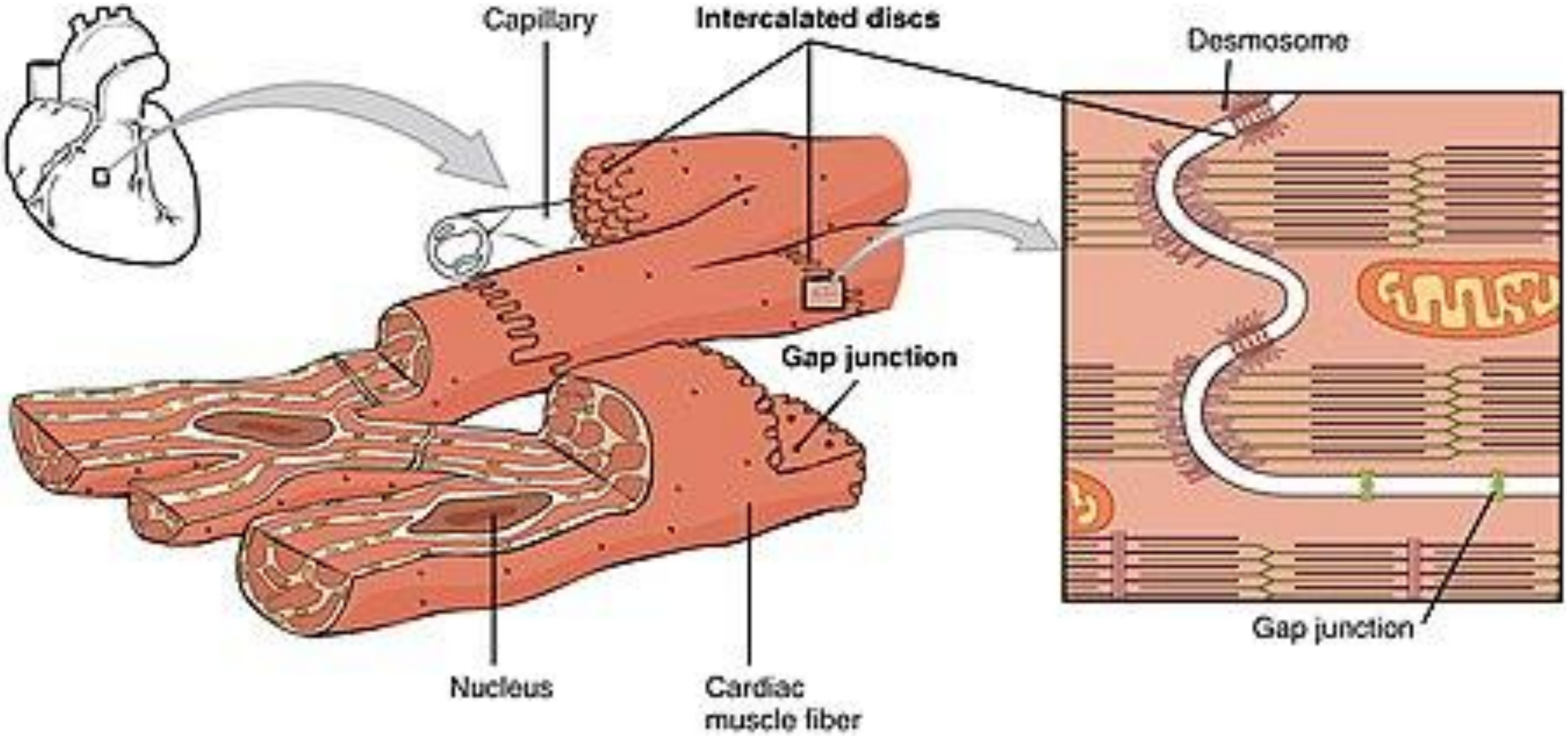
Mechanics of the heart and Blood pressure

Preclinical practice

Cardiomyocytes



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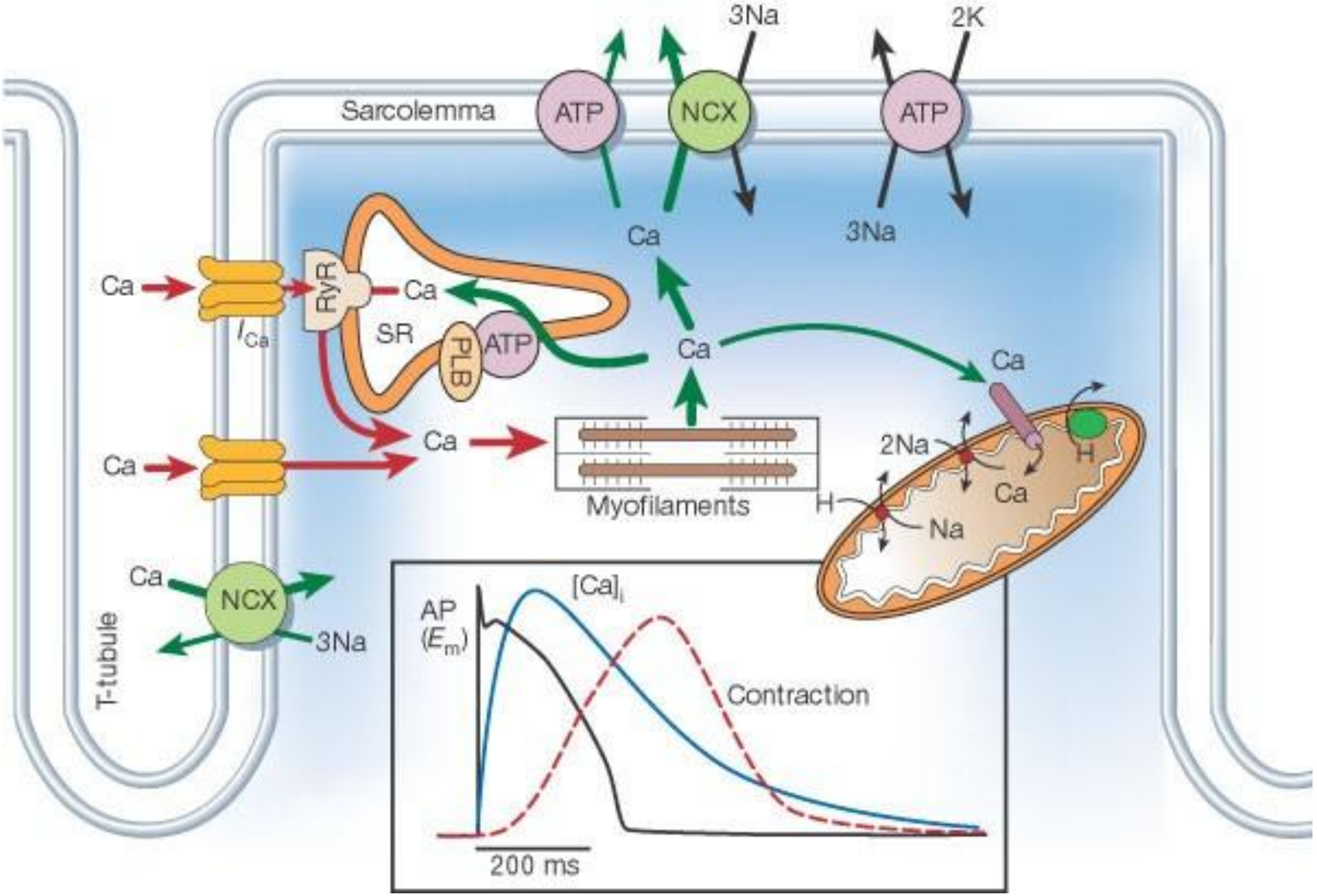
Cardiomyocytes



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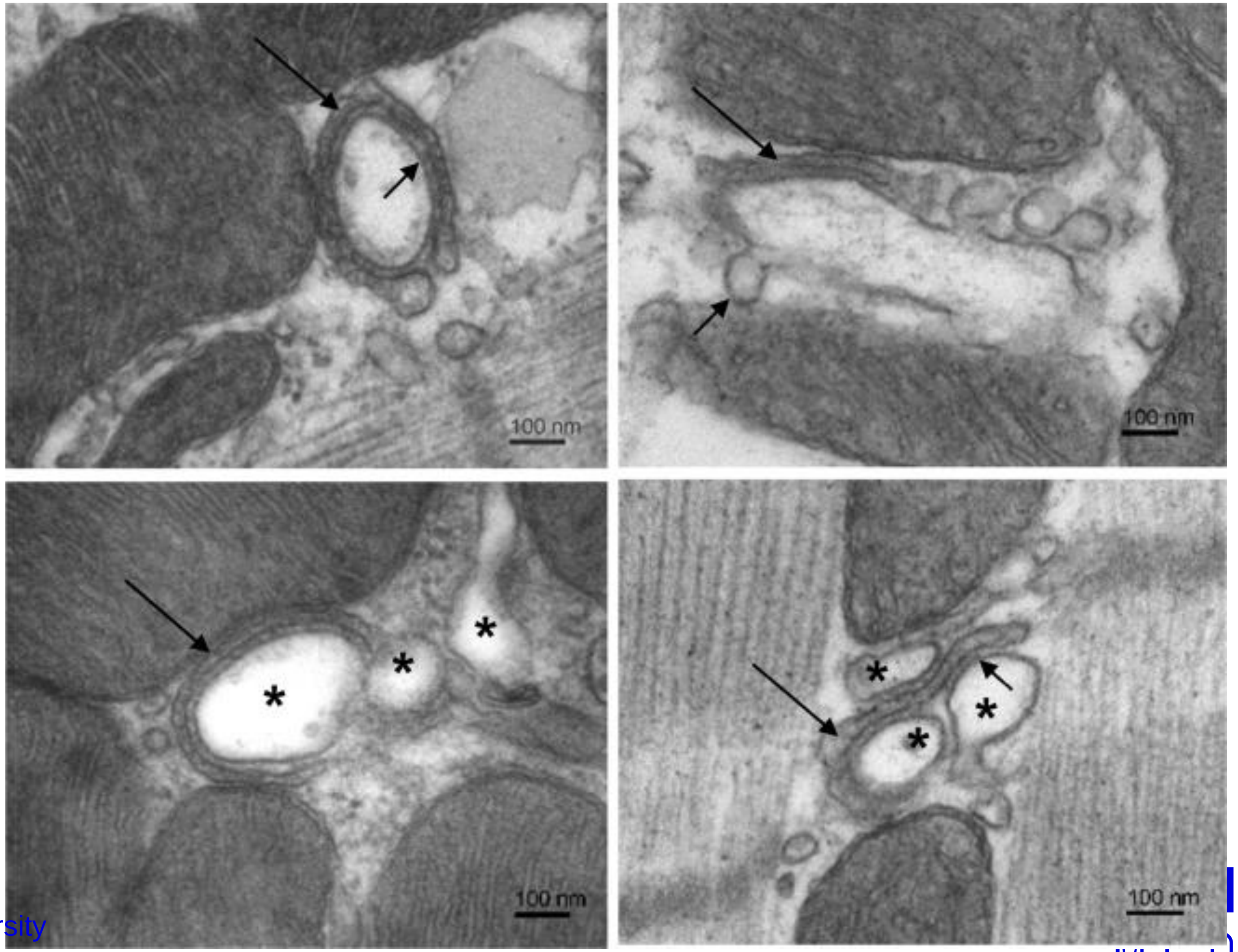
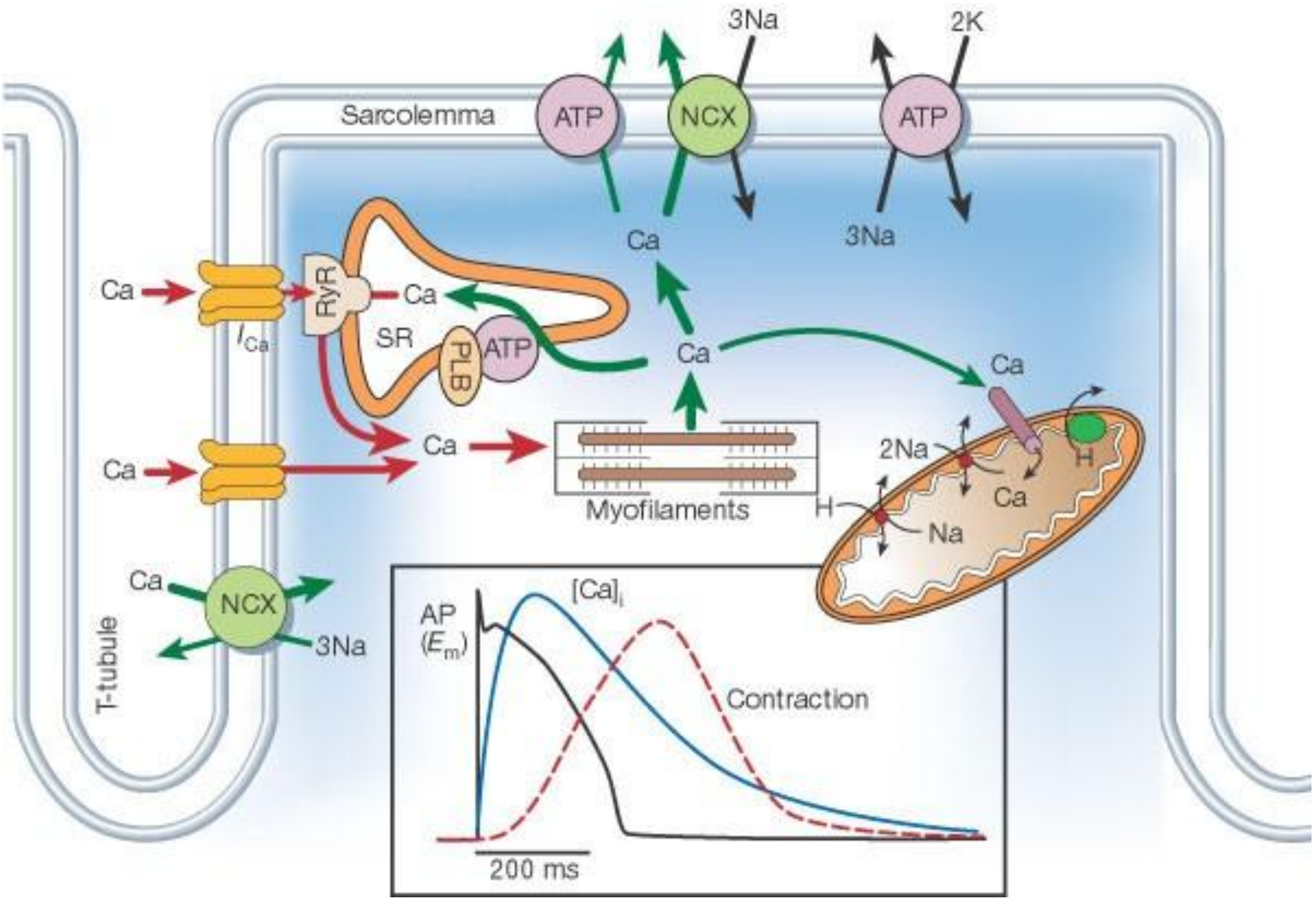
Cardiomyocytes

