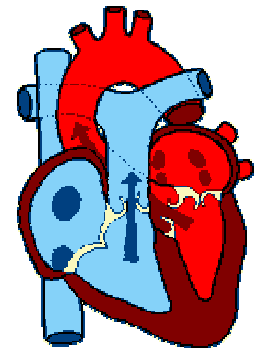
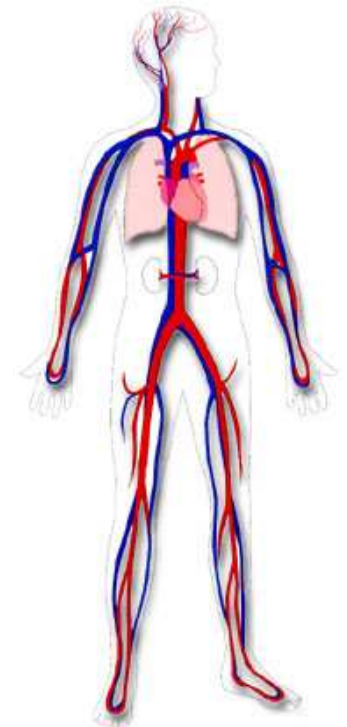


MUNI

Lectures on Medical Biophysics

Biophysics of cardiovascular system



Lecture outline

- Mechanical properties of blood vessels
- Reynolds number
- Blood flow in blood vessels
- Peripheral resistance of blood vessels
- Mechanical work and power of heart
- Capillary ultrafiltration
- Kidneys: renal work and glomerular ultrafiltration
- Blood pressure measurement

Mechanical properties of cardiovascular system

Closed circulation and transport system

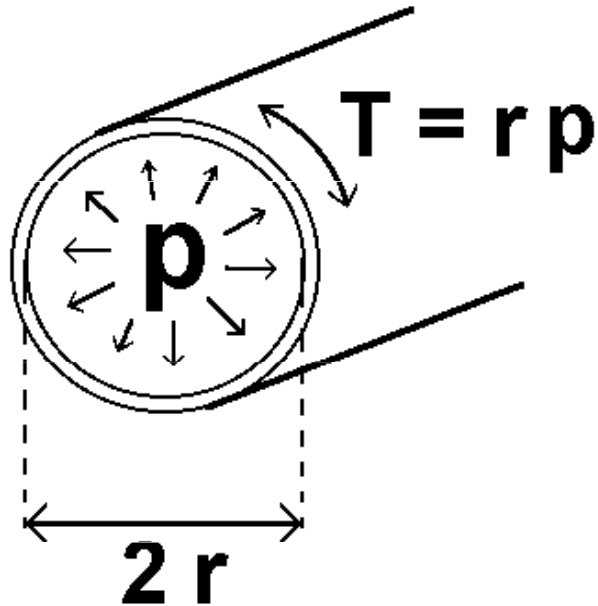
– Main parts:

- Heart muscle (myocardium)
- Closed system of blood vessels
- Blood

– Main functions:

- Supplying cells by nutrients and oxygen,
- Transport of hormones and other chemical signals,
- Removal of waste and side products from cells (tissues)
- Heat transfer - thermoregulation

Mechanical properties of blood vessels

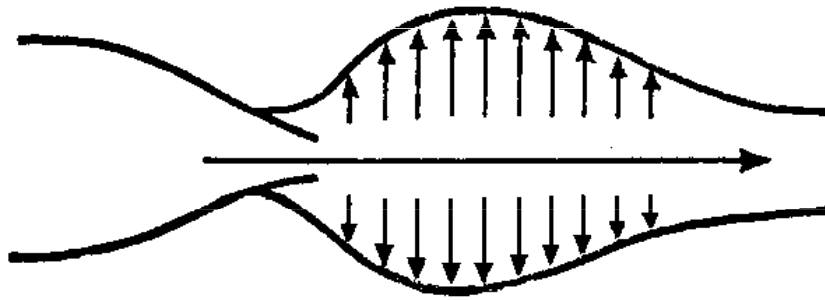


Laplace law – mechanical stress of blood vessel walls is directly proportional to the pressure and **vessel radius**

Tension T in walls of some blood vessels:

