میدان‌ها در حضور بدن

جلسه سیزدهم

درس بیوالکترومغناطیس

دکتر مهرداد ساویز

دو روش بیان خواص الکتریکی ماده

گذردهی مختلط

$$\varepsilon_{rc}{}' = \varepsilon_r{}'$$

$$\varepsilon_{rc}{}'' = \varepsilon_r{}'' + \frac{\sigma_i}{\omega\varepsilon_0}$$

تابع فرکانس

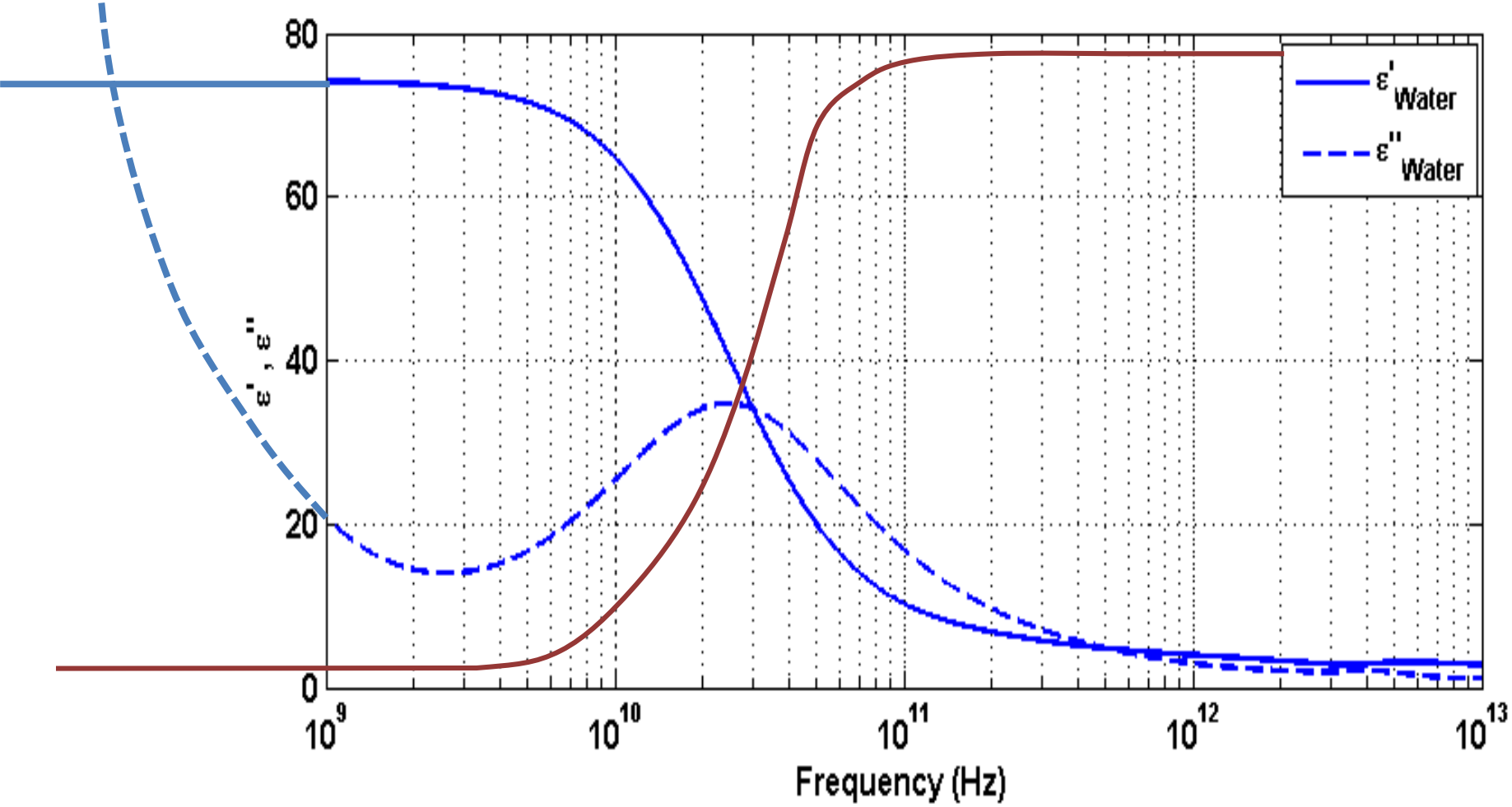
$$\varepsilon_{rc}{}' = \varepsilon_r{}'$$

