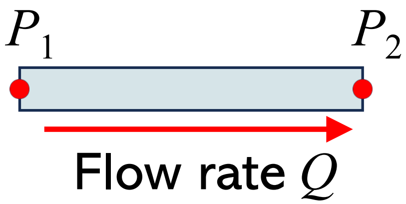
In addition to mechanics as the science of motion, another essential part is bioelectromagnetism, the electrophysiology of circulation, which deals with the electrical activity of the heart (cardiac conduction system).

General Physiology





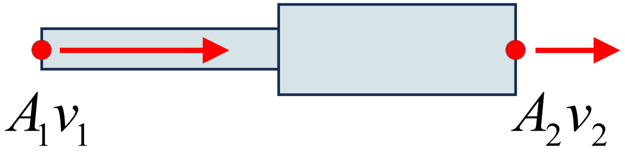
$$Q = \frac{\Delta P}{R} = \frac{P_1 - P_2}{R}$$



General Physiology

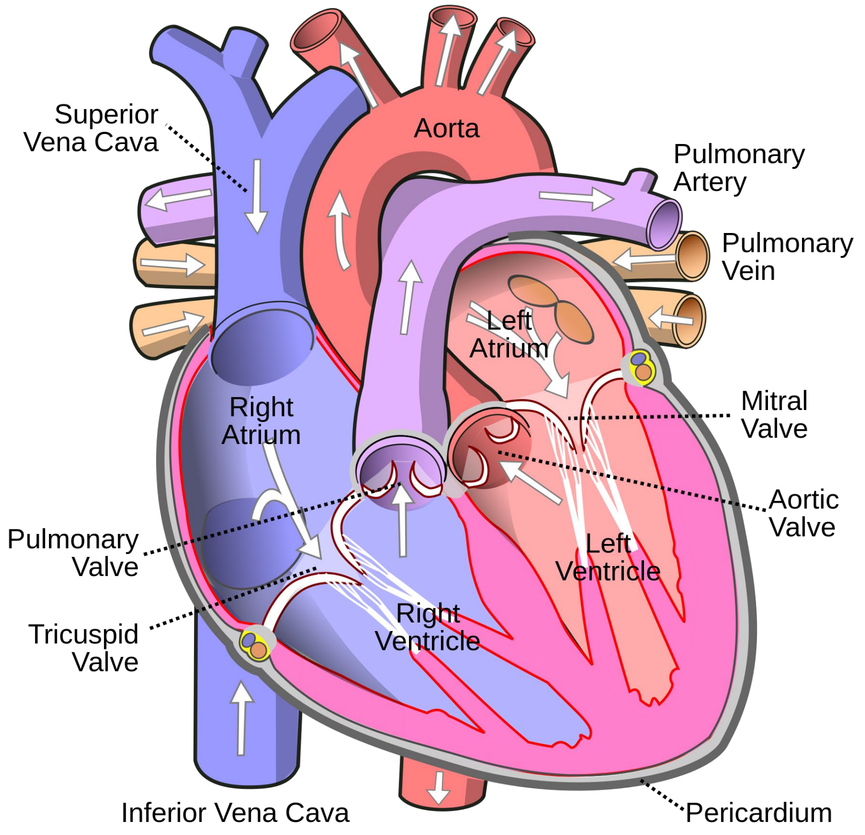
A. Characteristics of the vessel segments

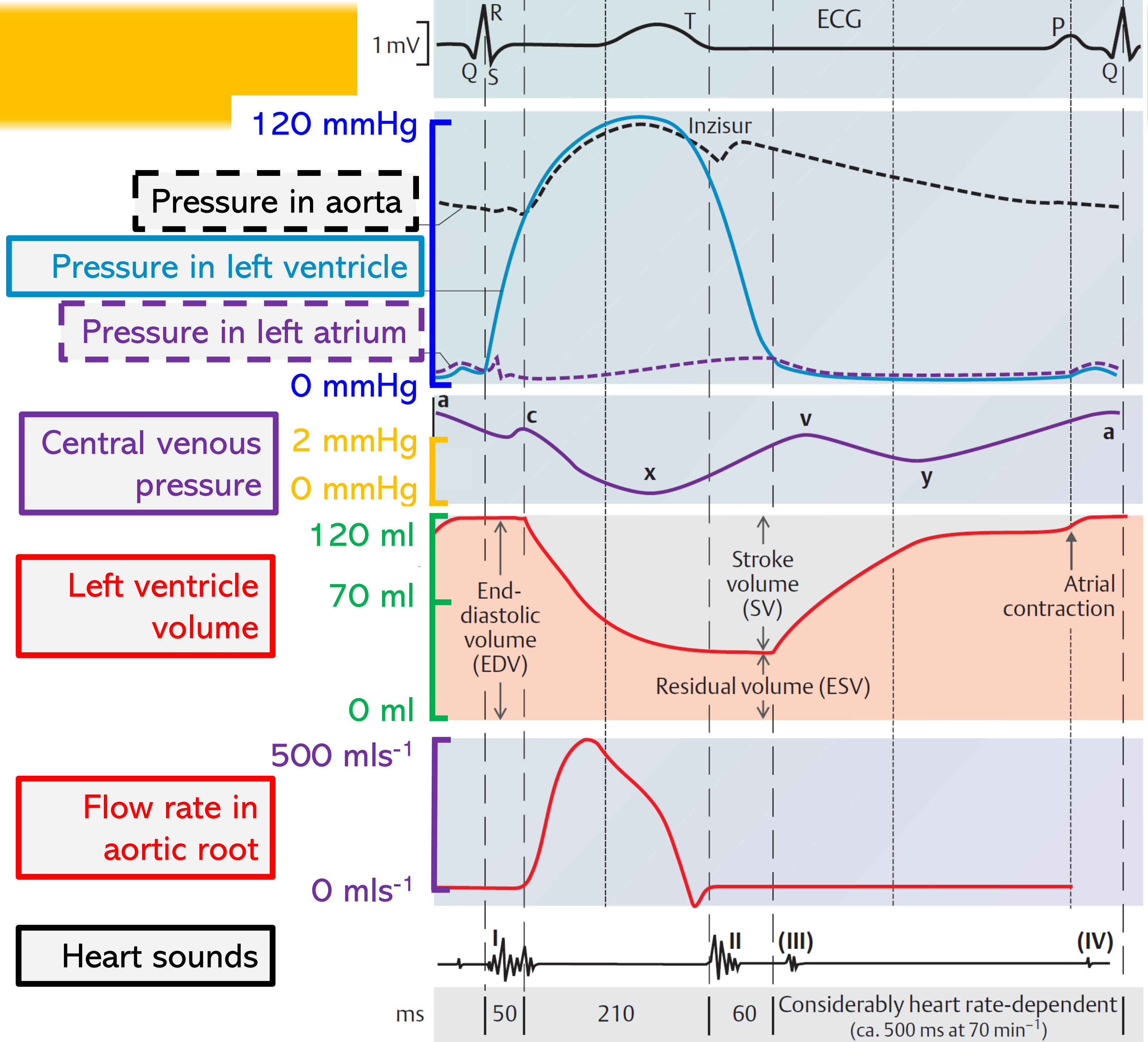
Continuity equation



$$A_1 v_1 = A_2 v_2 = Q$$

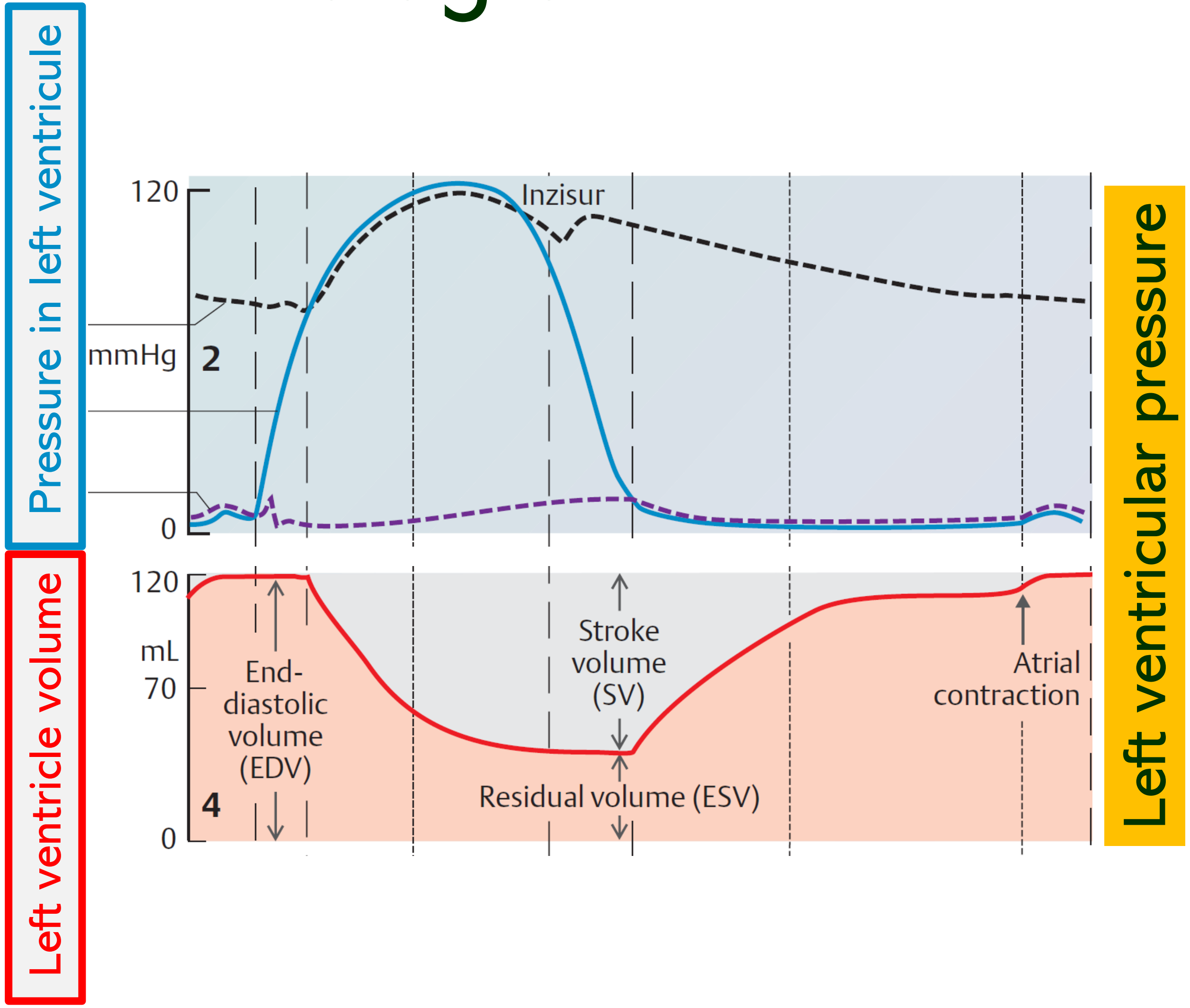
Cardiac Cycle

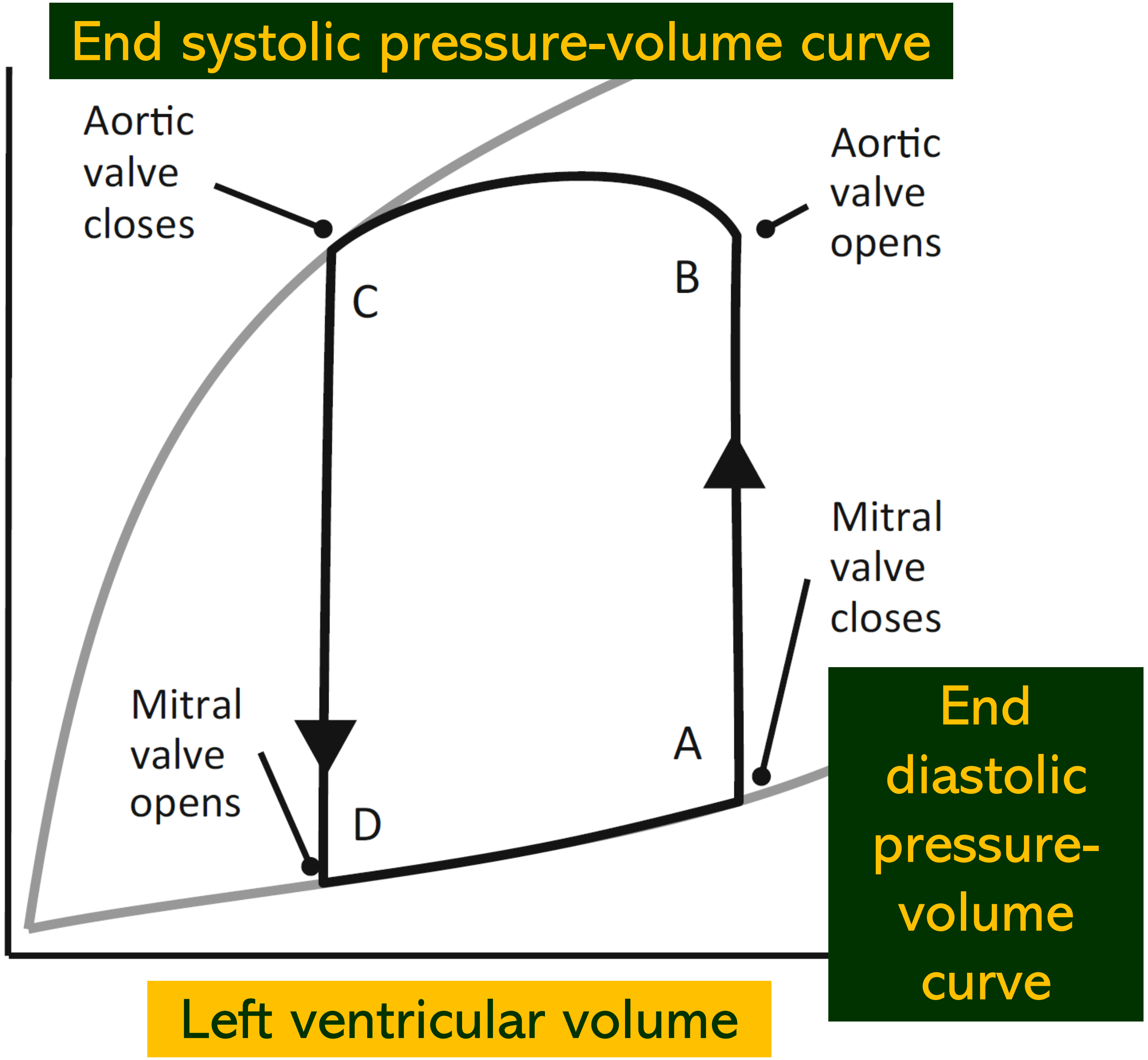




Cardiac Cycle

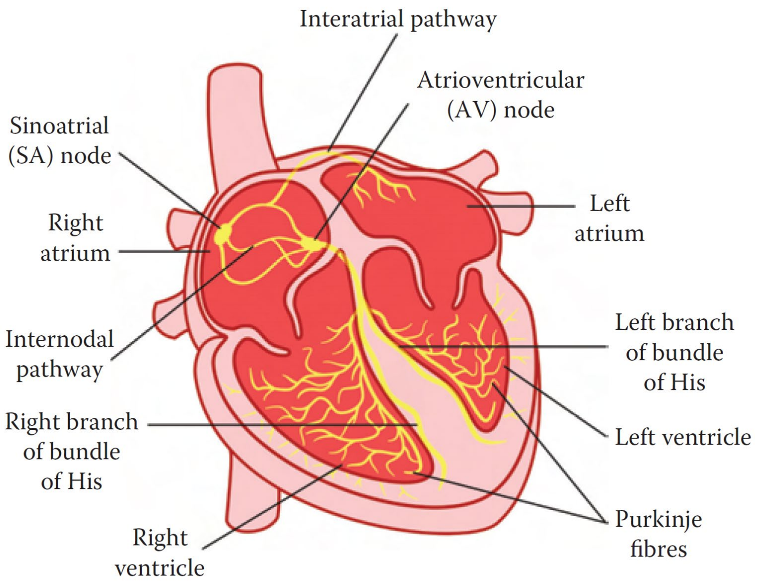
- P-V diagram



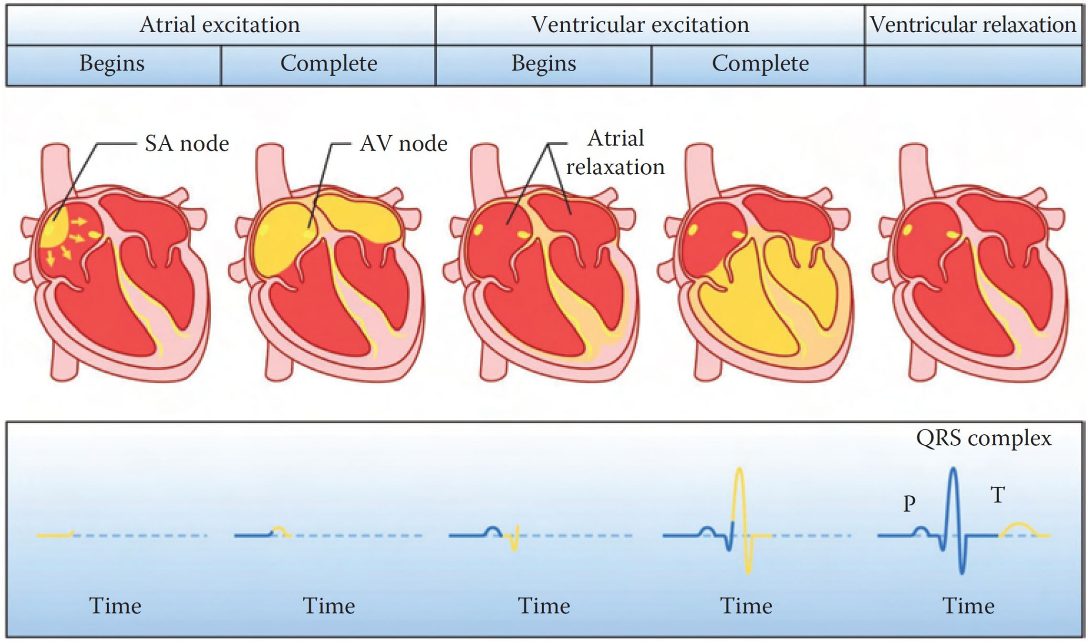


Cardiac Cycle

- Electrical events

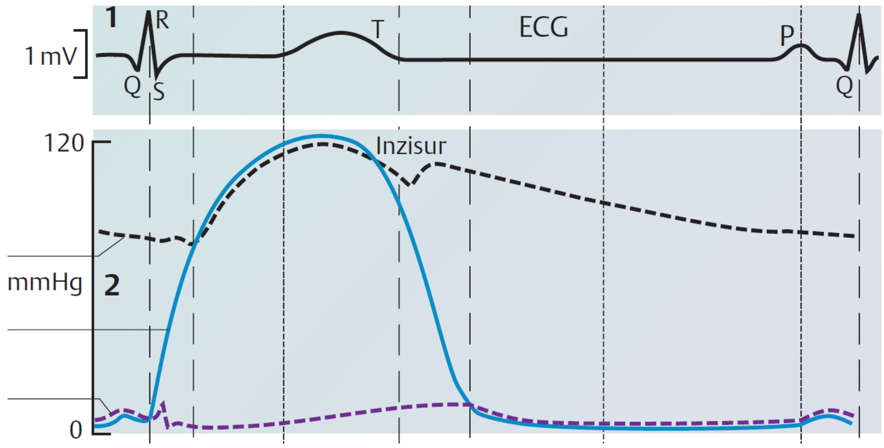


Conduction system



ECG wave generation

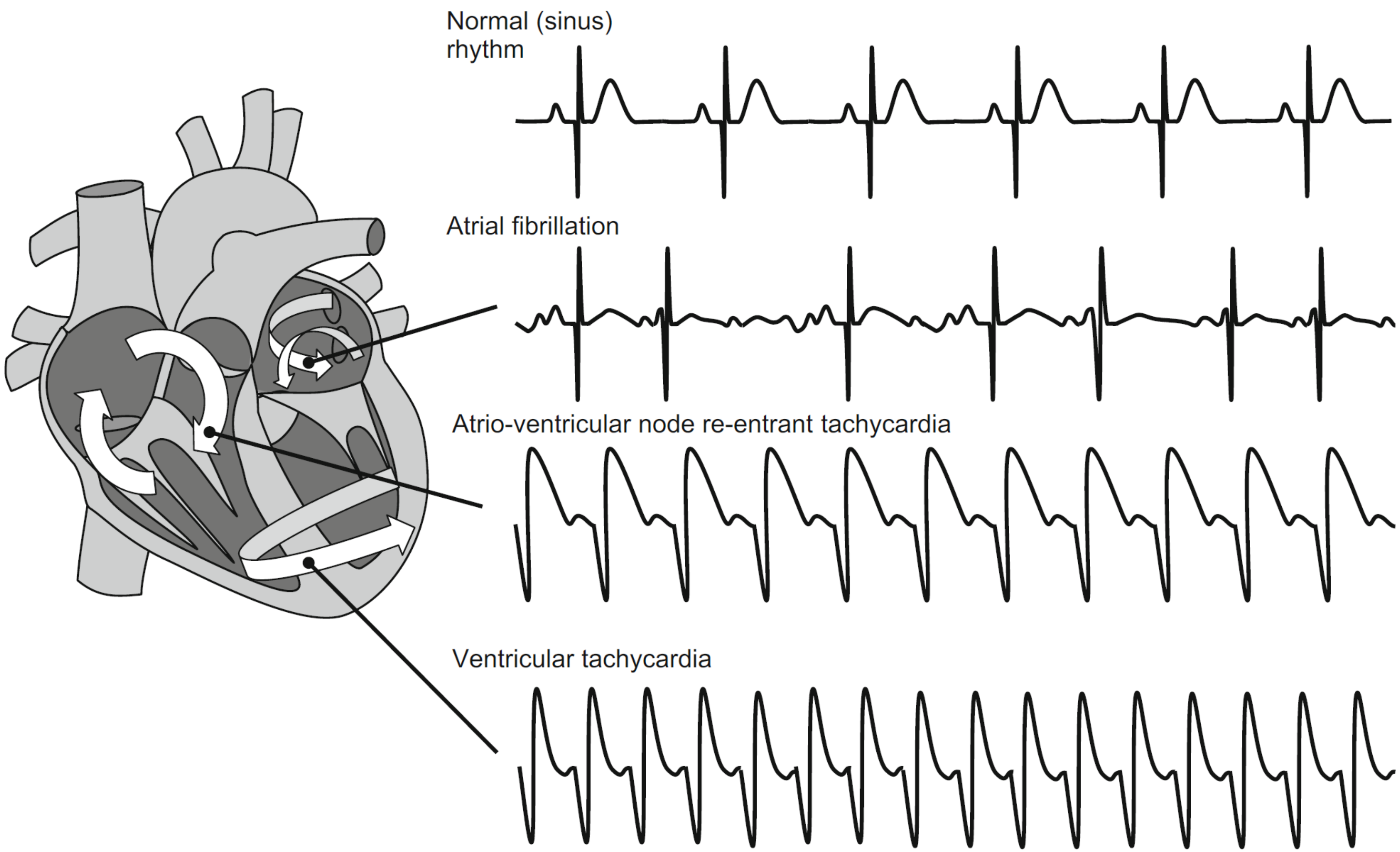
Correlation between mechanical and electrical events



https://doi.org/10.1201/b21917

Cardiac Cycle

- ECG – recording electrical events is important diagnostic instrument

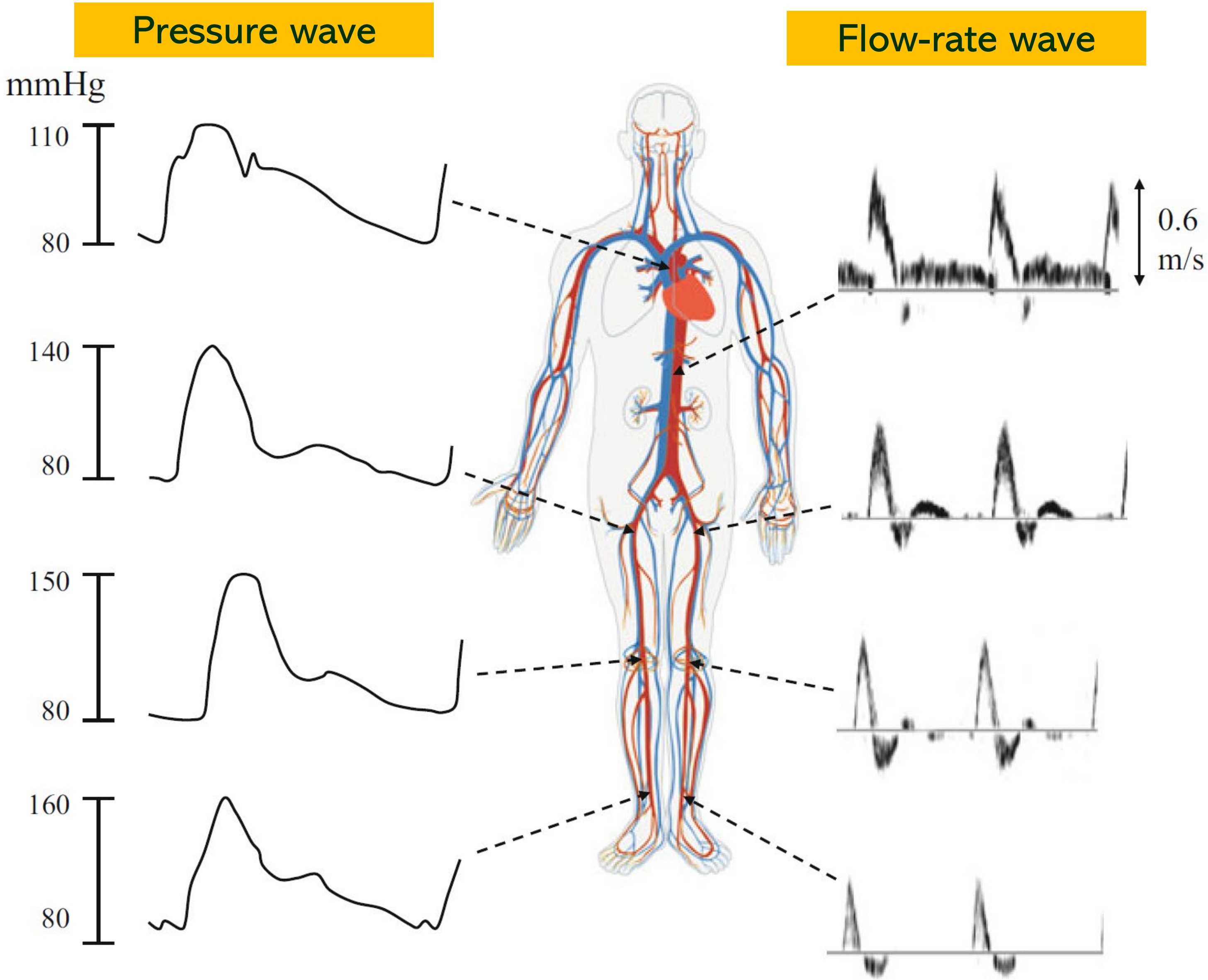


https://link.springer.com/book/10.1007/978-3-319-46407-7

Hemodynamic waves

- The heart pumps and the blood pulsates

Pressure pulse wave
vs.
flow-rate wave

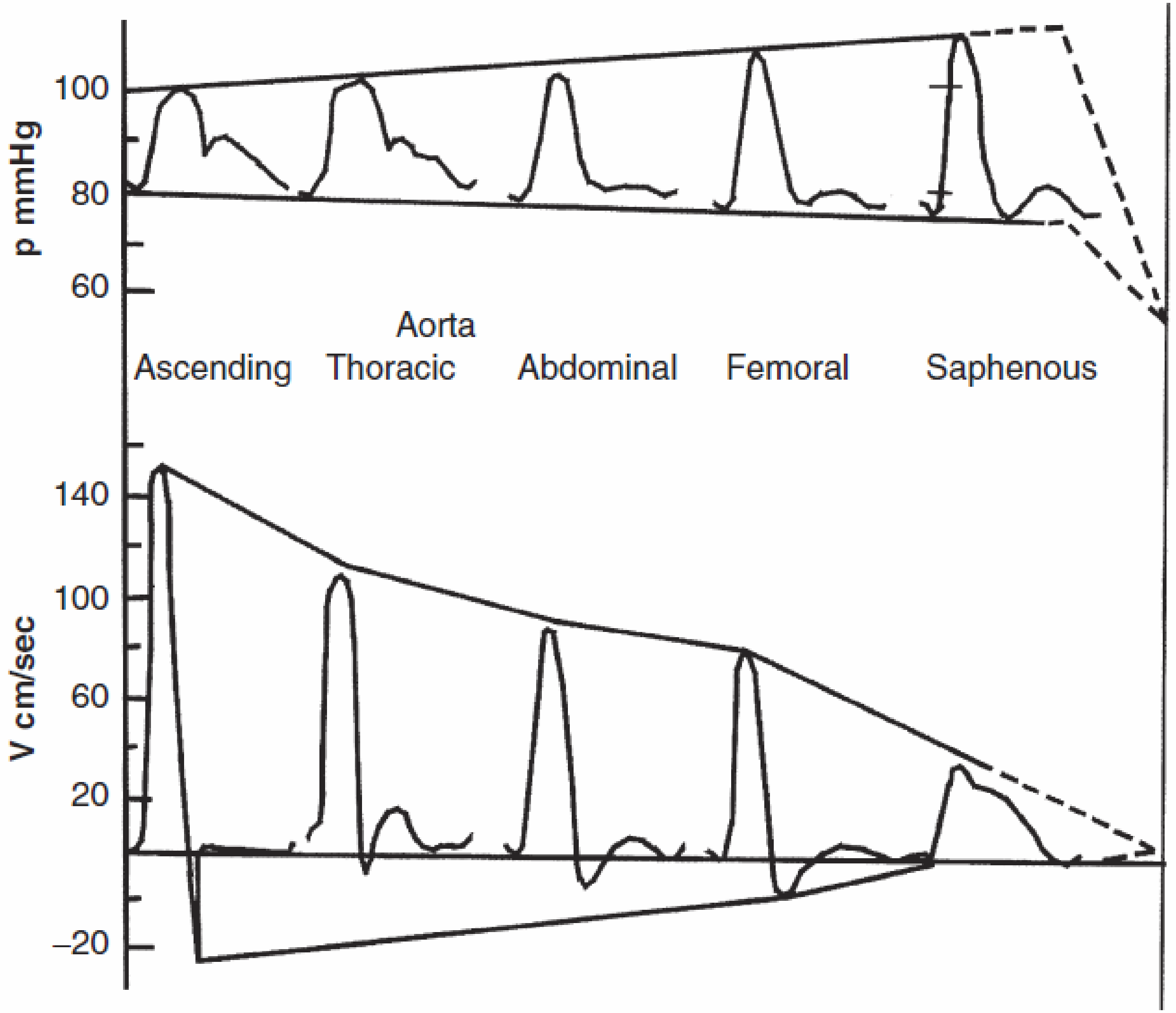


https://link.springer.com/book/10.1007/978-3-319-46407-7

Pressure pulse wave

- Energy conversion

blood flow kinetic energy
and blood pressure
potential energy



Mills, C. J., Gabe, I. T., Gault, J. H., Mason, D. T., Ross, J., Braunwald, E., & Shillingford, J. P. (1970). Pressure-flow relationships and vascular impedance in man. *Cardiovascular Research, 4*(4), 405-417. http://cardiovascres.oxfordjournals.org/content/4/4/405

