

Bioelectric phenomena.

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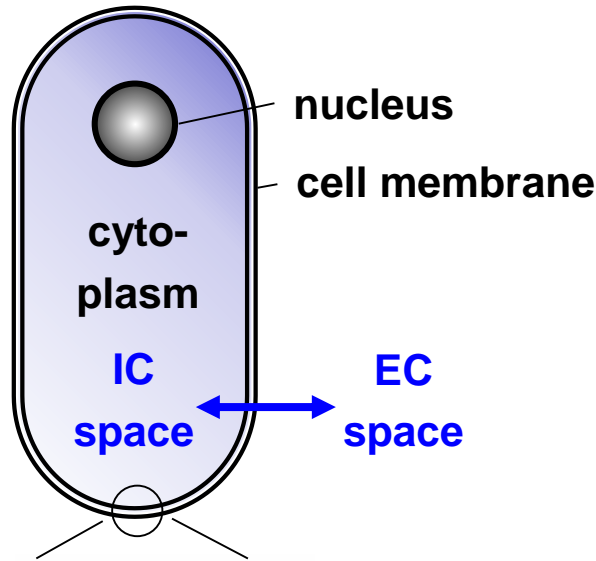
01. April 2026.



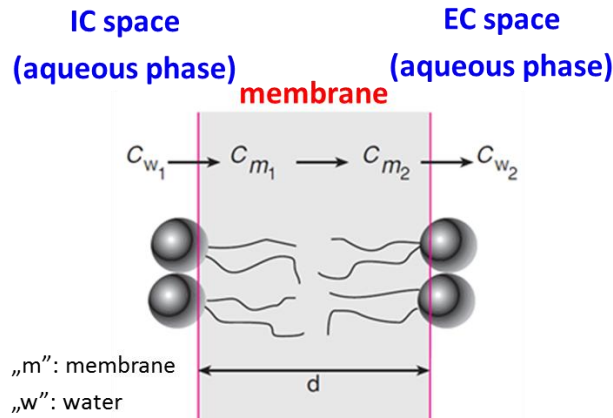
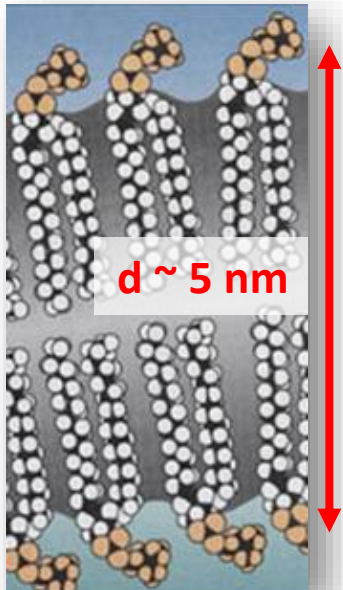
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Physical properties of the cell membrane

living cell



- **Noncovalent, cooperative structure:** phospholipid bilayer, vesicle formation, additional components (e.g. cholesterol, proteins)
- **Passive diffusion:** classical diffusion (**Fick's first law**)
- **Facilitated or mediated diffusion:** through biological membranes, through/with protein(like) **mediator molecules** (carrier or channel proteins)
- **Active transport:** the particle is transported **against a gradient** (chemical/electrochem.)



$$J_m = -D \cdot \frac{\Delta C}{\Delta x} = -D_m \frac{C_{m2} - C_{m1}}{d}$$

Permeability constant: p_m , [m/s] $p_m = \frac{D_m}{d}$

Partition coefficient: K $\frac{C_{m1}}{C_{w1}} = \frac{C_{m2}}{C_{w2}} = \text{const.}$
(between the membrane and aqueous phases)

$$J_m = -p_m \cdot K(c_{w2} - c_{w1}) = -p(c_{w2} - c_{w1})$$

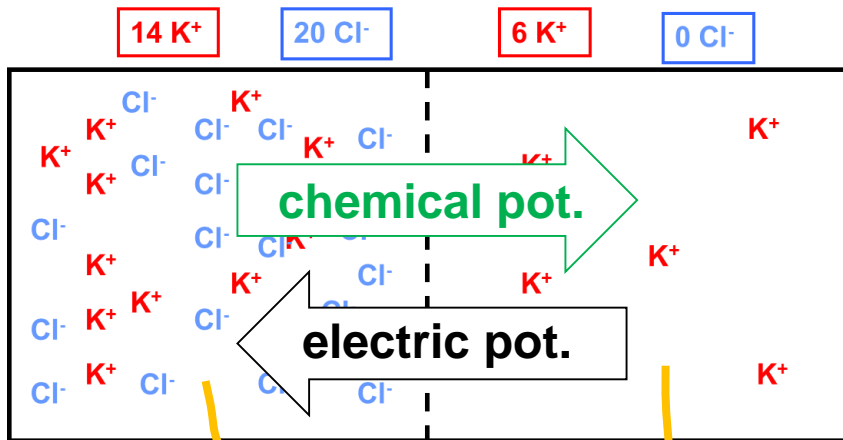
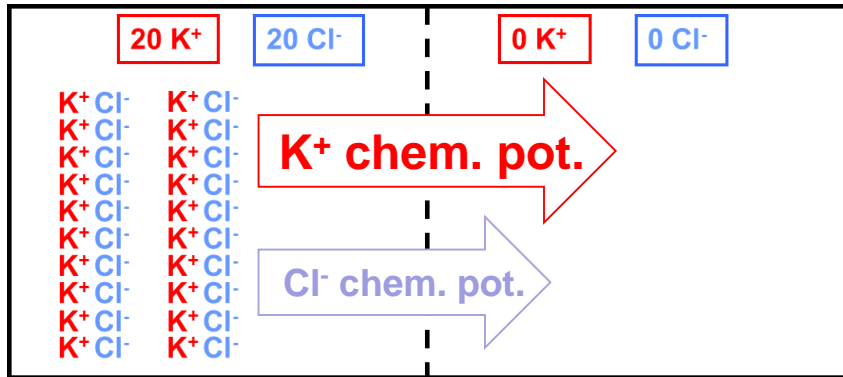
Aggregated permeability constant: p , [m/s]

$$p = K \cdot p_m$$

„permeability“

Passive diffusion of ions: electrochemical potential

Assume that the membrane is **only permeable to K⁺**.



$$J = -D \left(\frac{\Delta c}{\Delta x} + c \frac{z F \Delta \phi}{RT \Delta x} \right)$$

In equilibrium:

- concentration difference
 - electric potential difference
- exist between the two compartments.