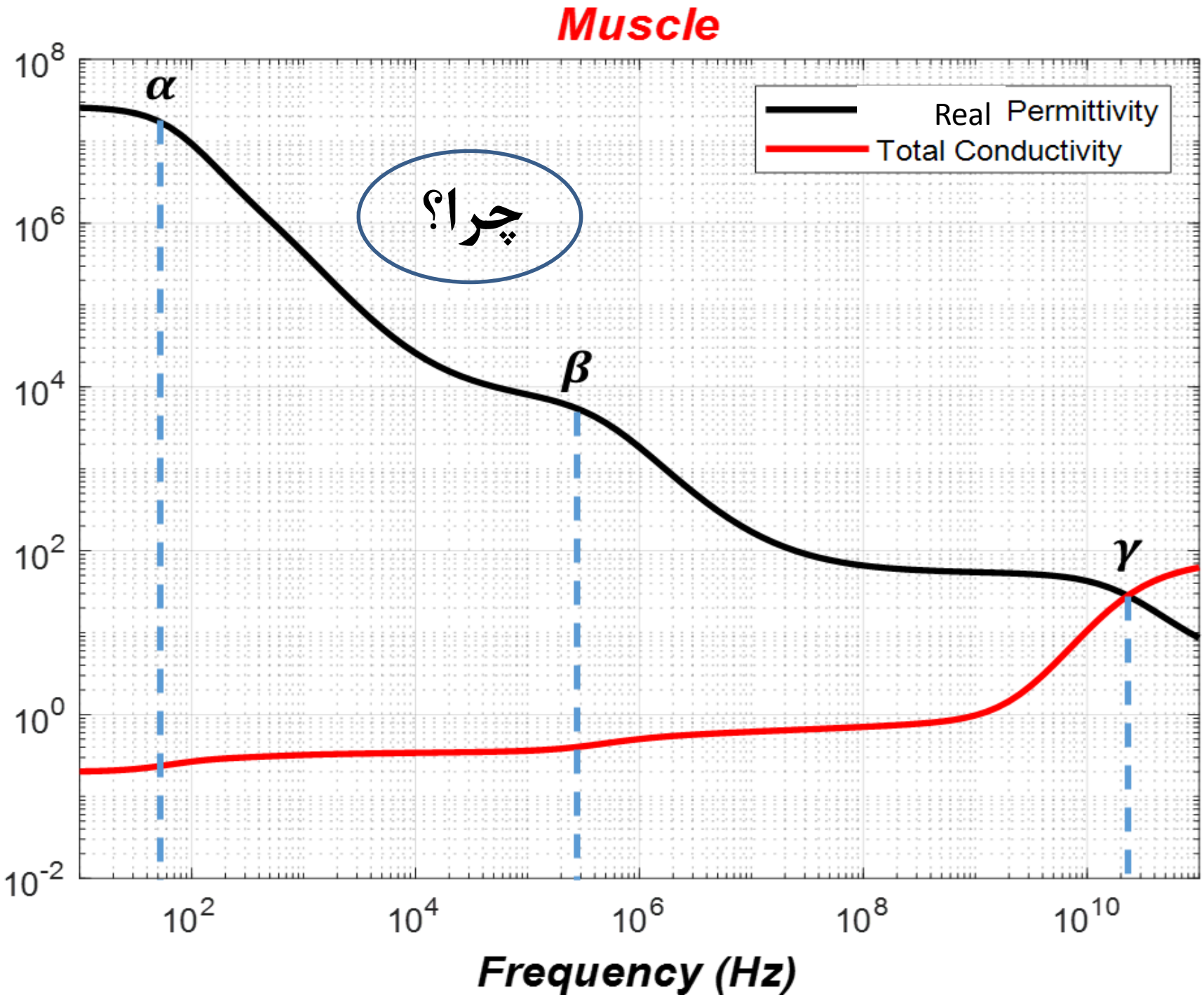
$$\sigma_{tot} = \omega\varepsilon_0\varepsilon_r{}'' + \sigma_i$$