Pressure pulse wave

- Energy conversion

blood flow kinetic energy
and blood pressure
potential energy

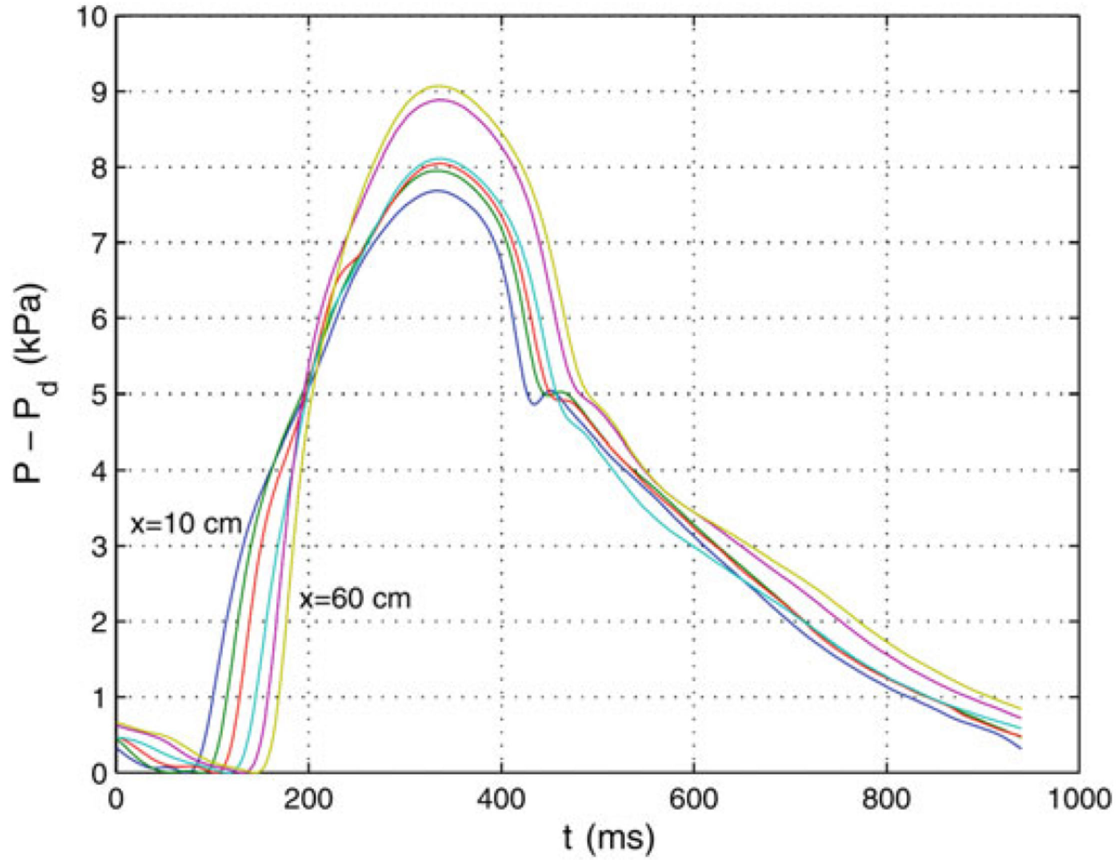
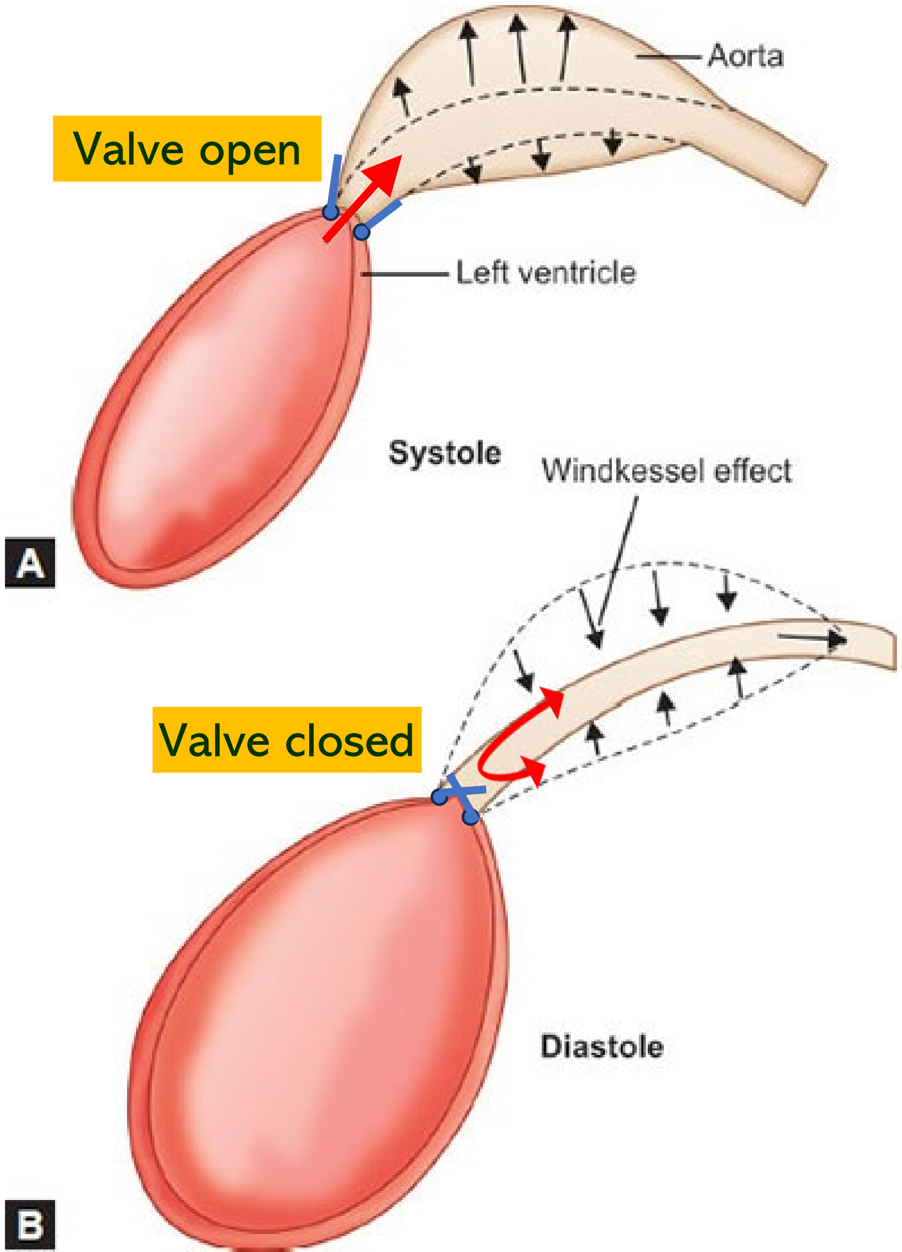


Fig. 4.7 Aortic pressure measured 10, 20, 30, 40, 50 and 60 cm downstream from the aortic valve plotted on as a function of time at different distances. The increase in pressure at the beginning of the waveform occurs at increasingly later times with distance demonstrating that the pressure propagates as a wave down the arterial tree. From Medical and Biological Engineering and Computing, An introduction to wave intensity analysis, Vol. 47, 2009, pp. 175–180, Parker KH, © International Federation for Medical and Biological Engineering 2009, with permission of Springer

Pressure pulse wave

- Windkessel effect

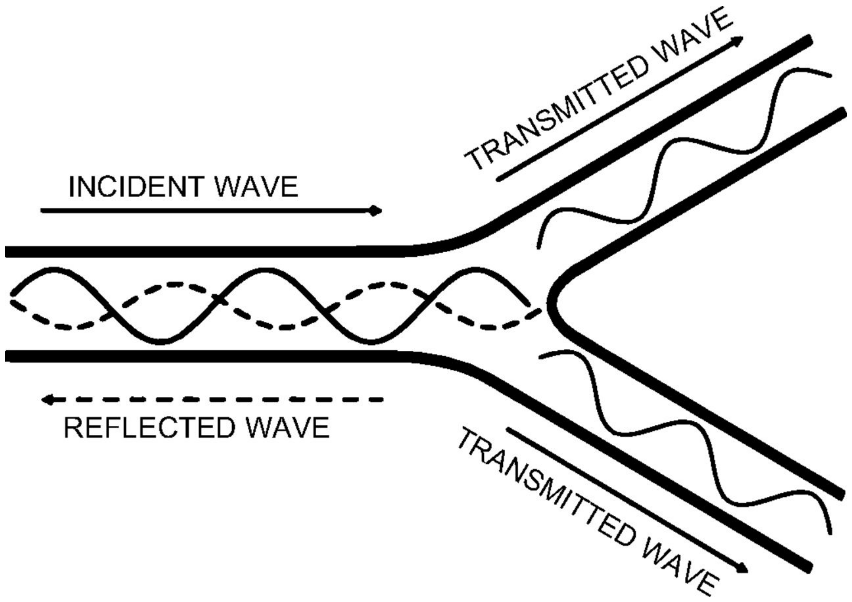
  smoothing (flow-rate)
  and prolonging (pressure)
  of the waves
  by releasing
  of the elastic energy
  stored in arteries
  within the
  deformation

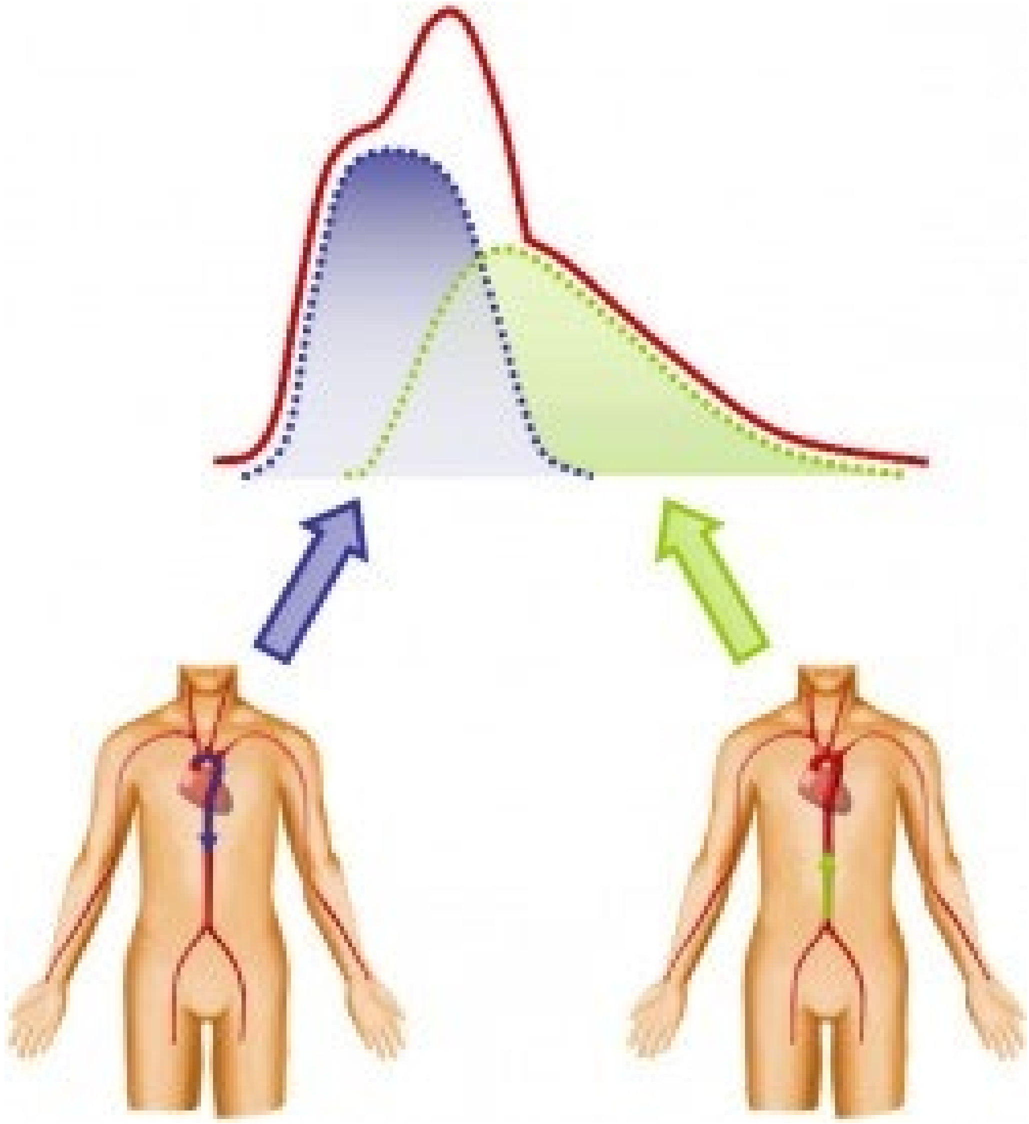


Pressure pulse wave

- Reflected waves

  pressure augmentation





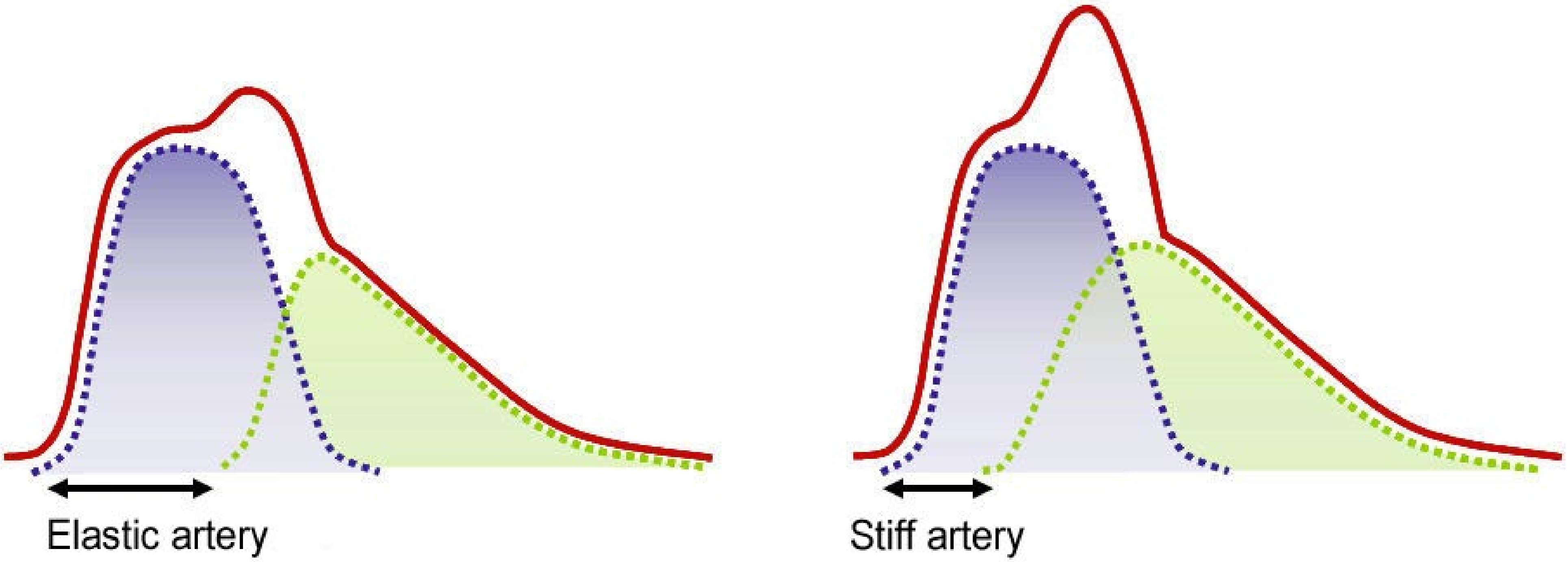
http://advan.physiology.org/content/37/4/321

http://www.complior.com/info-center

Pressure pulse wave

- Reflected waves

effect of age-relate stiffening ⇒ blood pressure elevation

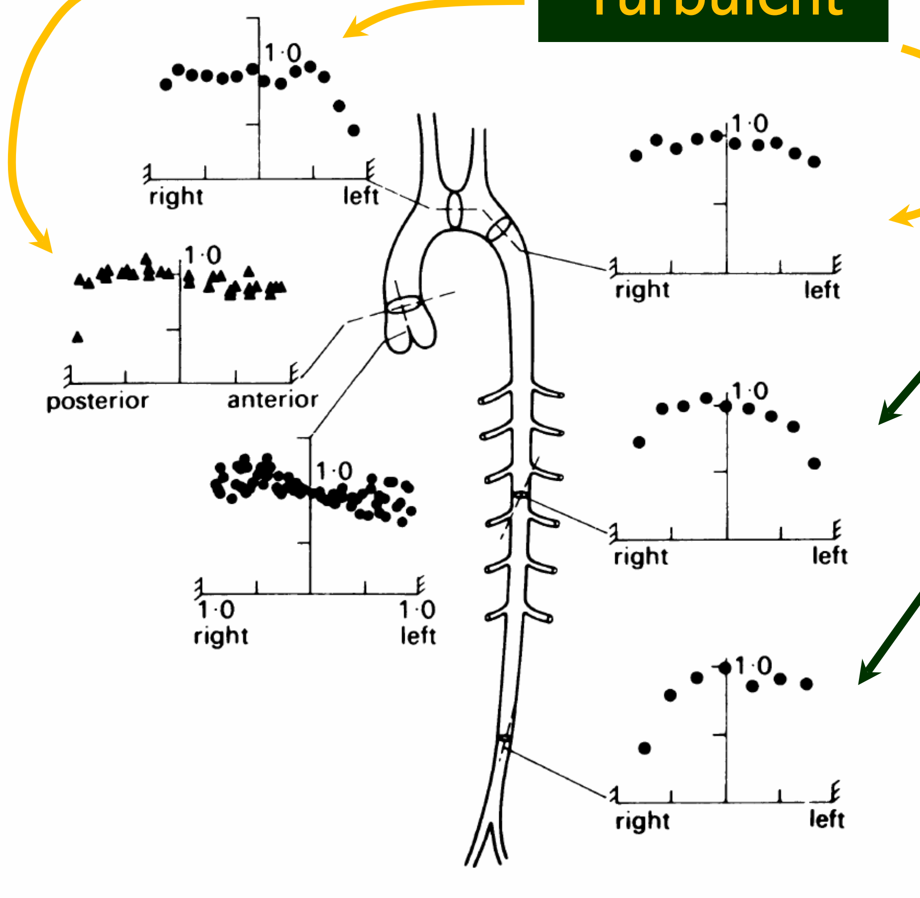


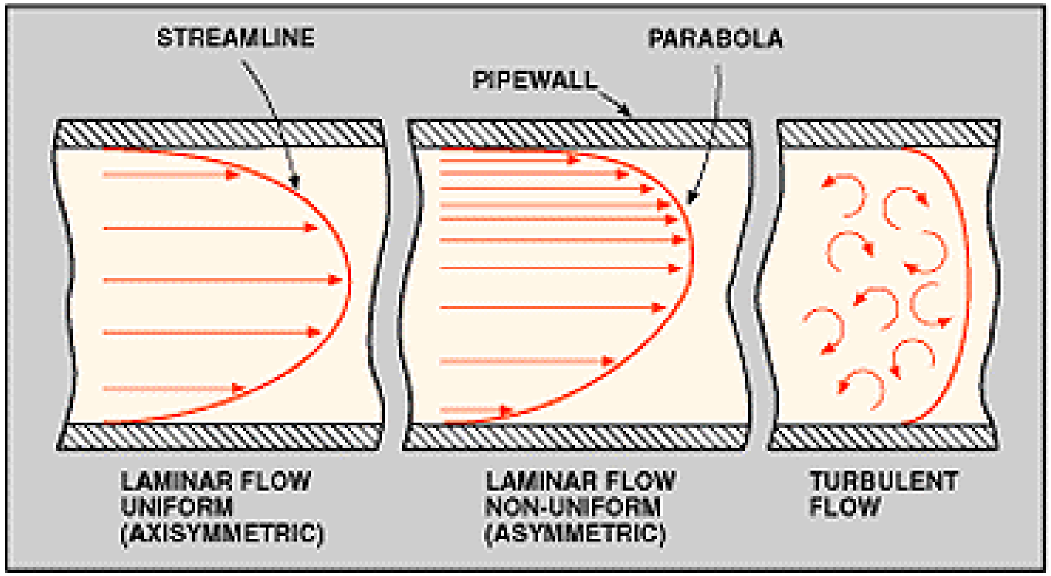
Blood flow

- Compliant system converts turbulent flow to laminar

Turbulent

Laminar

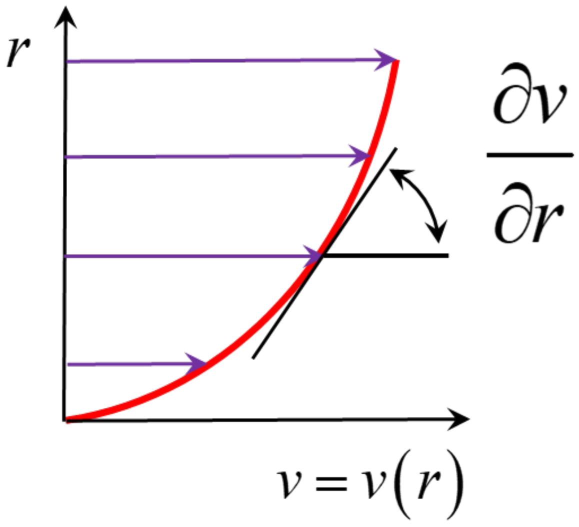




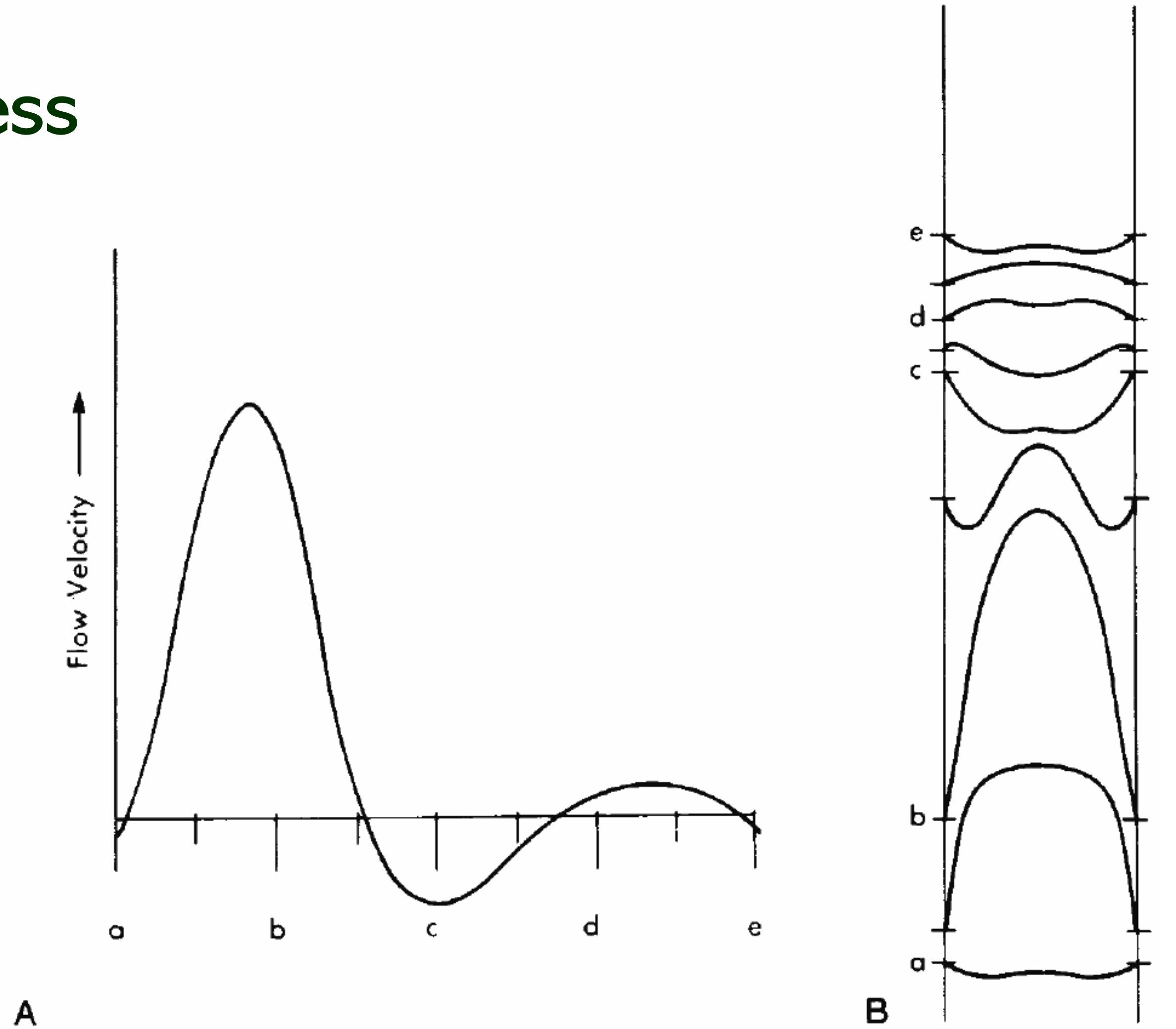
Blood flow

- Flow-rate and velocity oscillations

The velocity or flow rate per se
is not as important as the shear stress
exerted by the blood flow
on the arterial wall
(endothelial cells).



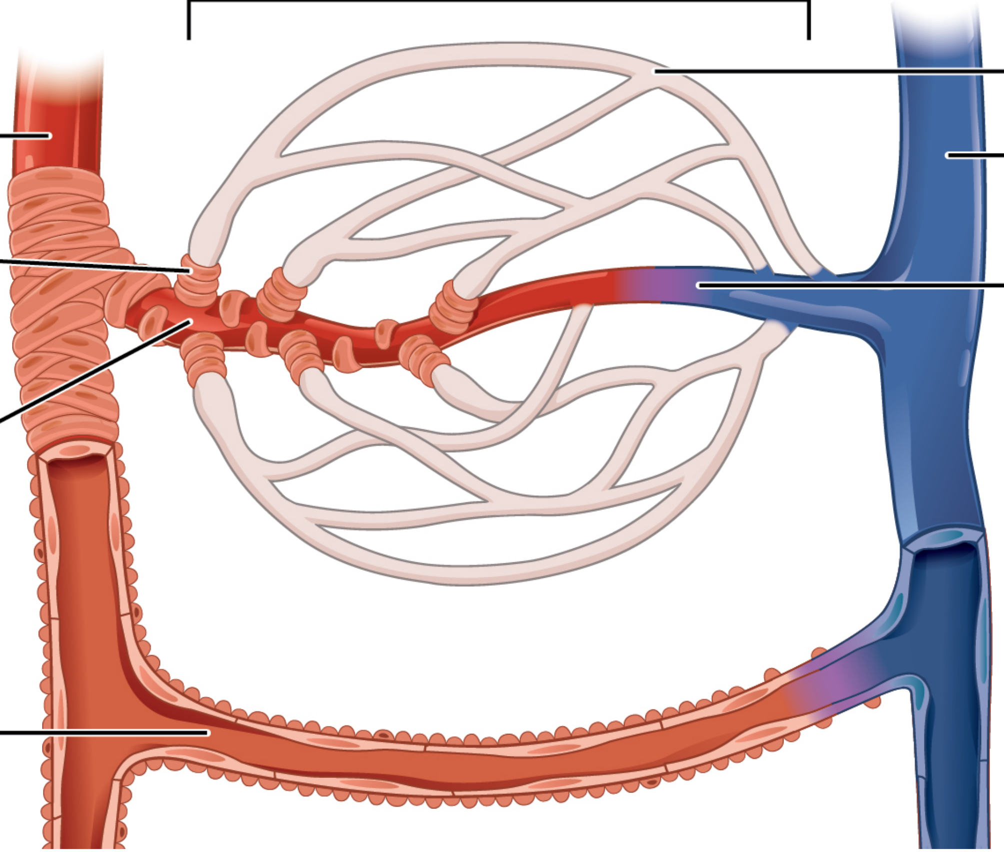
$$\sigma = \mu \frac{\partial v}{\partial r}$$



Microcirculation

- ## Capillary blood flow

capillaries allow the passage of substances from the blood vessel to the surrounding tissue and vice versa.