– cardiac dyads

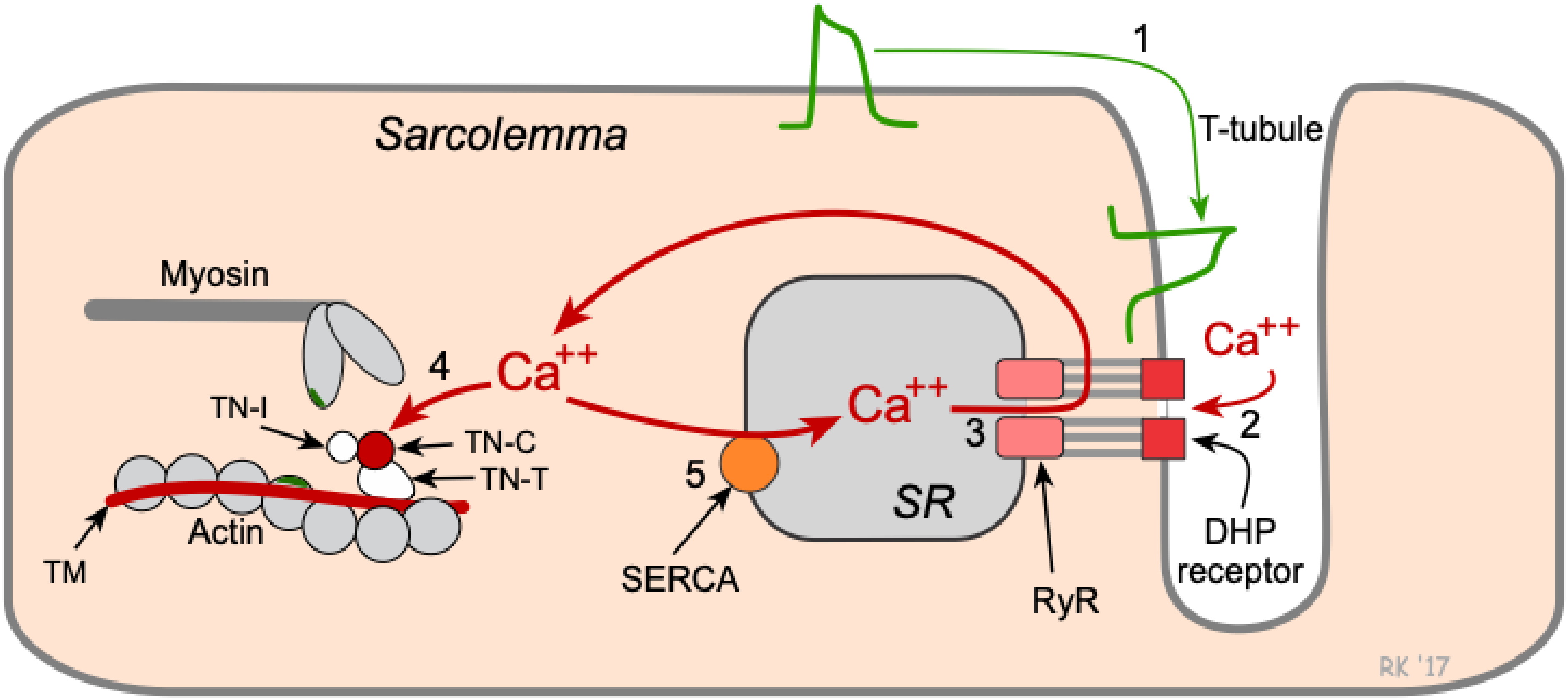


Cardiomyocytes



Excitation-Contraction coupling

– transfer of electrical signal to mechanical activity



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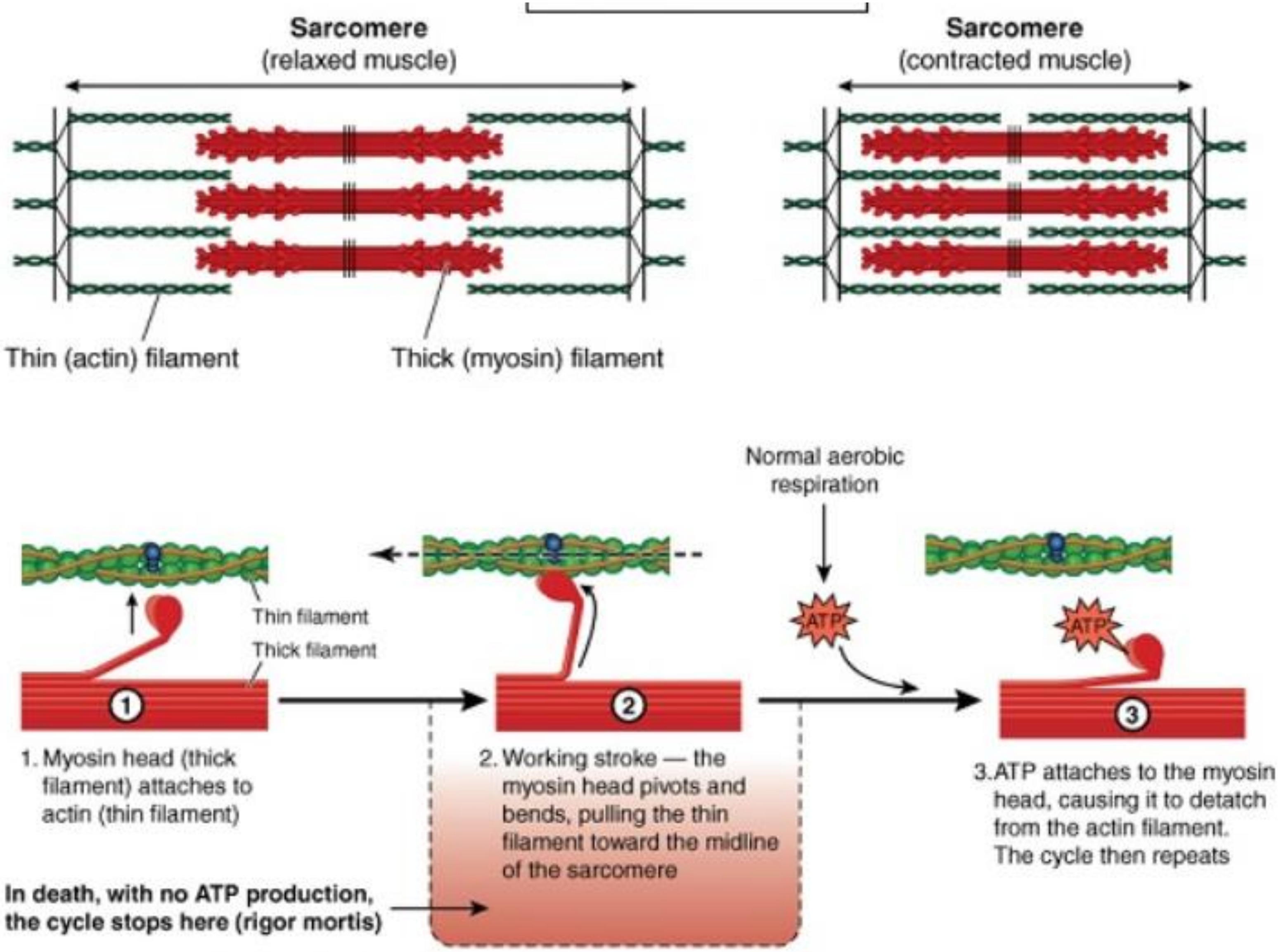
Contraction