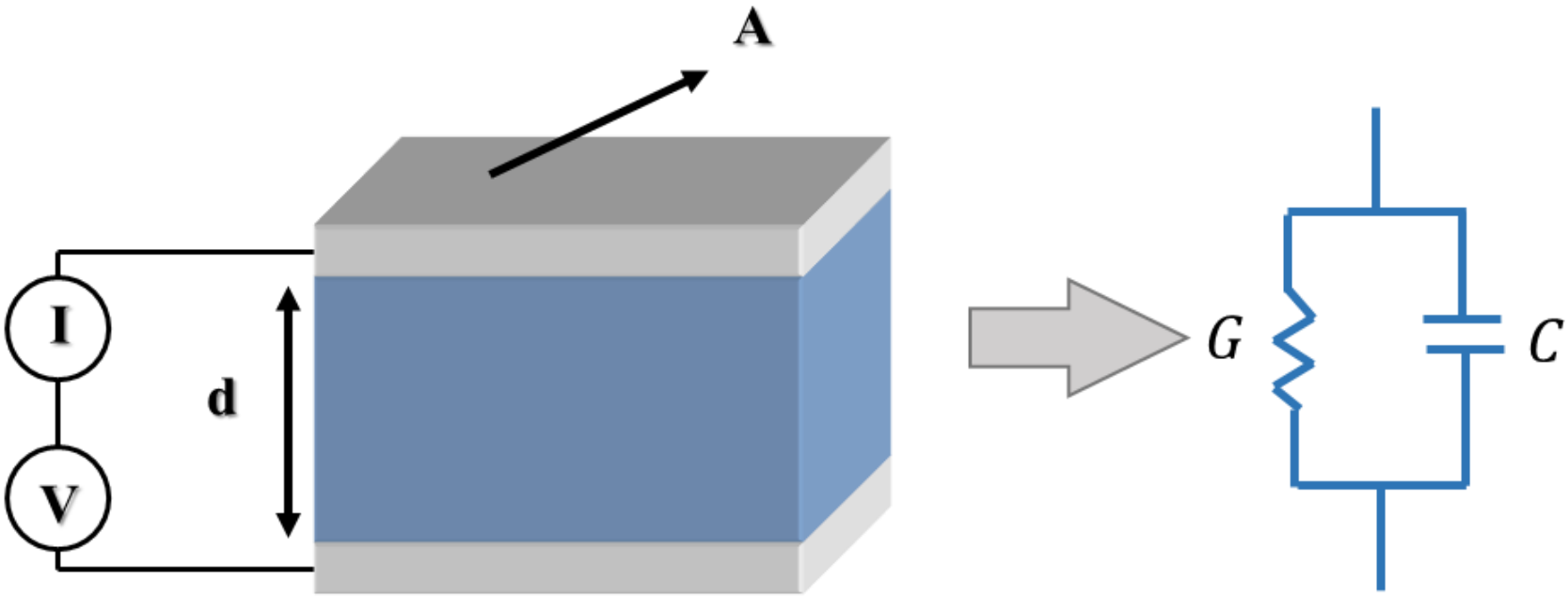
خواص آب دارای املاح از دو منظر

$$\varepsilon_{rc}'' = \varepsilon_r'' + \frac{\sigma_i}{\omega\varepsilon_0}$$

$$\sigma_{tot} = \omega\varepsilon_0\varepsilon_r'' + \sigma_i$$




Muscle
Real Permittivity
Total Conductivity
چرا؟
α
β
γ
10^8
10^6
10^4
10^2
10^0
10^{-2}
10^2
10^4
10^6
10^8
10^{10}
Frequency (Hz)