Chemical potential: μ

molar free enthalpy

$$\mu = \mu_0 + RT \cdot \ln(c)$$

μ_0 : standard chemical potential

- the chemical and electric potentials are of the same magnitude but oppositely directed.

Electrochemical potential: μ_e , [J/mol]

$$\mu_e = \underbrace{\mu}_{\text{chemical}} + \underbrace{zF\phi}_{\text{electric}}$$

z: charge of the ion

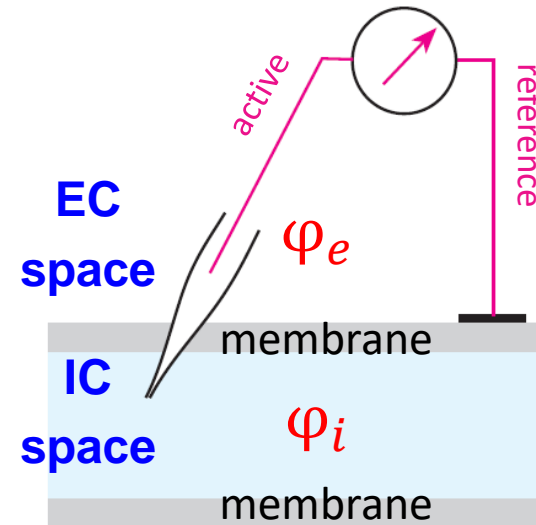
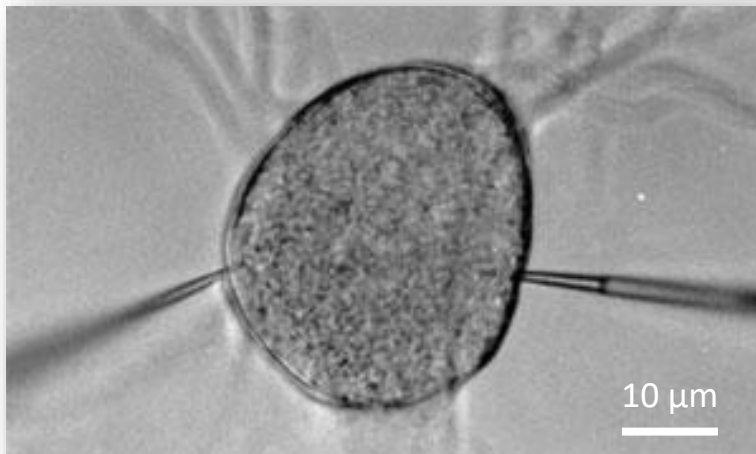
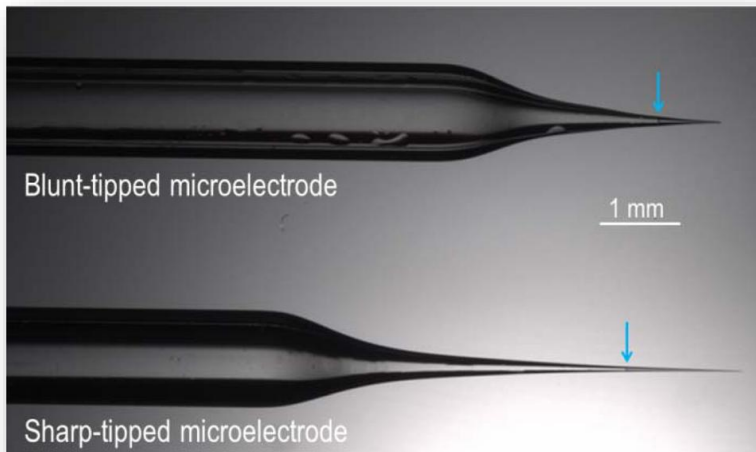
F: Faraday constant

ϕ : electric potential

Resting membrane potential

Measurement: with microelectrodes

- active
- reference



voltage = potential difference = „potential“

Observation: $\Delta\varphi = \varphi_i - \varphi_e < 0$

Cell	$\Delta\varphi$ (mV)
squid giant axon	-62
frog muscle	-92
rat muscle	-92

The intracellular space is more negative.

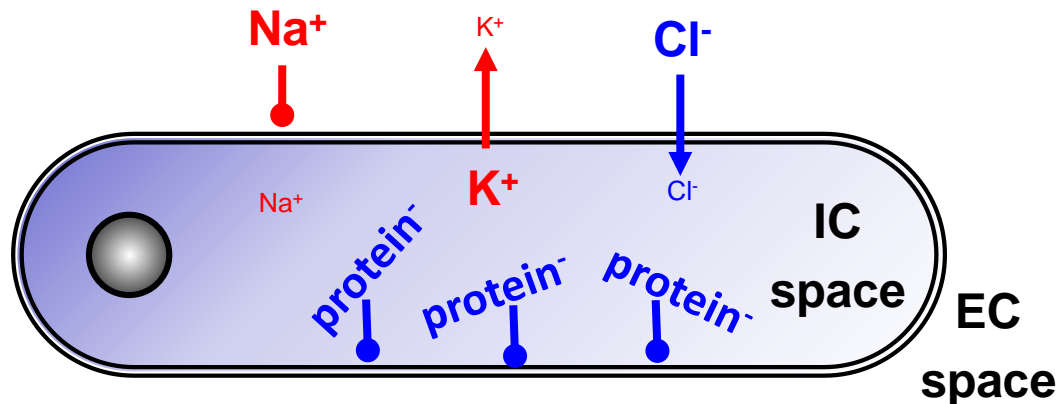
Resting membrane potential

Further observation: different ion concentrations on both sides of the membrane

cell	intracellular concentration (mmol/l)			extracellular concentration (mmol/l)		
	Na ⁺	K ⁺	Cl ⁻	Na ⁺	K ⁺	Cl ⁻
squid giant axon	72	345	61	455	10	540
frog muscle	20	139	3,8	120	2,5	120
rat muscle	12	180	3,8	150	4,5	110

Considering the ion distribution shown in the table above which physical model gives the best approximation of the resting membrane potential?

Model #1: Donnan-model: equilibrium ion distribution, intracellular protein anions



- The membrane is impermeable to certain ions ($p_{\text{protein}^-} = 0$).
- Electrochemical equilibrium is assumed.

Resting membrane potential

Equilibrium potential: calculated based on the #1 Donnan-model...

This is done by applying the Nernst-equation...