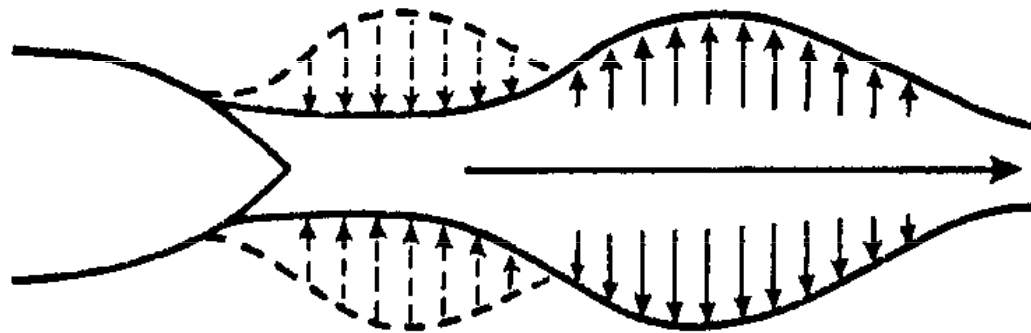
vessel	$r(\text{m})$	$p(\text{kPa})$	$T(\text{N}\cdot\text{m}^{-1})$
aorta	0.012	13	156
artery	0.005	12	60
capillary	6×10^{-6}	4	0.024
vein	0.005	2	10
vena cava	0.015	1.3	20

Elastic and muscular blood vessels



**Aorta behaves like
typical elastic vessel**

Arterioles are
muscular vessels able
of vasodilatation and
vasoconstriction



Reynolds number

- Blood flow: laminar (ordered)
- turbulent (chaotic, eddy)
- Reynolds (1883)
- Reynolds number (for a liquid flowing in a cylindrical tube):

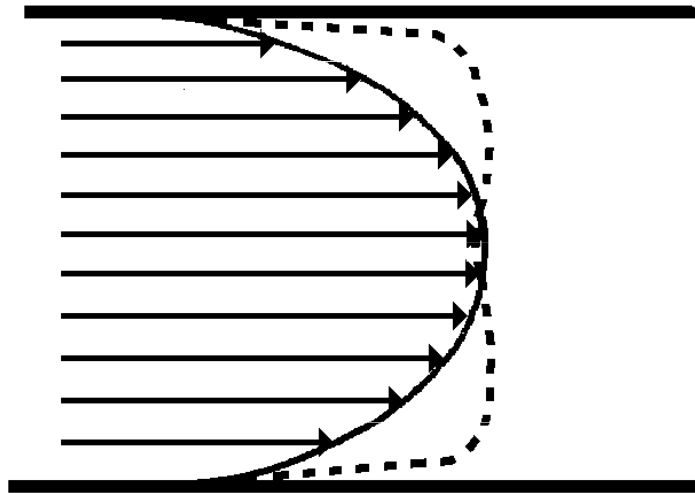
$$R_e = \frac{r v_s \rho}{\eta}$$

ρ – liquid density, v_m – mean flow rate, r – vessel radius, η – coefficient of dynamic viscosity

- Critical flow rate:

$$v_k = \frac{1000\eta}{r\rho}$$

Blood flow in blood vessels



The differences between theoretical and real flow rate profiles are given mainly by the fact that blood is a non-Newtonian liquid and is influenced by the distensibility and compliance of the vessel wall..

The flow rate profile changes during pulse wave.

We can obtain important diagnostic information from values of blood velocity and the shape of the flow rate curve.