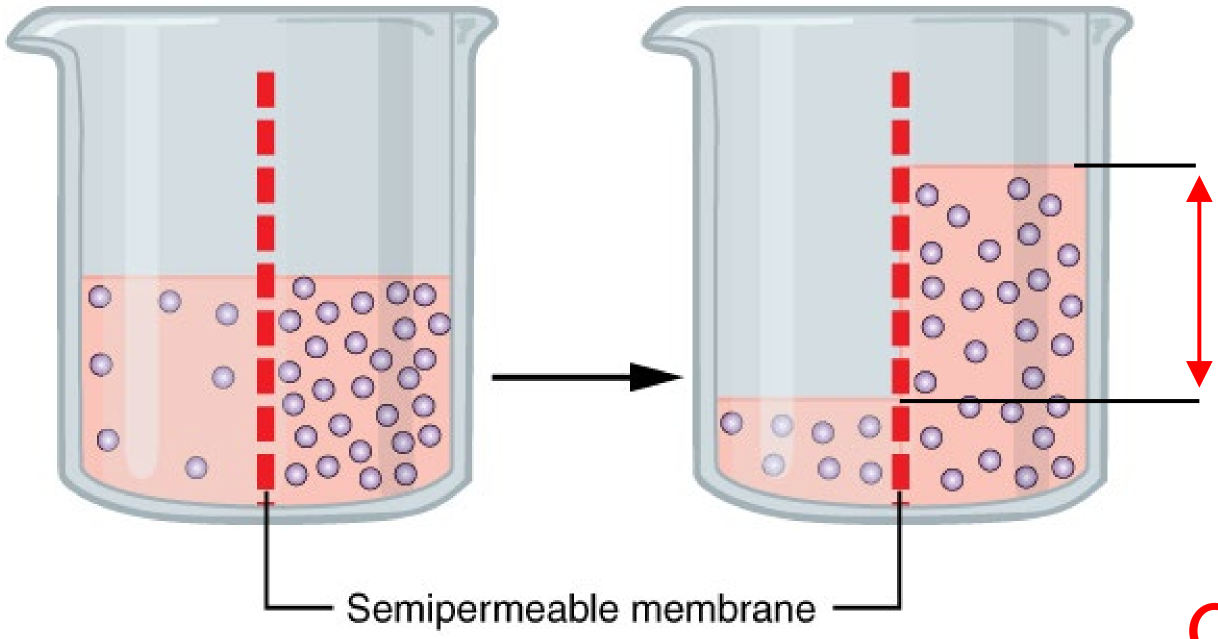


https://en.wikipedia.org/wiki/Microcirculation#/media/File:2105_Capillary_Bed.jpg

Microcirculation

- **Capillary blood flow**

  the flow is driven by osmosis

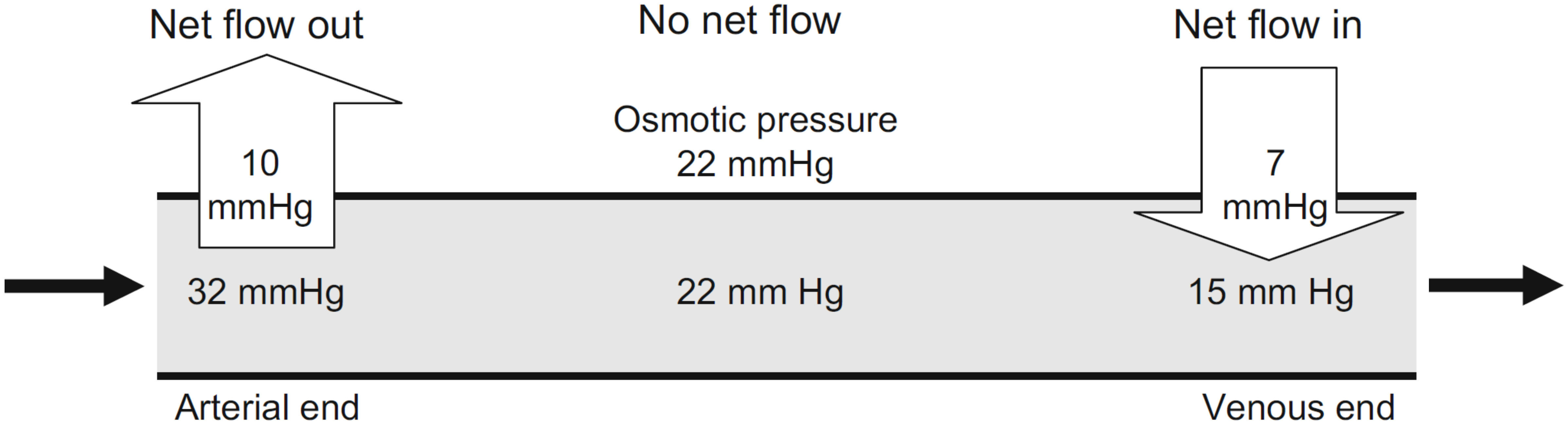


$$P = h\rho g$$

Osmotic pressure = hydrostatic pressure that leads to equilibration of solution concentrations.

Microcirculation

- Capillary blood flow

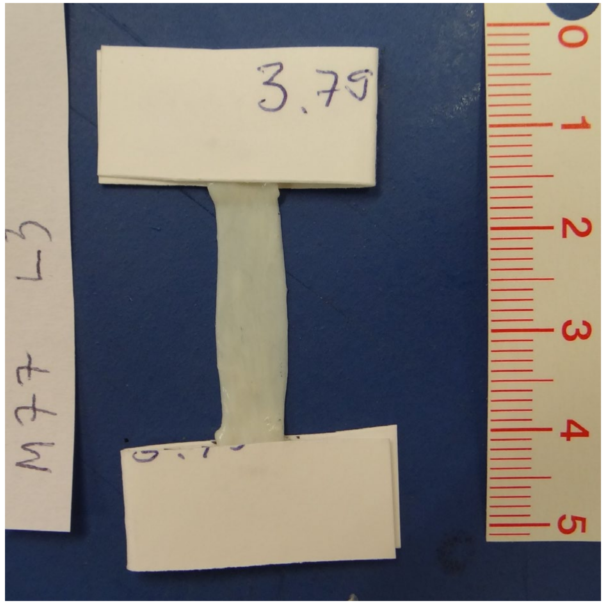


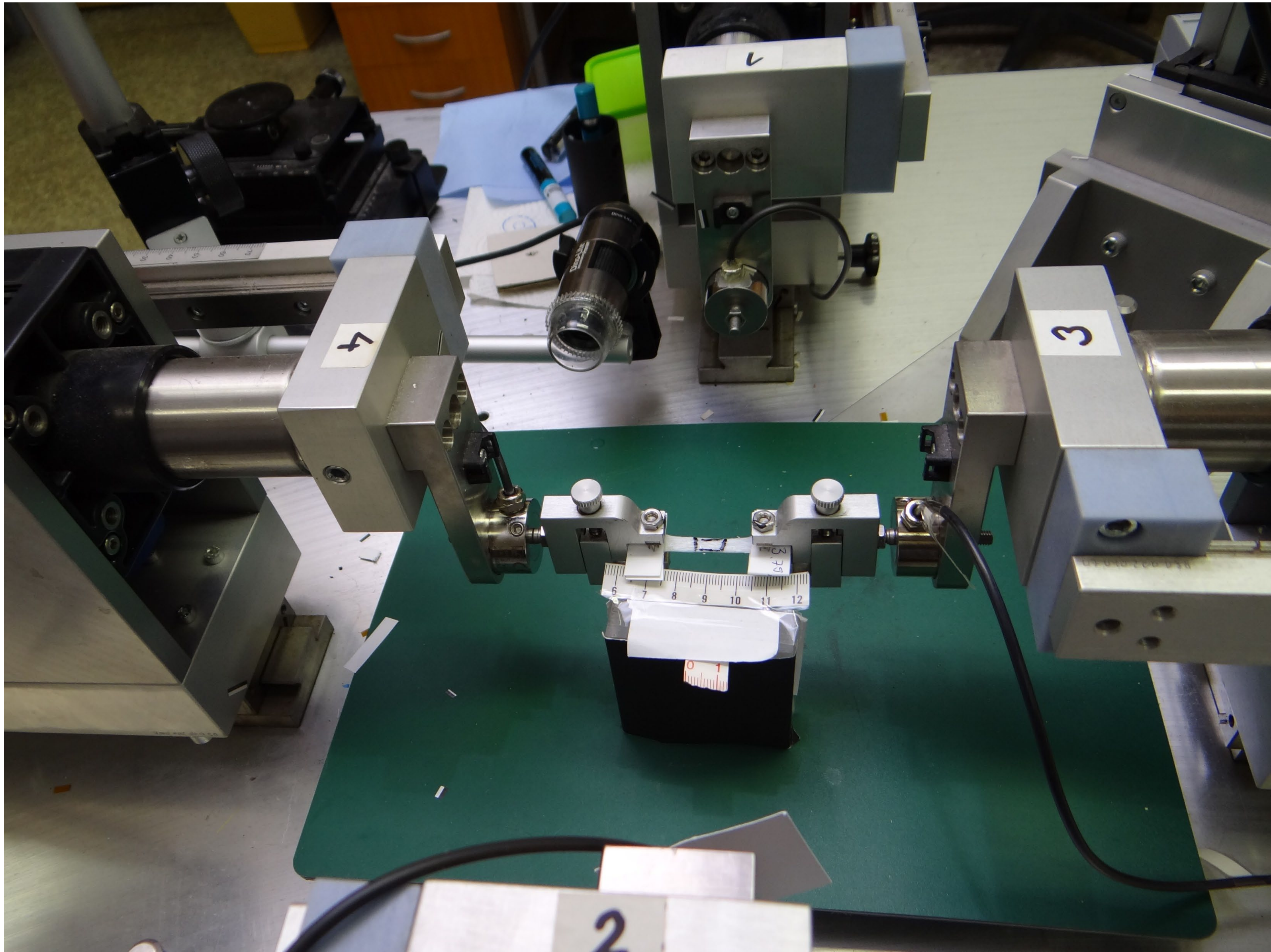
32 mmHg = 4.3 kPa   22 mmHg = 2.9 kPa   15 mmHg = 2 kPa

Biomechanics of the Blood Vessels

Mechanical behavior of arteries

- **Tensile test response**
  experimental setup

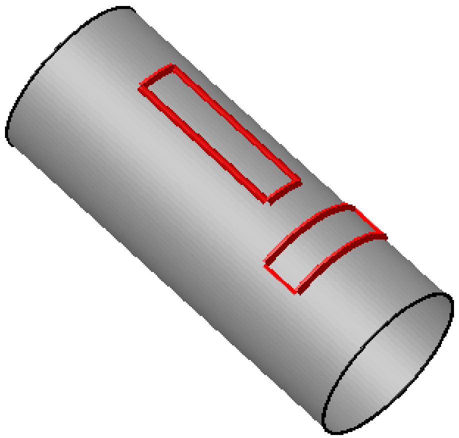


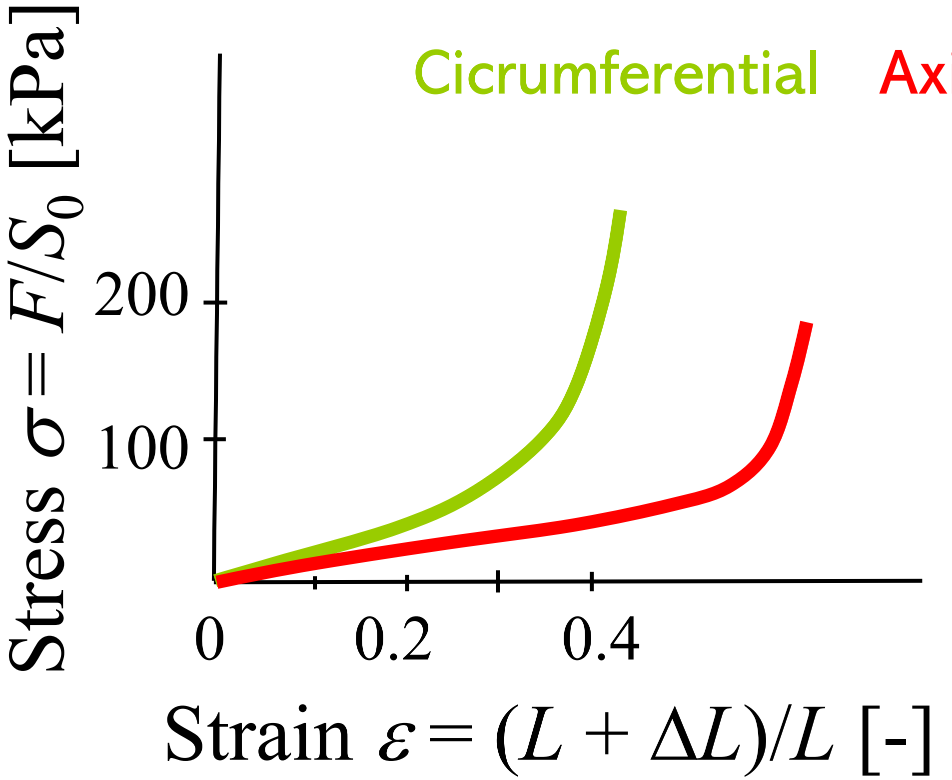


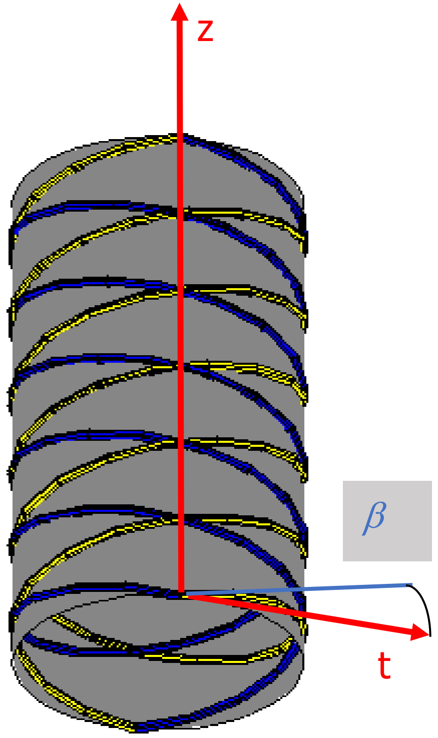
Mechanical behavior of arteries

- ## Tensile test response

  nonlinear and anisotropic behavior





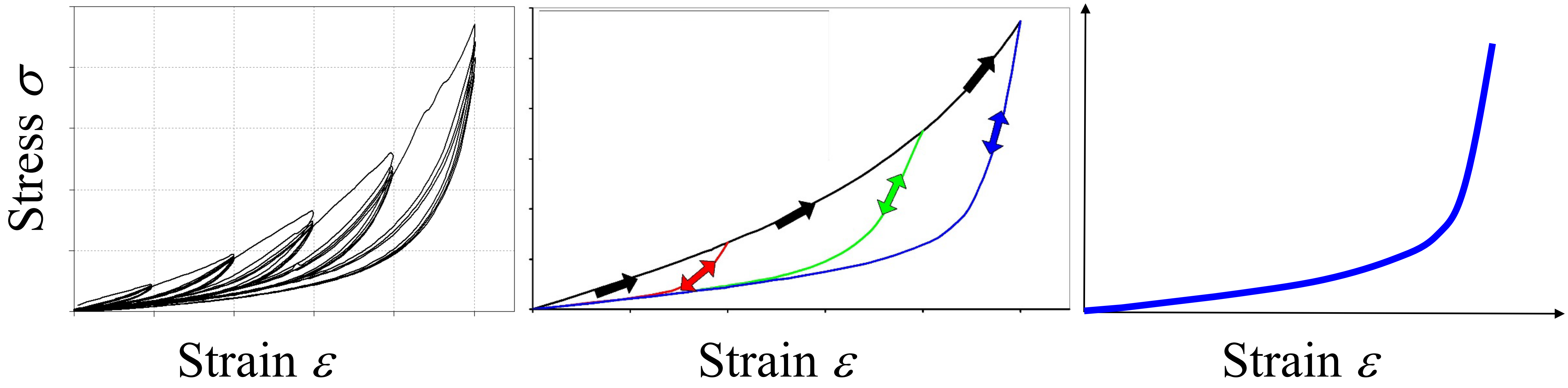


Example: Healthy young human abdominal aorta

Mechanical behavior of arteries

- **Tensile test response**

  inelastic phenomena are attenuated when repeating the same deformation history

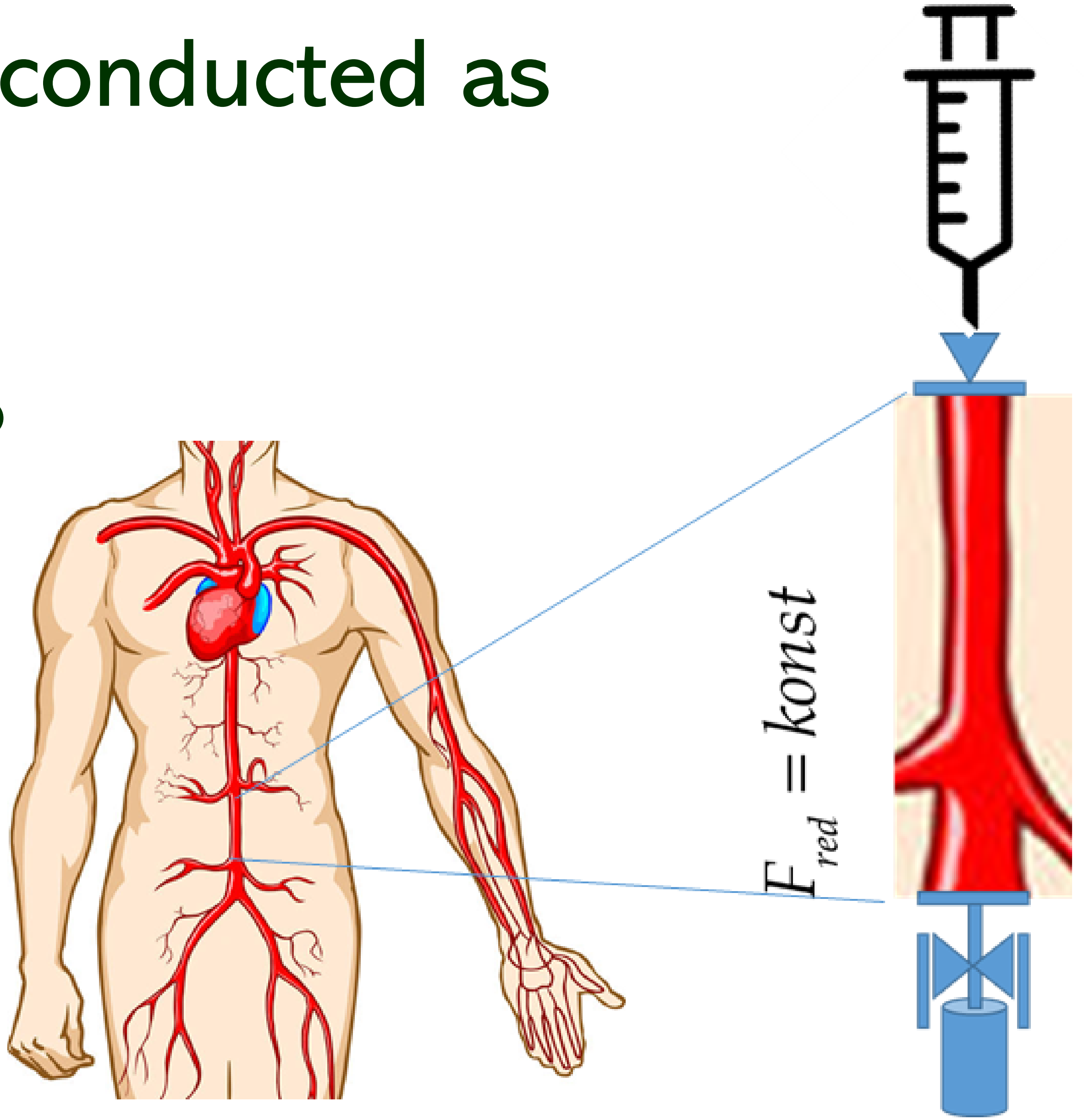


Mechanical behavior of arteries

- In vitro pressurization is conducted as inflation-extension test

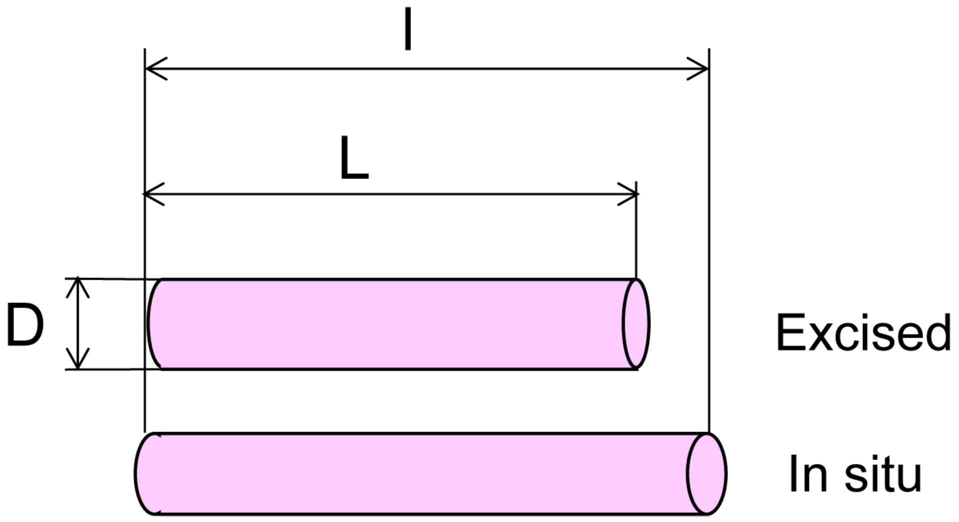
  that mimics artery loading in vivo

  because arteries grow axially pre-stretched



Mechanical behavior of arteries

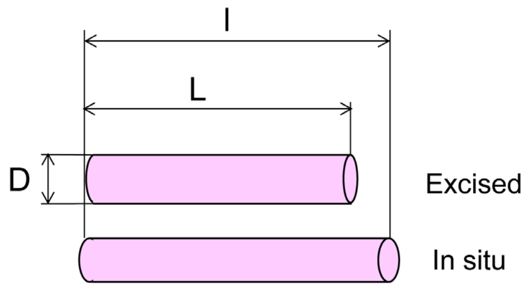
- Blood vessels in situ are longitudinally pre-stretched



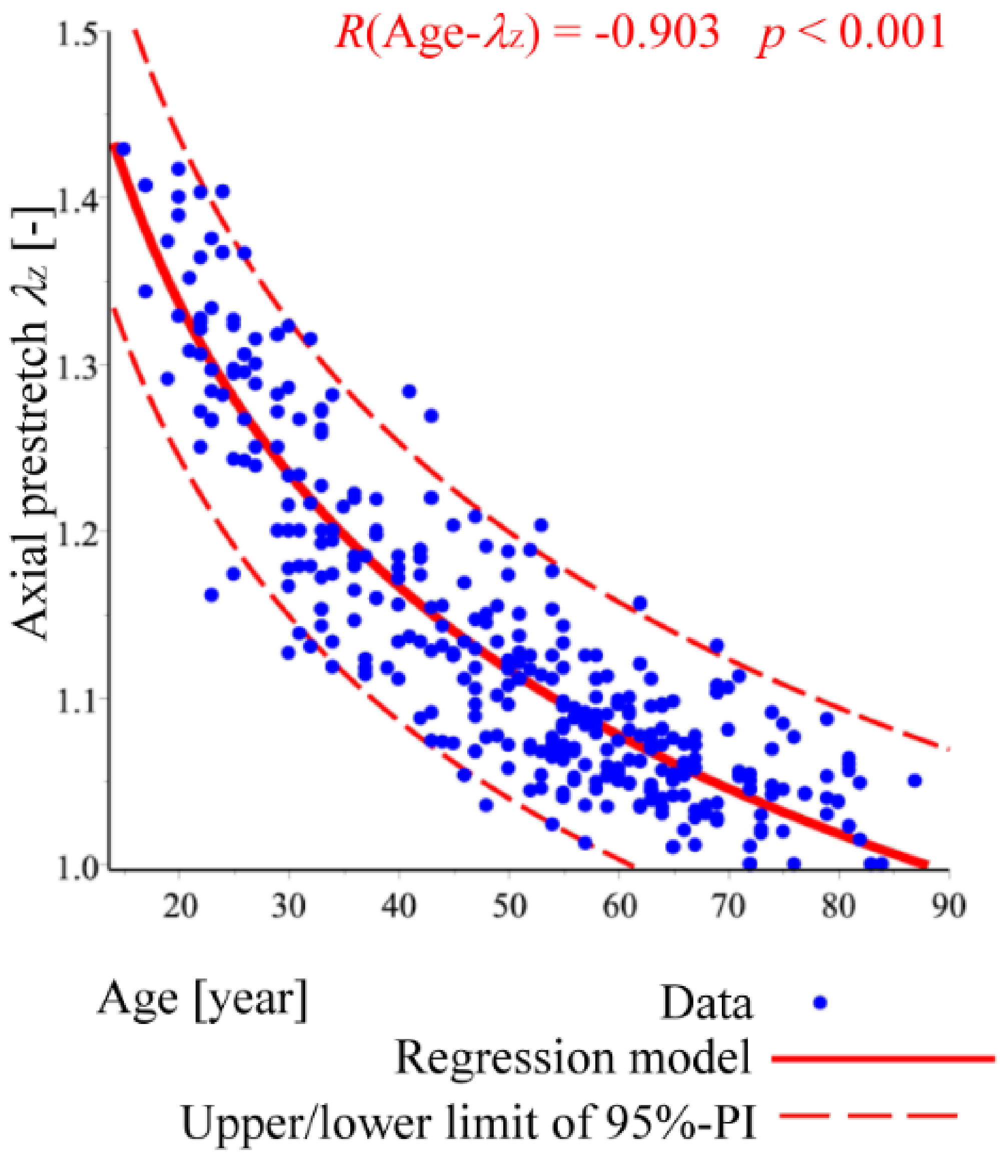
Prestretch $\lambda = \dfrac{l}{L}$

Mechanical behavior of arteries

- Blood vessels in situ are longitudinally pre-stretched

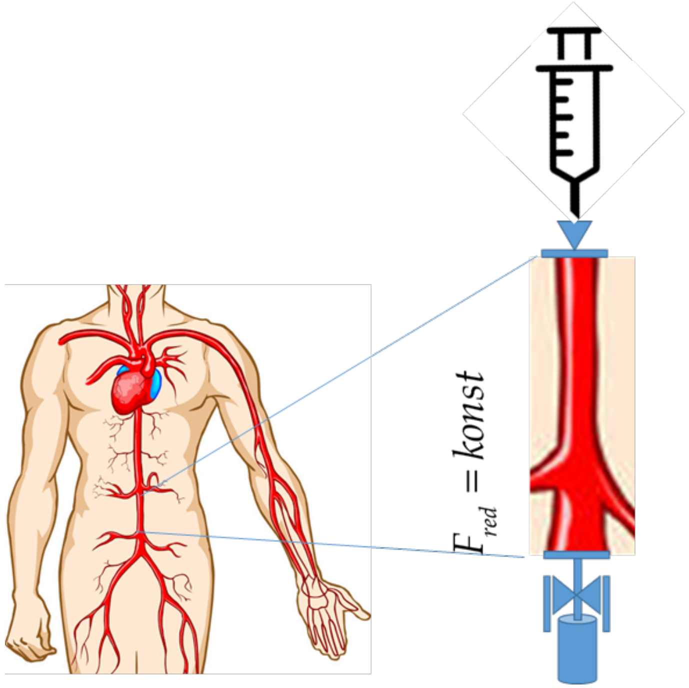


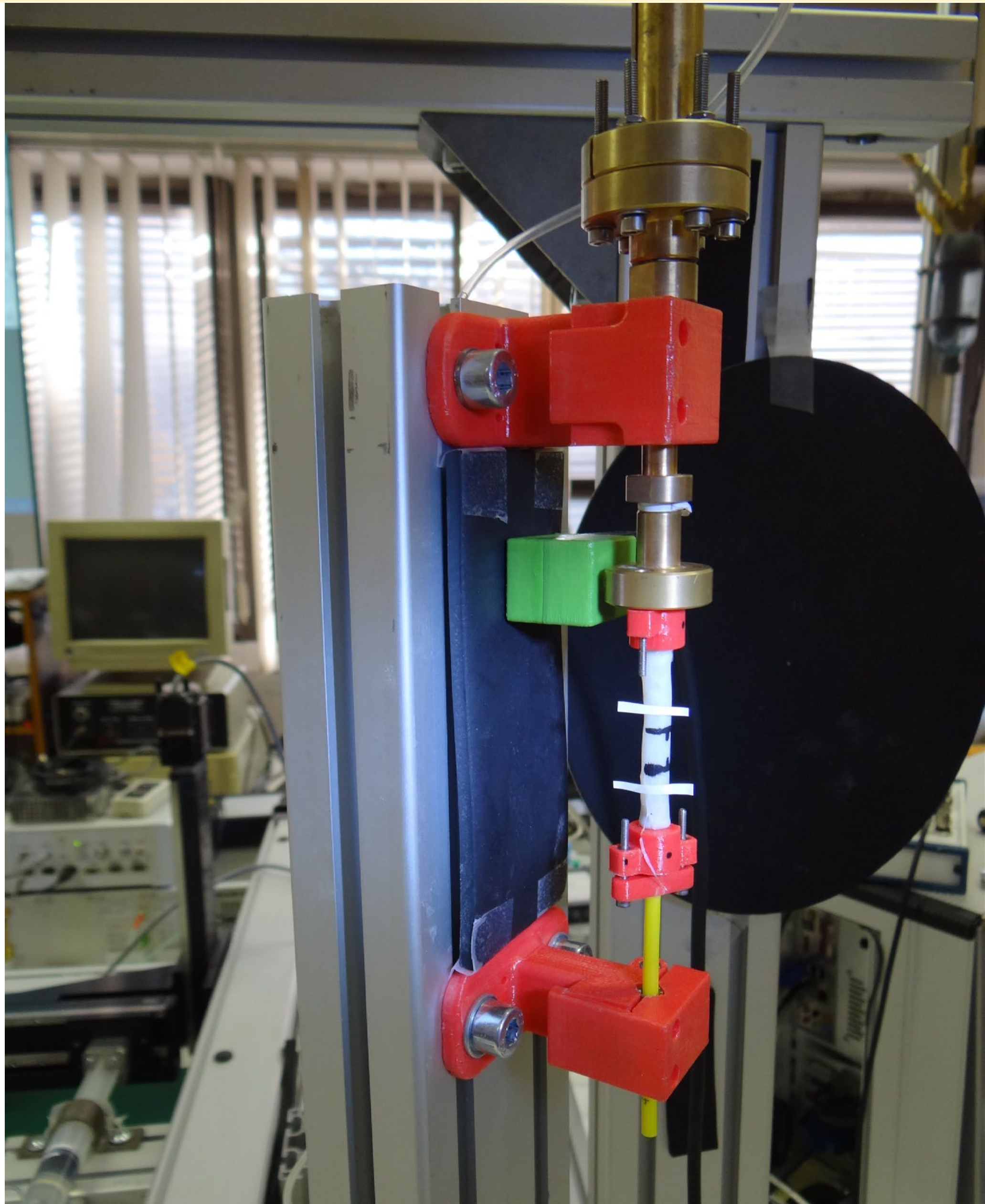
Prestretch $\lambda = \frac{l}{L}$



Mechanical behavior of arteries

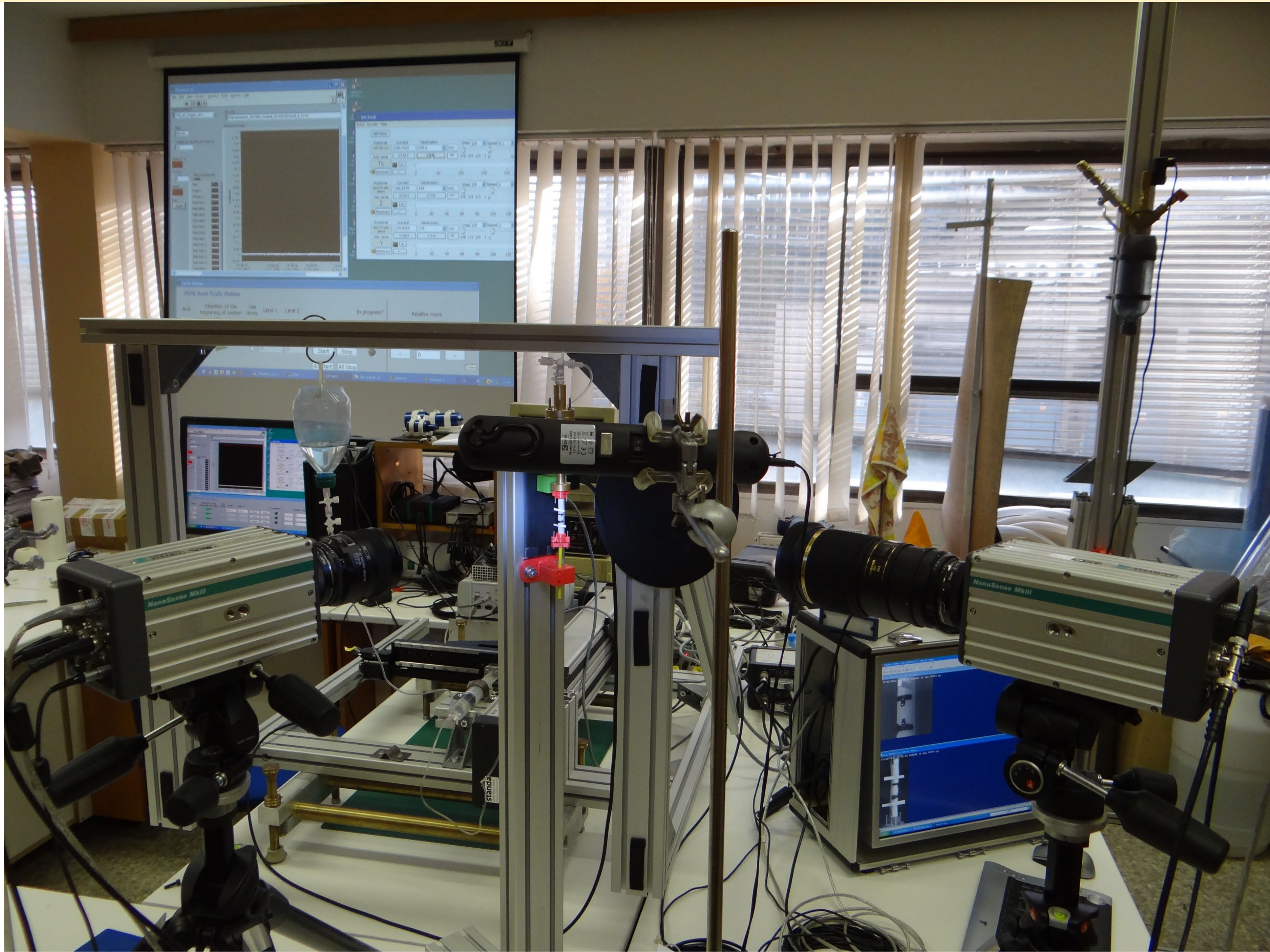
- In vitro pressurization as inflation-extension test