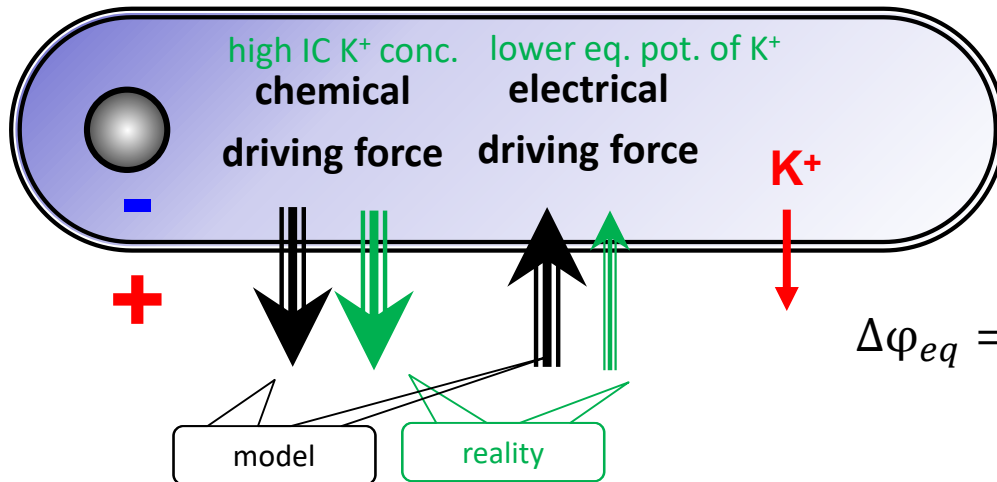
Nernst equation:
$$\Delta\varphi = \varphi_2 - \varphi_1 = -\frac{RT}{F} \ln \frac{c_2}{c_1}$$

let's calculate it for the K⁺ ions...

cell	intracellular concentration (mmol/l)			extracellular concentration (mmol/l)		
	Na ⁺	K ⁺	Cl ⁻	Na ⁺	K ⁺	Cl ⁻
squid giant axon	72	345	61	455	10	540

the Nernst-equation for the K⁺ ions

$$\Delta\varphi_{eq} = -\frac{RT}{F} \ln \frac{c_i}{c_e}$$



$$\Delta\varphi_{eq} = -\frac{8,31 \cdot 293}{96500} \ln \frac{345}{10} = -0,089 \text{ V} = \boxed{-89 \text{ mV}}$$

Measured membrane potential: -62 mV

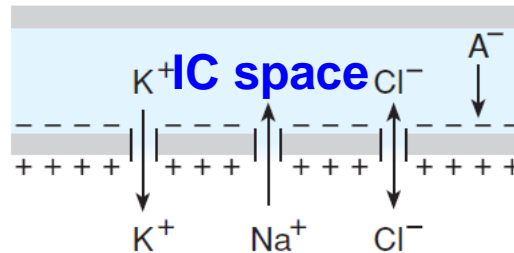
Outward flux of K⁺ should happen at -62 mV
The equilibrium model does not correctly describe the real situation!

The Goldman-Hodgkin-Katz (GHK) equation

Cell	$\Delta\varphi_{\text{equilibrium}}$ (mV) using the Nernst equation			$\Delta\varphi_{\text{membrane}}$ (mV)
	Na ⁺	K ⁺	Cl ⁻	
squid giant axon	+46	-89	-55	-62
frog muscle	+45	-101	-87	-92
rat muscle	+64	-93	-85	-92

No equilibrium at rest but the transport processes continue:

- outward flux of K⁺
- inward flux of Na⁺
- minor outward flux of Cl⁻



- **active transport:** requires energy (ATP)

Model #2: transport model: continuous diffusion of ions with different permeability (p)

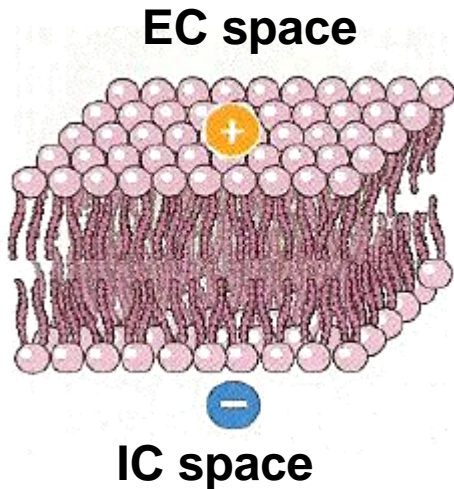
$$\Delta\varphi = \varphi_i - \varphi_e = -\frac{RT}{F} \ln \frac{p_{Na}c_{Na}^i + p_Kc_K^i + p_{Cl}c_{Cl}^e}{p_{Na}c_{Na}^e + p_Kc_K^e + p_{Cl}c_{Cl}^i} = -91 \text{ mV}$$

in frog muscle

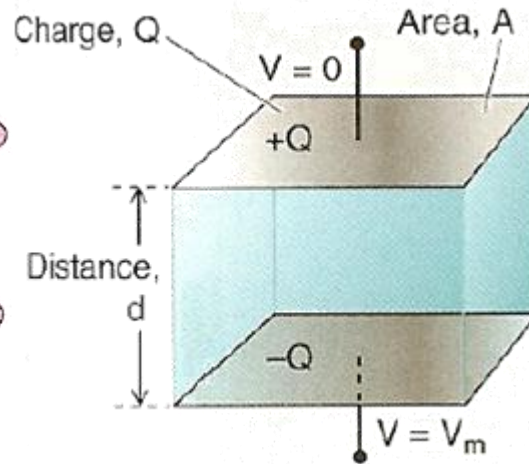
The calculation using the GHK equation is in agreement with the measurements.