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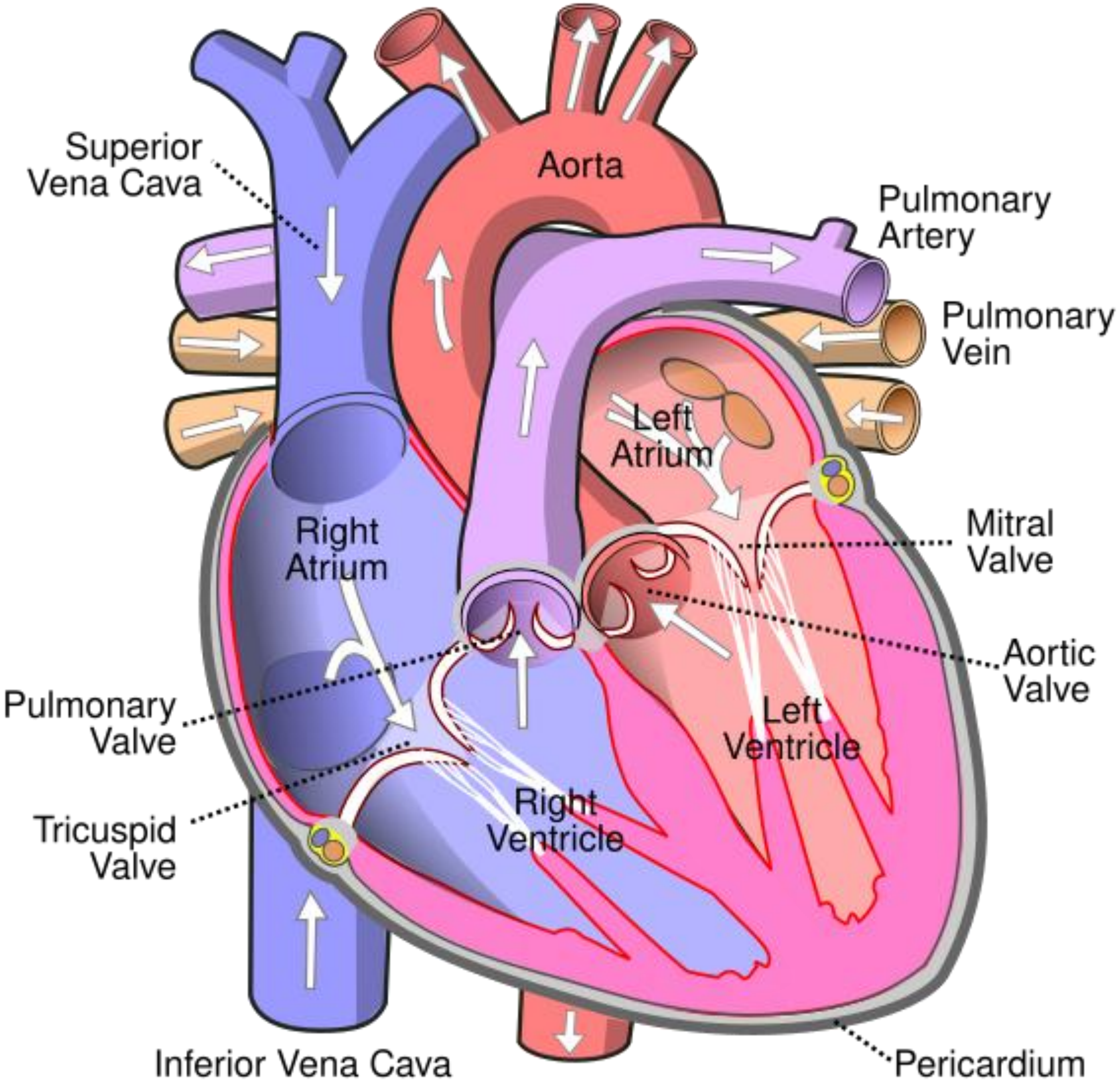
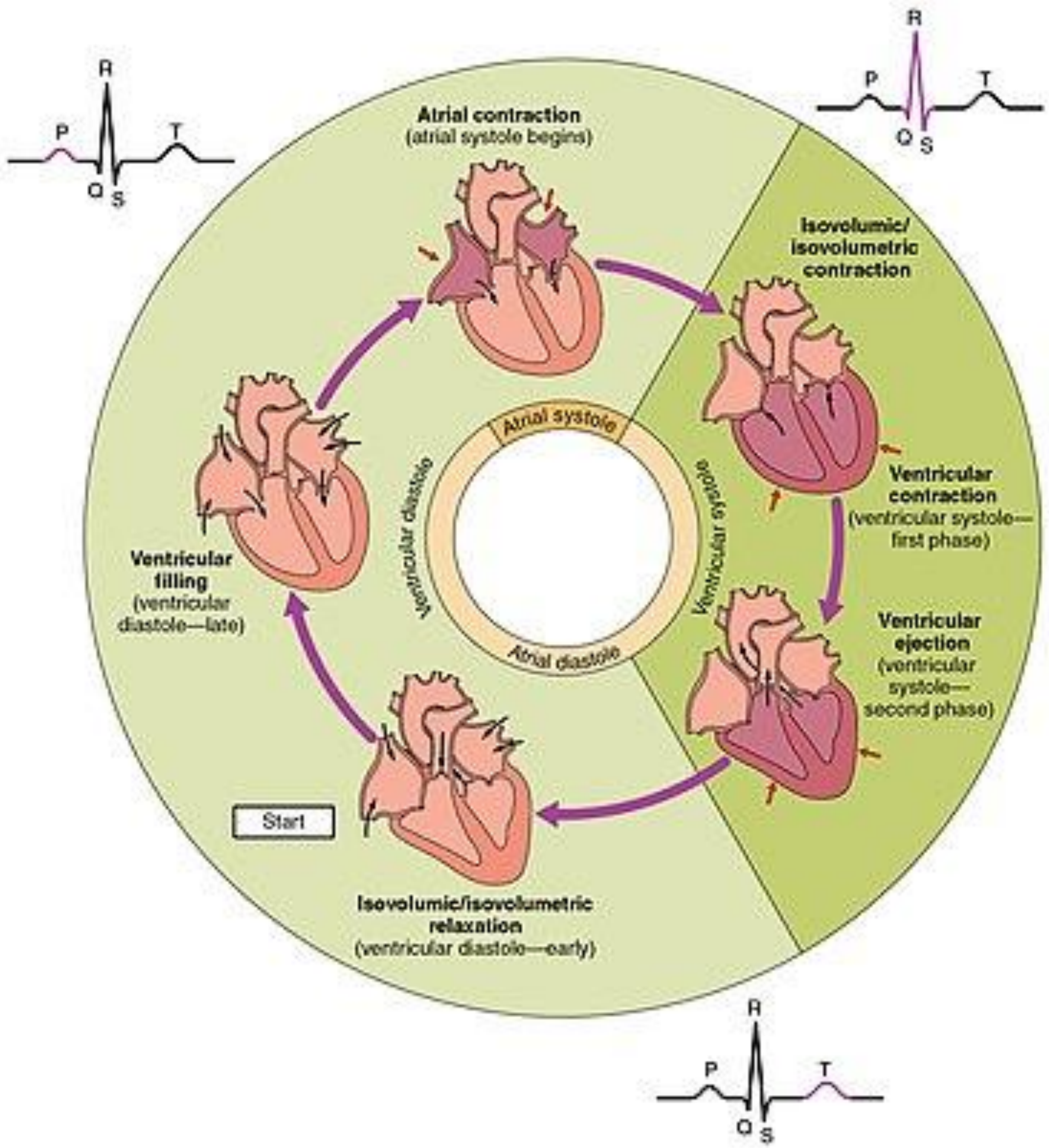
Heart


Superior Vena Cava
Aorta
Pulmonary Artery
Pulmonary Vein
Left Atrium
Right Atrium
Mitral Valve
Aortic Valve
Pulmonary Valve
Left Ventricle
Tricuspid Valve
Right Ventricle
Inferior Vena Cava
Pericardium

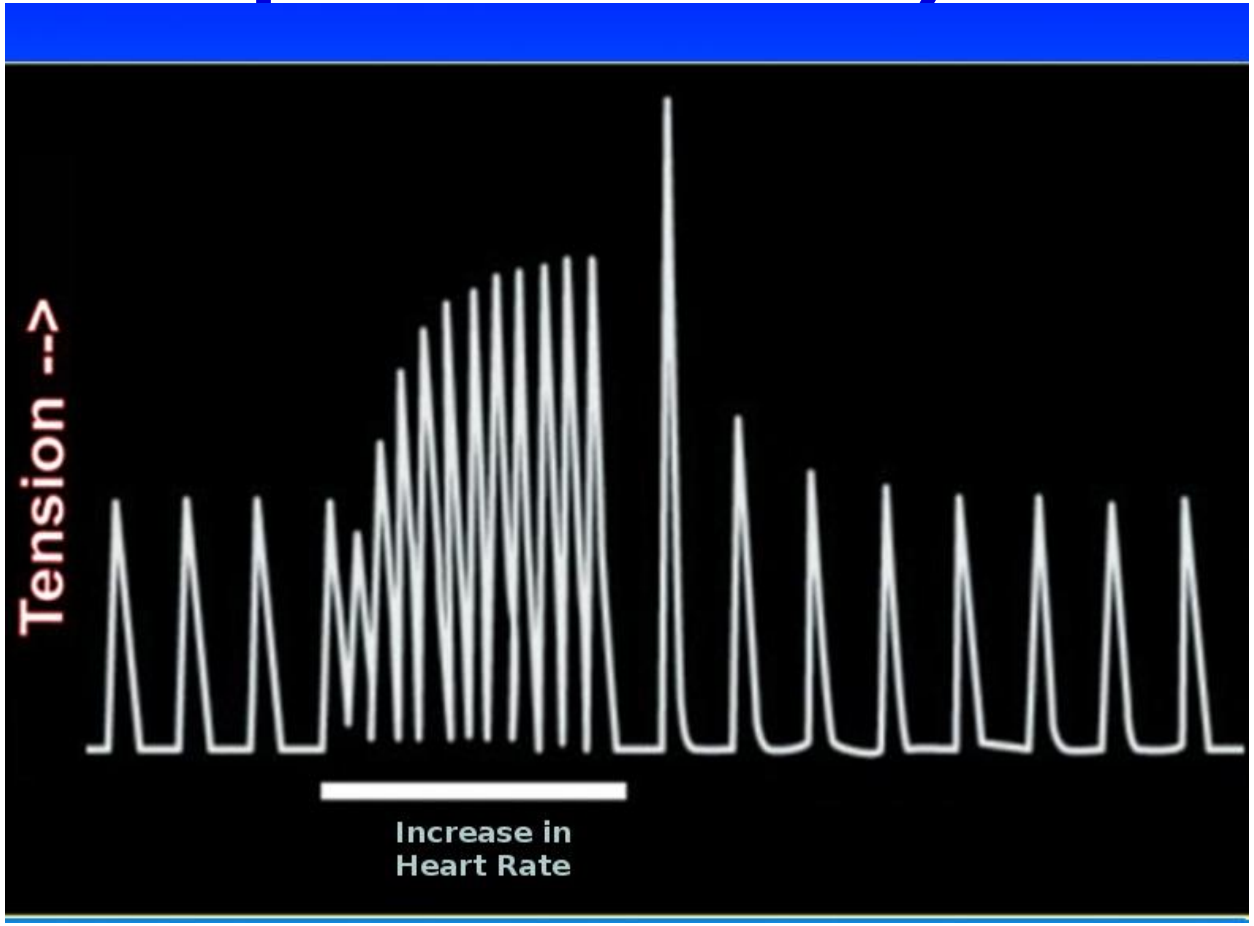
Cardiac cycle

- Isovolumic contraction (IVC):
  - Contraction of ventricular myocardium leads to an increase in intraventricular pressure
- Ejection (E):
  - Intraventricular pressure overcomes diastolic pressure in big arteries, semilunar valves open, and blood flows to the arteries
- Isovolumic relaxation (IVR):
  - Semilunar valves close, rapid decrease in intraventricular pressure even below pressure values in atria, AV valves open
- Inflow (I):
  - Inflow phase (ventricular diastole), atrial systole



Bowditch effect (staircase phenomenon)

- increase in heart rate increases the force of contraction generated by the myocardial cells with each heartbeat



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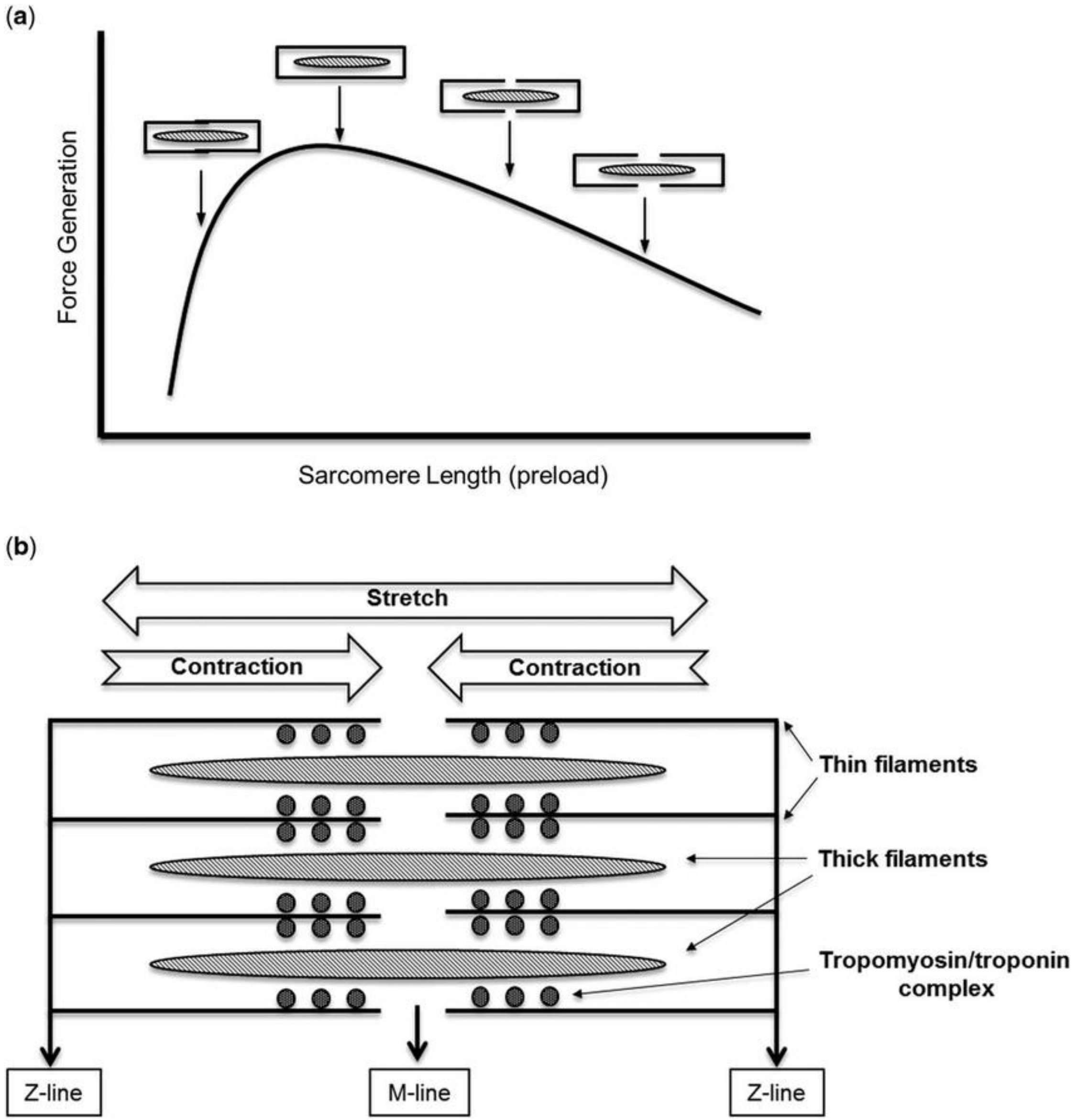
Frank-Starling mechanism