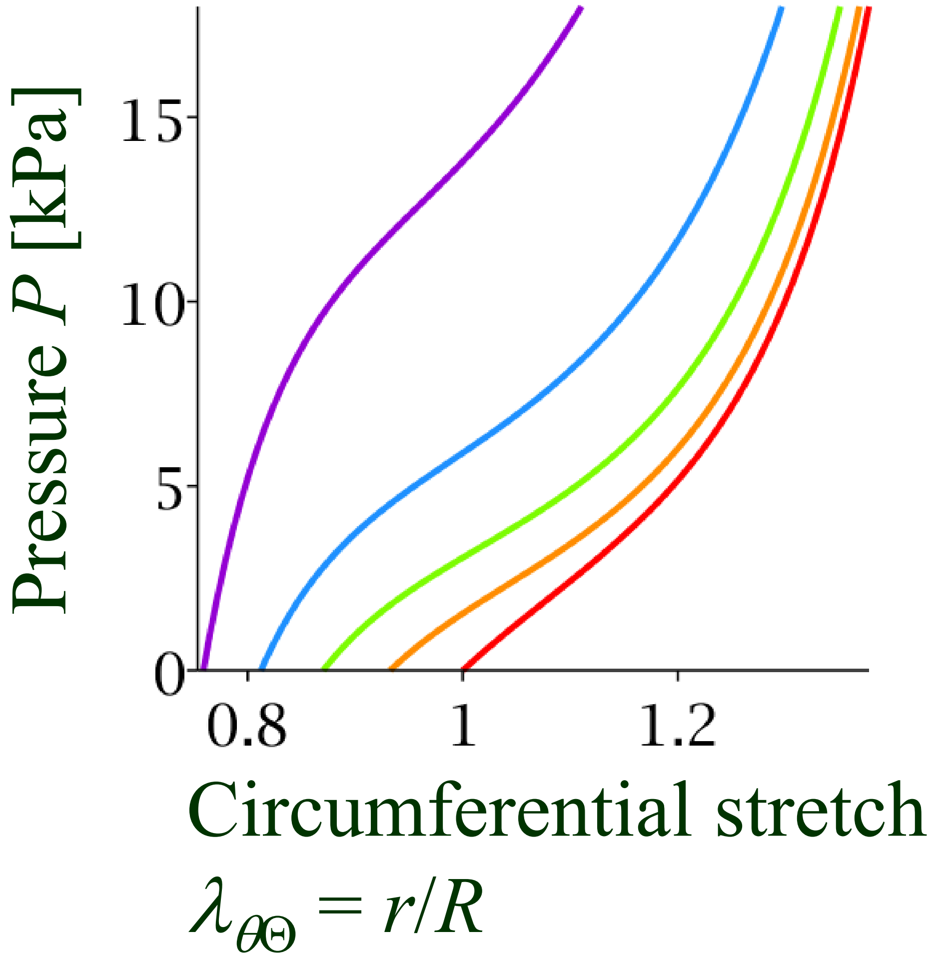
Mechanical behavior of arteries

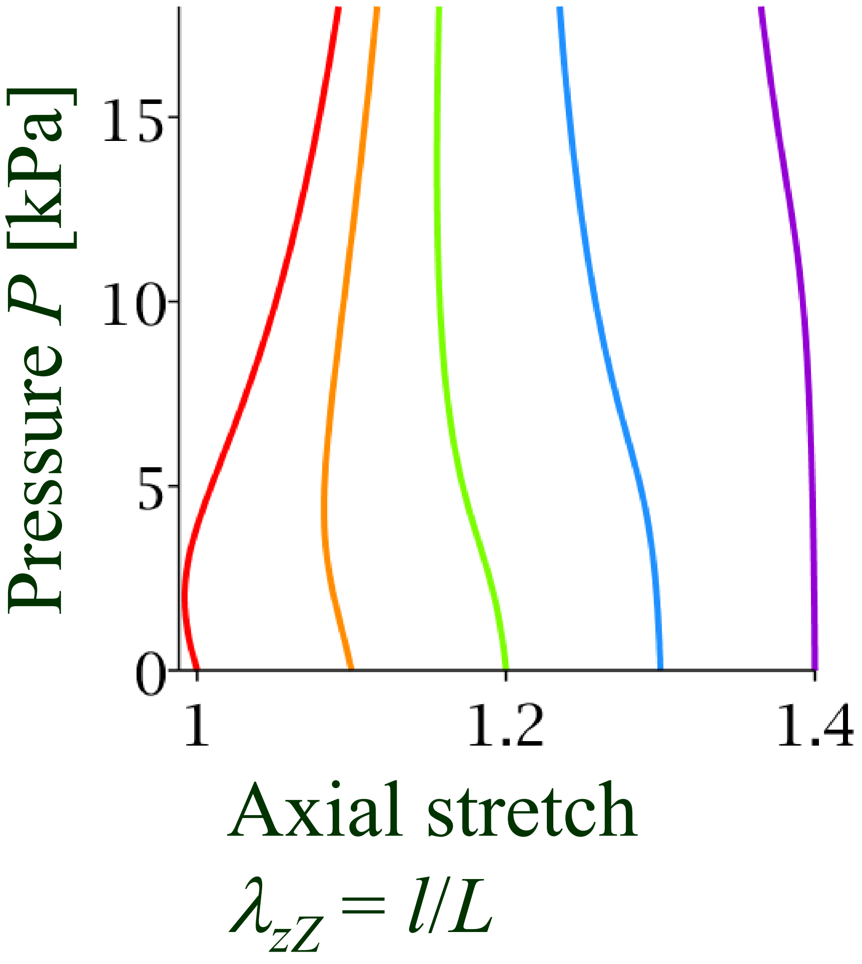
- In vitro pressurization as inflation- -extension test



Mechanical behavior of arteries

- Inflation-extension response





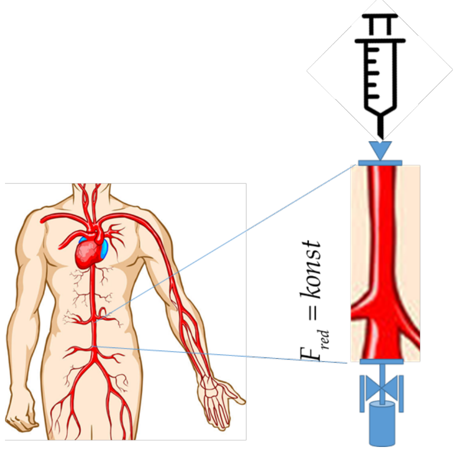
$F_{red}(\lambda_{zZ} = 1) = 0\ \mathrm{N}$

$F_{red}(\lambda_{zZ} = 1.1) = 0.74\ \mathrm{N}$

$F_{red}(\lambda_{zZ} = 1.2) = 2.2\ \mathrm{N}$

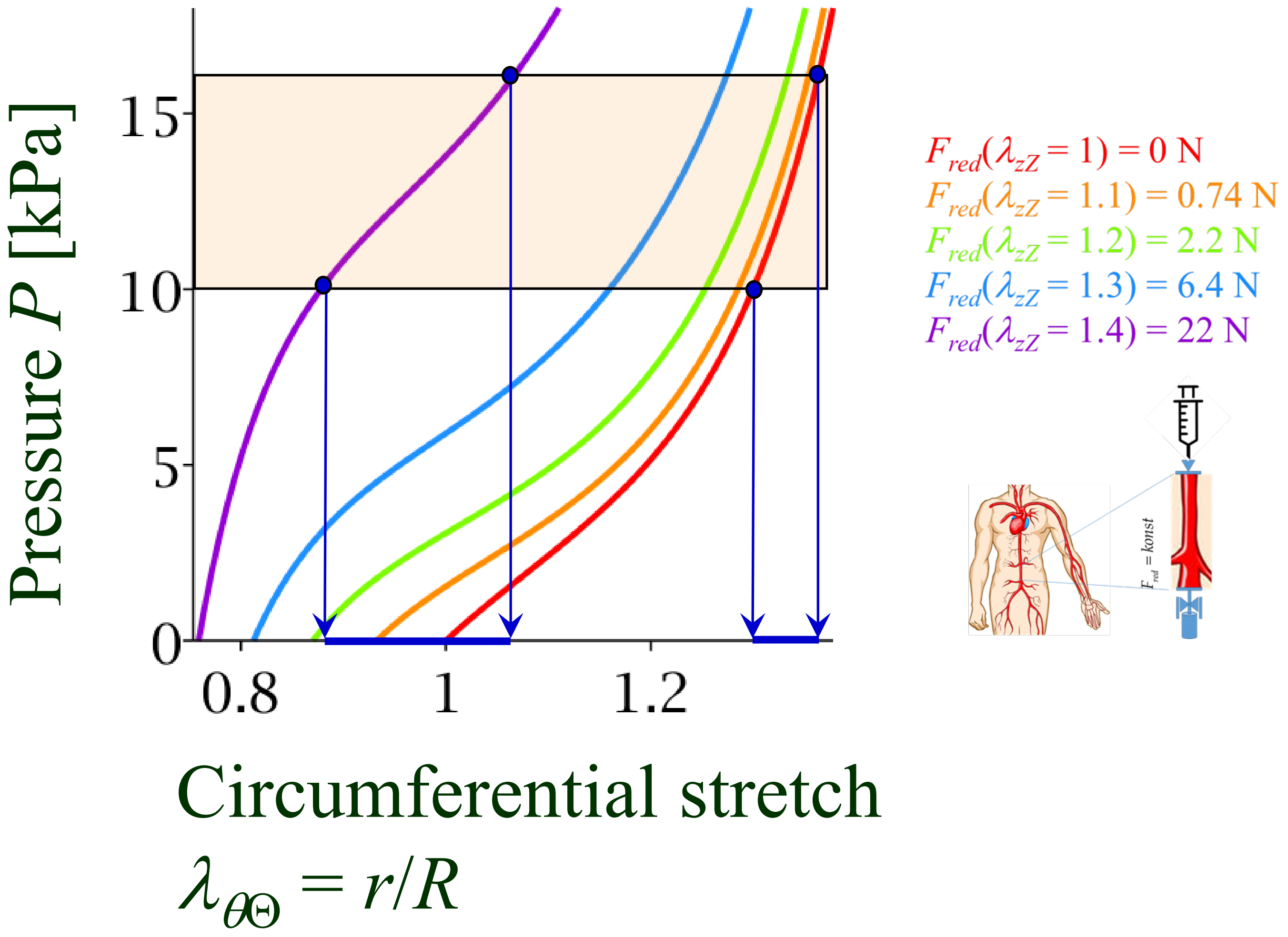
$F_{red}(\lambda_{zZ} = 1.3) = 6.4\ \mathrm{N}$

$F_{red}(\lambda_{zZ} = 1.4) = 22\ \mathrm{N}$



Mechanical behavior of arteries

- Results explain why arteries are pre-stretched
- Axially pre-stretched arteries are more compliant during pressurization



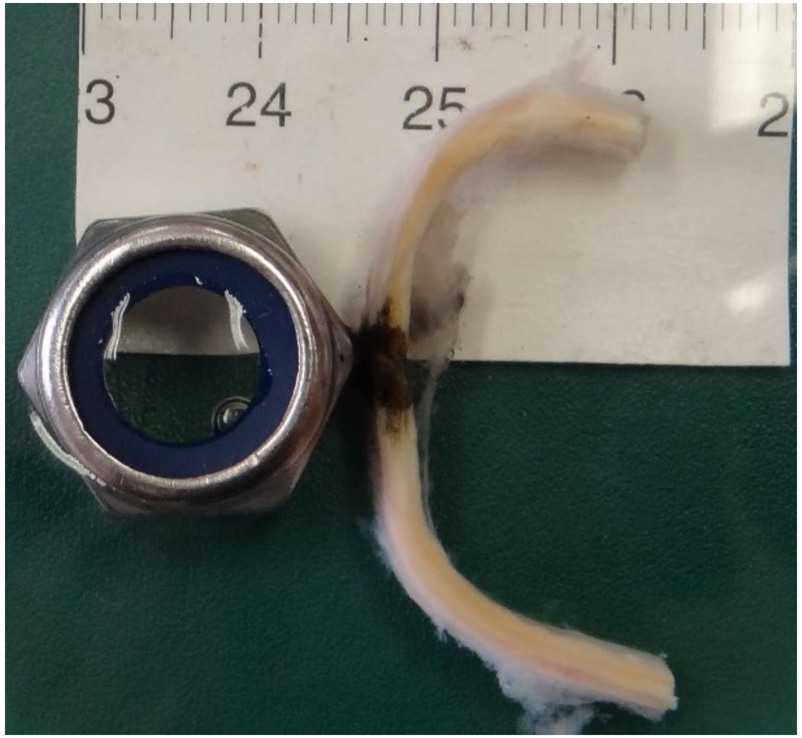
Mechanical behavior of arteries

- Tissues grow residually stressed

  arteries are excellent example

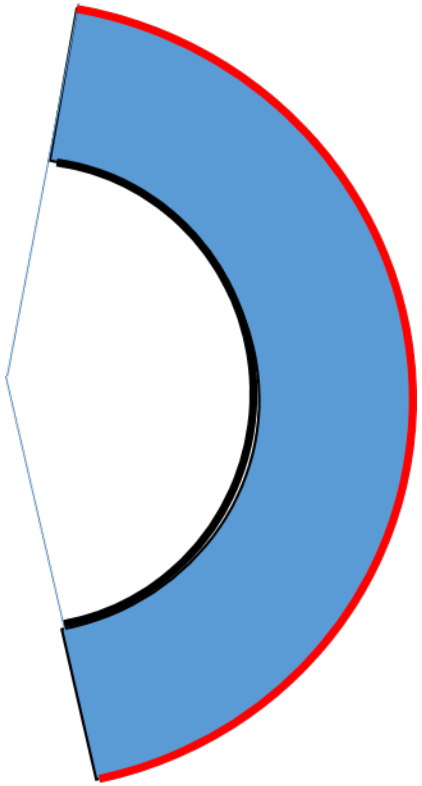
No load ≠ no stress

No load and no stress

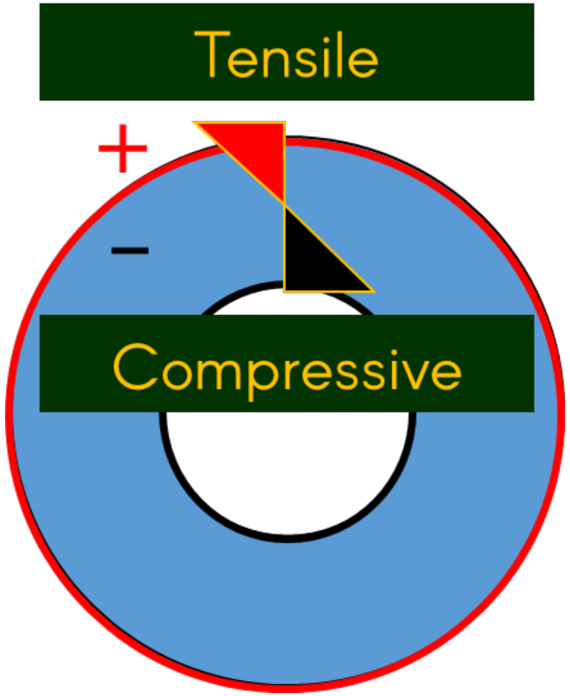


Mechanical behavior of arteries

- Tissues grow residually stressed



Bending moment will close the ring and will induce bending-like distribution of internal forces



Mechanical behavior of arteries

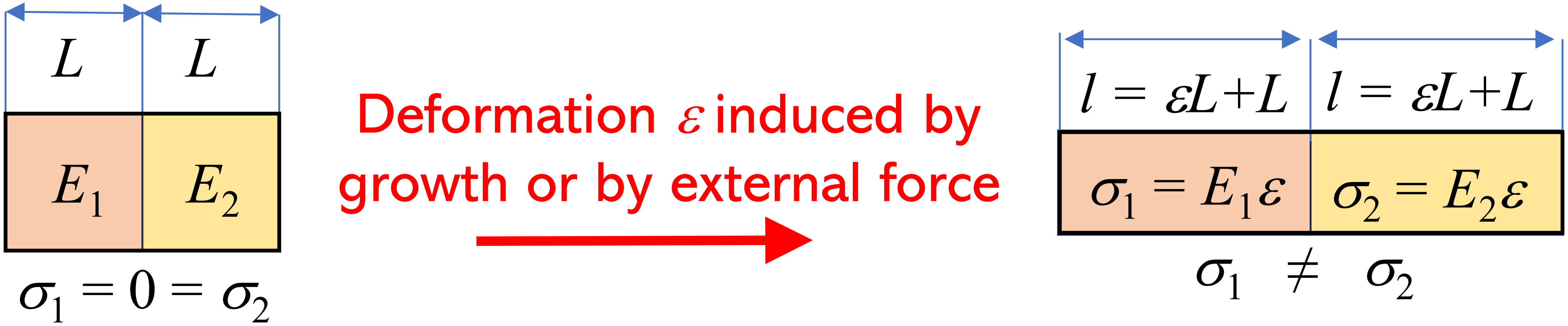
- Residual stresses are the result of the growth of tissue that has constituents with different properties but which in the continuous body carry the same macroscopic deformation

residual stress balances simple fact that different properties would result in the different deformation – there must be force which holds components together

Mechanical behavior of arteries

- ## Residual stress: simplified picture

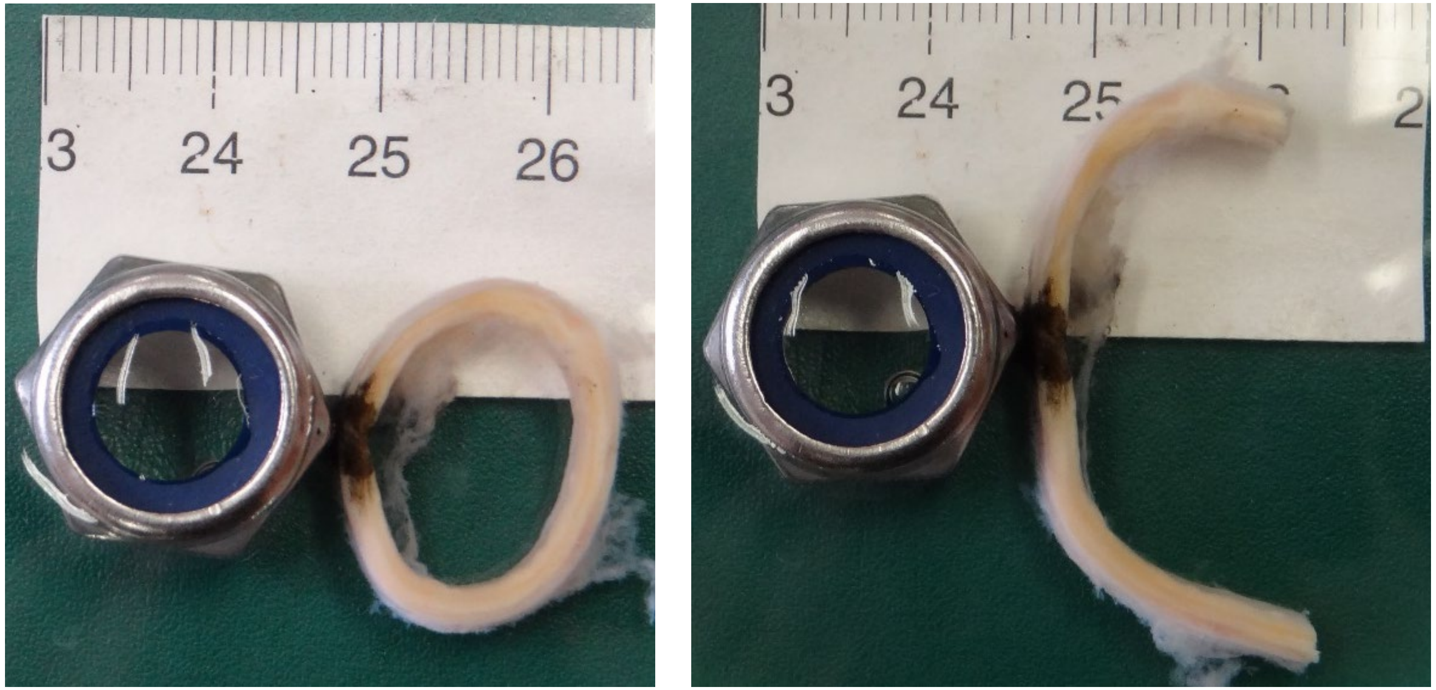
2 constituents in 1 body



residual stress balances the force at the boundary
of the mixture components

Mechanical behavior of arteries

- Residual stress holds constituents of the different properties in one continuous solid body. If continuity of the body is broken, the residual stress is released by the deformation:



arterial ring opens

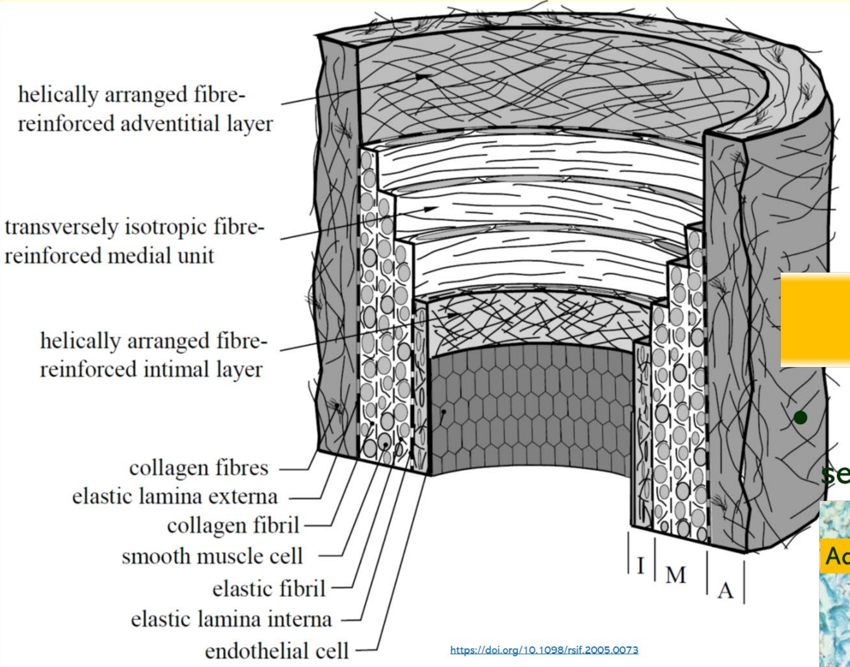
Mechanical behavior of arteries

- Remember the internal structure…

Blood vessels

- Internal structure

3-layered tube
-tunica intima
-tunica media
-tunica adventitia



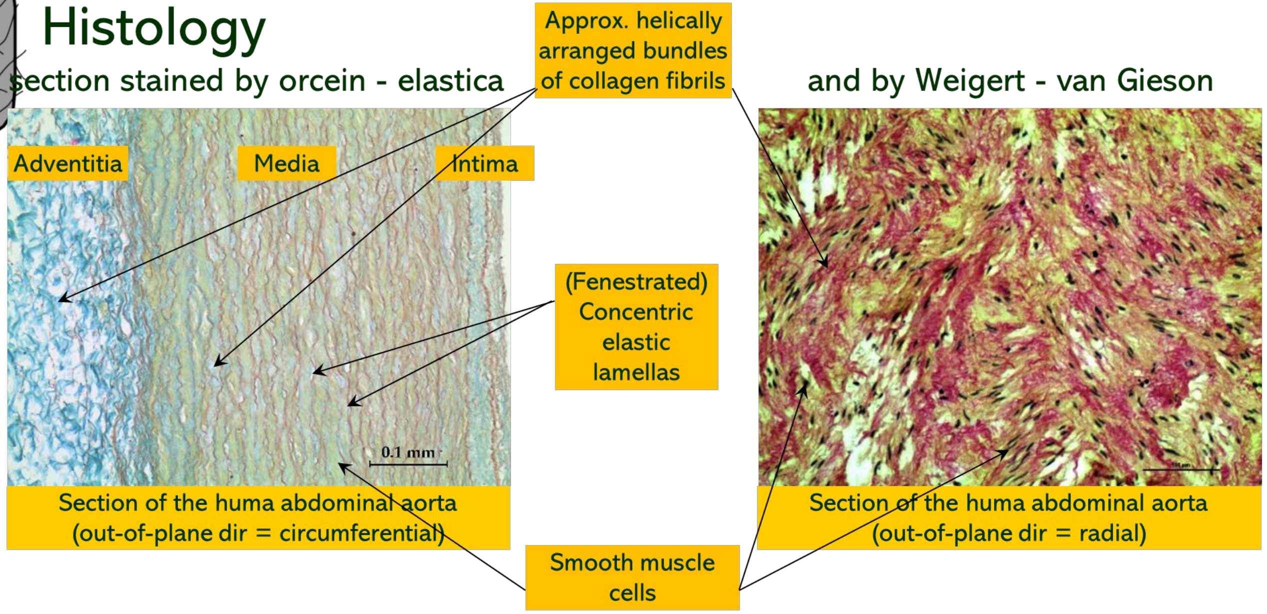
https://doi.org/10.1098/rsif.2005.0073

Blood vessels

- Histology

section stained by orcein - elastica

and by Weigert - van Gieson

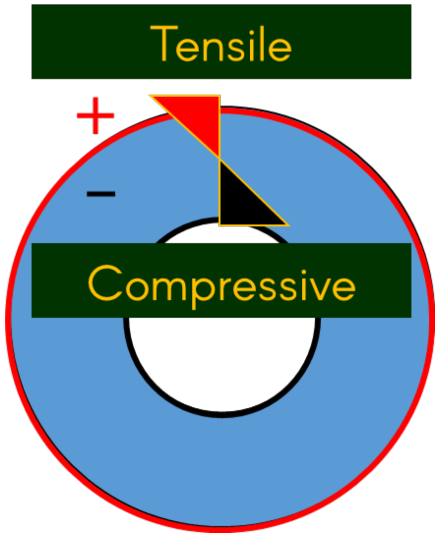


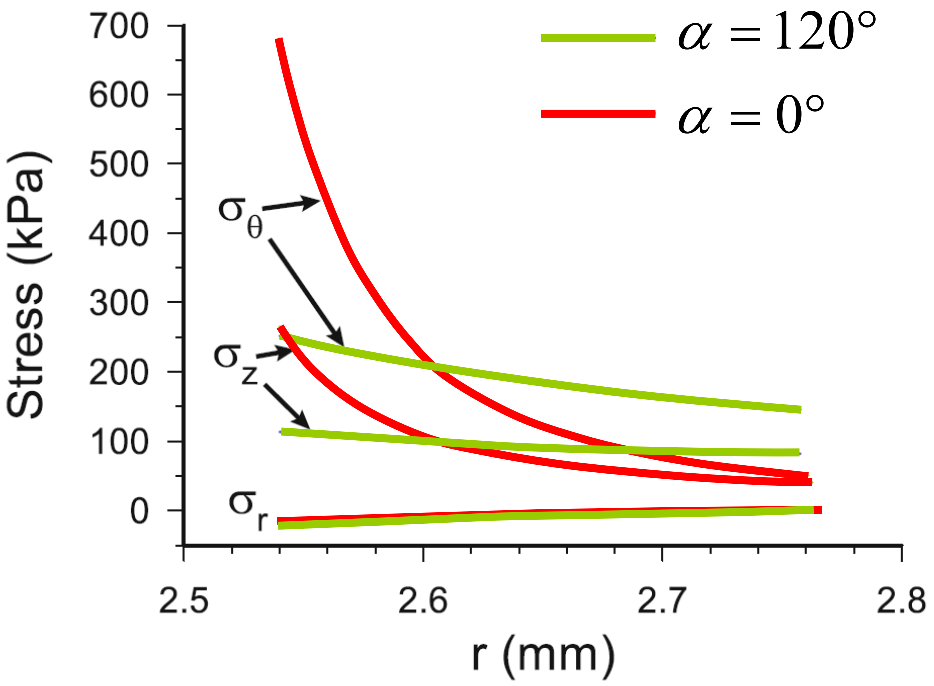
Section of the huma abdominal aorta (out-of-plane dir = circumferential)