The electric model of the cell membrane

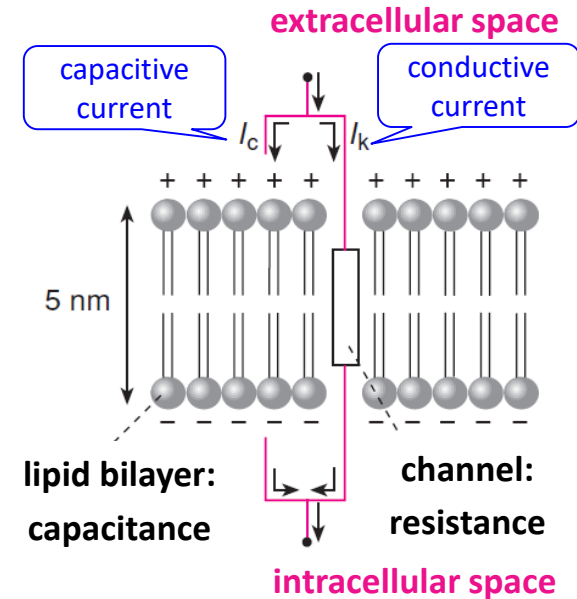
cell membrane



capacitor



electric model

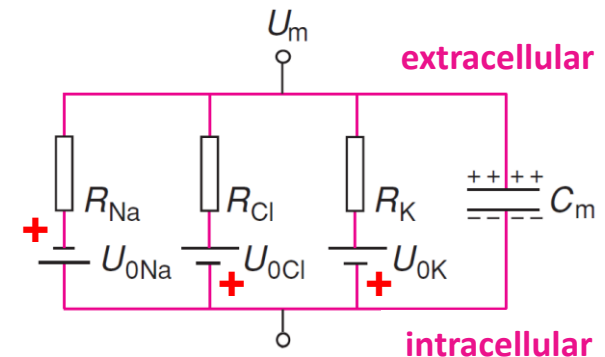


- different **transmembrane resistance (R)** in the case of the different ion channels

- **electric conductivity:** G (unit: Siemens) $G = \frac{1}{R}$

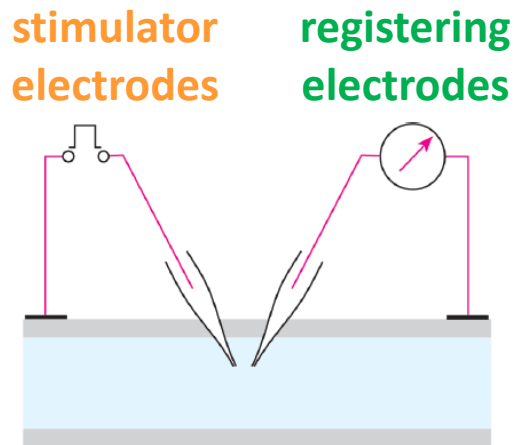
proportional to **permeability (p)**

- **specific conductivity:** sigma (unit: $1/(\Omega \cdot m^2)$) $\sigma = \frac{1}{R \cdot A}$



Model: RC-circuit

The change of the resting potential in time

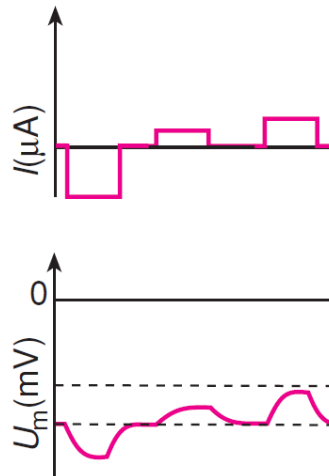


stimulation

I_{stim}

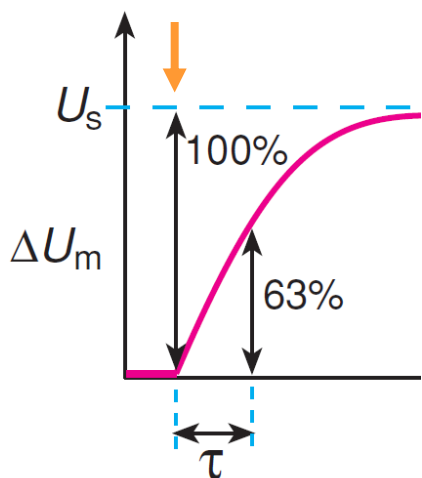
response

$\Delta\phi_m$

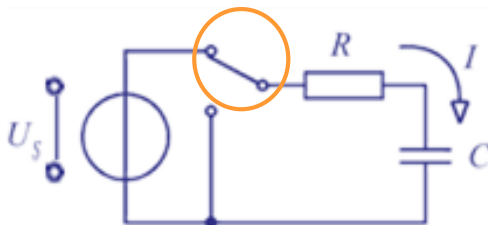


The amplitude of the response is proportional to the stimulating current, but shows a characteristic delay.

onset of stimulation



RC: „charge”



$$U_m(t) = U_s \cdot (1 - e^{-\frac{t}{\tau}})$$

saturation voltage

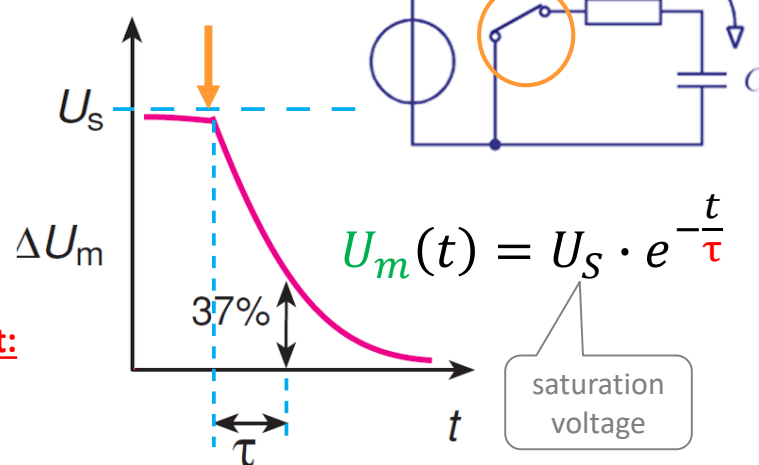
Time-constant:

tau: τ [s]

$\tau = R_m \cdot C_m$

RC: „discharge”