- As the sarcomere stretches, potential force generation increases, peaks, and then diminishes with overstretch



Preload

- The volume of blood received into the left ventricle from the left atrium (at the end of ventricular diastole)
- Initial stretching (sarcomere lenght) of the cardiac myocytes before contraction
- For estimation of myocardial wall stress we can use Laplace's Equation

- Affected by:
  - venous return and venous pressure (venous tone, blood volume, skeletal muscle pump, and respirátory pump)
  - end-diastolic volume
  - sympathetic activation

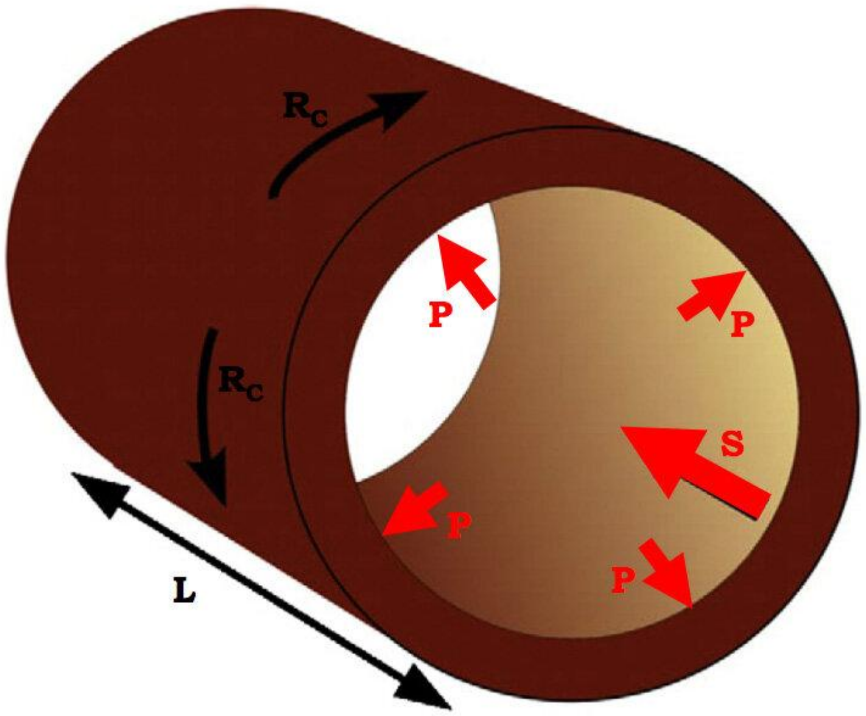
Afterload

- The force or load against which the heart has to contract to eject the blood

- Affected by:
  - arterial blood pressure

Blood pressure

- **Blood pressure (BP): pressure of blood on the vessel wall**
  (arterial BP – part of the energy of systole converted into lateral pressure on the vascular wall)



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Blood pressure

- is the pressure, measured in millimeters of mercury, within the major arterial system of the body

- **Systolic pressure**: the maximum blood pressure during contraction of the ventricles
- **Diastolic pressure**: the minimum pressure recorded just prior to the next contraction

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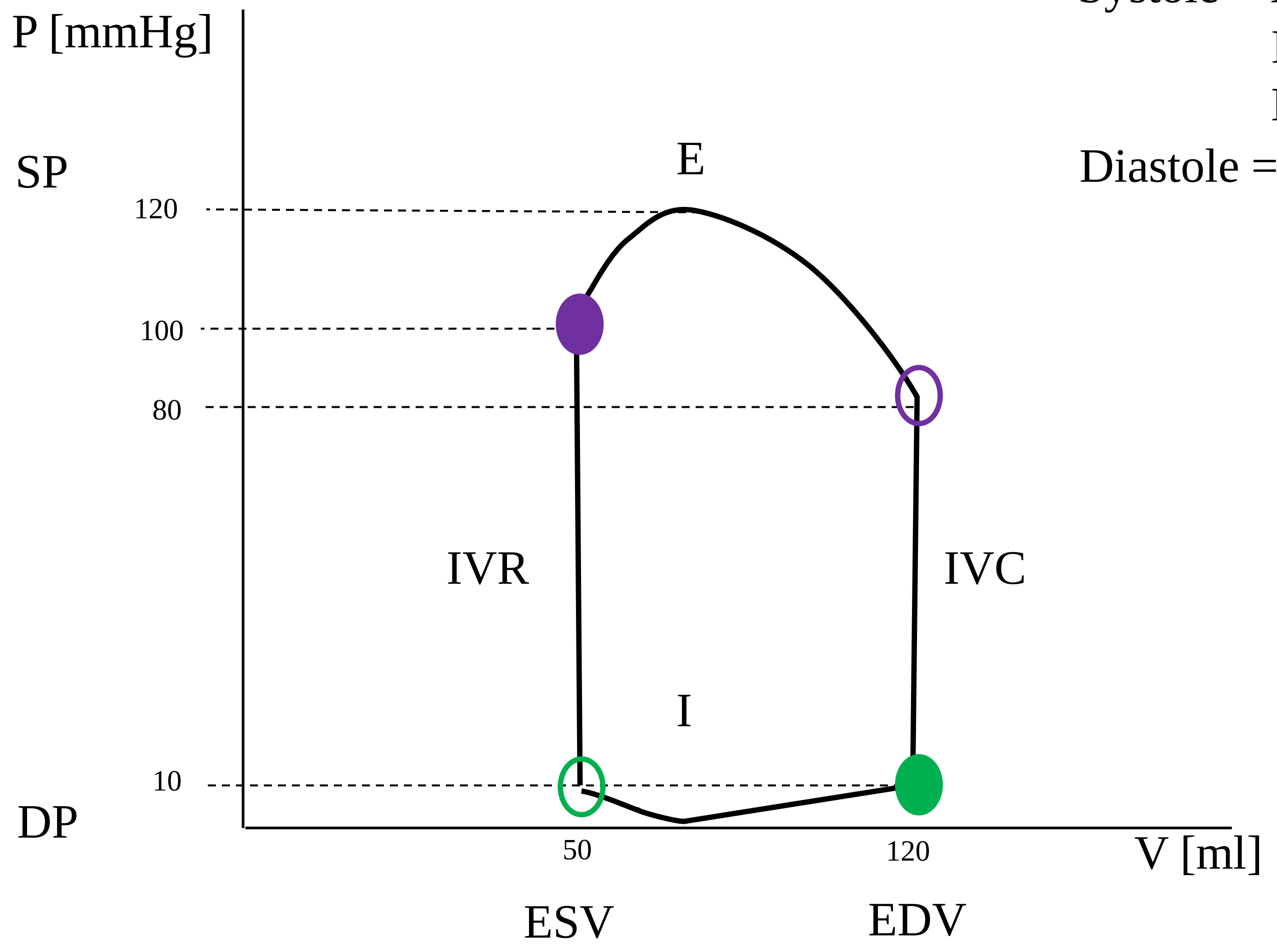
P-V diagram (Left ventricle)



Systole = IVC + E

IVC = 0.06 s

E = 0.21 s

Diastole = IVR + I

IVR = 0.07 s

I = 0.49 s

P-V diagram (Left ventricle)