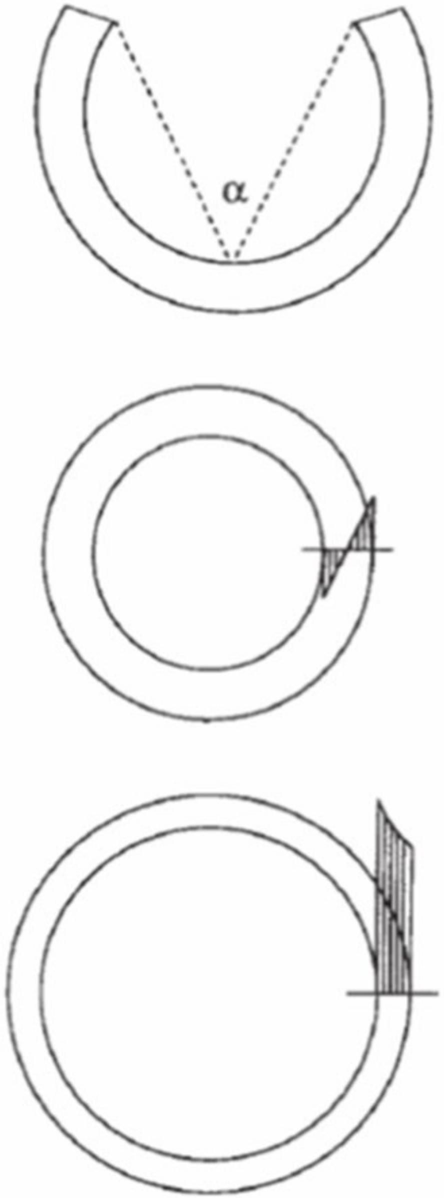
Section of the huma abdominal aorta (out-of-plane dir = radial)

Mechanical behavior of arteries

- Residual stress also has a physiological function It reduces stress peak at the inner radius





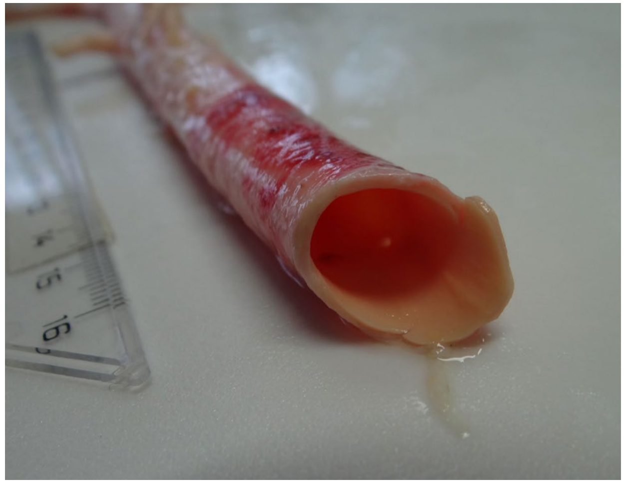


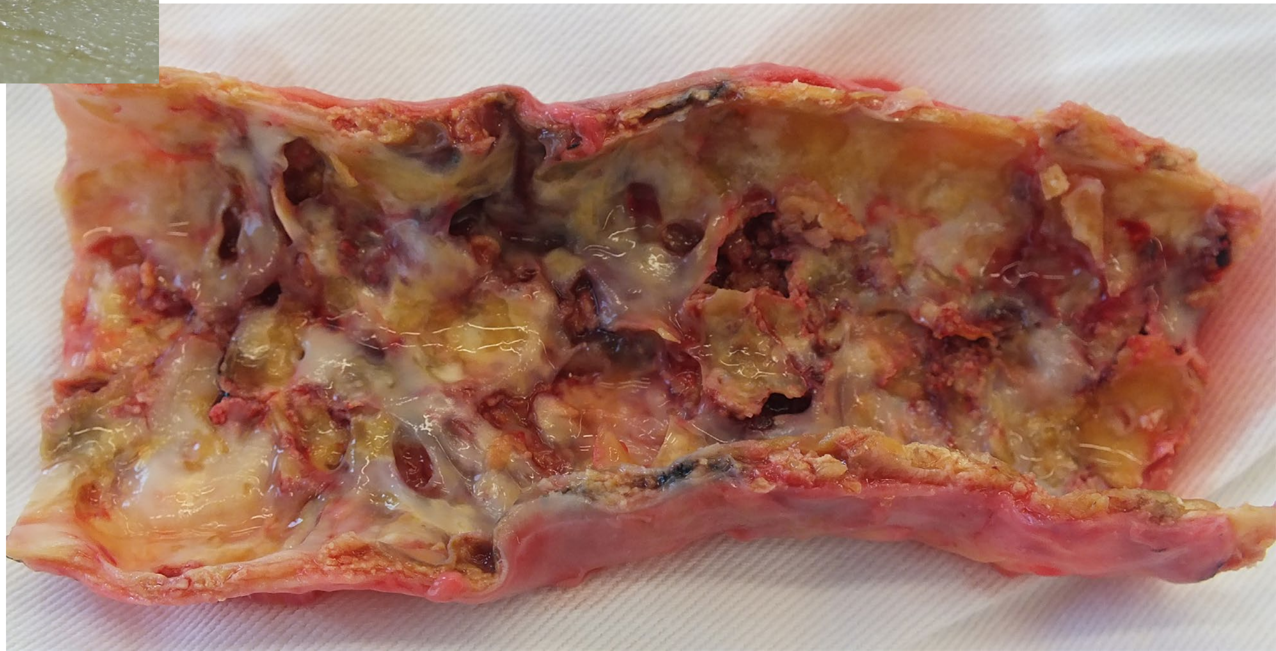
Residual stress brings about the conditions of pre-compressed state at the place of maximum tensile stress

Treatment of circulatory diseases and the contribution of mechanical engineering

Atherosclerosis (ATH)

- Plaque formation on the inner surface of arteries





develops on time scale
of decades

Atherosclerosis

- ATH develops as a consequence of endothelial damage or dysfunction

  damage can be mechanical → shear stress out of physiological limits
  damage can be chemical → oxidization of accumulated LDL

  development of ATH is always associated with inflammation processes (accumulation of monocytes and macrophages) that destroy and remove damaged cells and tissue

Atherosclerosis

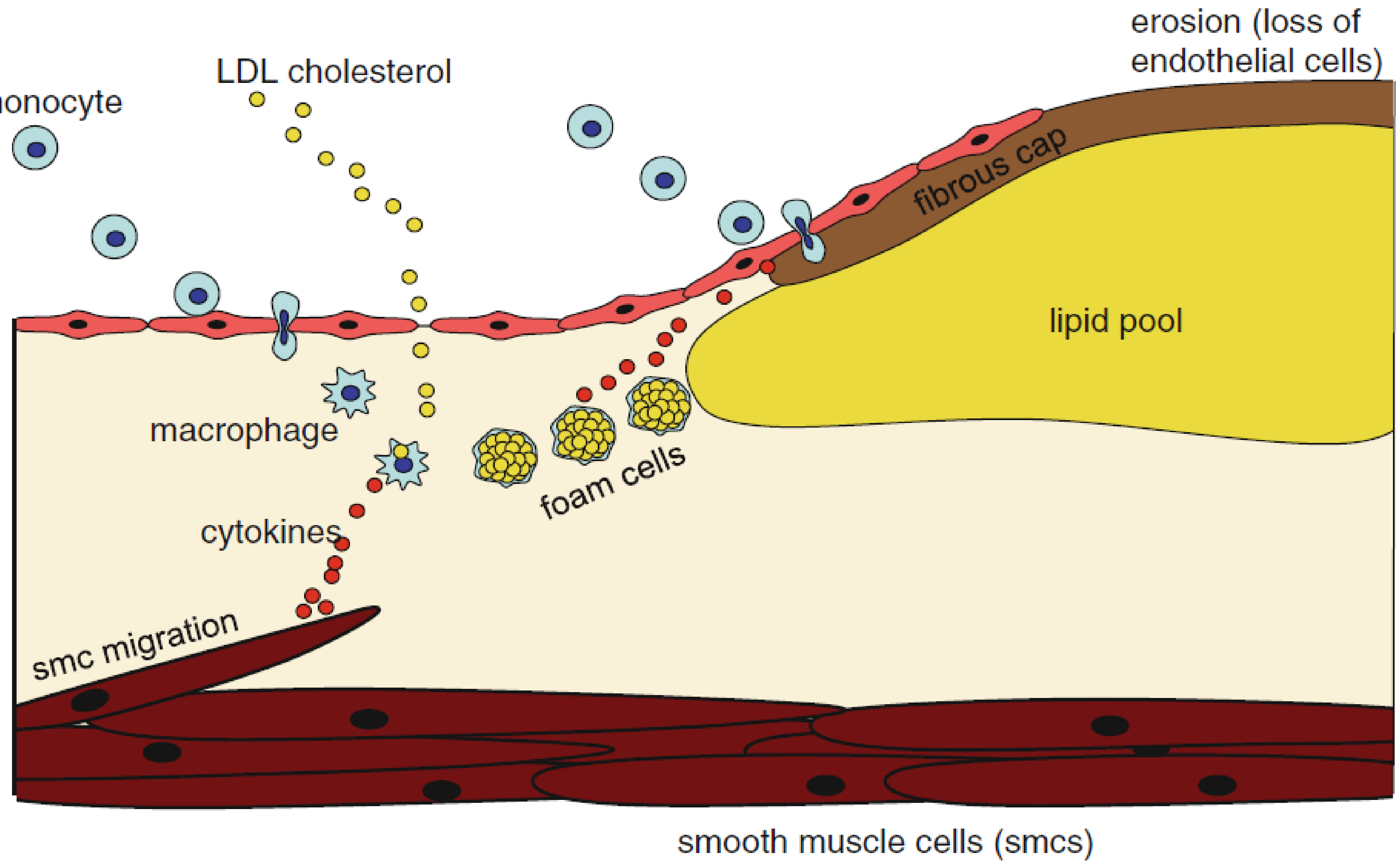
- Developed lesions consist of

  lipid particles

  calcium deposits

  and products

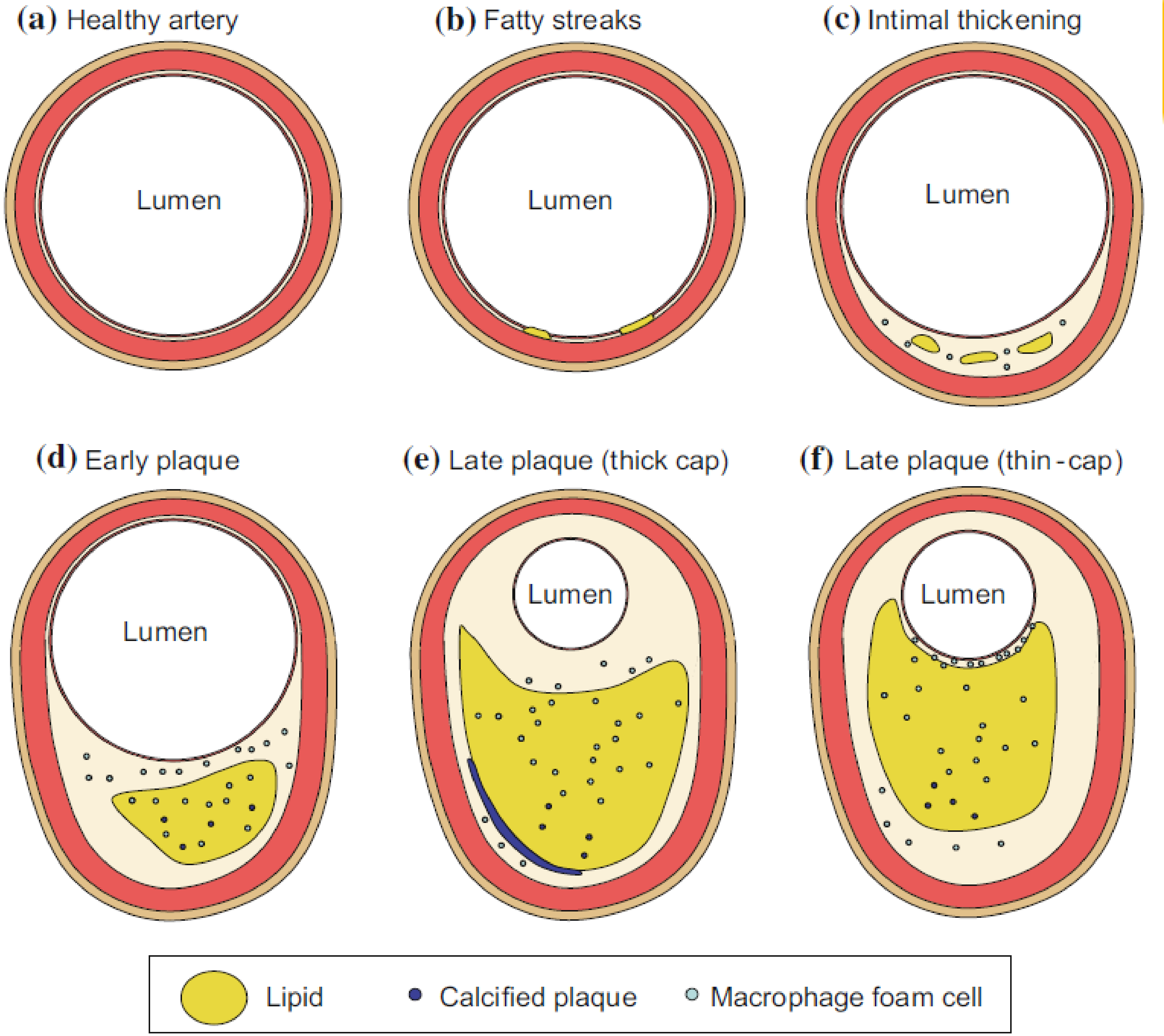
  od the inflammation



Atherosclerosis

- develops as a consequence of

mechanical damage
chemical damage
to
ENDOTHELIAL CELLS

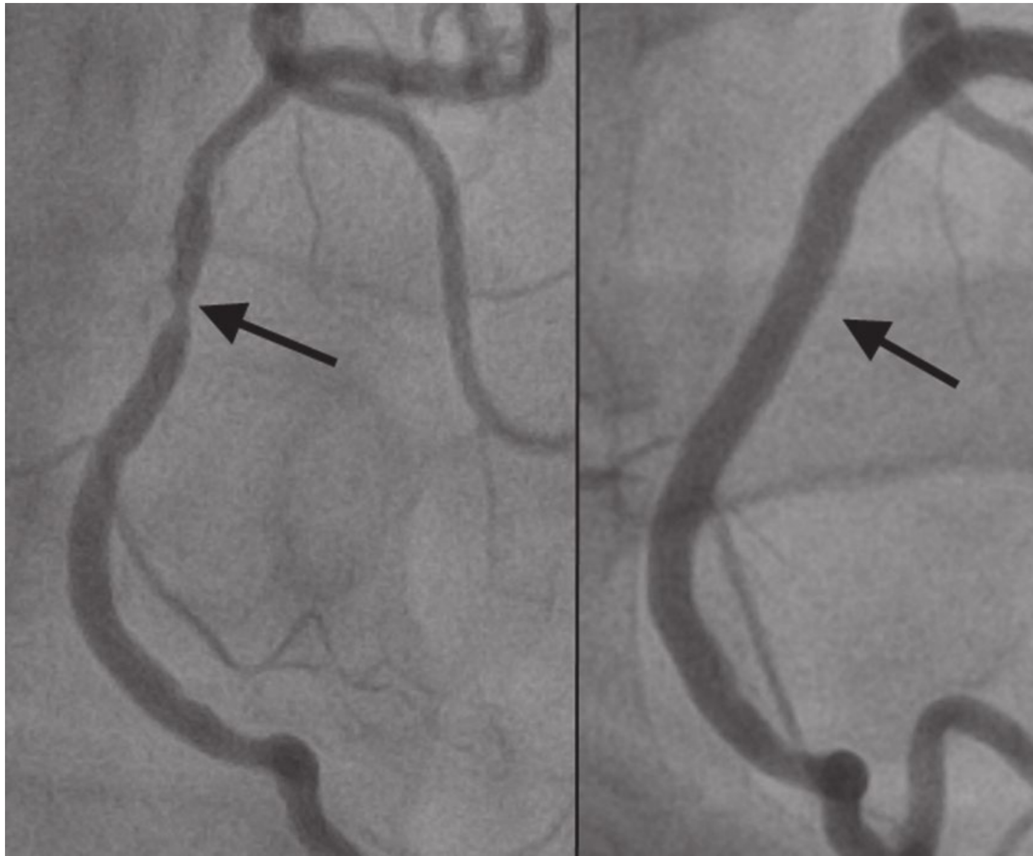


Atherosclerosis

- ATH creates obstructions in blood flow which reduce blood supply and can end in total occlusion (blockage)

ischemic disease = insufficient blood supply

coronary artery disease, limb ischemia, brain ischemia, kidney ischemia ,…

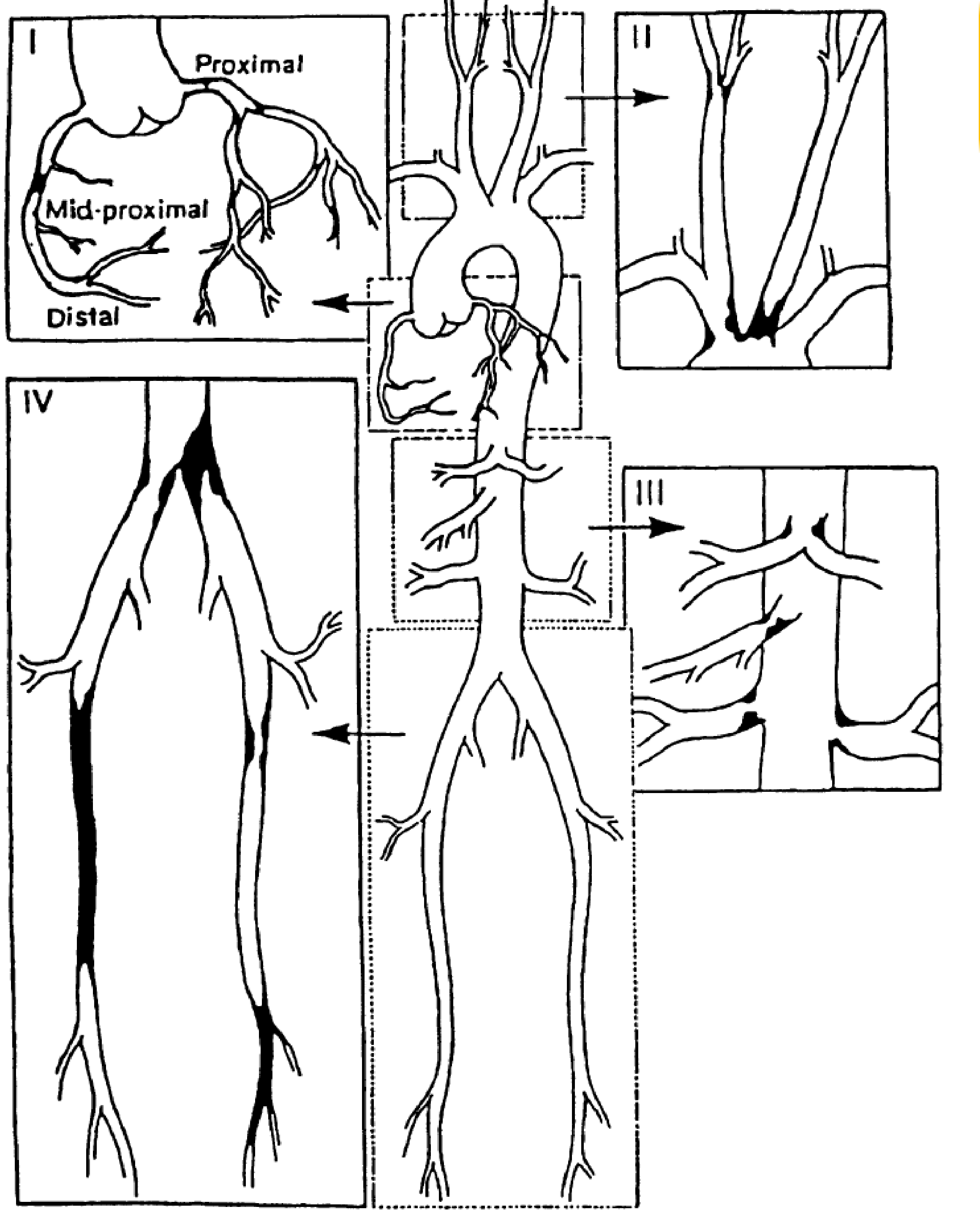


Atherosclerosis

- ATH creates obstructions

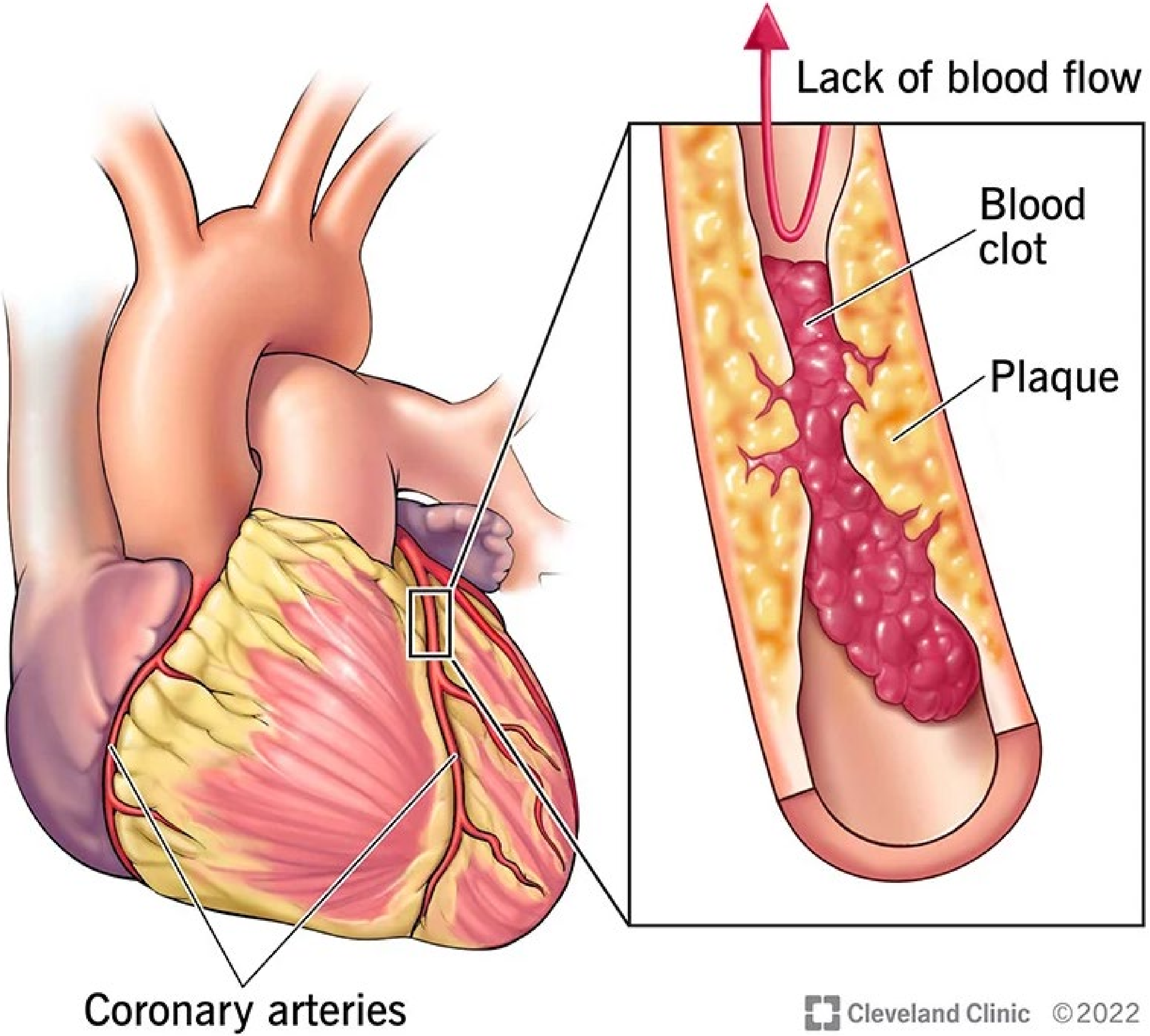
  ischemic disease = insufficient bloo

  coronary artery disease,
  limb ischemia,
  brain ischemia,
  kidney ischemia ,…



Atherosclerosis

- ATH plaque can rupture and the subsequent thrombus can suddenly block the artery completely, which is called an infarction (heart attack).



https://my.clevelandclinic.org/health/diseases/16898-coronary-artery-disease

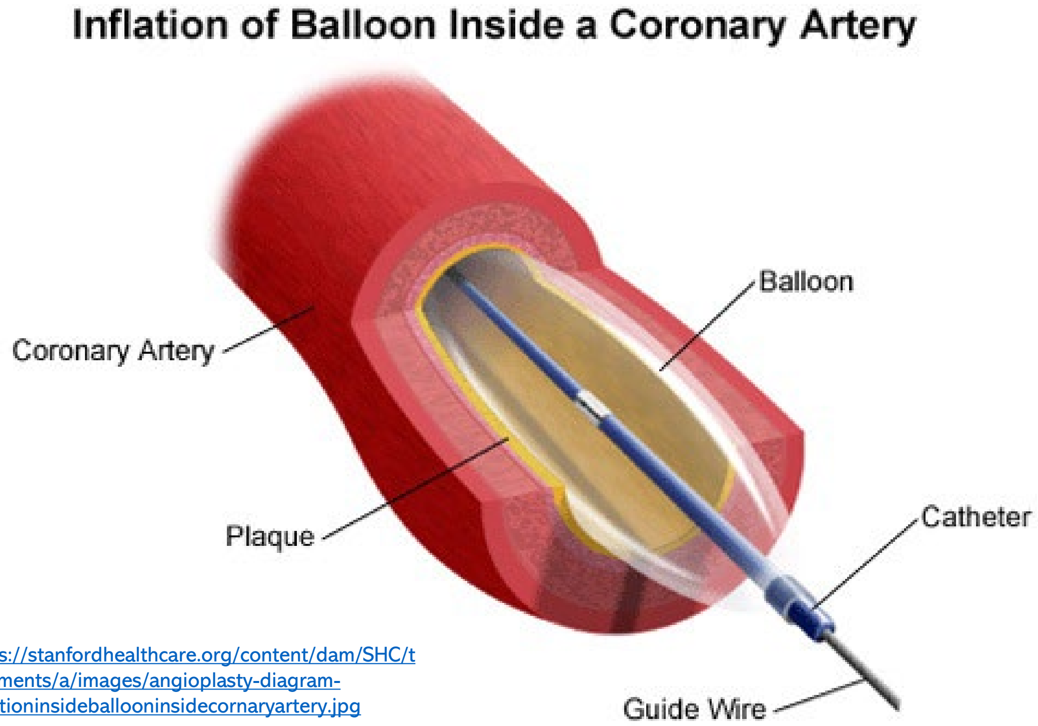
Revascularization

- To restore blood supply

  percutaneous intervention
  (stent, angioplasty → interventional cardiology)
  surgical procedures
  (bypass → cardiac/blood vessel surgery)
  endovascular stent-grafting
  (trans-catheter → endovascular surgery)

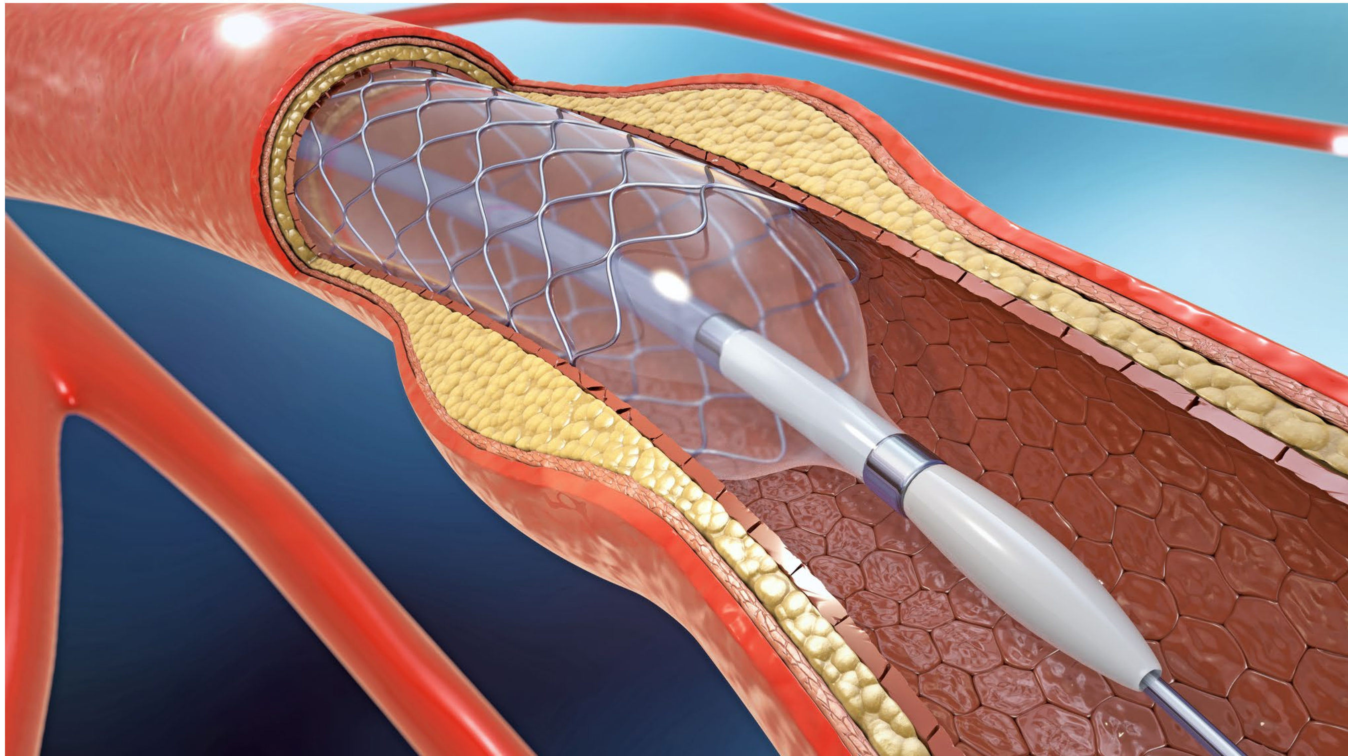
Revascularization

- Percutaneous intervention
  - angioplasty: artery distended by inflated balloon
  - stent deployment: wired tube is expanded at the narrowed place