end of stimulation

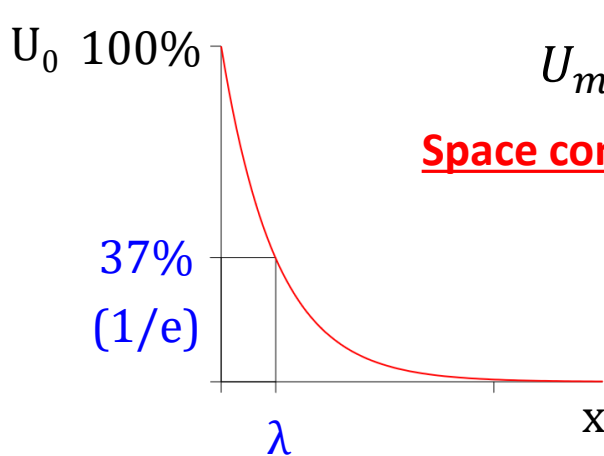
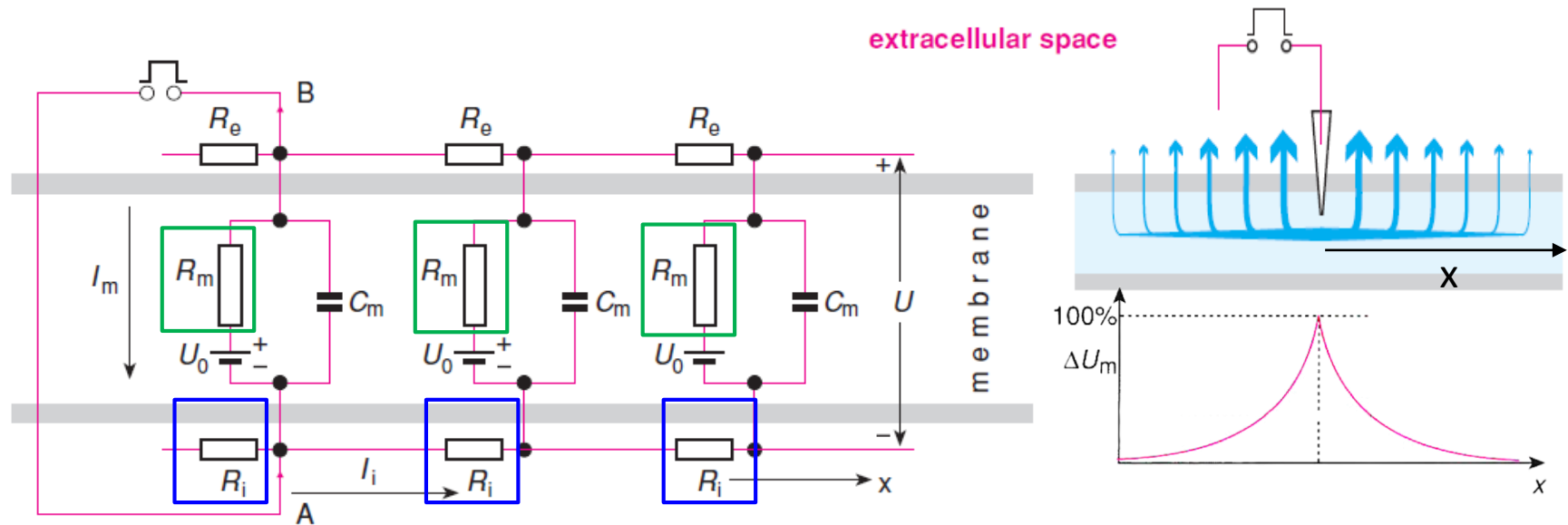


$$U_m(t) = U_s \cdot e^{-\frac{t}{\tau}}$$

saturation voltage

Propagation of a local potential change in space

Model of a larger membrane section:



$$U_m(x) = U_0 e^{-\frac{x}{\lambda}}$$

Space constant: lambda, λ [cm]

$$\lambda \sim \sqrt{\frac{R_m}{R_i}}$$

R_m : transmembrane resistance
 R_i : intracellular resistance

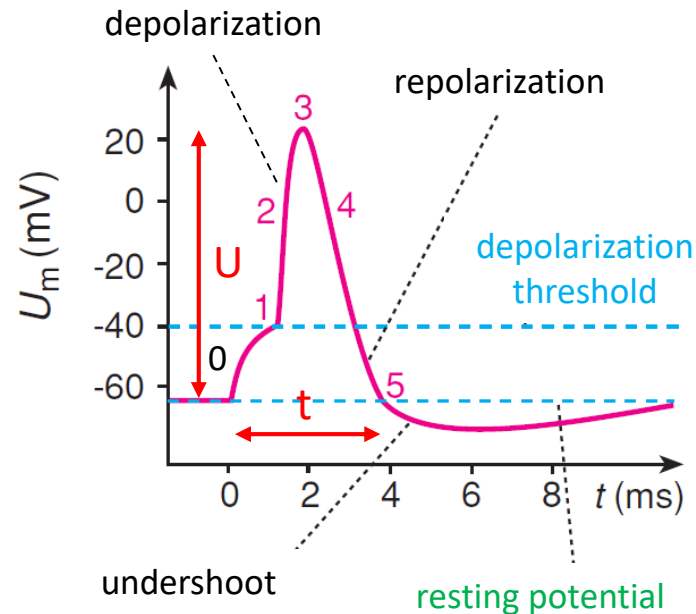
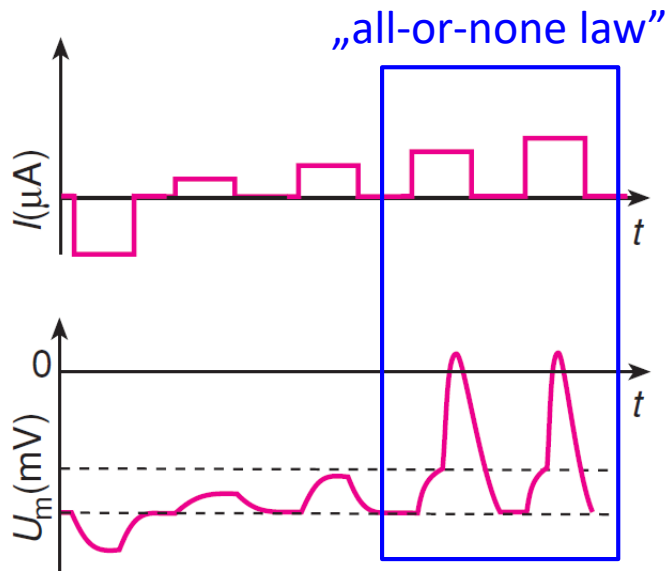
Aim: to increase the value of λ .

When $R_m \uparrow$ or $R_i \downarrow$: potential propagation is improved.

Examples: **myelin sheath** or **larger cell diameter**.