Blood flow in an obstructed blood vessel

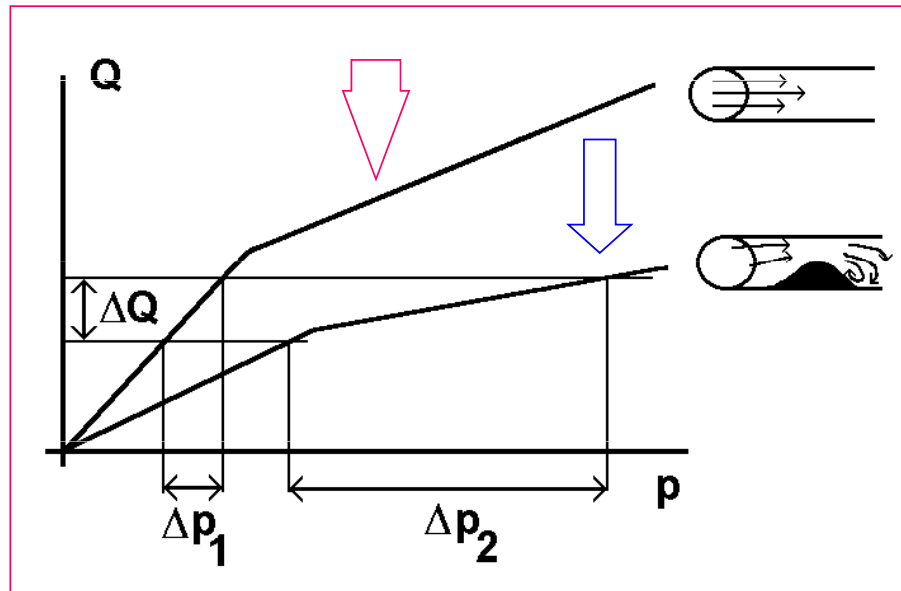
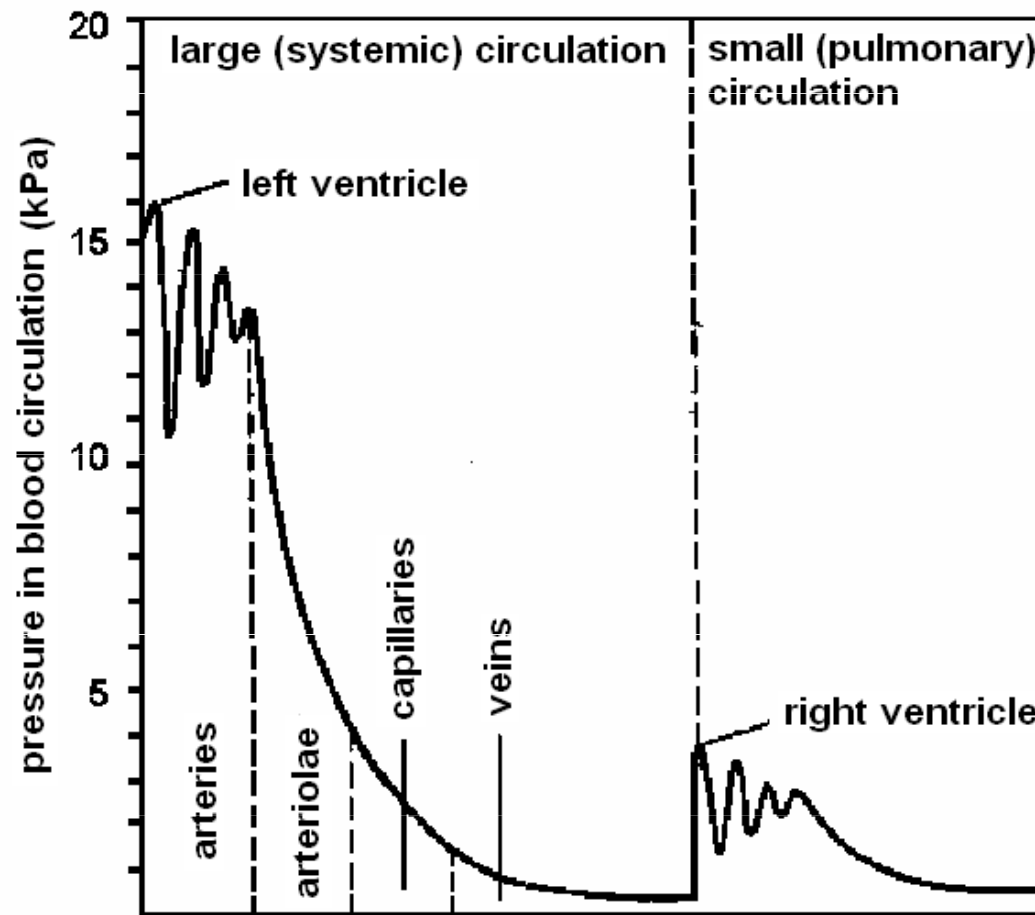


Fig. after Cameron
et al., 1999

The upper curve represents blood flow in a vessel without atherosclerotic stenosis (narrowing), the lower one in a vessel with stenosis.

We need bigger increase of pressure Δp for the same increase in blood flow ΔQ (volume per time unit).