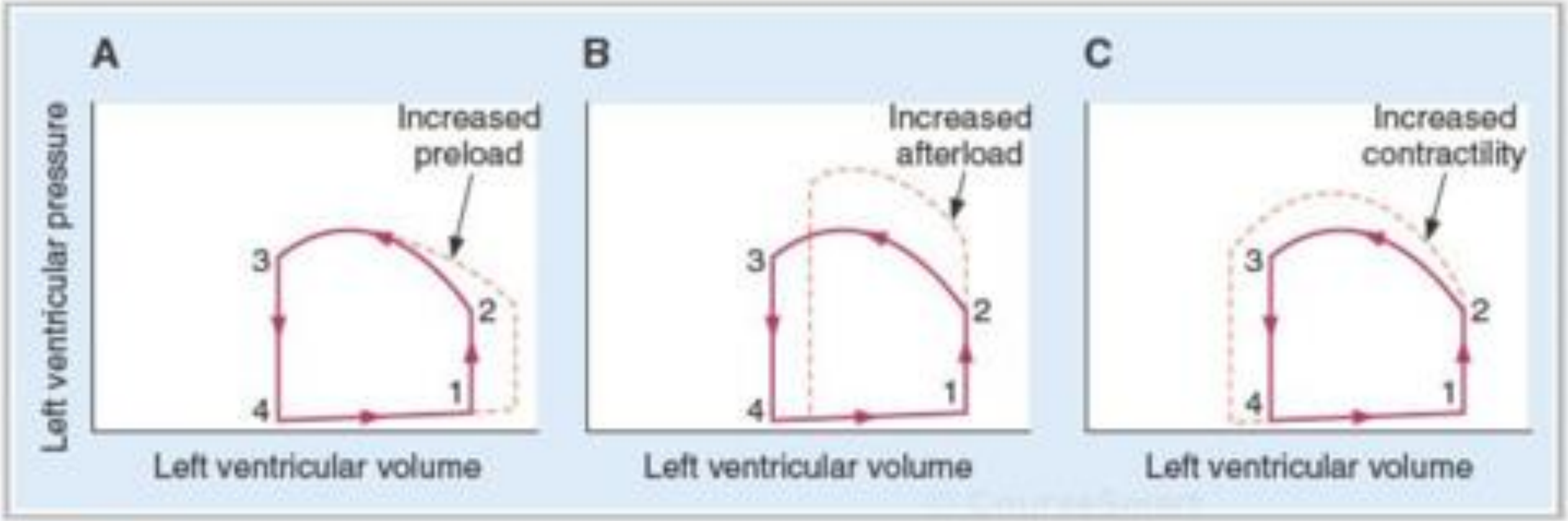
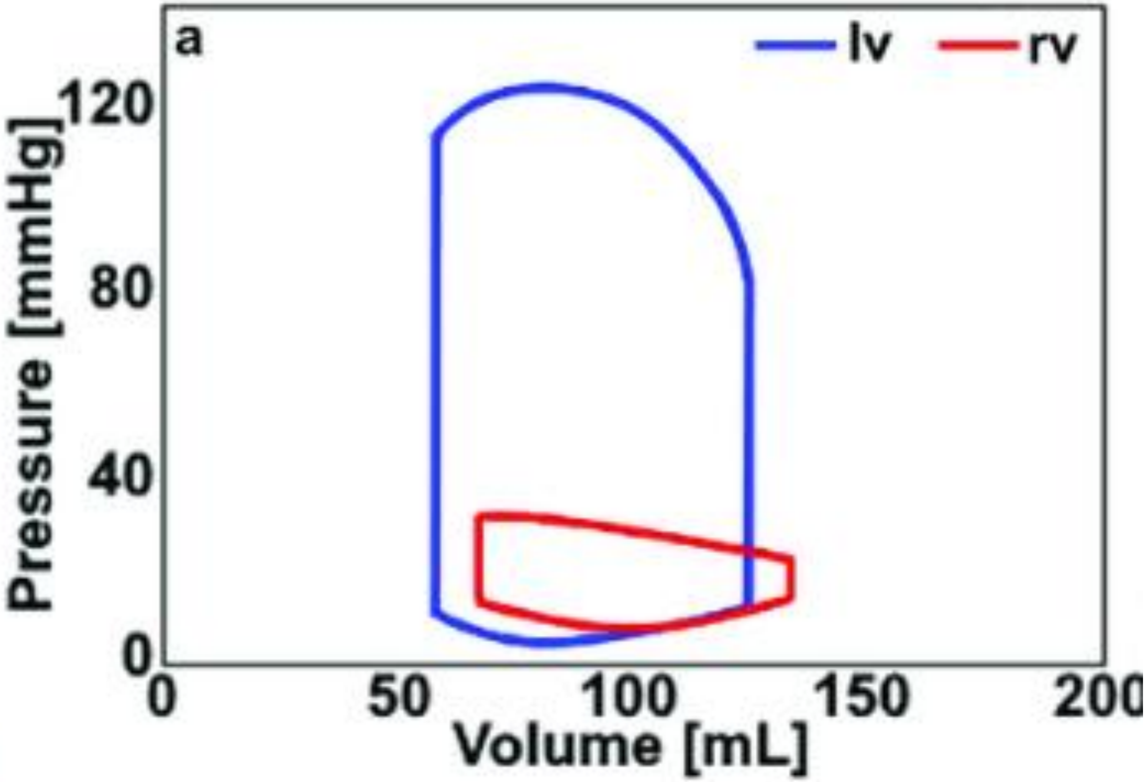
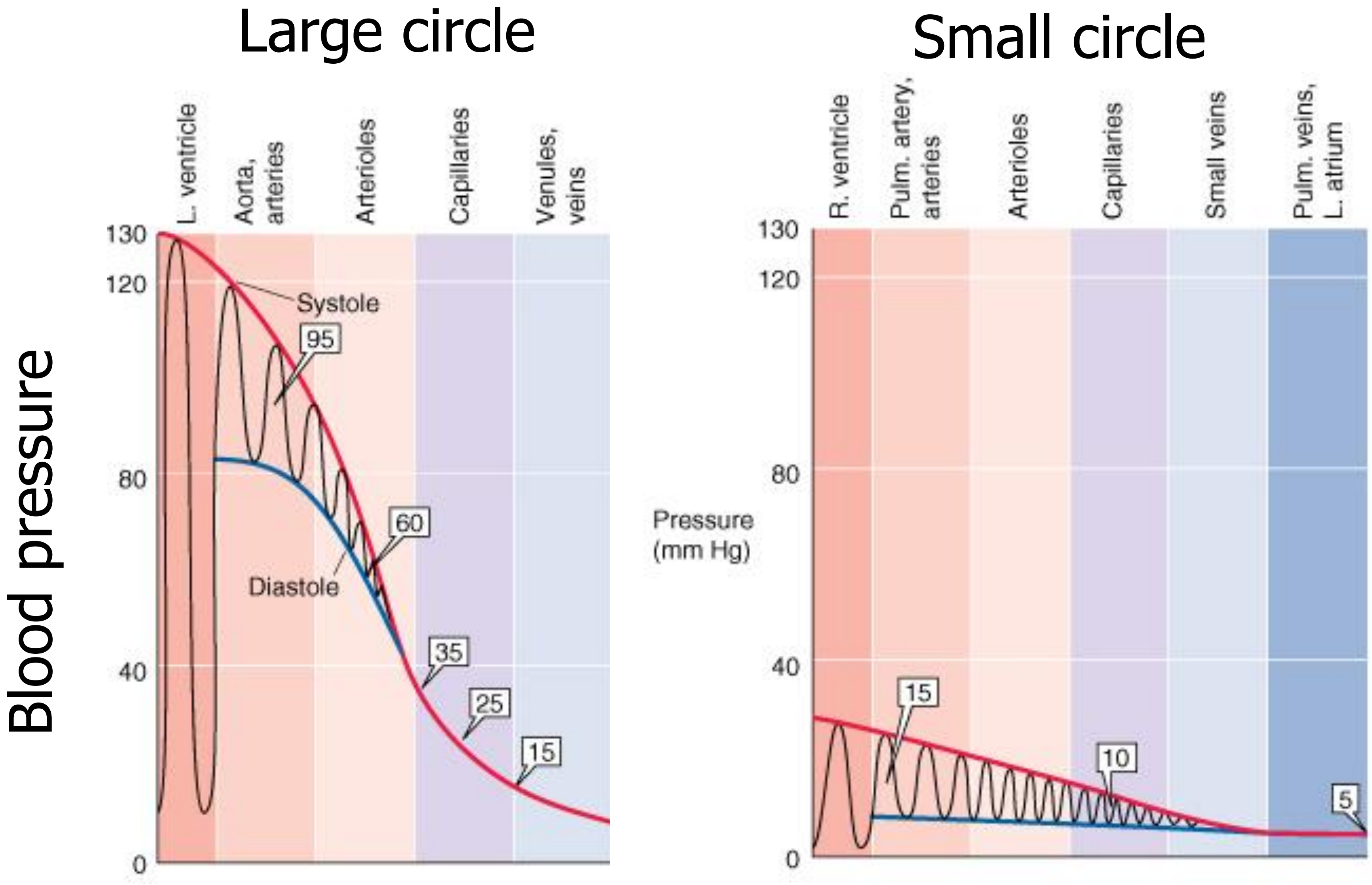


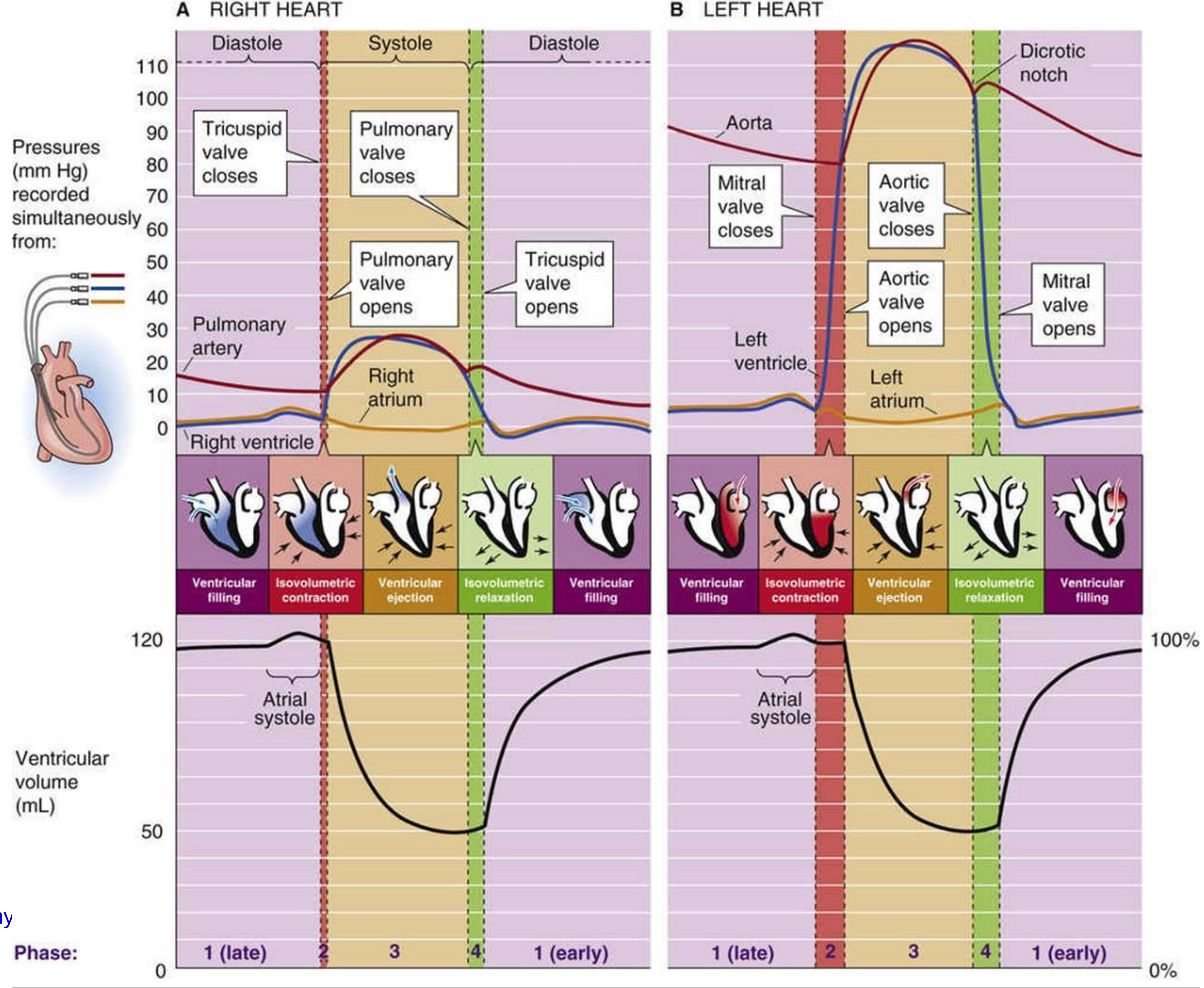
FIGURE 3-10 Effects of changes in (A) preload, (B) afterload, and (C) contractility on the ventricular pressure–volume loop.

P-V diagram





Boron and Boulpaep, Medical physiology


A RIGHT HEART
B LEFT HEART
Diastole
Systole
Diastole
Pressures (mm Hg) recorded simultaneously from:
110
100
90
80
70
60
50
40
30
20
10
0
Tricuspid valve closes
Pulmonary valve closes
Pulmonary valve opens
Tricuspid valve opens
Pulmonary artery
Right atrium
Right ventricle
Dicrotic notch
Aorta
Mitral valve closes
Aortic valve closes
Aortic valve opens
Mitral valve opens
Left ventricle
Left atrium
Ventricular filling
Isovolumetric contraction
Ventricular ejection
Isovolumetric relaxation
Ventricular filling
120
100%
Atrial systole
Ventricular volume (mL)
50
0
0%
Phase:
1 (late)
2
3
4
1 (early)

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Blood pressure

- a function of cardiac output (CO) and total peripheral resistance
  - SBP is determined mainly by CO
  - DBP is determined mainly by TPR

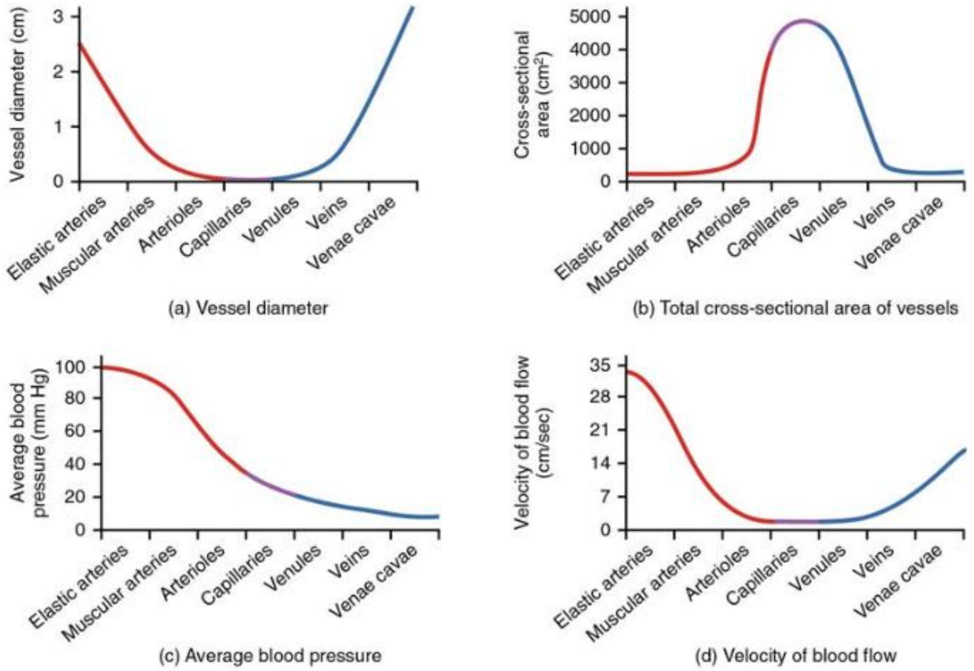
Blood pressure = Cardiac output (CO) * Total peripheral resistence (TPR)

CO = Heart rate (HR) * Stroke volume (SV)