Action potential

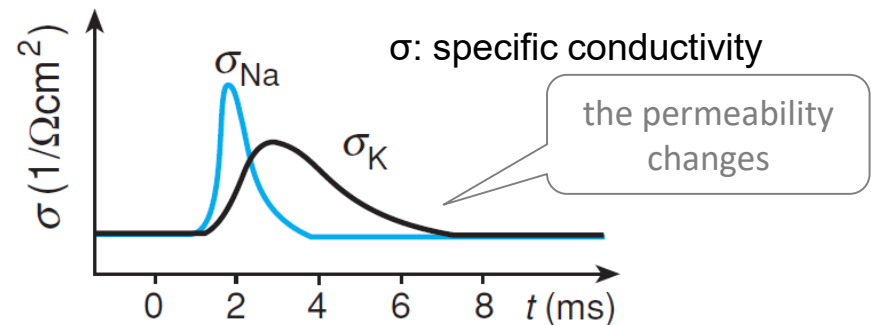
For stimuli above threshold: generalized change of the membrane potential



$t \sim 1-5$ ms
(skeletal muscle and neuron)
 $U \sim 100$ mV

0: local change of membrane potential

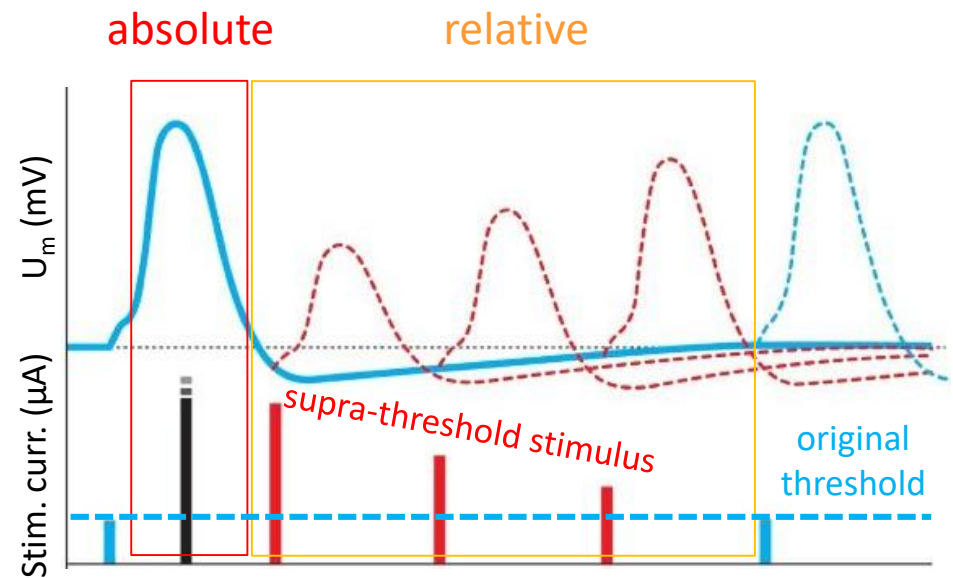
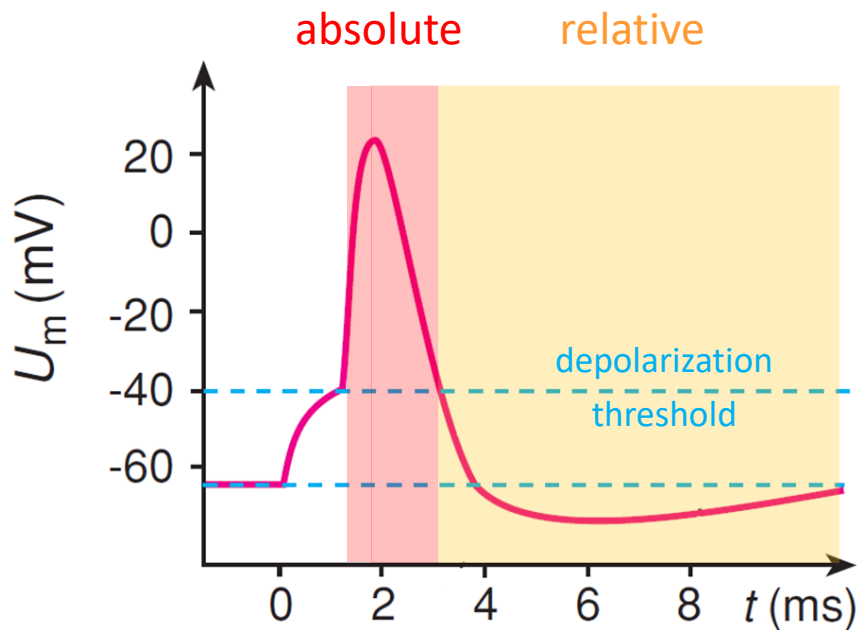
- 1: **volt. gated Na^+ ch. open (Na^+ : in)**
- 2: **volt. gated K^+ ch. open (K^+ : out)**
- 3: **Na^+ ch. inactivation (partial)**
- 4: **Na^+ channel closure**
- 5: **K^+ channel closure (delayed)**



Properties of the action potential #1

Unaltered ion concentration: the transported ions diffuse away far from the membrane. During the AP only the permeability changes (GHK).

Refractory period: the cell is not excitable.