Pressure in individual segments of blood circulation



Peripheral impedance (resistance) of blood vessels

Analogy of electrical impedance ($R = U/I$)

Pressure p is an analogy of voltage U

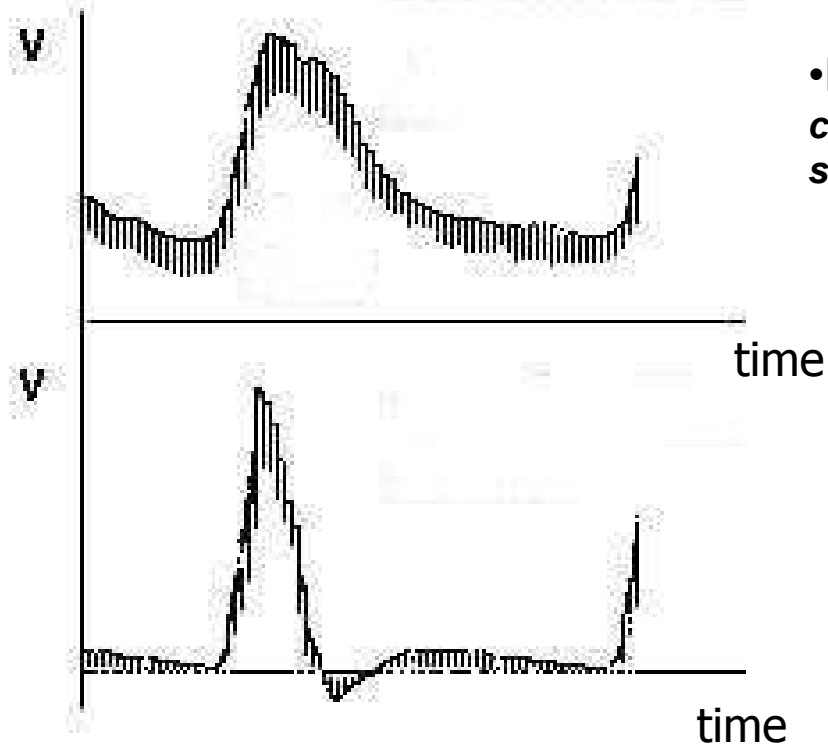
Blood flow volume Q ($\text{m}^3 \cdot \text{s}^{-1}$) is an analogy of electric current I

$$R = \Delta p / Q$$

Considering the Hagen-Poiseuille formula for flow volume:

$$Q = \frac{\pi r^4 \Delta p}{8 \eta \Delta l} \Rightarrow \frac{\Delta p}{Q} = \frac{8 \eta \Delta l}{\pi r^4}$$

Peripheral resistance of blood vessels



• **Low vascular impedance**
*characteristic for brain, liver,
spleen and kidney arteries*

• **High vascular impedance**
*characteristic for arteries of
skeletal muscles*

Peripheral resistance of blood vessels

- Percentage of total peripheral resistance estimated for individual segments of blood circulation:
 - arteries 66 %
 - (among those arterioles 40 %)
 - capillaries 27 %
 - veins 7 %
- In **vasodilatation**, R decreases – heart load decreases
- In **vasoconstriction**, R increases – heart load increases

Mechanical work and power of heart

- **Mechanical work of heart muscle:**

Some very small work dW is done against external pressure p during ejection of very small blood volume dV :

$$dW = pdV$$

The whole work during a systole:

$$W = \int pdV \quad ??????$$

Very small part of this work is transformed into kinetic energy of the blood ejected.

Estimation of heart work during one systole

– $p = \text{const.} \Rightarrow W = p_m \Delta V,$

p_m is mean blood pressure at the beginning of aorta

– Left ventricle

Right ventricle

$$p_m = 13.3 \text{ kPa}$$

$$p_m = 2.7 \text{ kPa}$$

$$\Delta V = 70 \text{ ml}$$

$$\Delta V = 70 \text{ ml}$$

$$W = 0.93 \text{ J}$$

$$W = 0.19 \text{ J}$$

– Mechanical energy of ejected blood volume W_k :

$$= 0.009 \text{ J}$$

$$= 0.0018 \text{ J}$$

(since $W_k = 1/2 \rho v_m^2 \Delta V$, $\rho = 1.06 \times 10^3 \text{ kg} \cdot \text{m}^{-3}$, $v_m = 0.3 \text{ m} \cdot \text{s}^{-1}$, resp. $0.22 \text{ m} \cdot \text{s}^{-1}$ in pulmonary artery)