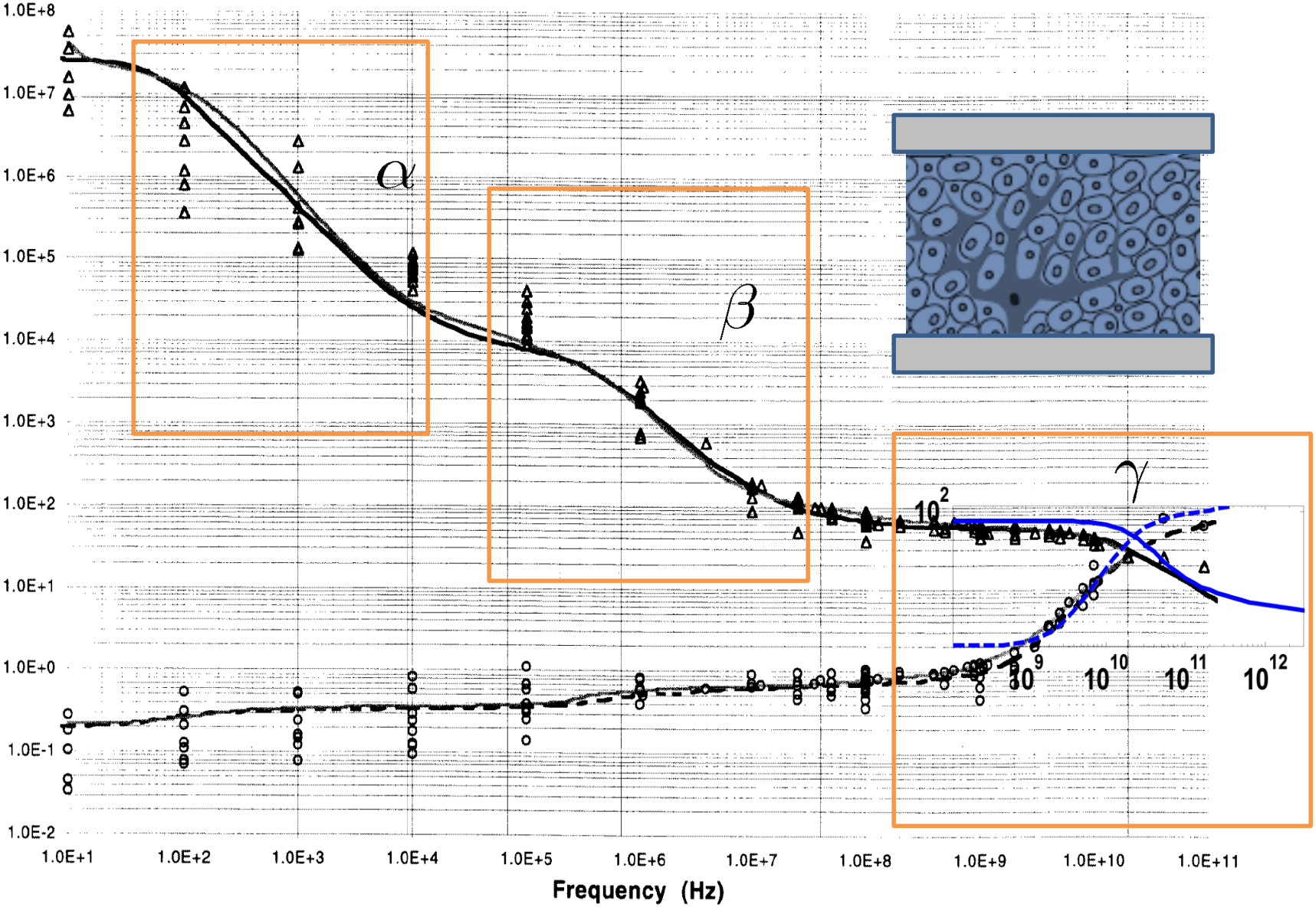
$$Y_{means} = \frac{I}{V} = G_{means} + j\omega C_{means}$$