Total peripheral resistence

- consist of resistence from all vessels
- the narrower tube (↓ diameter) → the ↑ pressure needs to be exerted to maintain the flow
- determined by **the Hagen-Poiseuille law** for tube resistance

$$R = \frac{8 \cdot \eta \cdot L}{\pi \cdot r^4}$$



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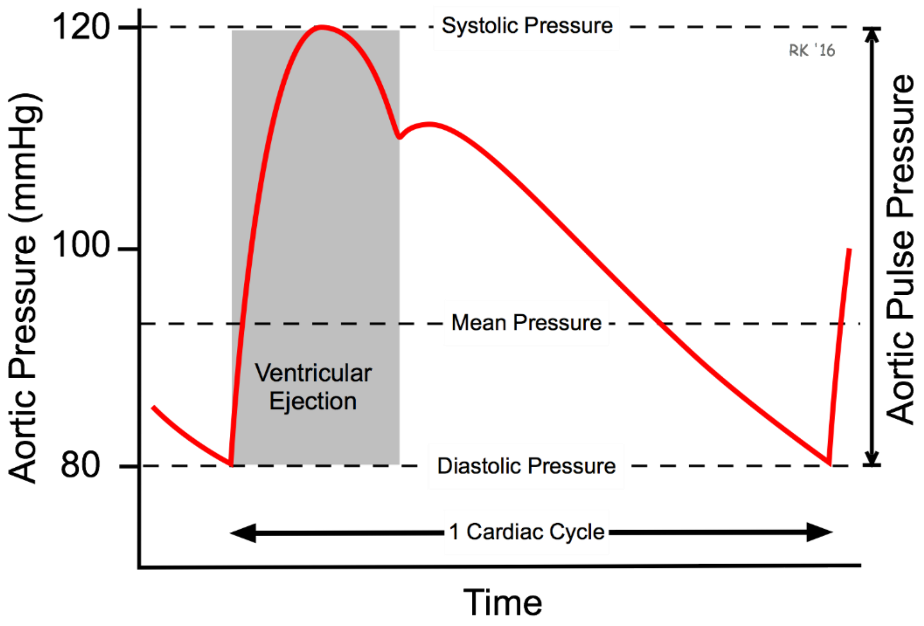
Arterial blood pressure

- stable blood flow thanks to aortic compliance
  - the aorta expands and holds the ejected blood volume (change of kinetic energy into elastic) and during diastole, it contracts and moves the blood further into the bloodstream (change of elastic energy to kinetic)

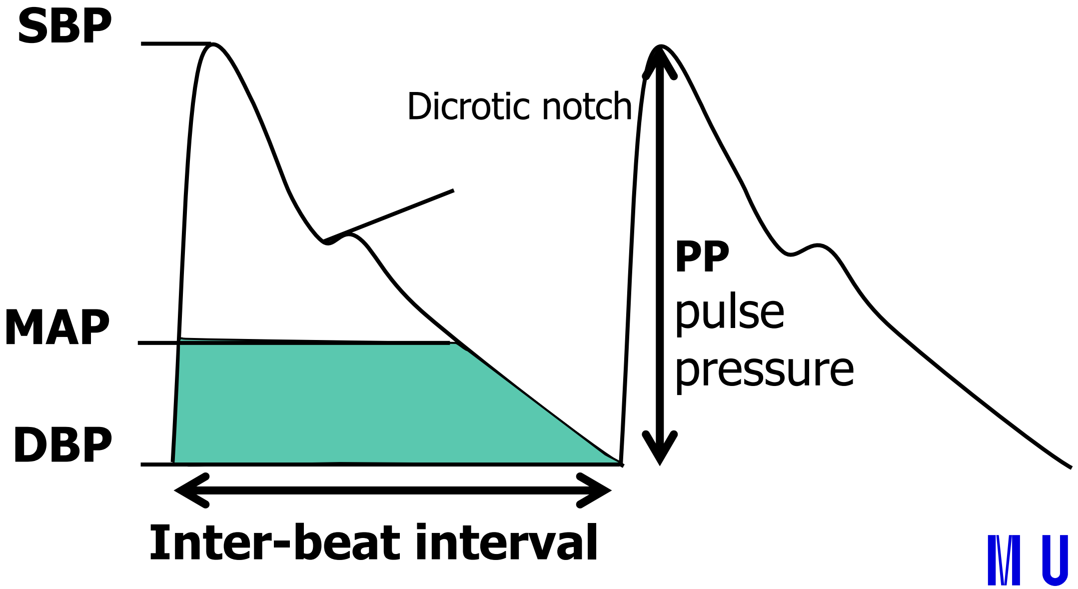


Arterial blood pressure curve

- Pulse wave
  - arises when the blood is expelled from the left ventricle into the circulation during the systolic phase

- **Mean arterial pressure (MAP): mean value of blood pressure in the inter-beat interval** (IBI) – integral of the BP curve; **area above MAP = area below MAP**
  aproximation: MAP = DBP + 1/3 PP (PP = SBP – DBP)

- **Definition:**
  - **SBP (systolic BP)**
    maximum of BP in the inter-beat interval
  - **DBP (diastolic BP)**
    minimum of BP in the inter-beat interval



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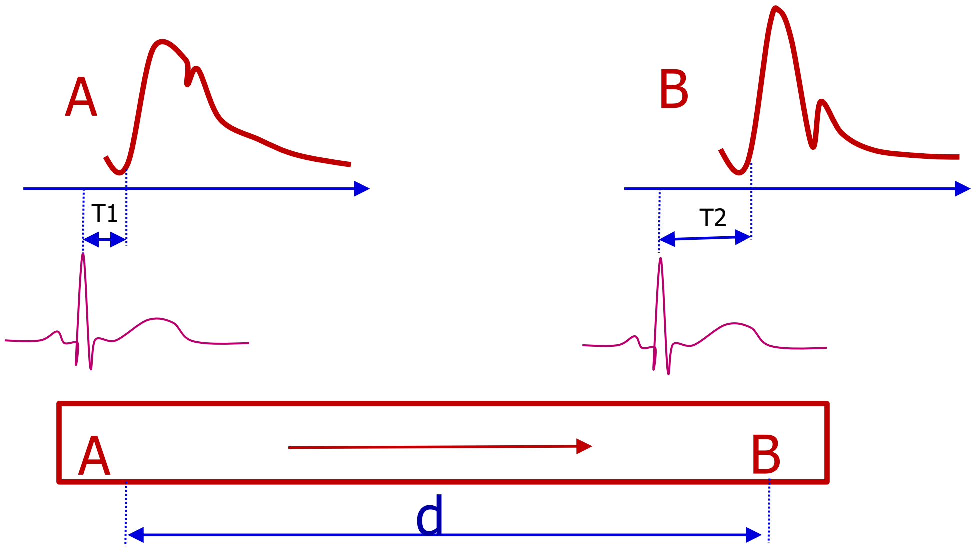
Pulse wave velocity (PWV)

- The pulse wave propagation rate (PWV) is measurable, around 4 m/s in the aorta.
  - Beware, the actual speed of blood flow is significantly lower, it is around 80-100 cm/s in the aorta to 0.03 cm/s in capillaries
- The peripheral pulse wave velocity is 10-20 m/s (depending on the site of measurement)
- Measureable by inderect method: Sphygmography with ECG

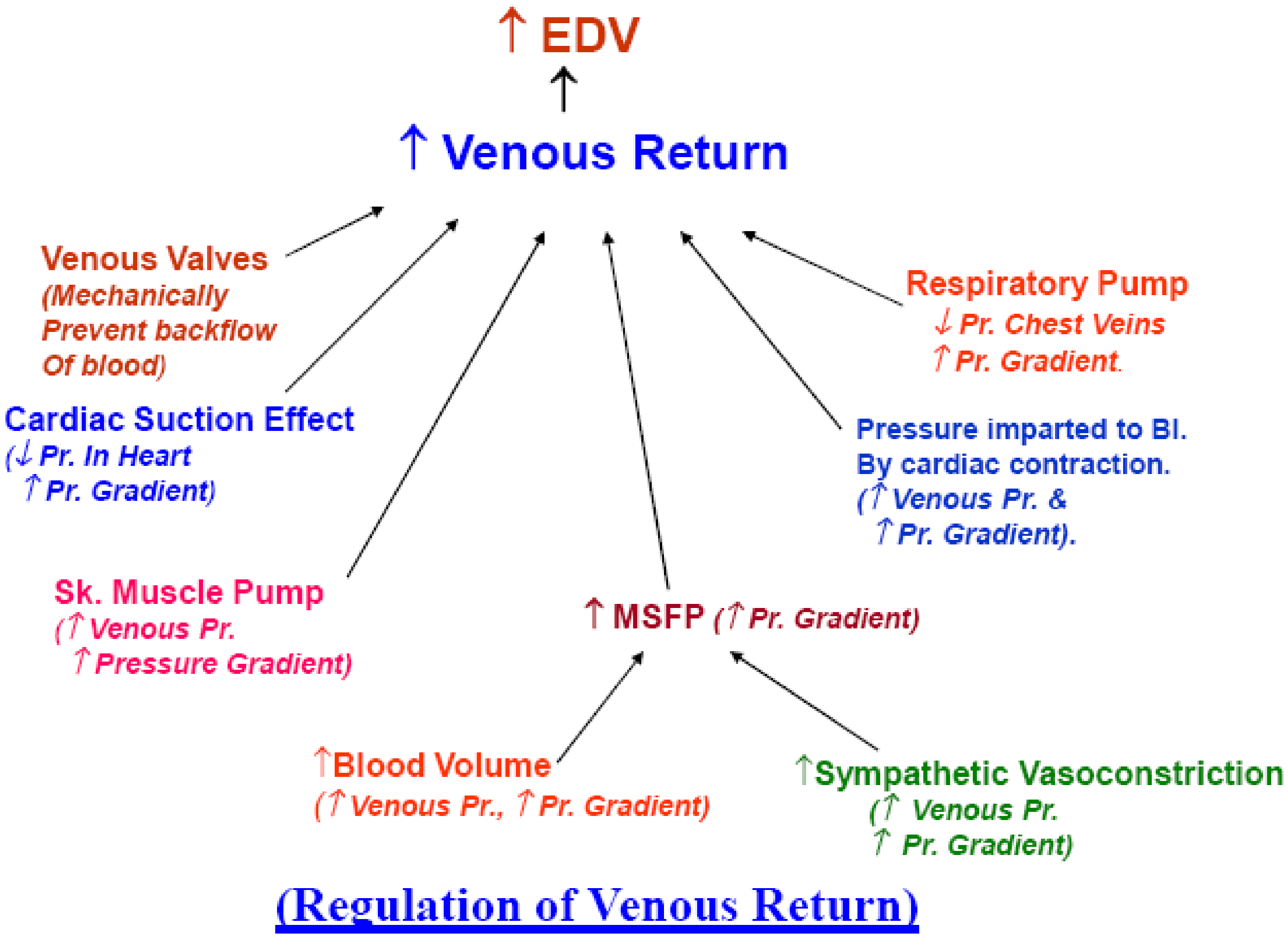


PWV= d/ (T2-T1)

Blood pressure in veins

- low pressure system
- peripherial pressure in veins is usually between 8 and 10 mmHg
- central vein pressure is aproximately 0–6 mmHg