Power of heart

- Mechanical power of heart
(for pulse rate 70 min^{-1}) 1.3 W
- Total power of heart
(at rest conditions) 13 W
- Total power of human organism
(at rest conditions) 115 W

Work and efficiency of myocardium

- Energy necessary to maintain tonus of myocardium:

$$\alpha \int T dt$$

- T – mechanical tension of heart walls (tonus) [$\text{N}\cdot\text{m}^{-1}$], t - time

- Total energy necessary:

$$E_c = \int p dV + \alpha \int T dt$$

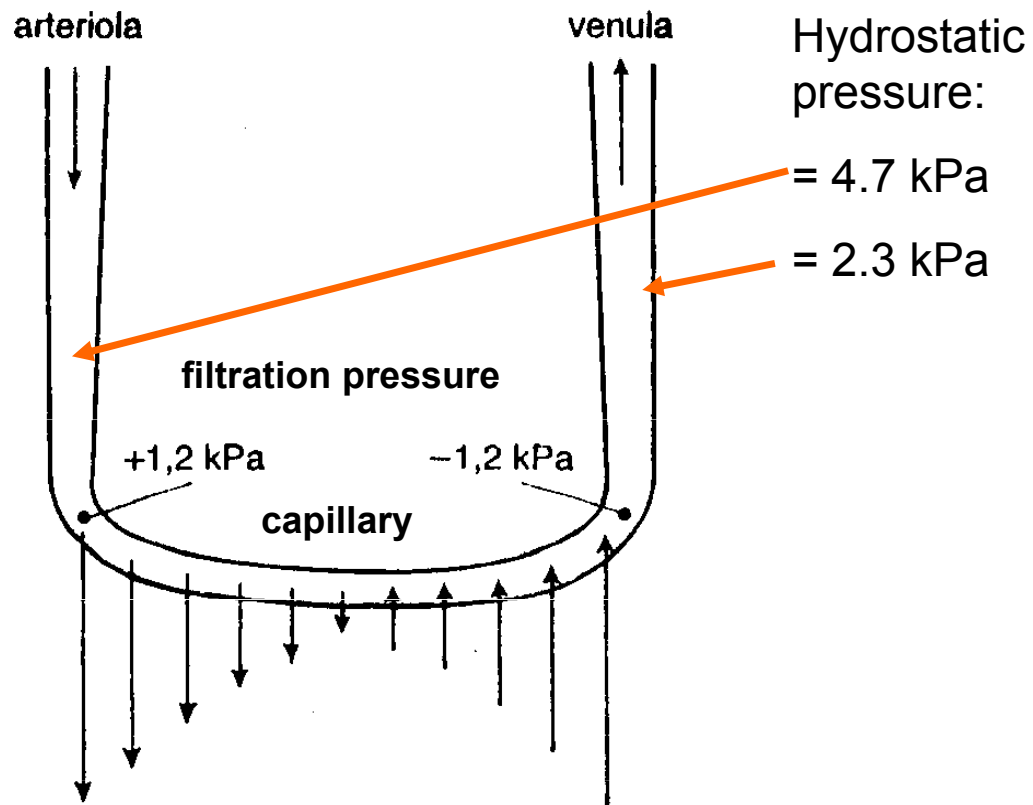
- Mechanical efficiency: W/E_c (max. 10 %)

Capillary ultrafiltration

	pressure [kPa]	
	arterial end	venous end
hydrostat. pressure	4.7	2.3
oncotic pressure	-3.5	-3.5
filtration pressure	1.2	-1.2
	filtrate enters interstitium	filtrate leaves interstitium

Filtration process in capillary loop

Oncotic pressure
= 3.5 kPa



!!!!!!!!!!!!



Oedemas arise due to low protein level in blood plasma, which causes low oncotic pressure and increases so the filtration pressure.

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Kidneys: renal work and glomerular ultrafiltration

- The osmotic work necessary to transfer a substance from a medium with substance concentration C_2 to the medium with substance concentration C_1 . (It is transfer of needful substances from primary urine back to the blood.)