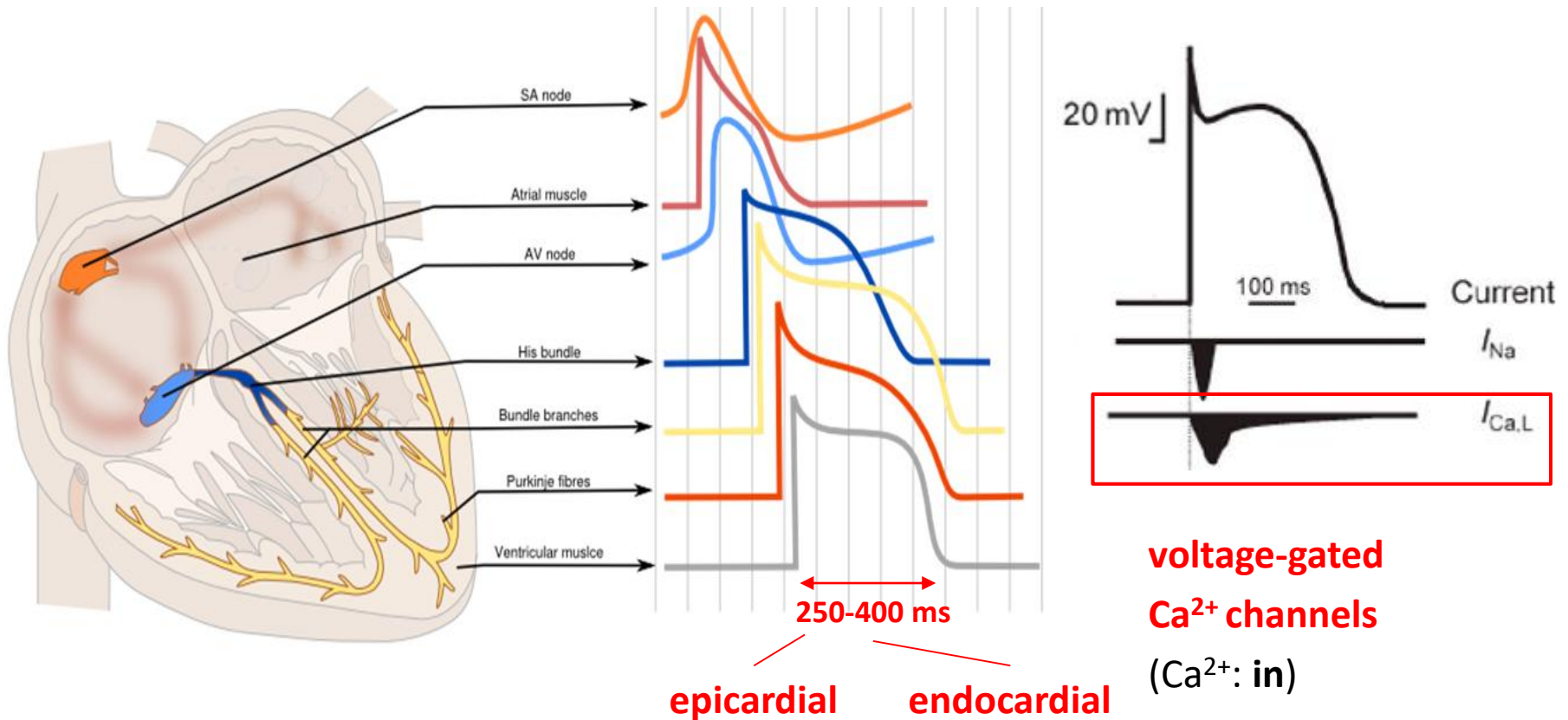


- **absolute:** voltage-gated Na^+ channels are inactivated (infinite threshold)
- **relative:** AP with supra-threshold stimulus
Reopening of the closed voltage-gated Na^+ channels.

prevents the backpropagation of action potential

Properties of the action potential #2

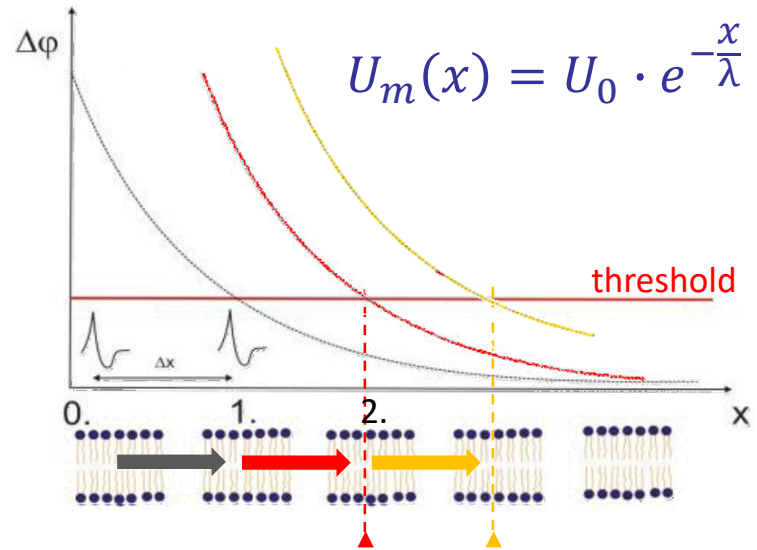
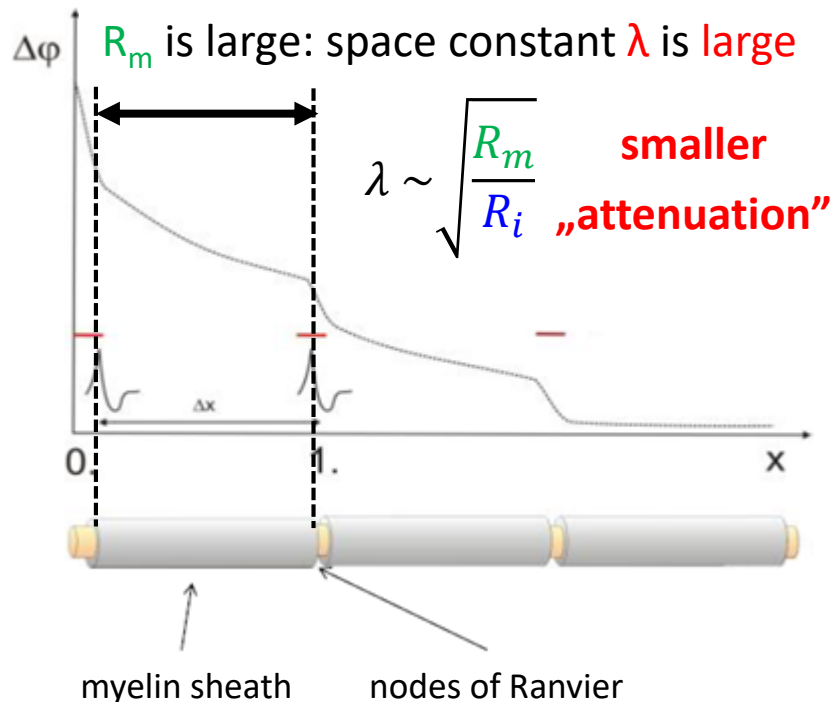
Special action potential: ventricular cardiomyocytes



The propagation of the action potential

Properties:

- AP shape is independent from stimulus
- propagates far without attenuation
- much faster than hormonal response



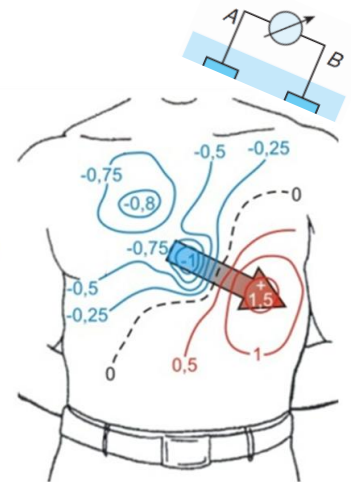
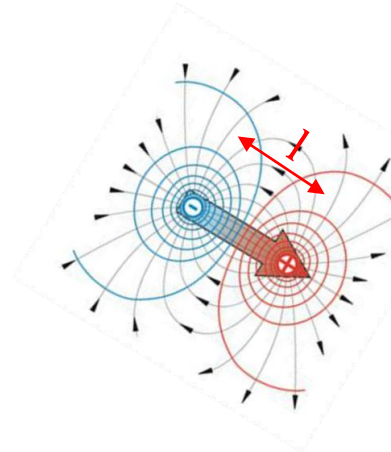
fiber	diameter (μm)	Speed (m/s)
α	15	70-120
β	8	30-70
γ	5	15-30
δ	<3	12-30
No sheath	<1	0.5-2