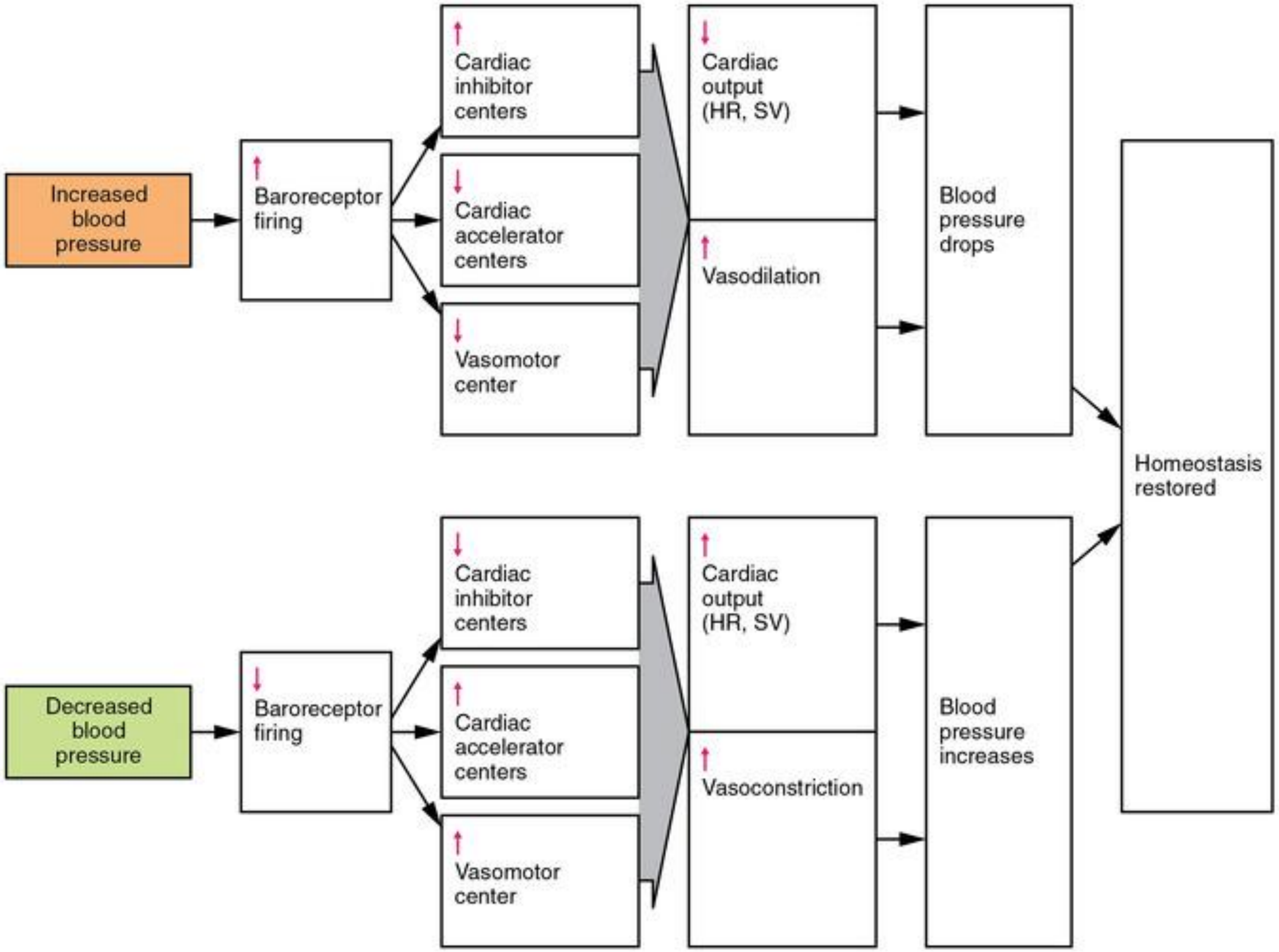
Blood pressure in veins



Blood pressure regulation

- Short-term – neural control – baroreceptors, chemoreceptors
  - by realising chemical substances (norepinephrine, acetylcoline, NO, neuropeptide Y)
  - Bainbridge reflex (larger filling of atria results in tachycardia and release of ANP)
- Middle- and long-term – hours or days
  - Vasoactive substance
  - Affecting effective circulating fluid (volume) – RAAS system

Short-term BP control – baroreflex



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BP control – compounds

- vasoconstrictors
  - Epinephrine (α1 receptors), serotonin, norepinephrine, antidiuretic hormone, angiotensin II, and endothelins

- vasodilators
  - Epinephrine (β2 receptors), atrial natriuretic peptide, histamine, bradykinins, prostaglandins, arginine (→NO)

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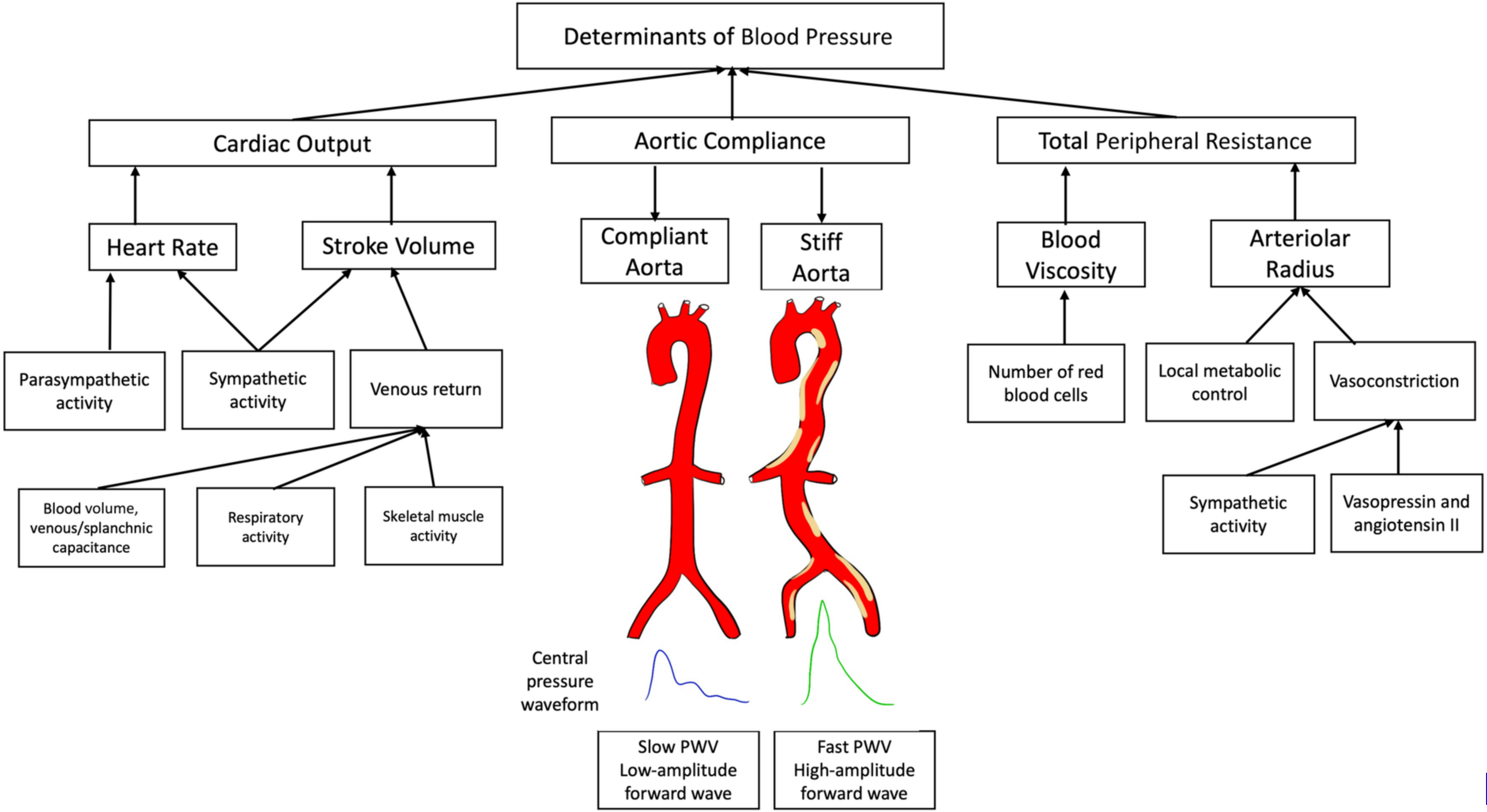
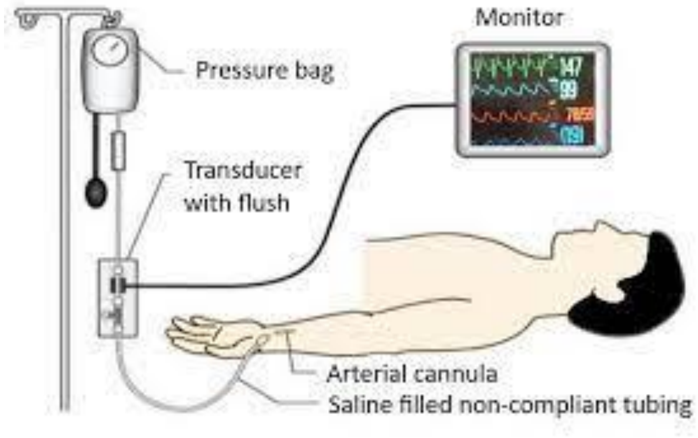
Blood pressure changes

- Short-term influences
  - blood volume – influence on cardiac output (bleeding, dehydration)
  - external pressure to the vessels – intrathoracic and intraabdominal pressure (cough, defecation, childbirth, artificial ventilation)
  - position – orthostasis/clinostasis: redistribution of blood due to gravity
  - CNS – emotions, mental stress, …
  - physical exercise – BP changes depend on intensity, duration and type of exercise
  - heat (↓ TPR), cold (↑ TPR)
  - alcohol, drugs,…
- Long-term influences
  - age (the fastest changes during childhood and adolescence, in adults slow increase in SBP)
  - sex (men have higher BP)
  - genetic background


Determinants of Blood Pressure
Cardiac Output
Aortic Compliance
Total Peripheral Resistance
Heart Rate
Stroke Volume
Compliant Aorta
Stiff Aorta
Blood Viscosity
Arteriolar Radius
Parasympathetic activity
Sympathetic activity
Venous return
Number of red blood cells
Local metabolic control
Vasoconstriction
Blood volume, venous/splanchnic capacitance
Respiratory activity
Skeletal muscle activity
Sympathetic activity
Vasopressin and angiotensin II
Central pressure waveform
Slow PWV Low-amplitude forward wave
Fast PWV High-amplitude forward wave

Methods of the arterial BP measurement

- Invasive
  - arterial catether



Methods of the arterial BP measurement

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- Non-invasive
  - Palapation (only SBP, sphygmomanometer)
  - Auscultatory (sphygmomanometer, stethoscope)

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  - Oscillometric

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  - Oscillometric

  - Photoplethysmographic/Peňáz/volume-clamp method

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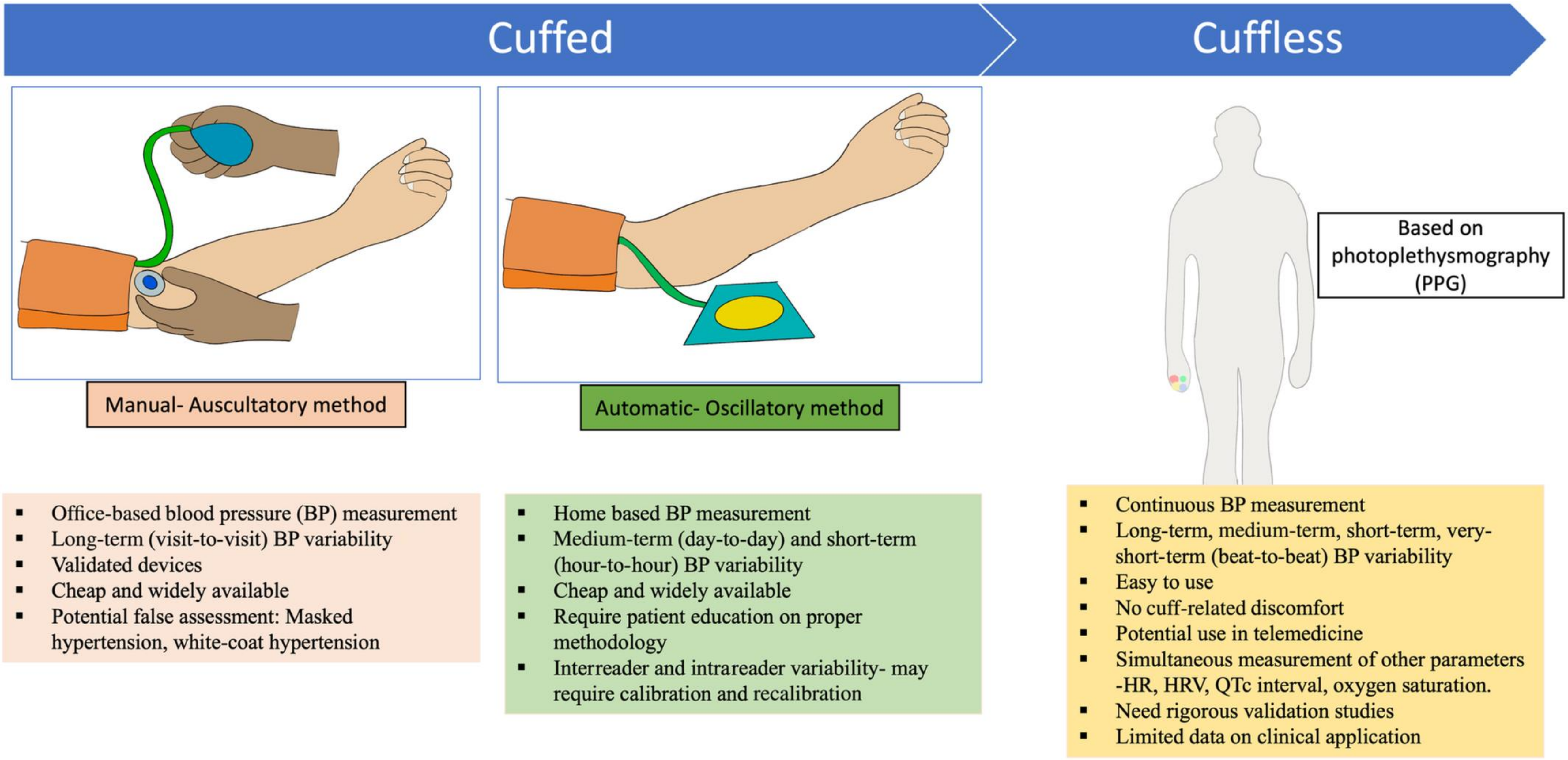