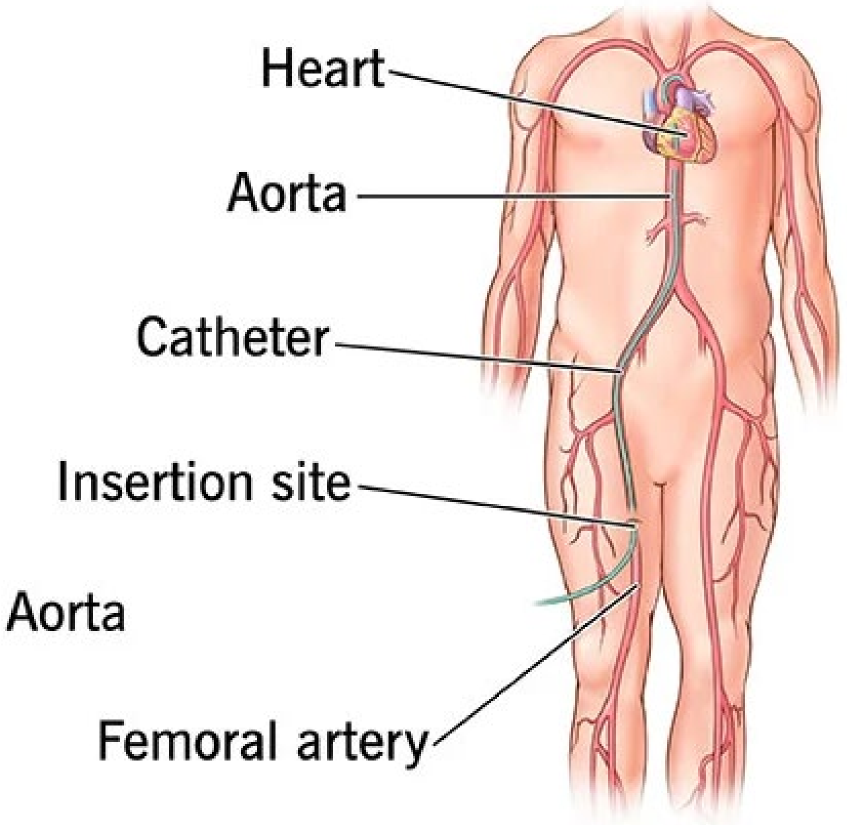
https://stanfordhealthcare.org/content/dam/SHC/treatments/a/images/angioplasty-diagram-inflationinsideballooninsidecornaryartery.jpg

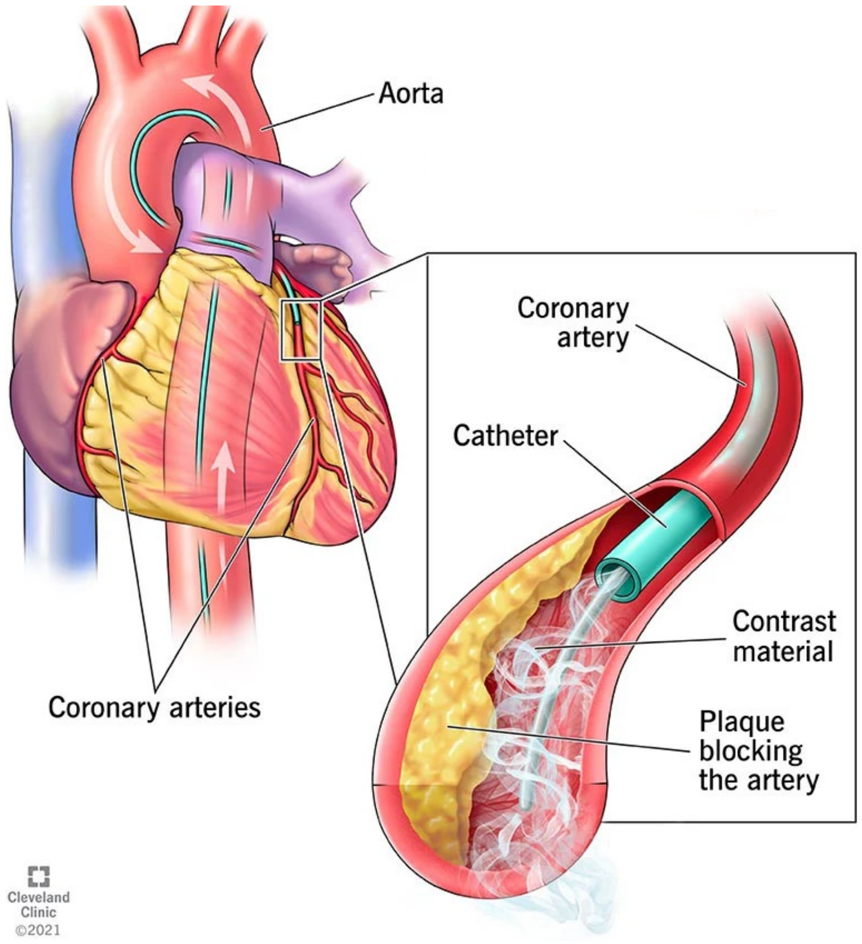
https://ahvsc.com/wp-content/uploads/2021/05/iStock-999350286.jpg



Revascularization

- Percutaneous intervention - catheterization

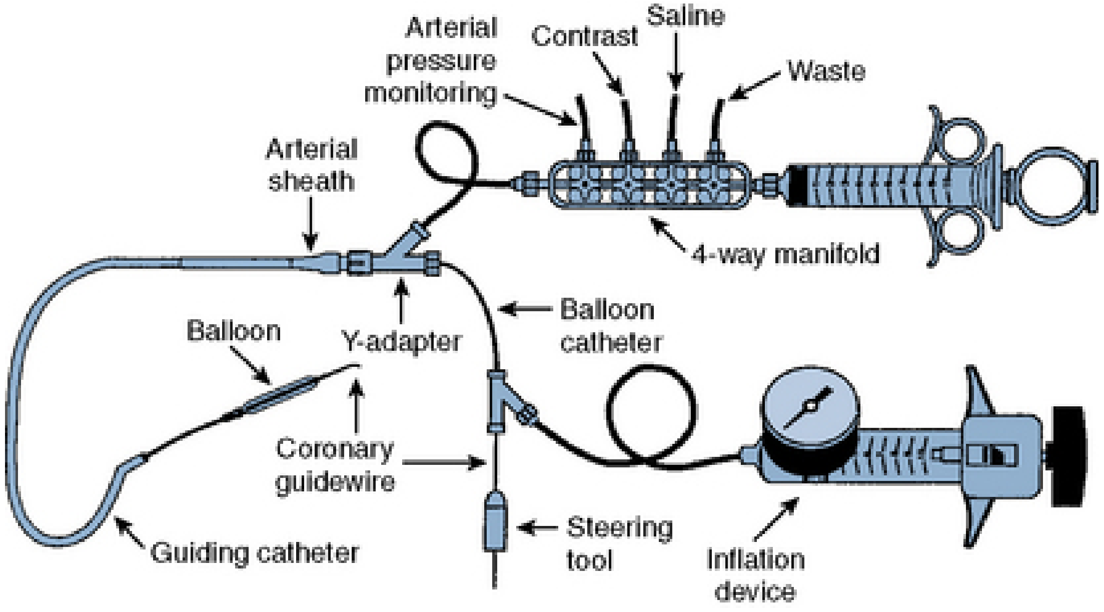


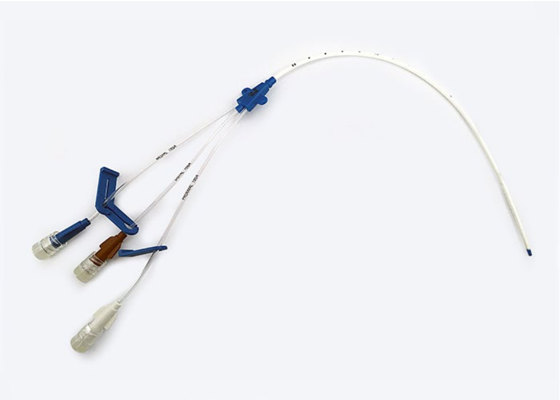


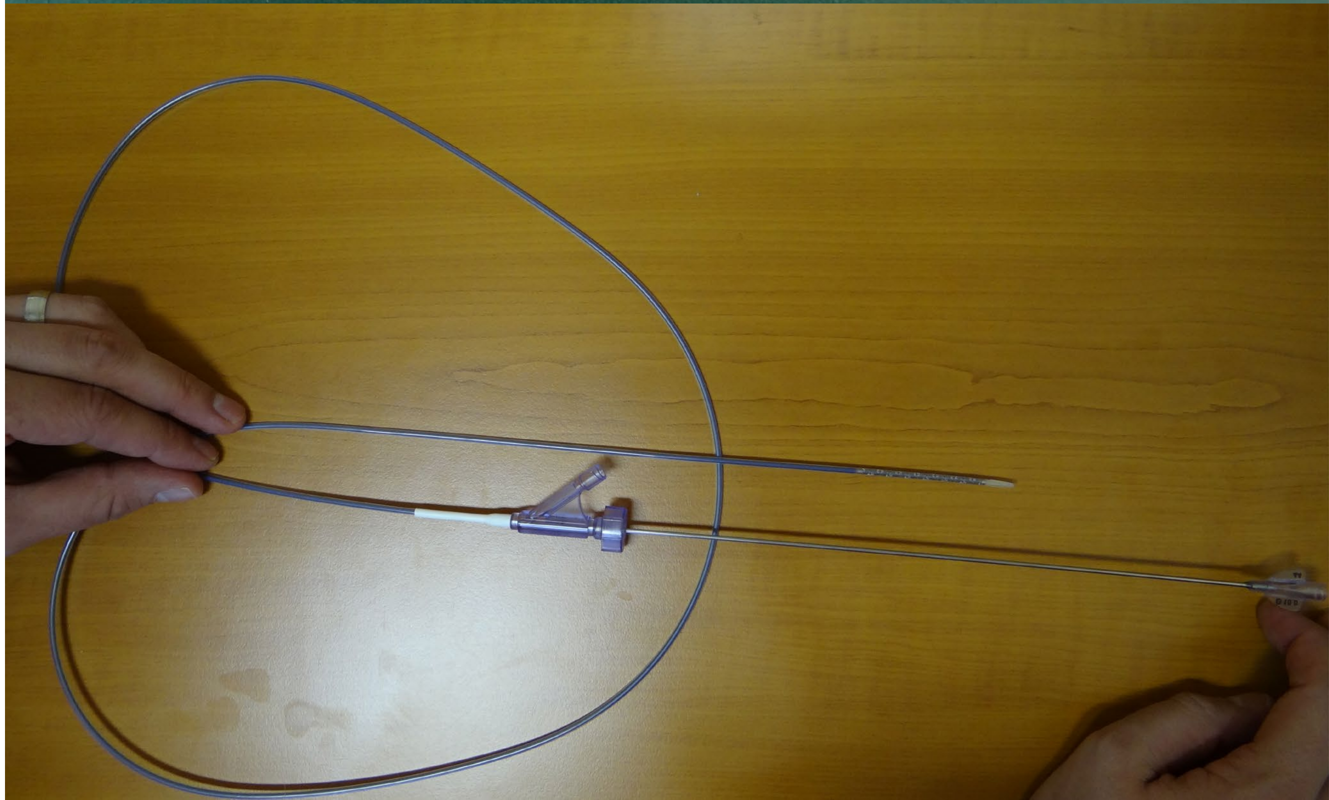
https://my.clevelandclinic.org/-/scassets/images/org/health/articles/16832-cardiac-catheterization

Revascularization

- Percutaneous intervention - catheterization

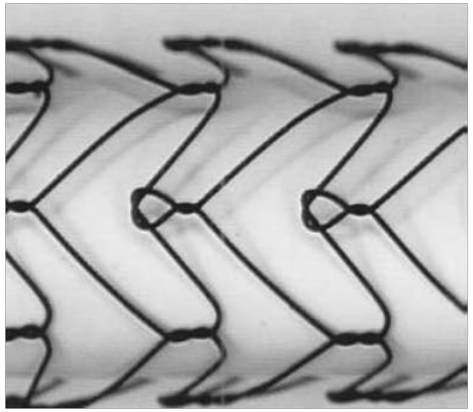




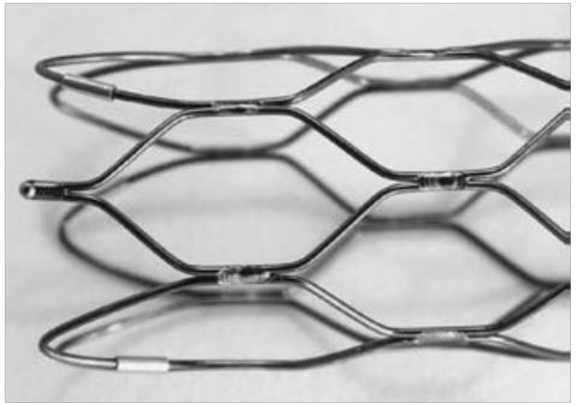


Revascularization

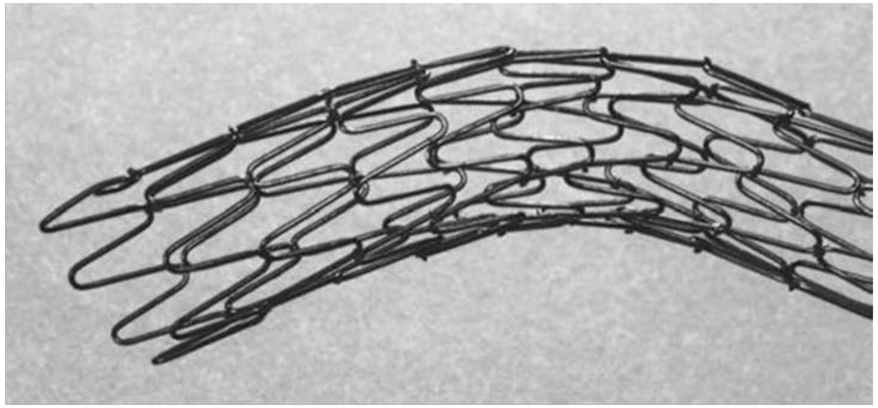
- Percutaneous intervention - stent



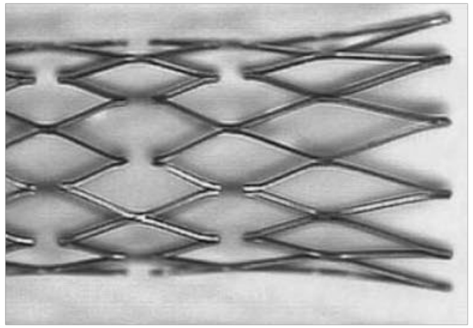
ZA stent (Cook)



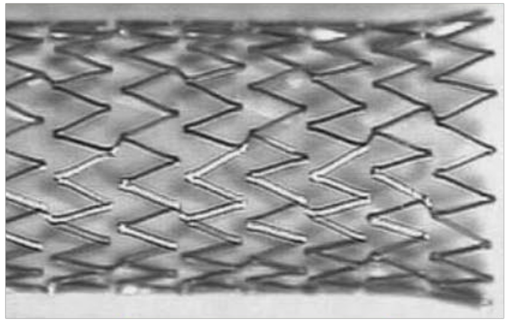
Symphony (Boston Scientific)



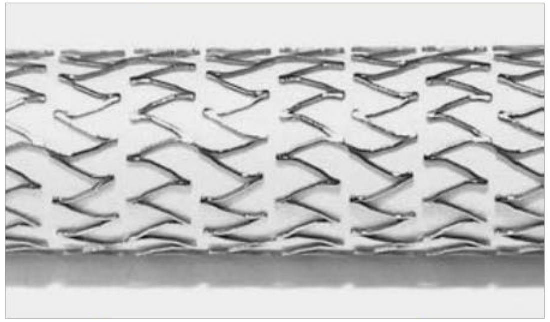
Cragg stent (MinTec)



NiTi Memotherm (Bard Angiomed)



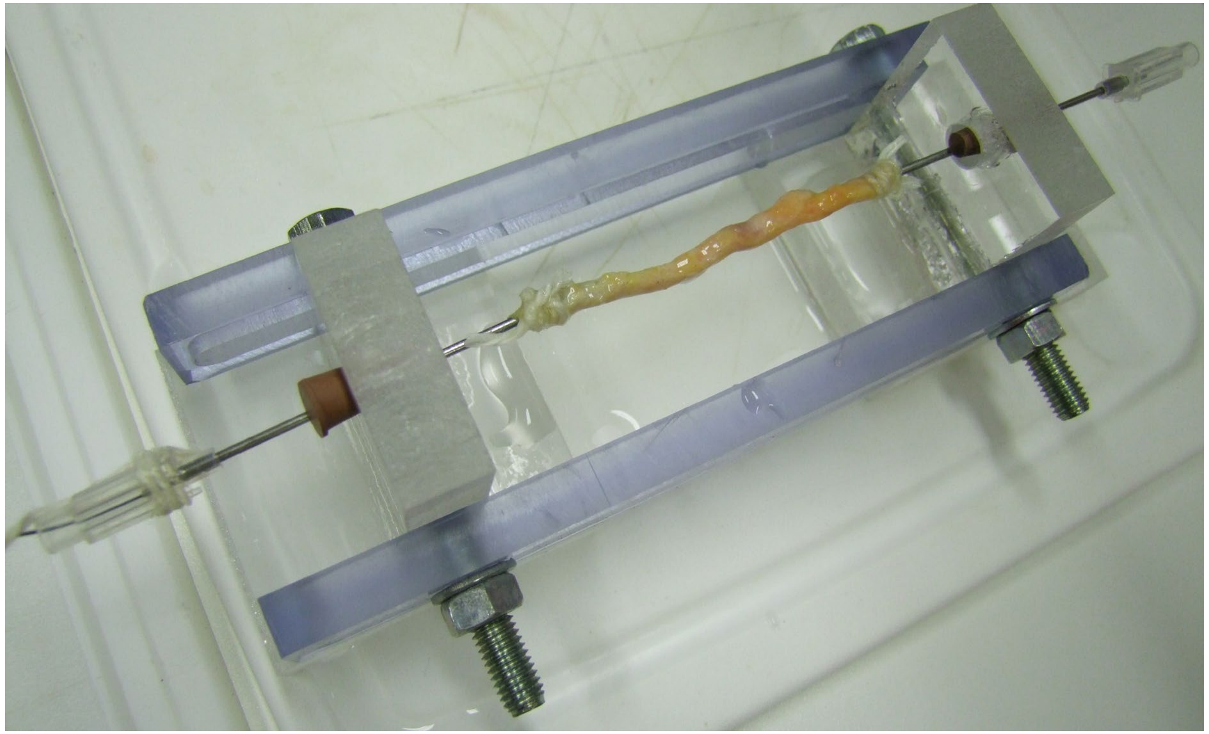
SMART (Cordis)



Jostent SelfX (Jomed)

Revascularization

- Engineering: Applied biomechanics
  development of new materials and designs



Revascularization

- Engineering:
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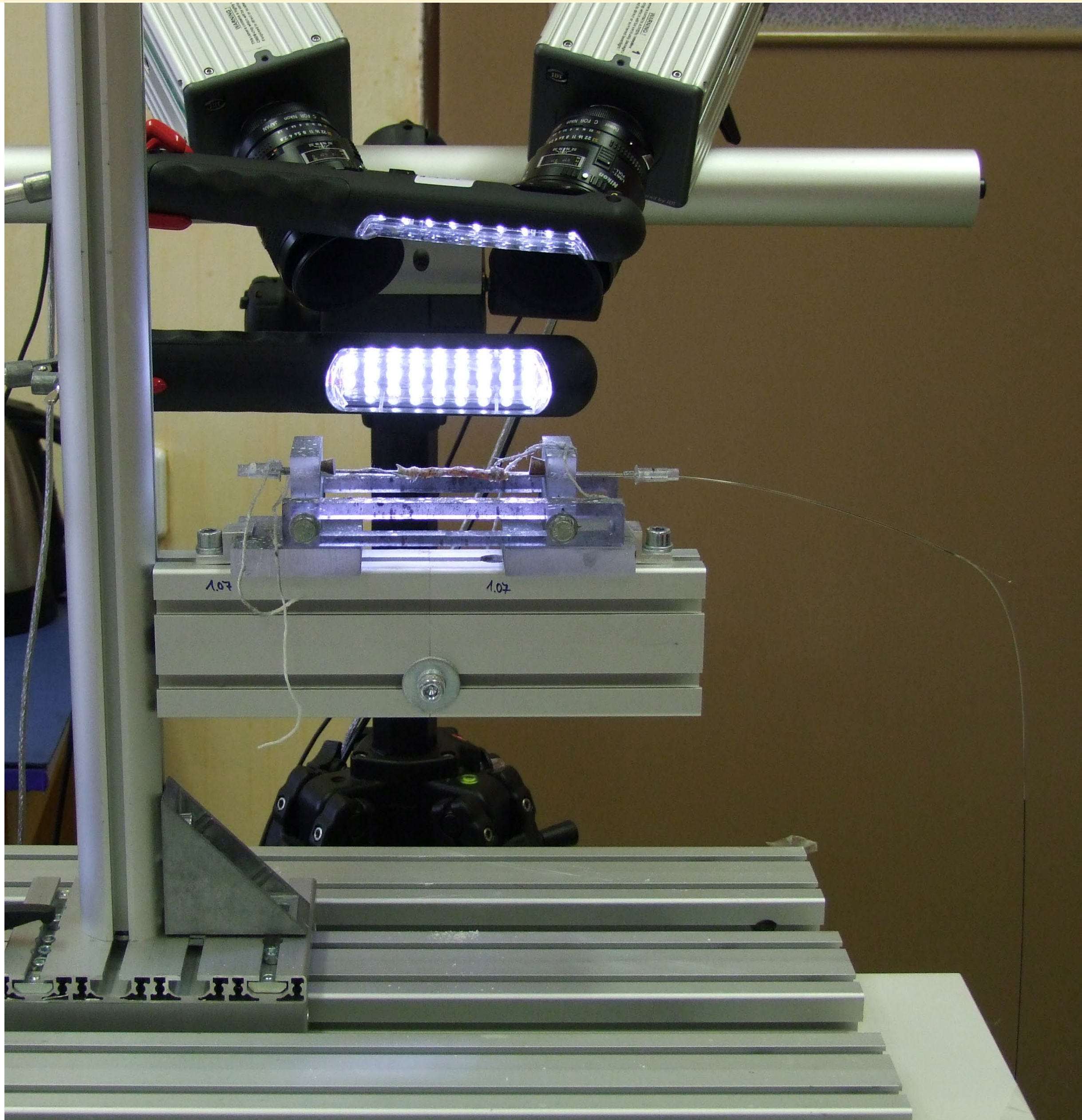
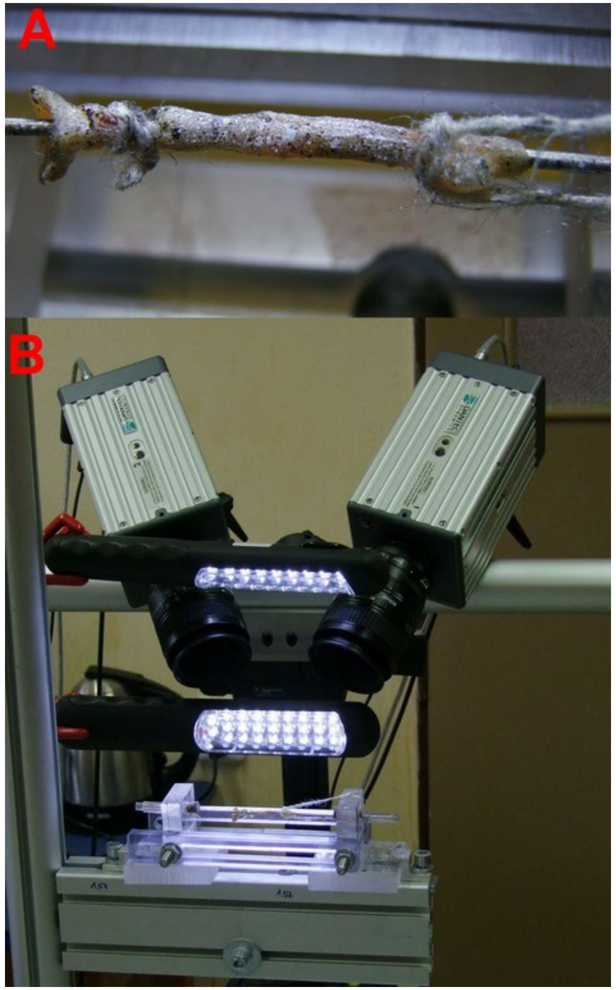