Medical application of bioelectric phenomena

Electric signals on the body surface (diagnostics):

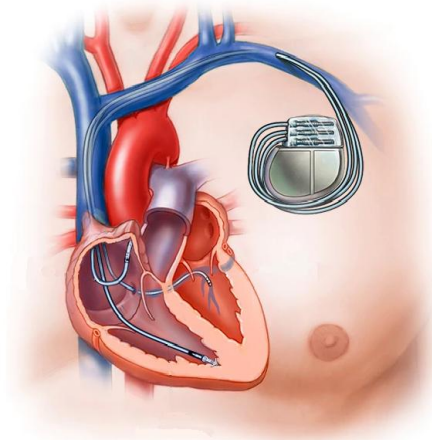
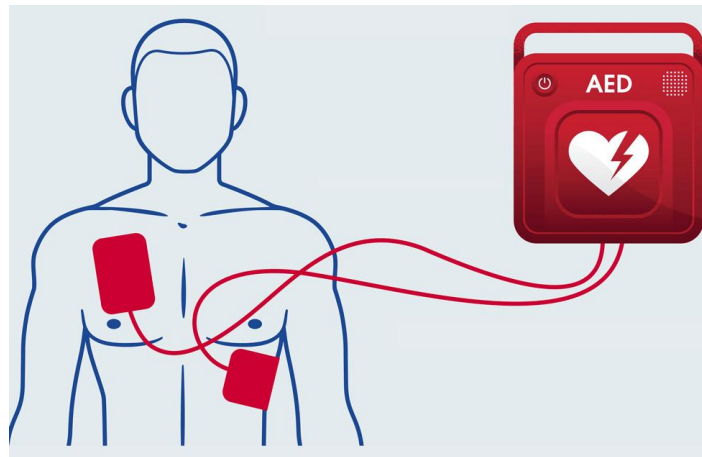
- **Electrocardiography (ECG)**
- Electroencephalography (EEG)
- Electromyography (EMG)
- Electrooculography (EOG)
- Electroretinography (ERG)

Origin:
dipole-
moment:
 $d = Q \cdot l$



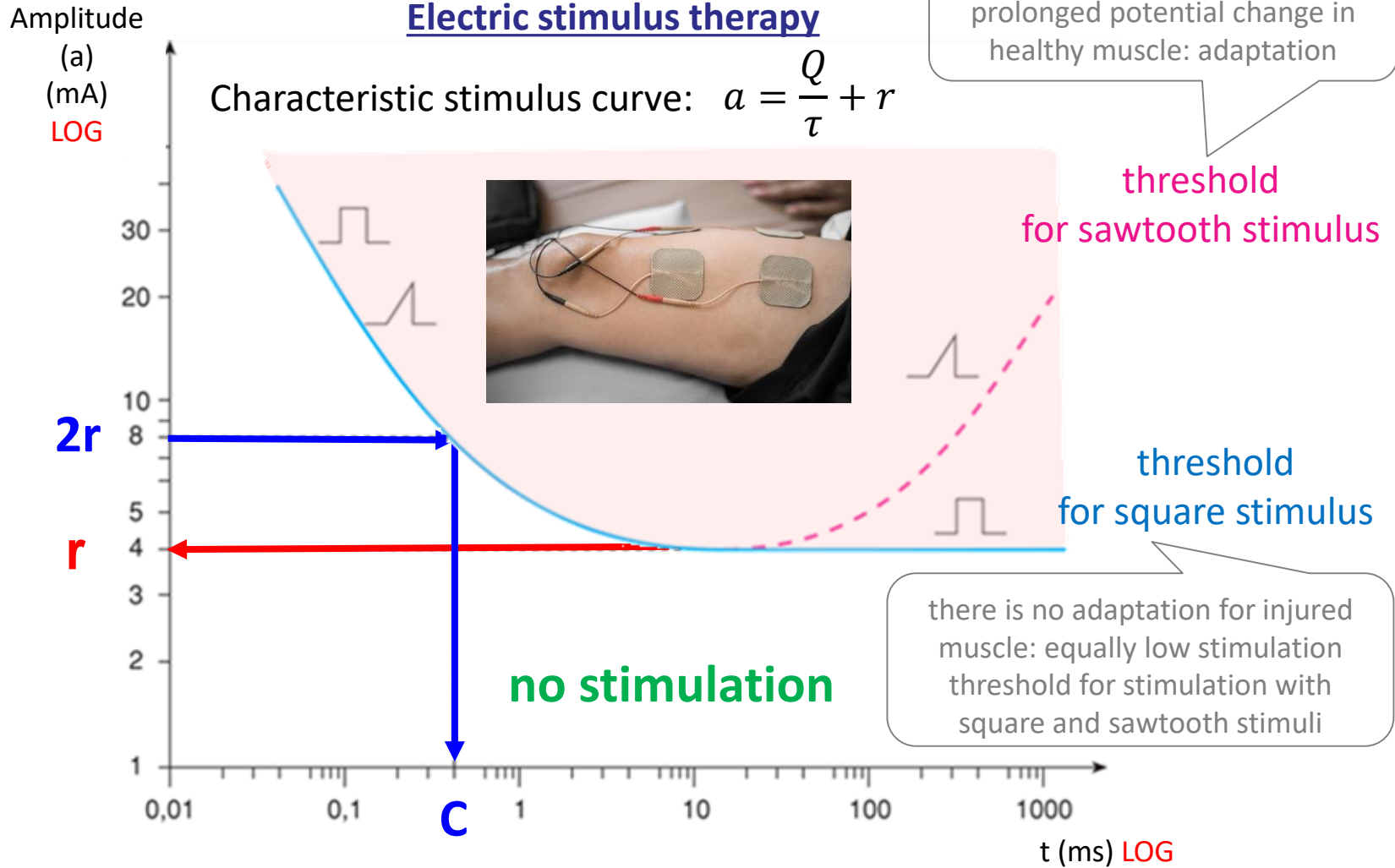
Electric stimulation (therapy):

- Galvanic treatment (DC)
- Iontophoresis (DC)
- HF-thermotherapy (AC)
- Electric surgery (AC)
- **Electric stimulus therapy (pulse)**
- **Defibrillator (pulse)**
- **Pacemaker (pulse)**



Pulse therapy

Electric stimulus therapy



- **rheobase (r):** minimal electric current that elicits (muscle) stimulation
- **chronaxie (C):** time to 2x rheobase

FEEDBACK

THANK YOU!