$$= \frac{A}{d}[\sigma_{tot} + j\omega\varepsilon_0\varepsilon_{rc}']$$

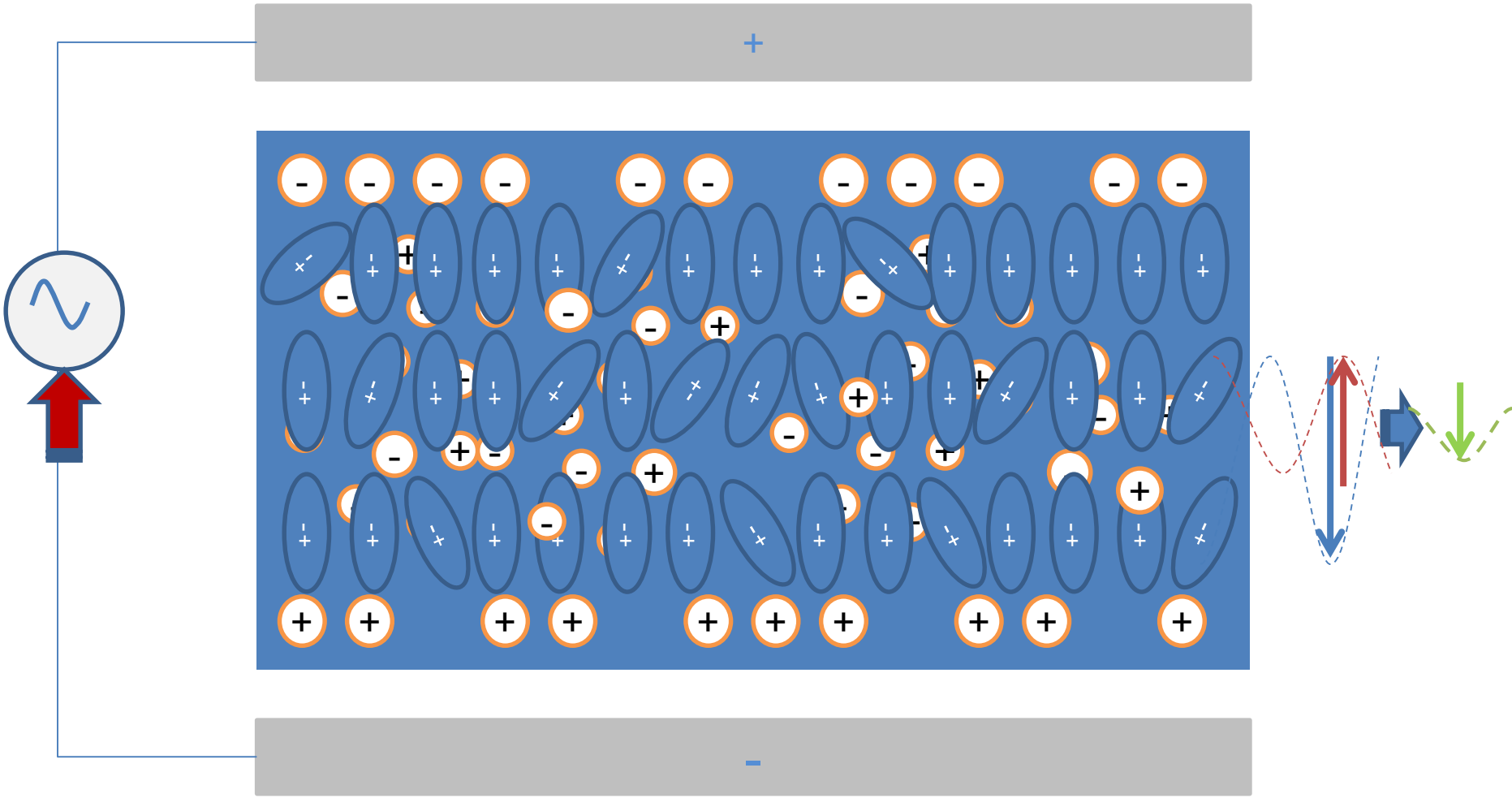
$$= j\omega\varepsilon_0\frac{A}{d}\left[\varepsilon_{rc}' + \frac{\sigma_{tot}}{j\omega\varepsilon_0}\right]$$