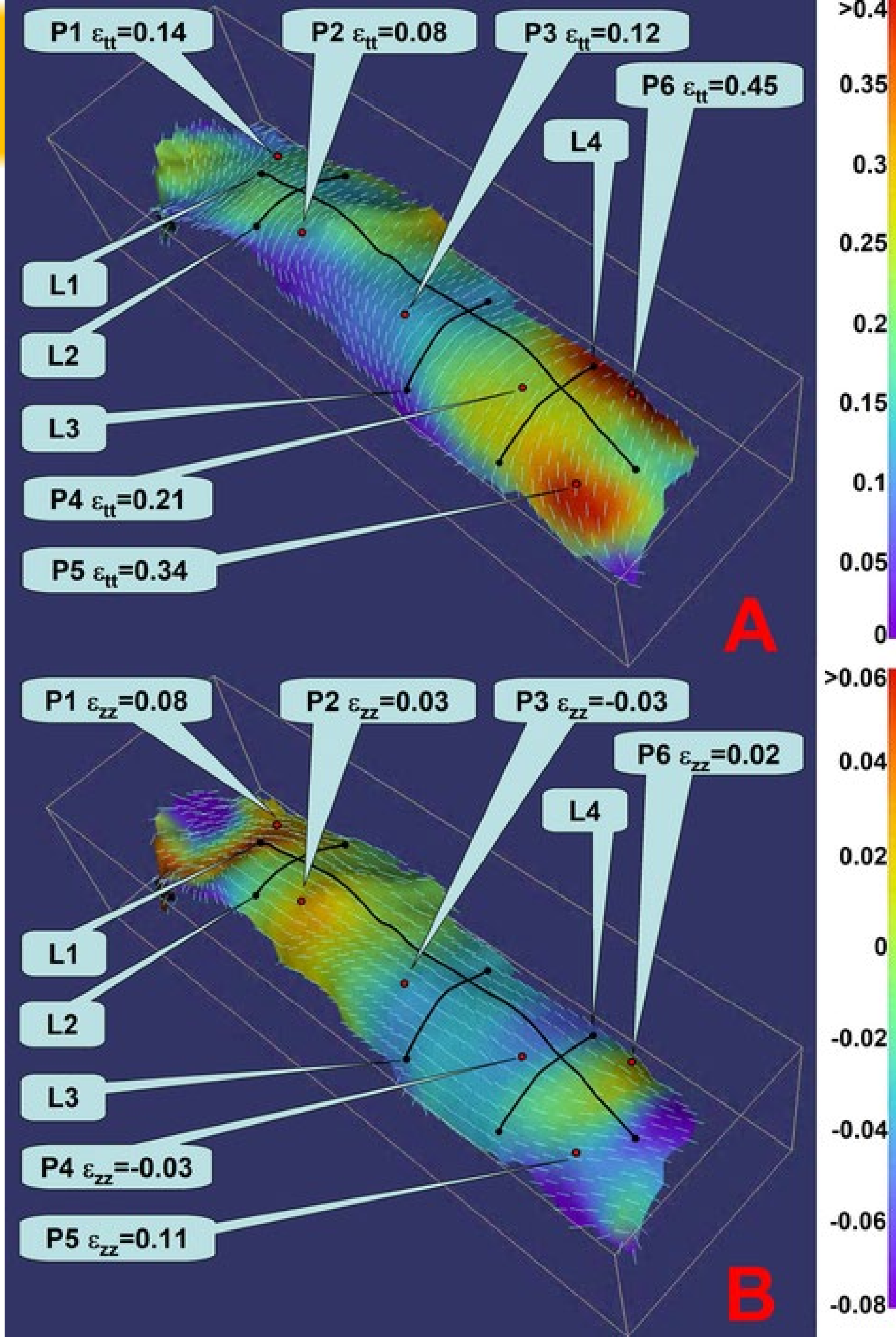
Revascularization

- Applied biomechanics

description of the mechanical interaction between stent and artery wall

overloading can induce restenosis



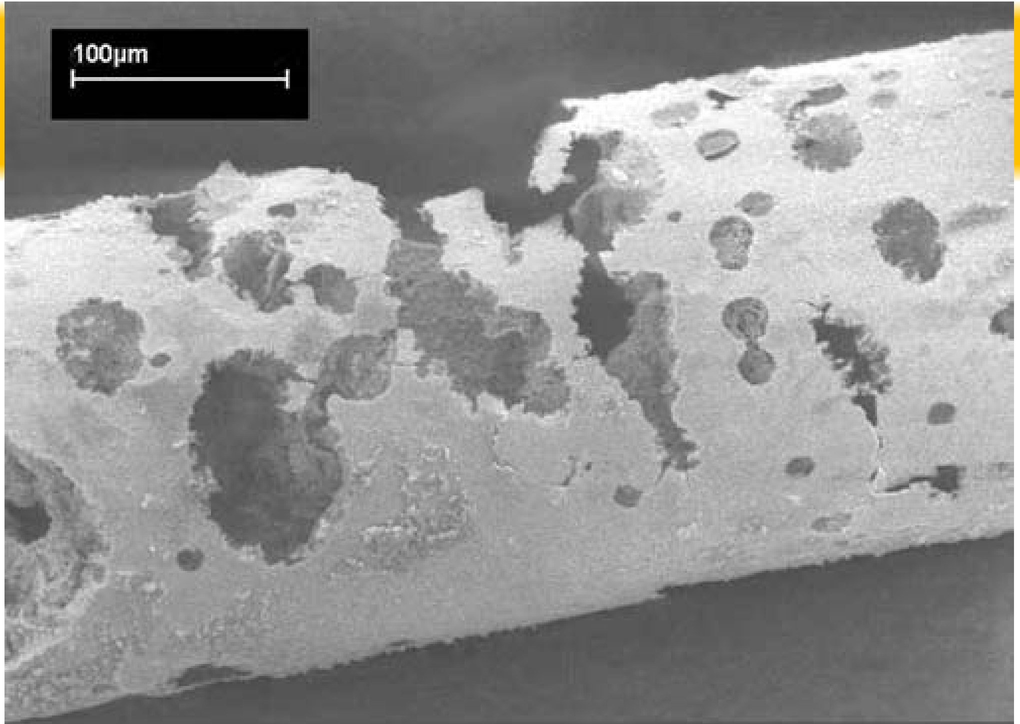


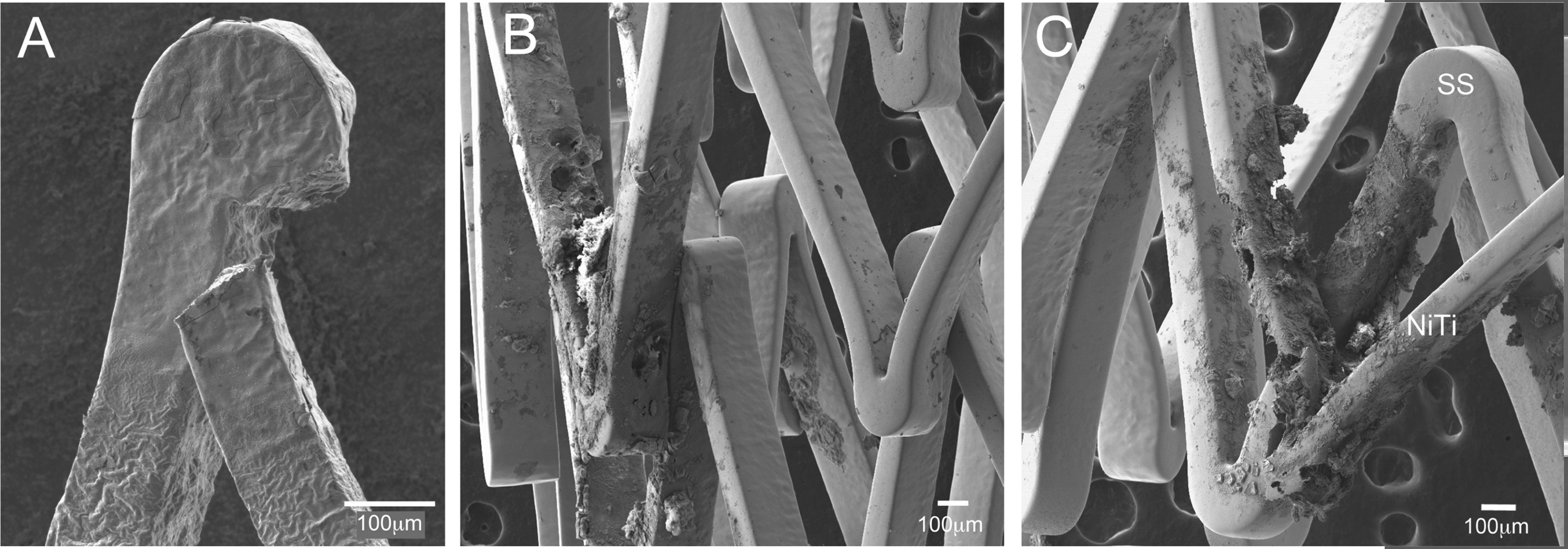
Revascularization

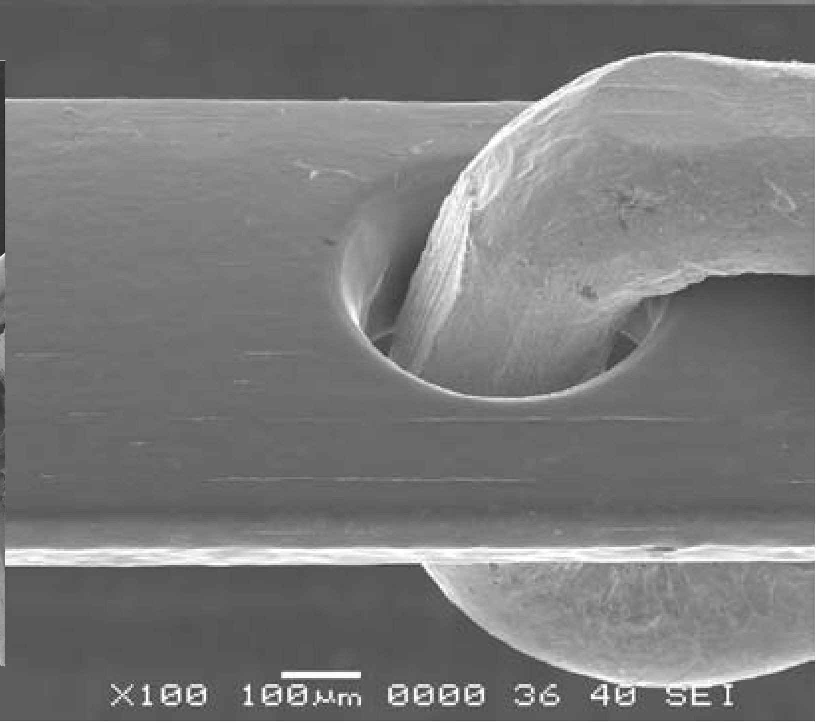
- Applied biomechanics

  safe service life

  corrosion and/or fatigue





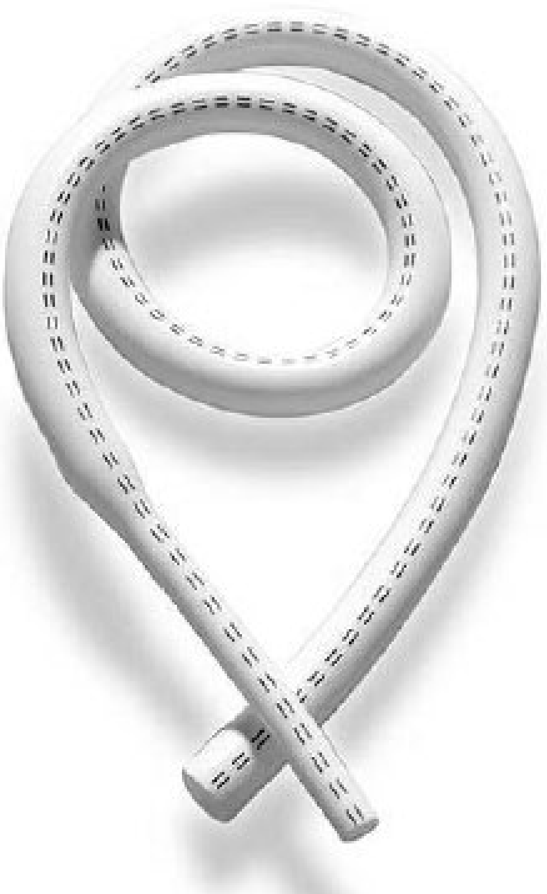


Revascularization

- Applied biomechanics: replacements

  new
  design and
  development
  of materials

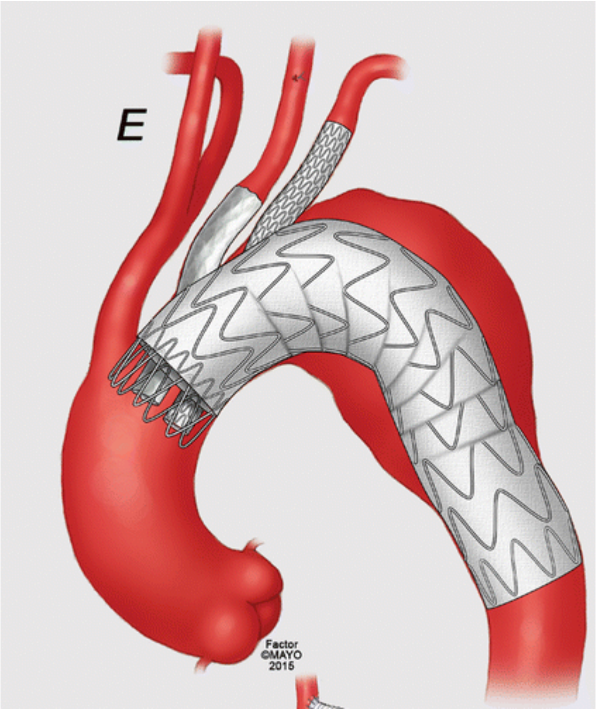


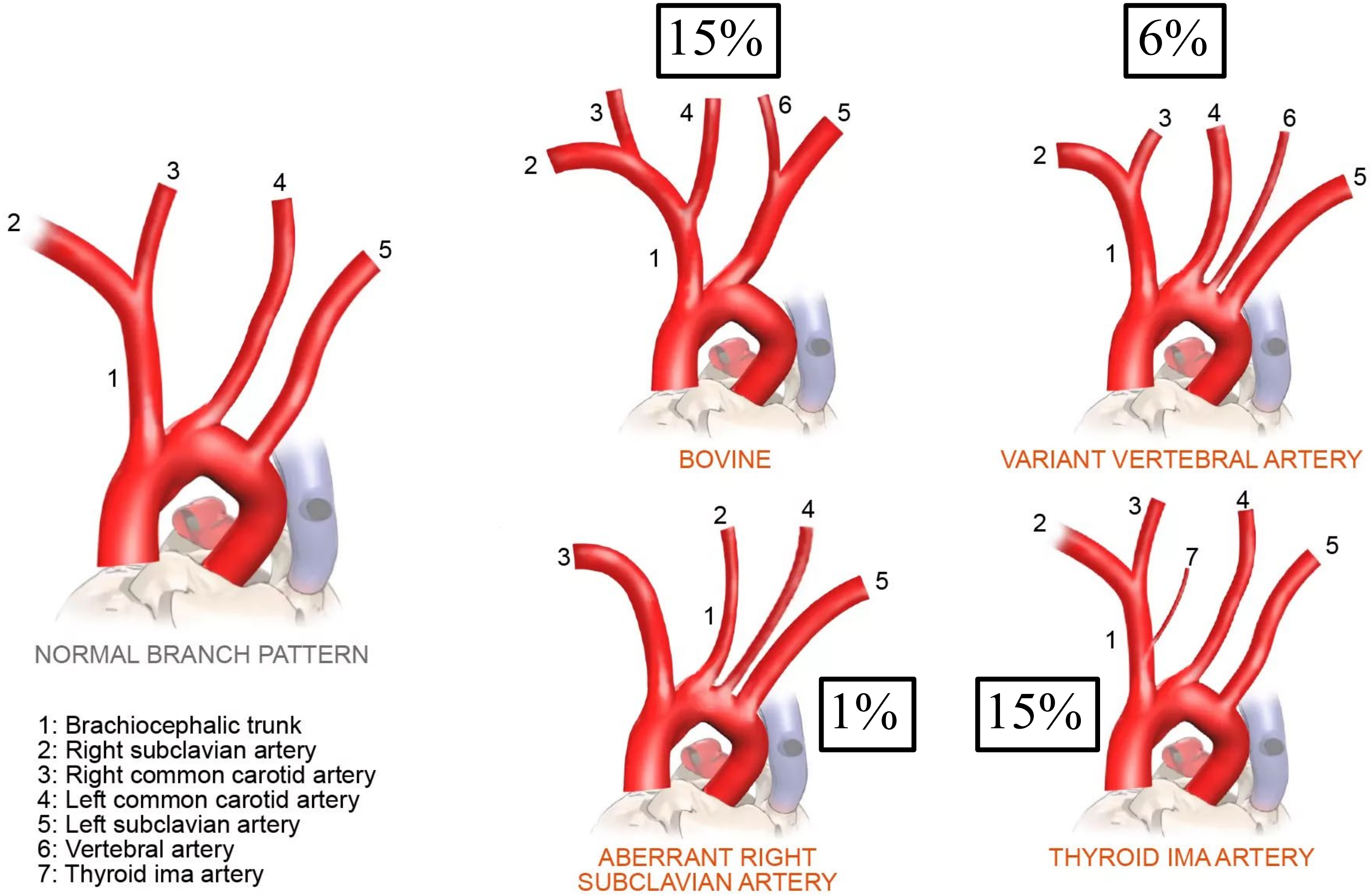



Revascularization

- Applied biomechanics

  personalized designs
  for complex geometries
  3D printing

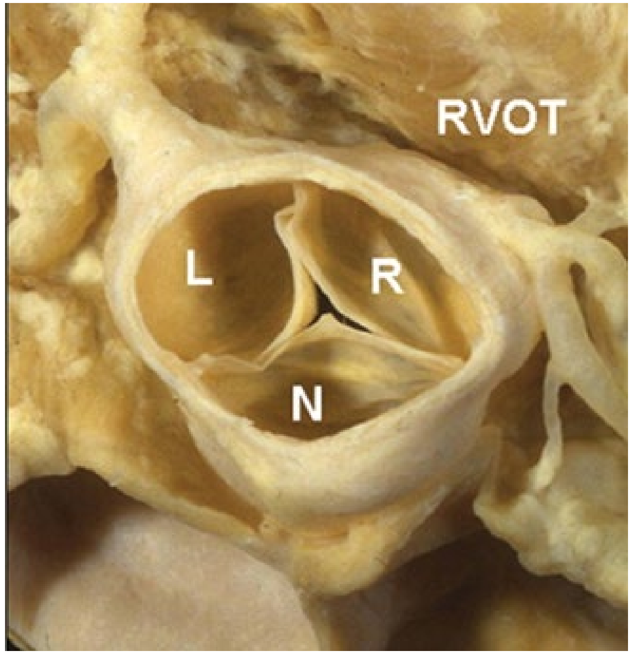


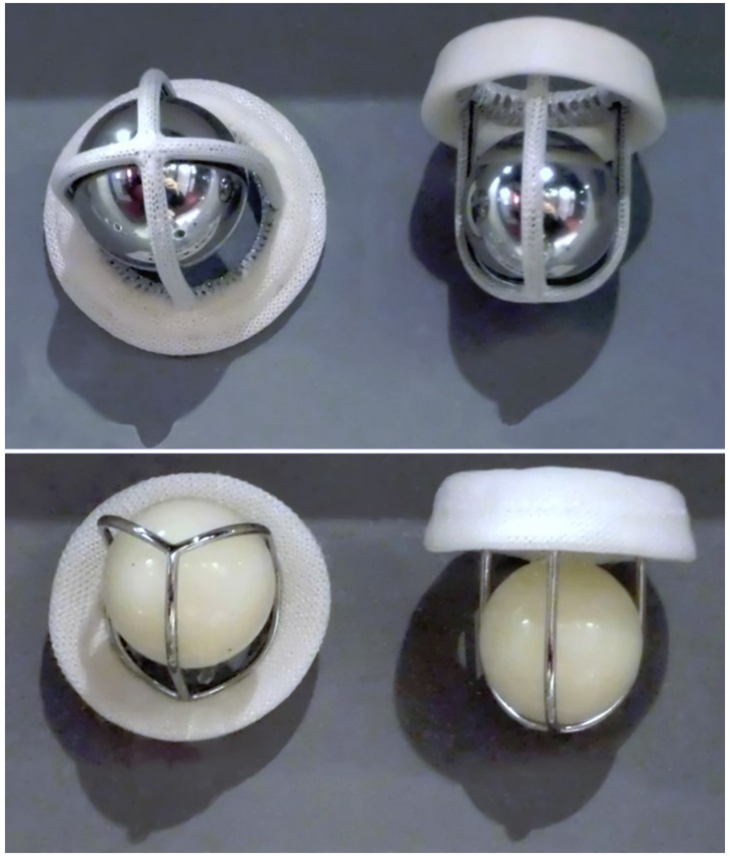


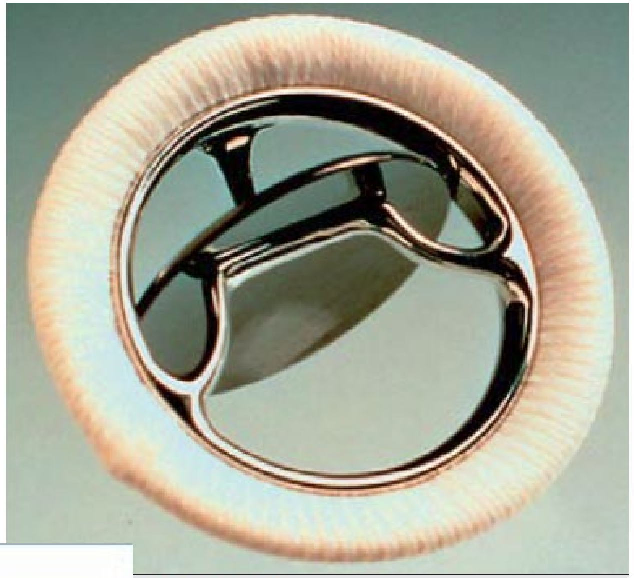
https://www.primalpictures.com/blogs/anatomical-variations-aortic-arch-branching-patterns/

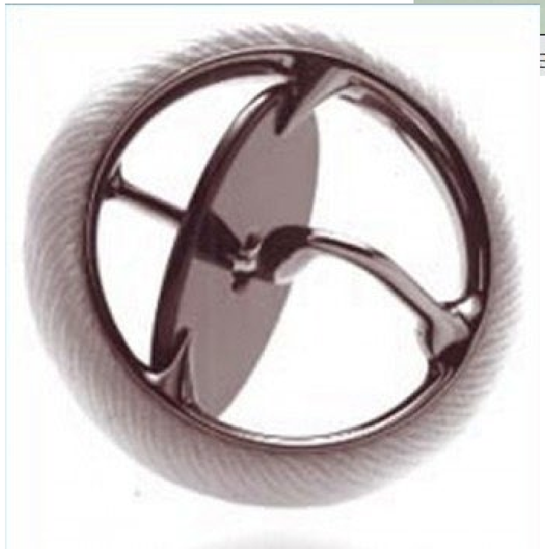
Valve intervention

- Applied biomechanics: prosthetic valves



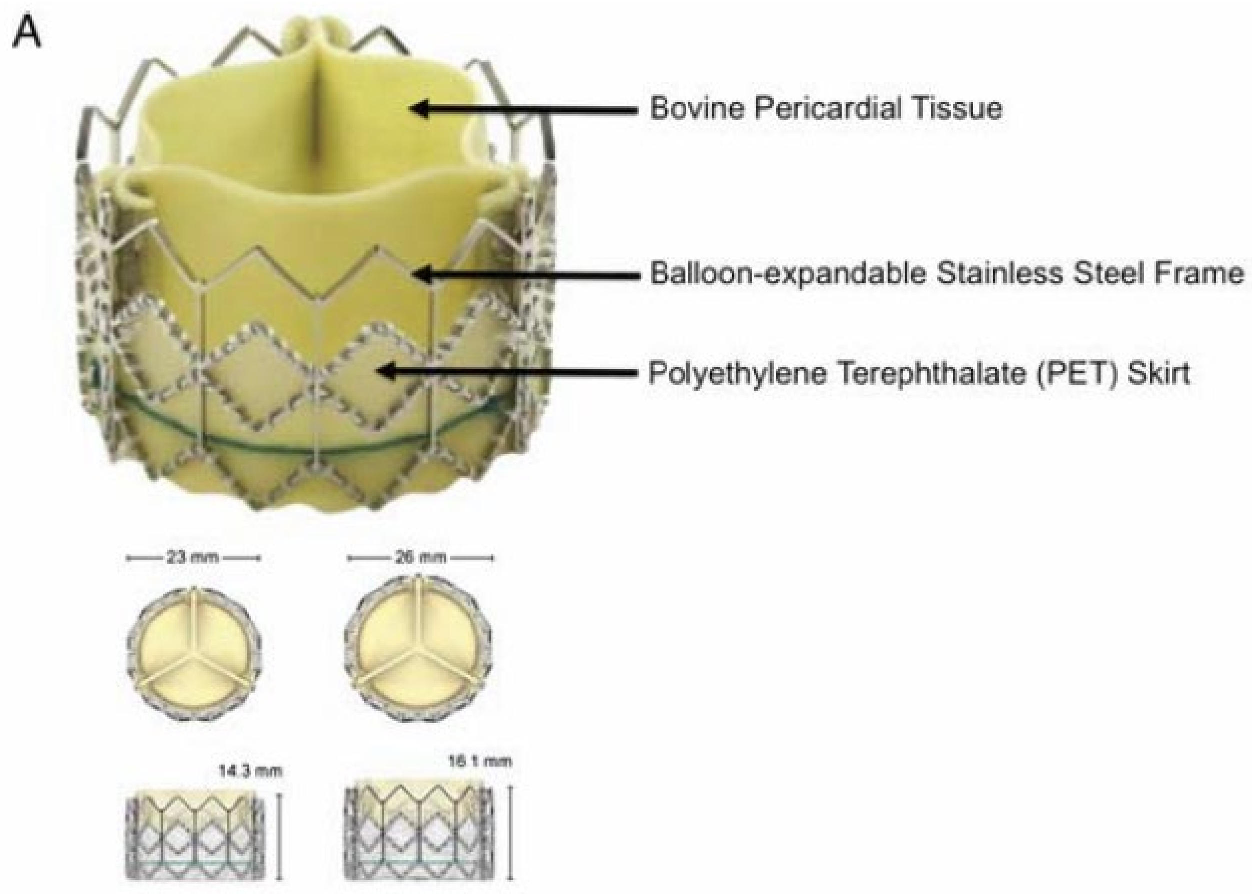



ey tilting disc



Valve intervention

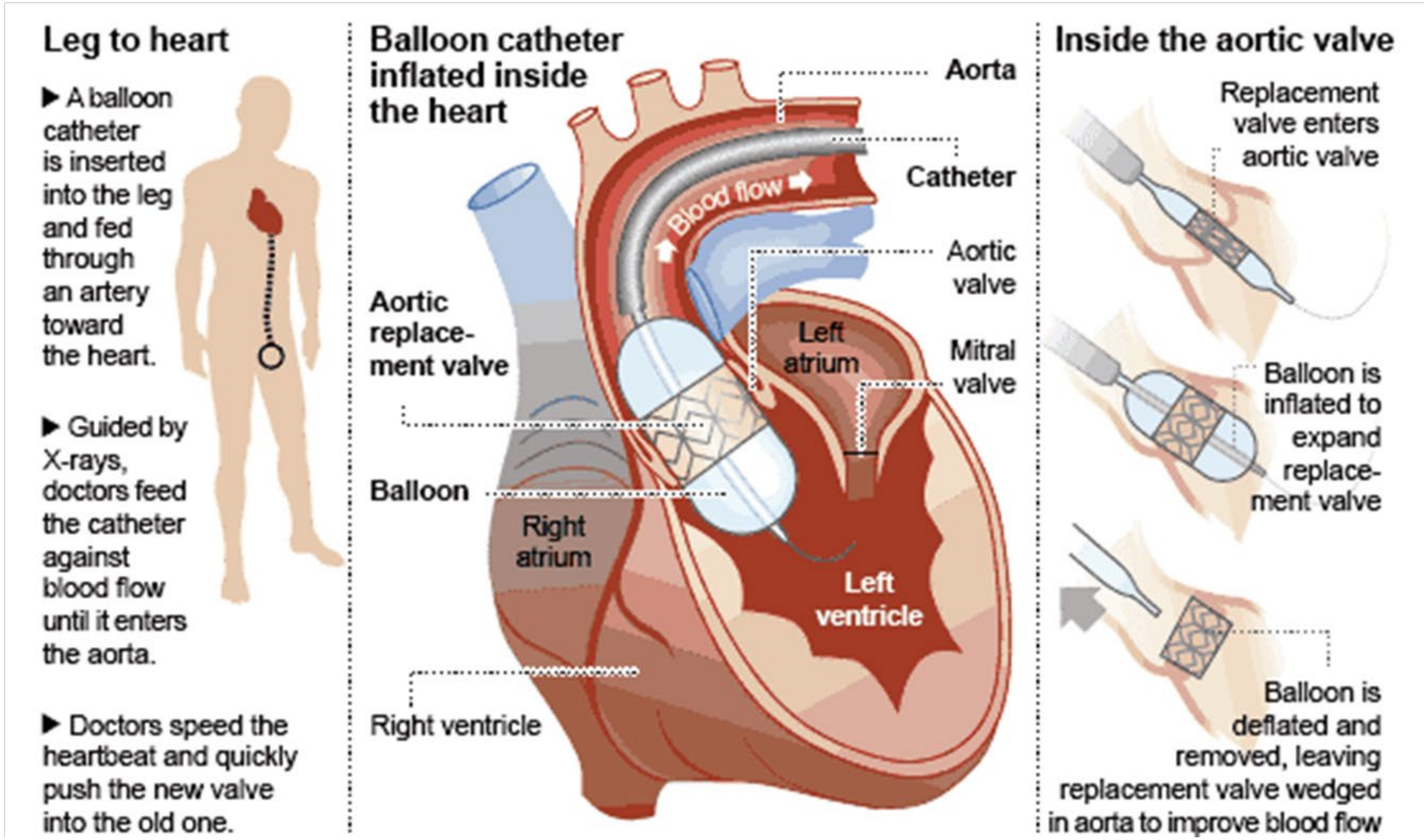
- Applied biomechanics: bioprosthetic valves



Valve intervention

- Applied biomechanics: bioprosthetic valves

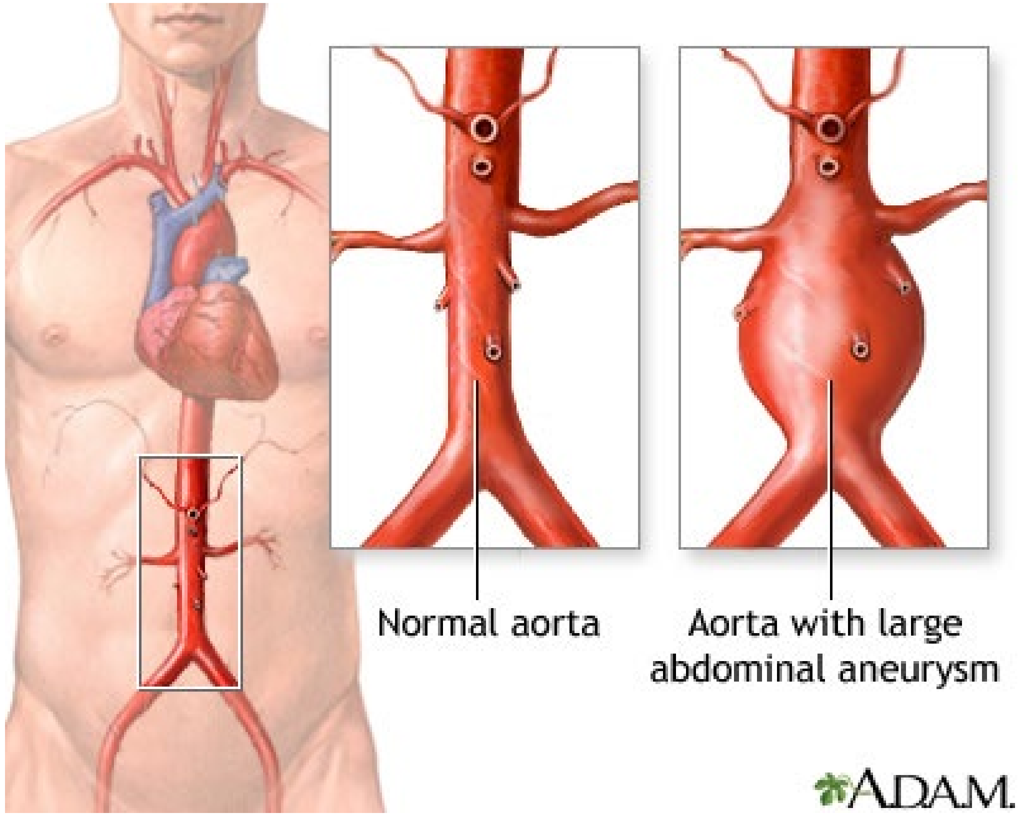
Transcatheter aortic valve replacement (TAVR)