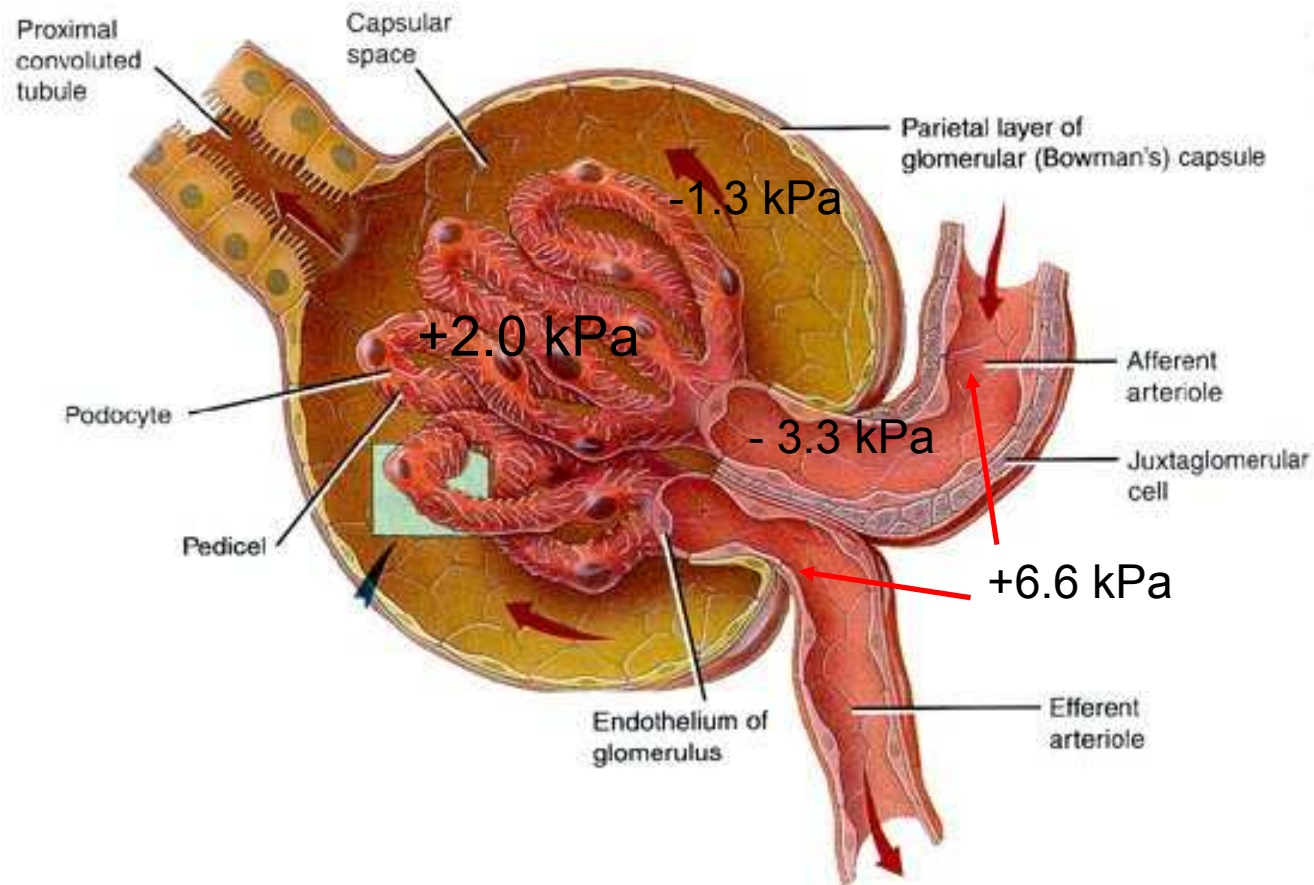
$$W = 2.3 nRT \log C_1/C_2$$

- Glomerular ultrafiltration:**

Hydrostatic pressure in glomerular capillaries is about 6.6 kPa (50 mmHg). The following pressures have opposite effect: hydrostatic pressure in Bowman's capsule – 1.3 kPa (10 mm Hg) and oncotic pressure of plasma proteins – 3.3 kPa (25 mm Hg), so the resulting filtration pressure in glomerulus is **2 kPa (15 mmHg)** under normal circumstances.