Cuffed
Cuffless
Based on photoplethysmography (PPG)
Manual- Auscultatory method
Automatic- Oscillatory method
▪ Office-based blood pressure (BP) measurement
▪ Long-term (visit-to-visit) BP variability
▪ Validated devices
▪ Cheap and widely available
▪ Potential false assessment: Masked hypertension, white-coat hypertension
▪ Home based BP measurement
▪ Medium-term (day-to-day) and short-term (hour-to-hour) BP variability
▪ Cheap and widely available
▪ Require patient education on proper methodology
▪ Interreader and intrareader variability- may require calibration and recalibration
▪ Continuous BP measurement
▪ Long-term, medium-term, short-term, very-short-term (beat-to-beat) BP variability
▪ Easy to use
▪ No cuff-related discomfort
▪ Potential use in telemedicine
▪ Simultaneous measurement of other parameters -HR, HRV, QTc interval, oxygen saturation.
▪ Need rigorous validation studies
▪ Limited data on clinical application

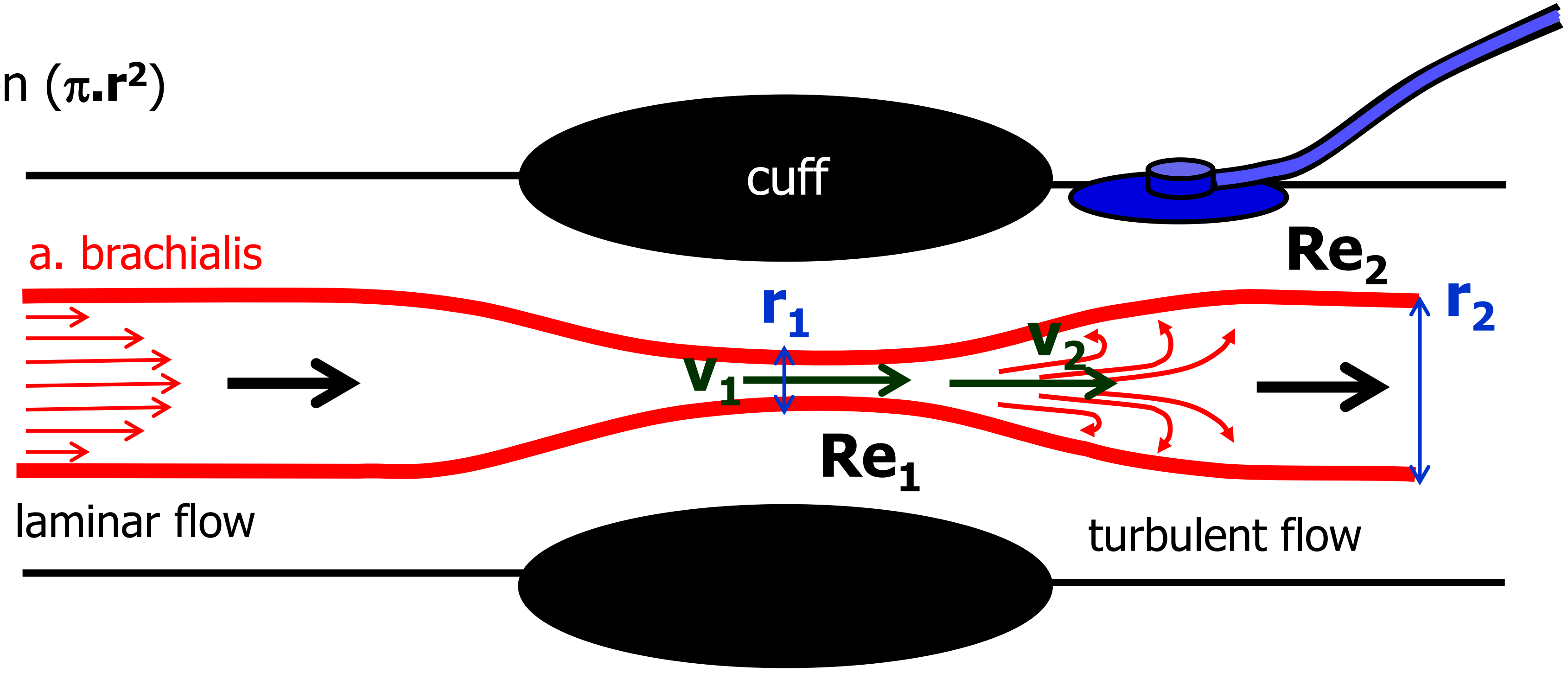
Basic principle: Laminar / turbulent flow

(Korotkoff sounds in auscultatory method; oscillation in oscilometric method).

$$Re = \frac{v \cdot S \cdot \rho}{\eta}$$

laminar flow Re < 2000
turbulent flow Re > 3000

Reynolds number Re: predicts the transition from laminar to turbulent of flow
v: velocity of blood flow
S: area of vascular lumen ($\pi . r^2$)
ρ: density of blood
η: viscosity of blood
(lower in anemia)



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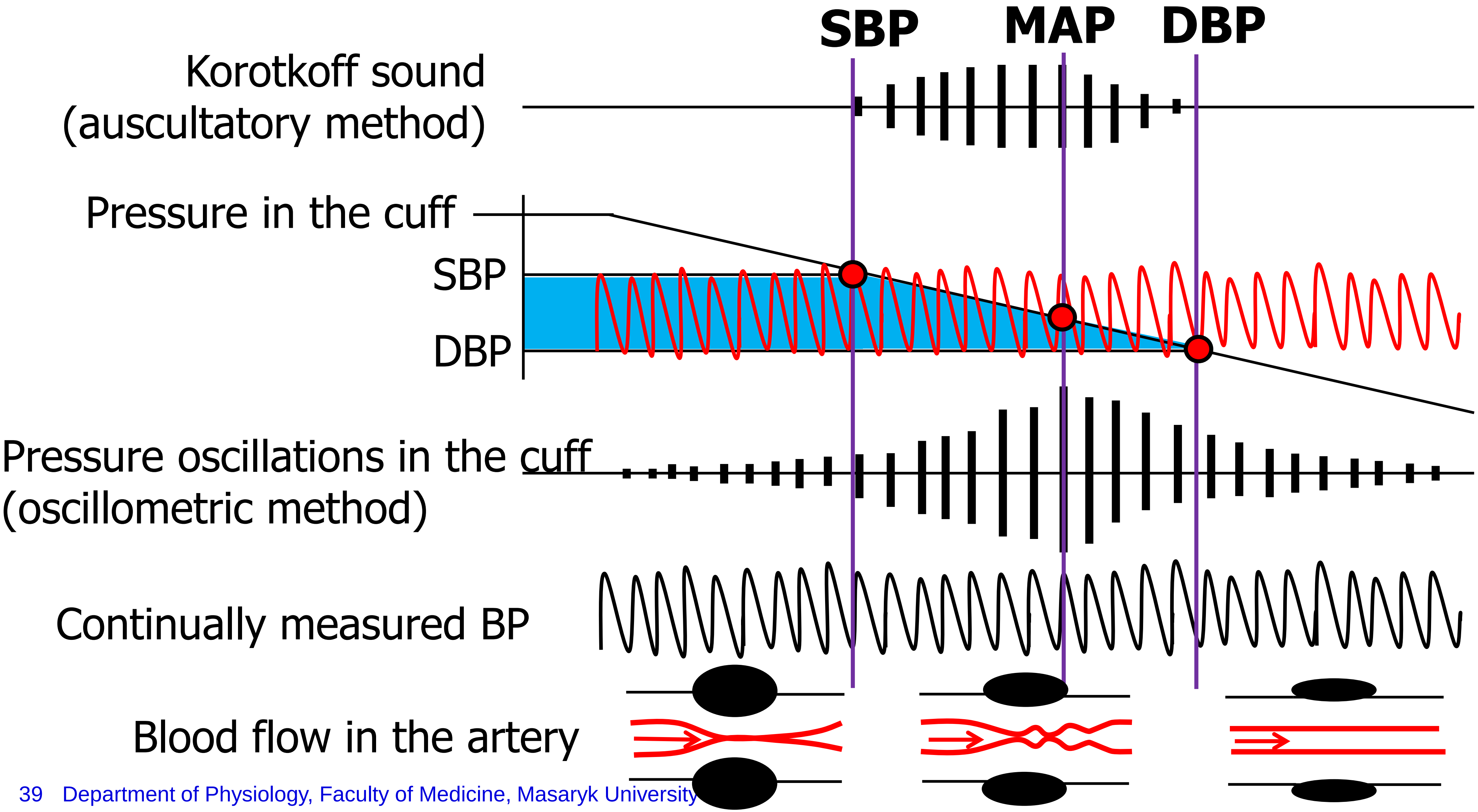
Principles of BP measurement



Photoplethysmographic/Peňáz/volume-clamp method

- **Volume-Clamp**: A principle/method to maintain constant arterial volume by applying counter-pressure
- **Photopletysmography** - measures blood volume changes in tissue using light absorption
- Peňáz method – combination of both allowing continuous blood pressure meassurements

Assesmemt of BP varaibility

- Very short term – from continous BP measurement
  - Neurohormonal factors (baroreflex, sympathetic activation)
  - Nitric oxide, renin-angiotensin-aldosterone system
  - Enviromental, behavioral, and emotional factors
- Short tem (within 24-h)
  - Neurohormonal factors (baroreflex, sympathetic activation)
  - Environmental, behavioral, and emotional
  - Circadian rhythm

Assesmemt of BP varaibility

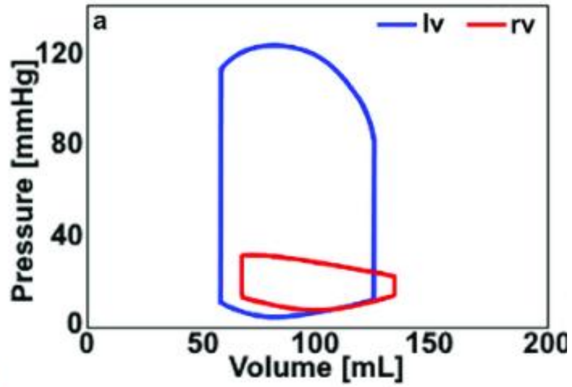
- Medium term (day to day)
  - drugs
  - vascular factors (endothelial damage, arterial compliance)
  - age
- Long tern (visit to visit)
  - drugs
  - seasonal changes
  - vascular factors (endothilial damage, arteriál compliance)
  - age

Rules for BP measurement

- Environment: pleasant room temperature, quiet surroundings
- Position: the patient sits with his back leaning backwards, both legs are on the floor, forearm rests on a surface
- Reasonable cuff size, correct positioning at heart level
- The measurement happens at rest and starts after 5 – 10 minutes of sitting down
- Measurement by auscultatory method
  - Inflate the cuff to a pressure 30 mmHg higher than the pressure at which the radial pulse disappeared
  - The pressure reduction rate in the cuff is 2 – 3 mmHg/s
  - The pressure value is determined with 2 mmHg accuracy
- The BP should be measured 3 times at least five minutes apart and the final BP value is a mean value of the last two measurements

Take home message

- more means more (higher frequency/filling of the heart → larger contraction)



- systolic pressure: highest
- diastolic: lowest

- auscultatory method – gold standart

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