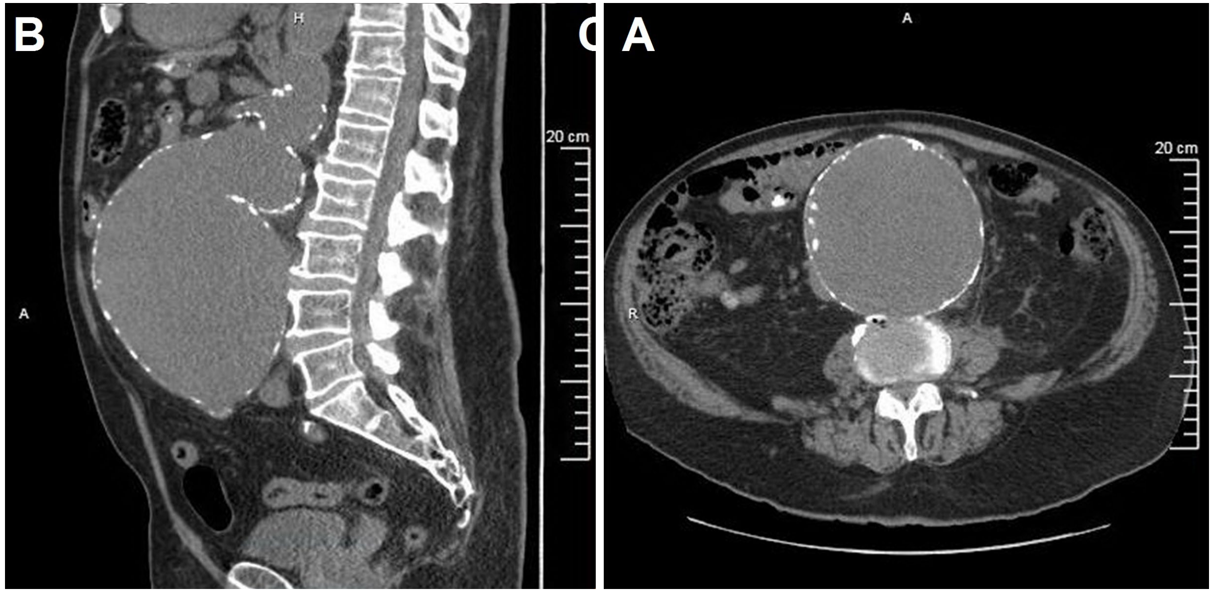
Aneurysm

- Applied biomechanics: advice on decision-making

Computational assessment of aneurysm rupture risk



https://medlineplus.gov/ency/article/000162.htm

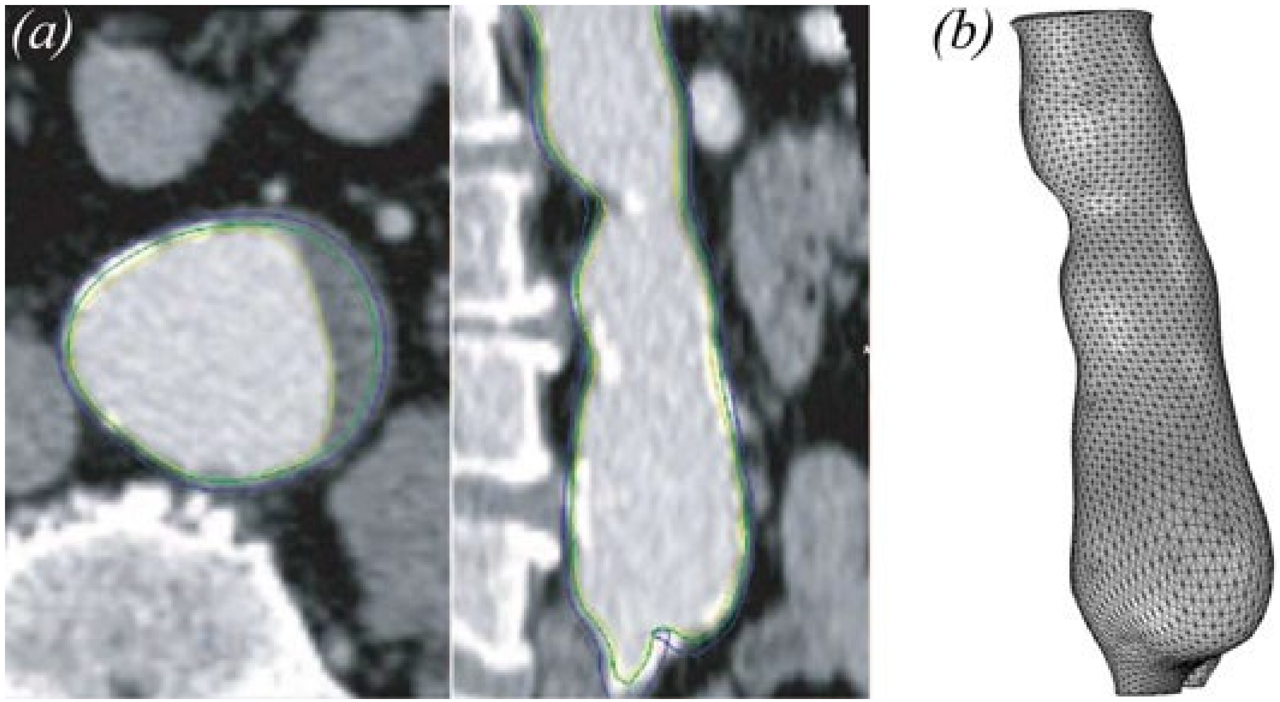


https://www.swjpcc.com/imaging/2016/7/6/medical-image-of-the-week-massive-abdominal-aortic-aneurysm.html

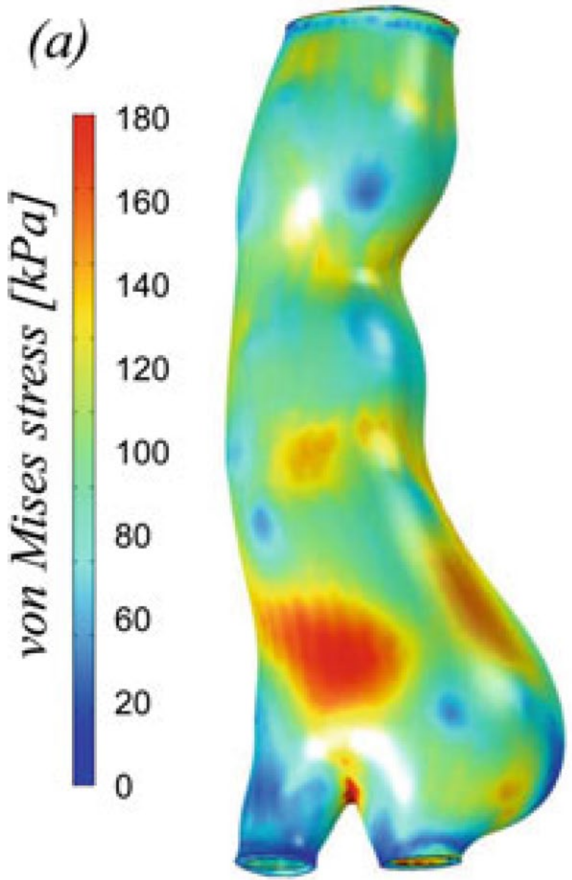
Aneurysm

- Computational assessment of aneurysm rupture risk

  Medical-imaging-based (personalized) models



https://link.springer.com/book/10.1007/978-3-030-70966-2



Aneurysm

- Computational assessment of aneurysm rupture risk

Patient-specific models

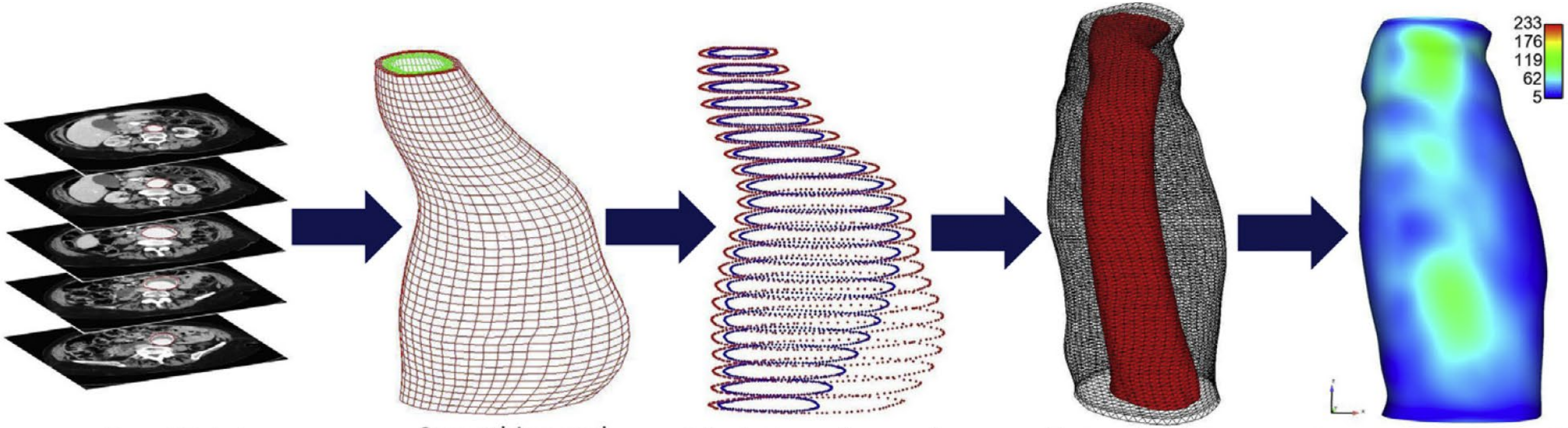
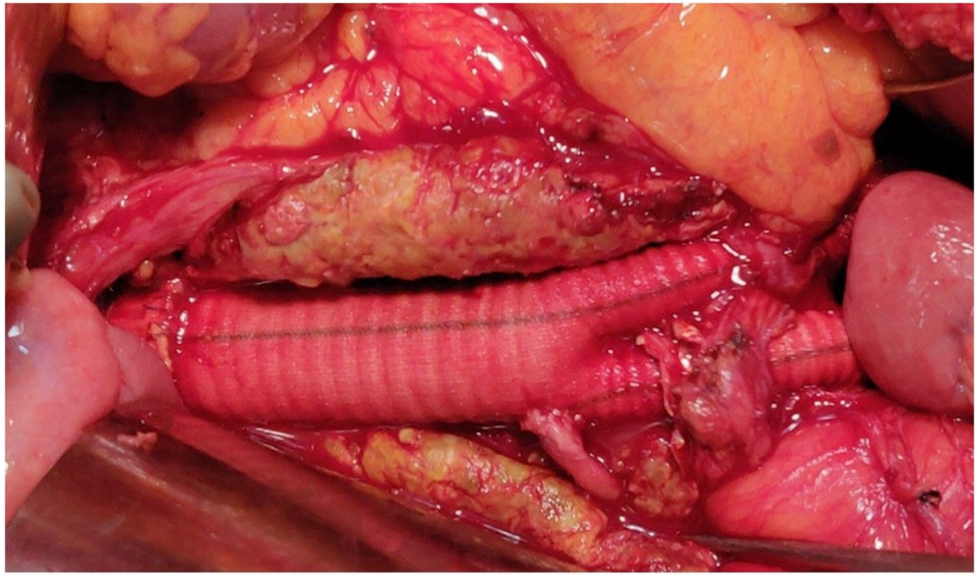


Fig 1. Stages of the patient-specific analysis process: computed tomography (*CT*) angiography (CTA) scan stack; point cloud extraction and smoothing and geometric analysis; outer aortic wall creation and intraluminal mesh creation; percentage volume thrombus calculation; and wall stress analysis.

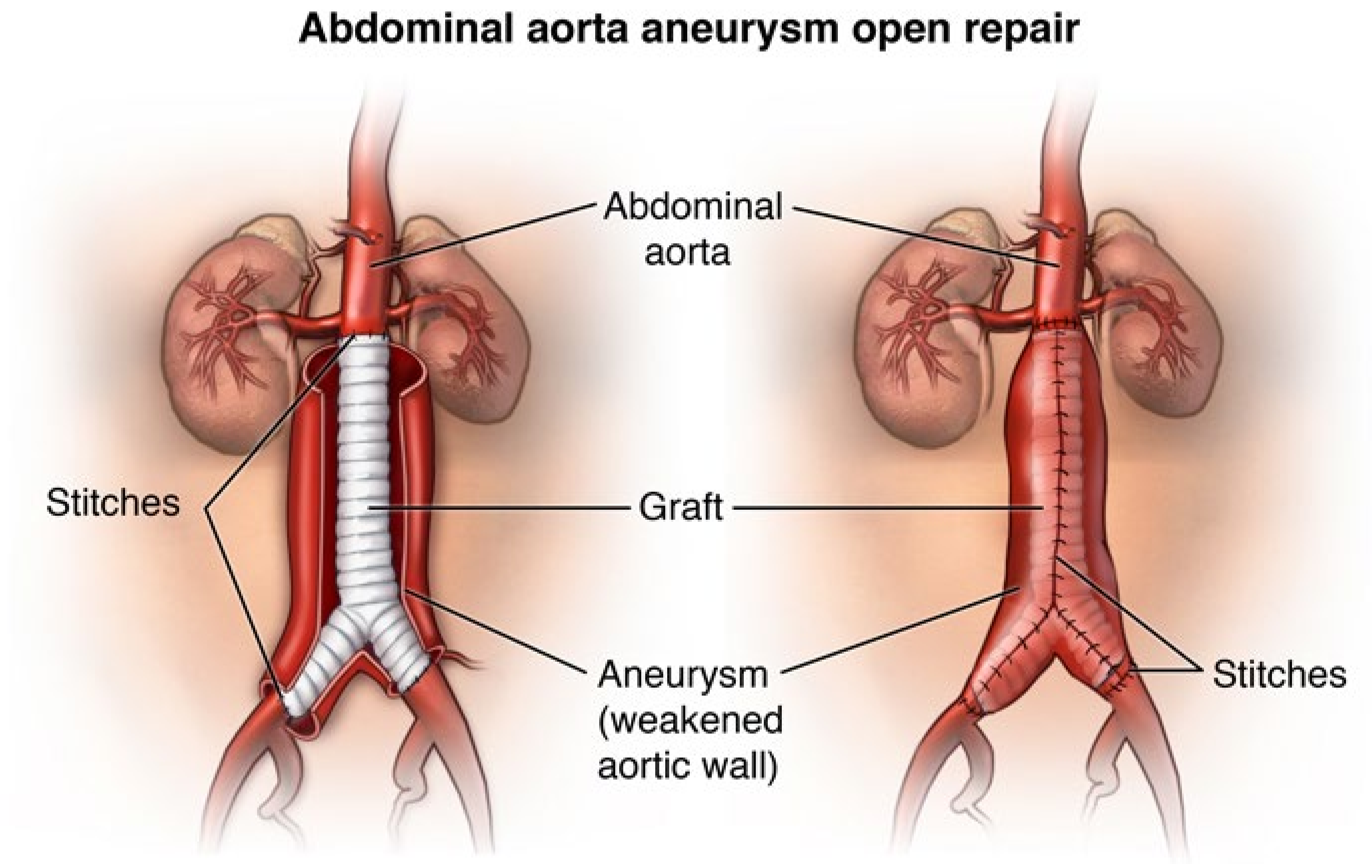
https://doi.org/10.1016/j.jvs.2017.08.069

Aneurysm

- Options in abdominal aneurysm treatment:
  open surgery



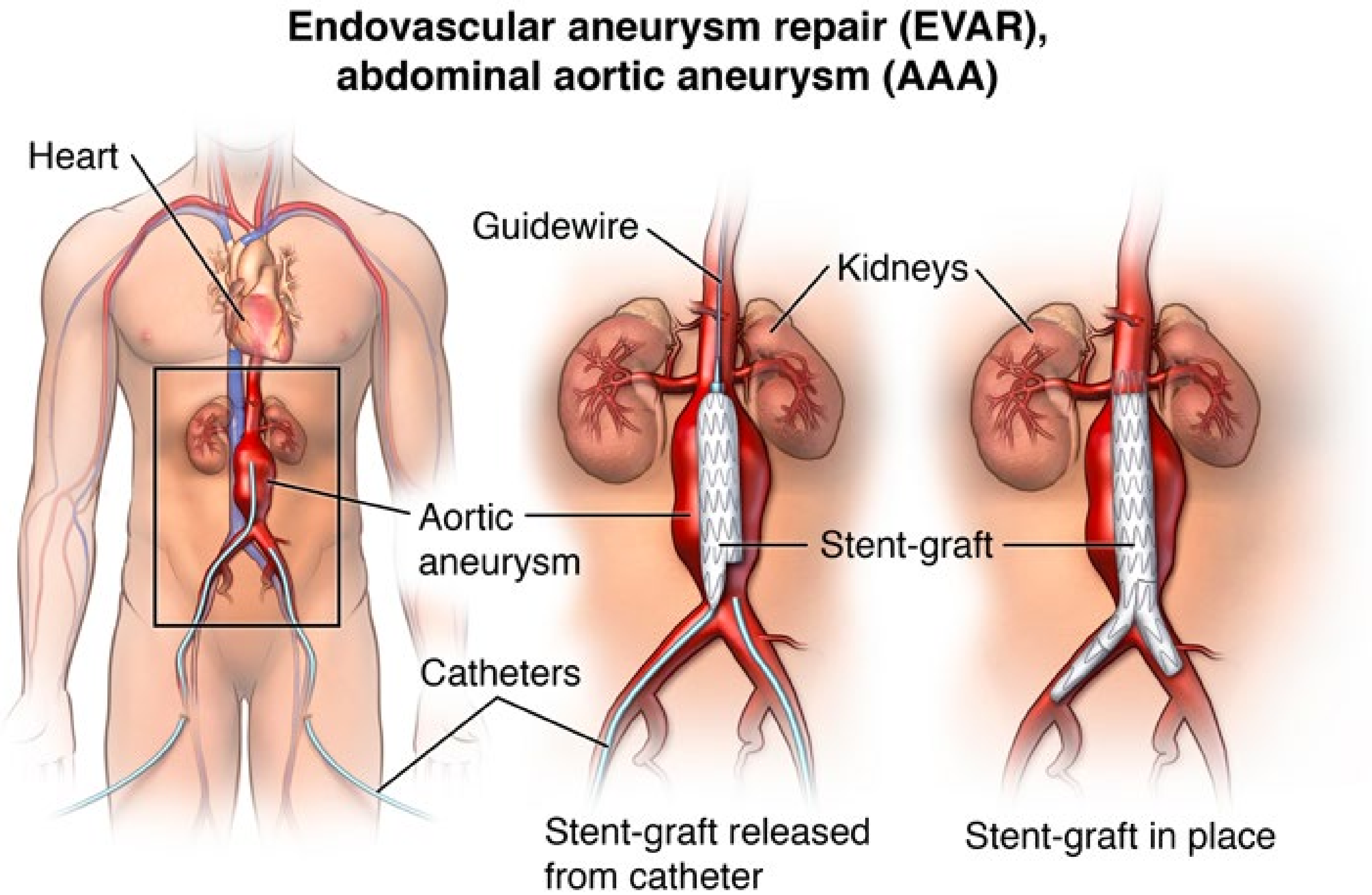
https://www.kauveryhospital.com/ima-journal/ima-journal-november-2022/abdominal-aortic-aneurysm/



https://www.stanfordchildrens.org/en/topic/default?id=abdominalaorticaneurysm-85-P08247

Aneurysm

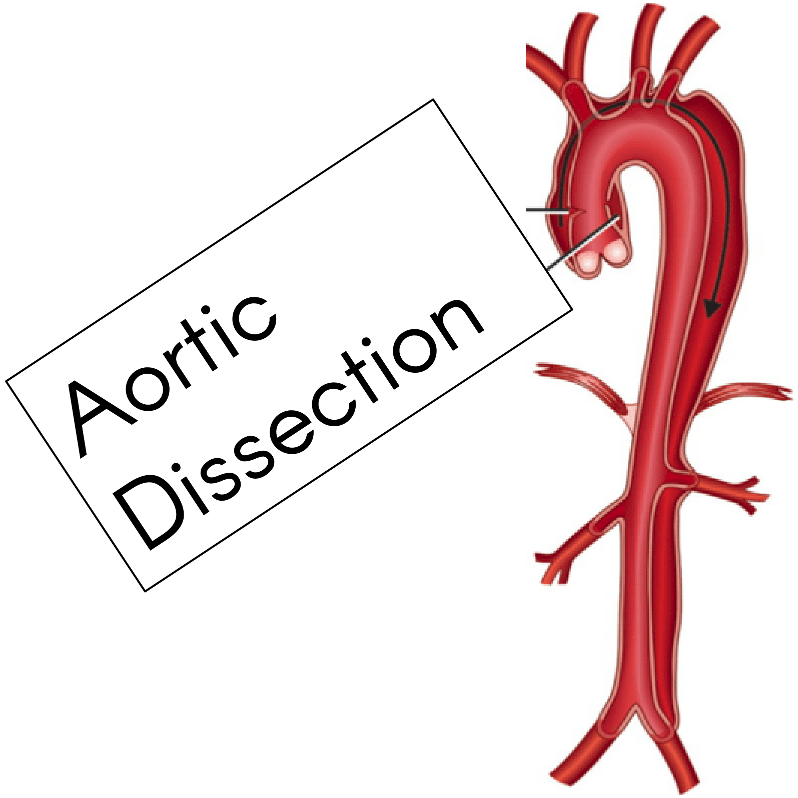
- Options in abdominal aneurysm treatment: EVAR

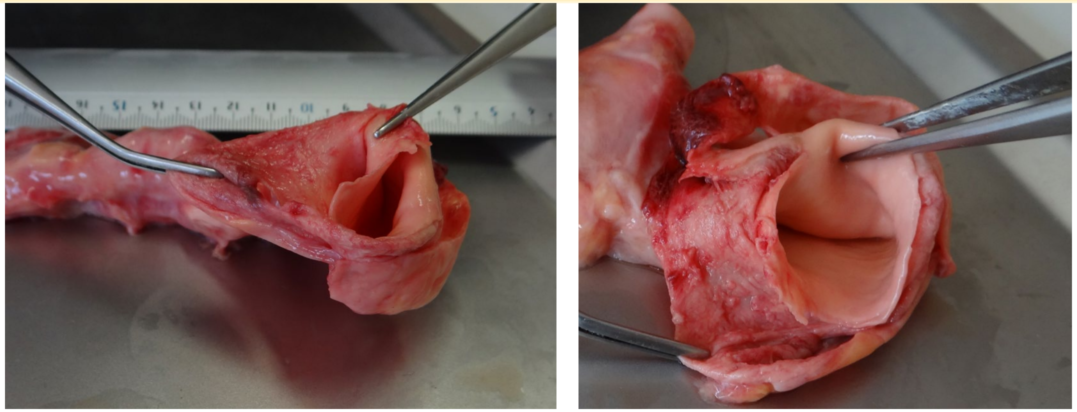


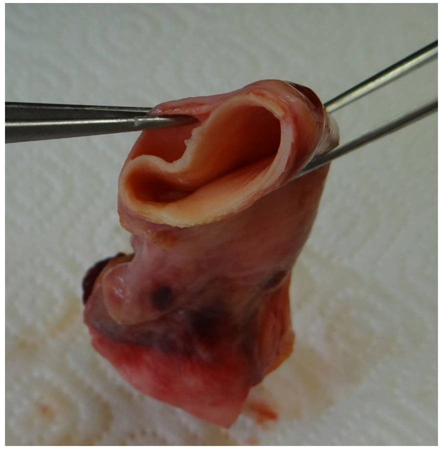
https://www.bryanhealth.com/locations/physician-offices/bryan-heart/get-care-treatment/vascular/vascular-surgery--interventions/

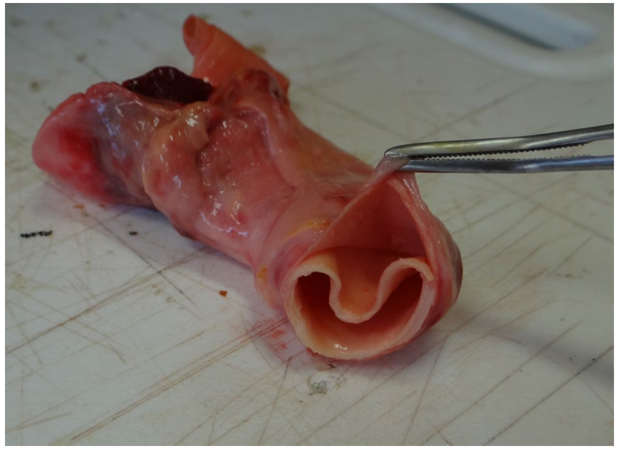
Aortic dissection

- Applied biomechanics:
  assessment of delamination properties – risk of the dissection



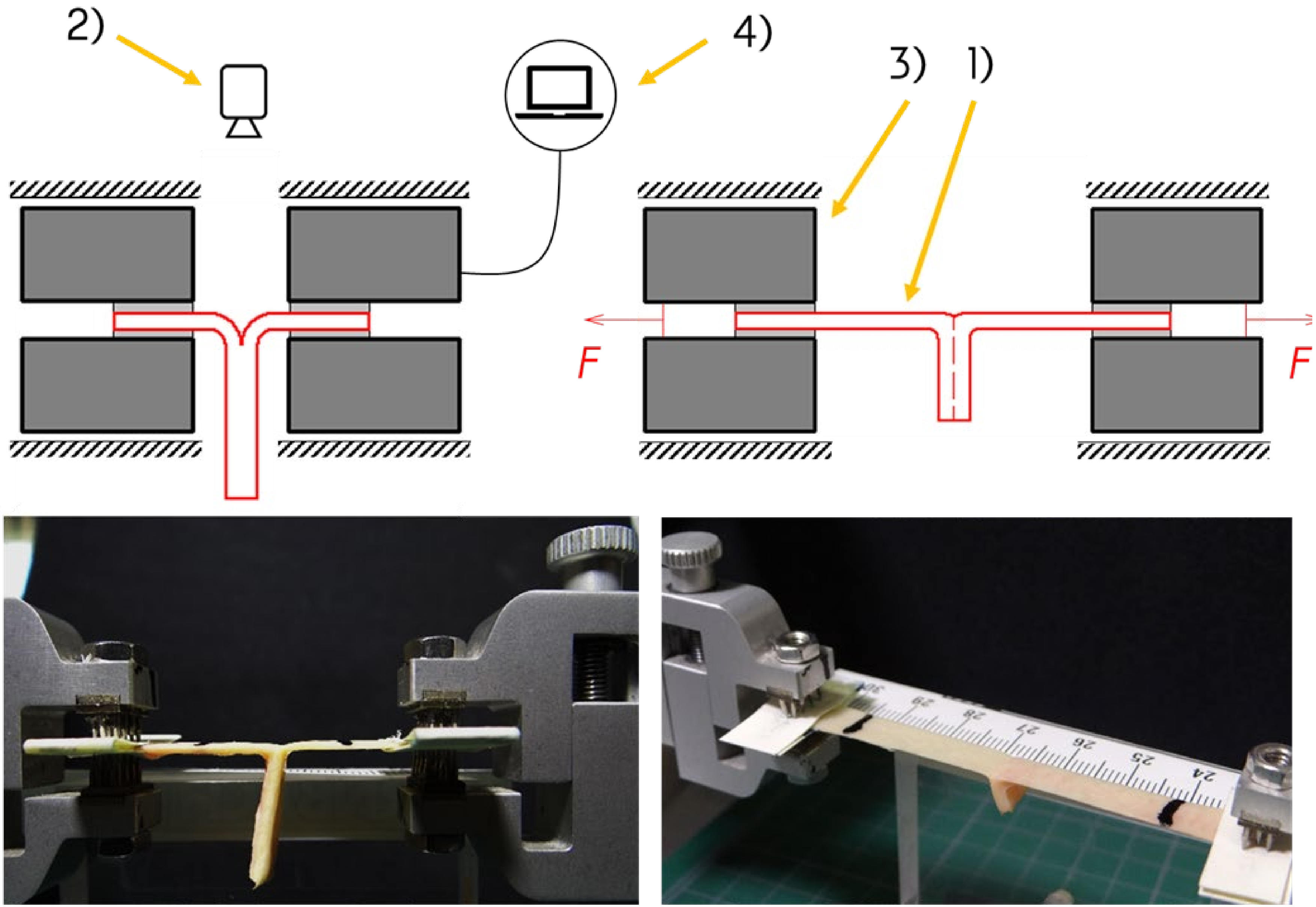






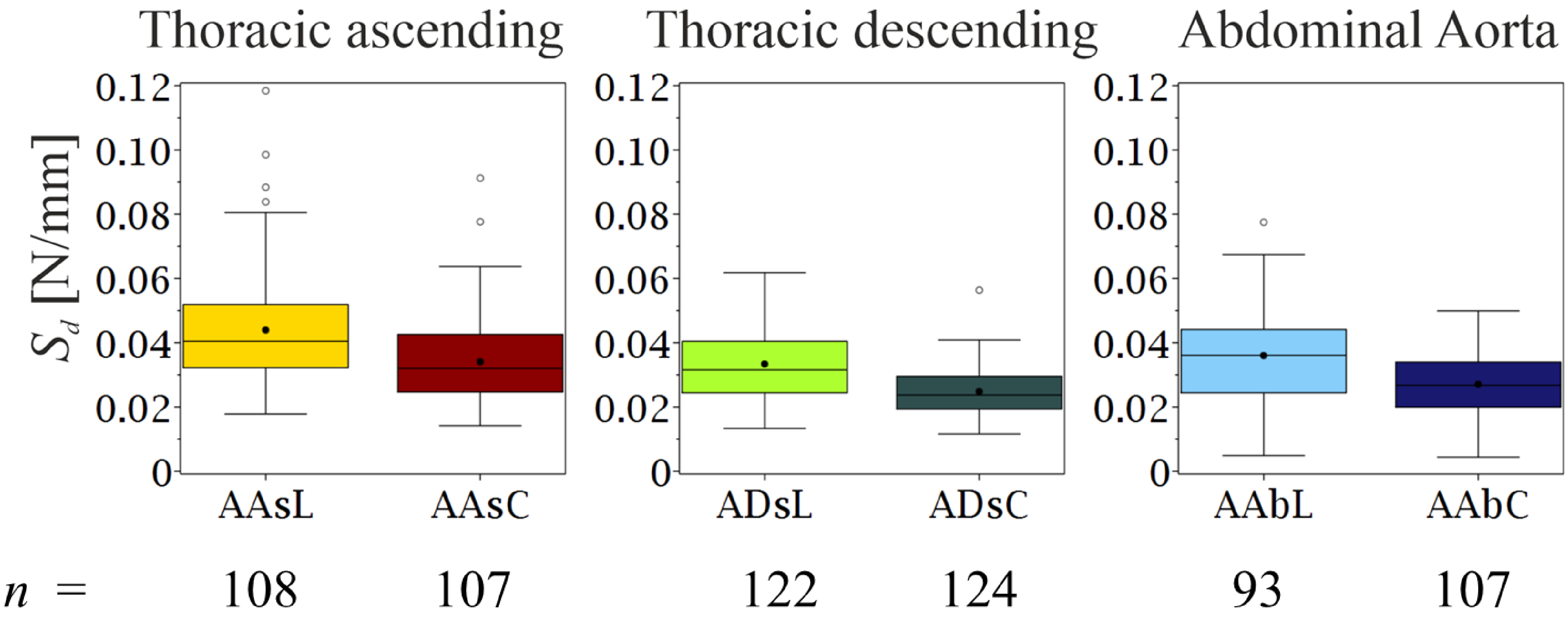
Aortic dissection

- Applied biomechanics: assessment of delamination properties of the human aorta



Aortic dissection

- Assessment of delamination properties of the human aorta



Conclusion

Cardiovascular biomechanics

- Mechanics is the science that studies motion, the movement of anything, anywhere.
- Biomechanics deals with movement in biological systems or the motion of these systems as such.
- The motion that biomechanics deals with can occur at the level of molecular and cellular biology, tissues, organs or the whole organism.

Cardiovascular biomechanics

- Cardiovascular biomechanics is wherever blood motion is concerned: the induction of blood motion by cardiac pumping, the conduction of blood in blood vessels, the manifestations of blood flow such as blood pressure, blood flow velocity, the motion of cells and chemicals carried by blood.
- In our lecture, we learned about basic physiological principles and mentioned diseases that can occur when a biological system operates outside its physiological limits. Returning the system's behavior to these boundaries can in many cases be ensured or supported by interventions using knowledge and results of mechanical engineering.