Glomerulus

<http://coe.fgcu.edu/faculty/greenep/kidney/Glomerulus.html>



Blood pressure measurement

- Pressure is defined as a force acting on unit area in a gas or liquid.

$$p = F/A \quad [\text{N}\cdot\text{m}^{-2}],$$

where F is the force acting on the area A .

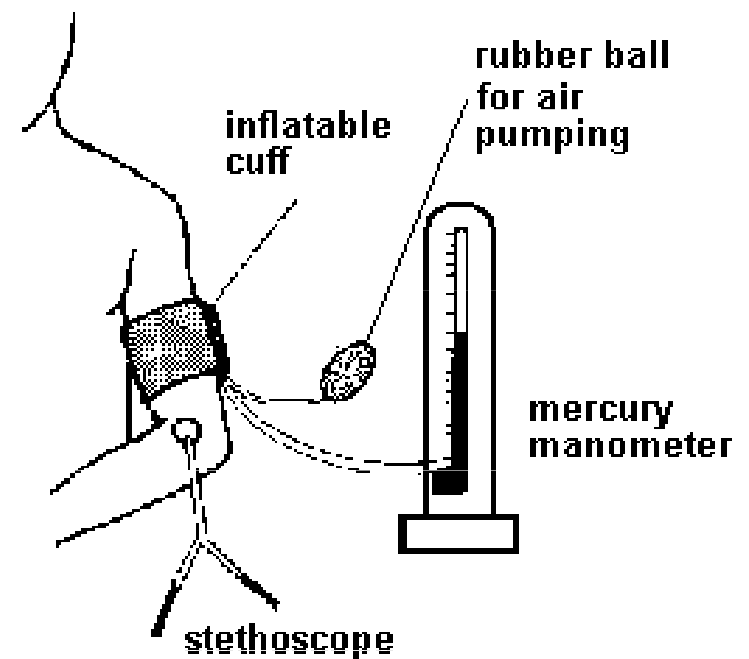
- In the SI system, the pressure is measured in $\text{N}\cdot\text{m}^{-2}$, the unit is called **pascal [Pa]**.
- The most common way of indicating pressure in medicine is by the height of mercury column in millimetres - mmHg.
- $1 \text{ mmHg} = 1 \text{ torr} = 133.3 \text{ Pa}$

Blood pressure measurement

- In arteries, the blood pressure oscillates between a maximum value, i.e. systolic pressure, and a minimum value of the pressure, i.e. diastolic blood pressure.
- The time-course of the blood pressure changes is periodical but non-sinusoidal.
- The difference between the systolic and diastolic pressures is maximal at the beginning of aorta; the pressure fluctuates in the range of 10.5 to 16 kPa, i.e. 80 to 120 mmHg.
- The mean value of blood pressure in lung artery represents only one fifth of the blood pressure in the aorta.

Riva-Rocci method

An inflatable cuff with manometer is put on the arm above the elbow (heart level), inflated to a pressure higher than the systolic pressure in *a. brachialis*. Blood flow is stopped. The pressure in the cuff is gradually decreased. At **systolic pressure**, blood starts to flow through the artery. The turbulent flow produces acoustic noise - **Korotkoff sounds**, audible in a stethoscope placed in the elbow pit. As pressure in the cuff is decreased the sounds become louder, culminate and gradually decrease, disappearing altogether at the **diastolic pressure** (laminar flow renewed). The maximum loudness is at mean arterial pressure.



Riva-Rocci method

- The Riva-Rocci method can be objectified and automatized for patient monitoring. The cuff is regularly inflated by a small compressor (e.g., every ten minutes) and the Korotkoff sounds are recorded by a microphone. Measured values of systolic and diastolic pressures can be displayed (in simple devices) or stored in the instrument memory and evaluated later. This method is called **Holter monitoring** of blood pressure.
- In small children, this auscultation method can fail. In this case, we can use the Doppler flow detectors to detect blood flow in the artery compressed by the cuff.

Direct measurement of blood pressure

- Invasive measurement of BP is a **direct method**. A thin, flexible catheter or probe must be inserted into the blood vessel. Its free end usually is connected to a transducer (capacity or piezoelectric) but it is also possible to insert a piezoelectric transducer directly into the vessel. This method is rather risky, so that it is used relatively seldom. However, it is the only method which allows measurements of pressure in veins or inside the heart.

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