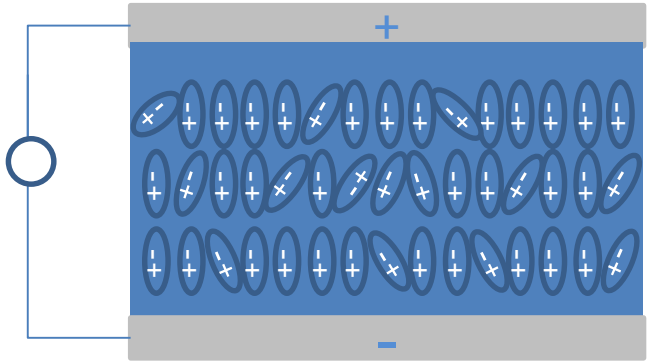
$$= \frac{A}{d}j\omega\varepsilon_0\varepsilon_{rc}^{meas}$$

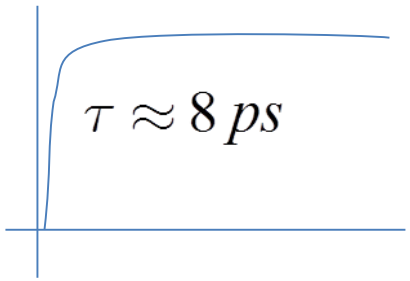
خواص الکتریکی بافت‌های زیستی

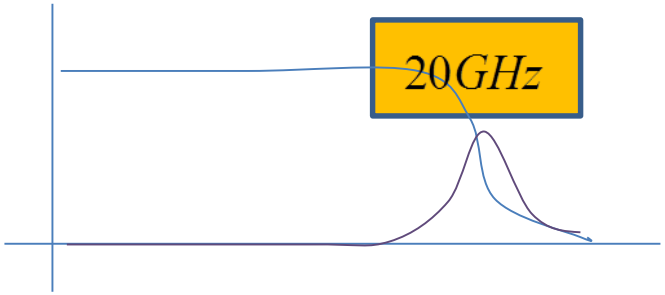


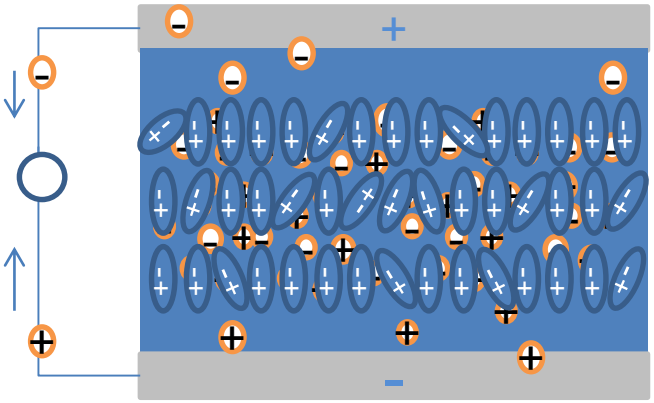
S Gabriel, R W Lau, and C Gabriel, "The dielectric properties of biological tissues: III," *Phys. Med. Biol.*, vol. 41, pp. 2271-93, 1996.



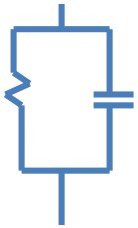


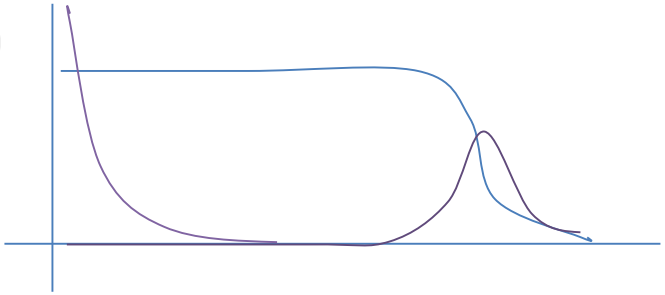


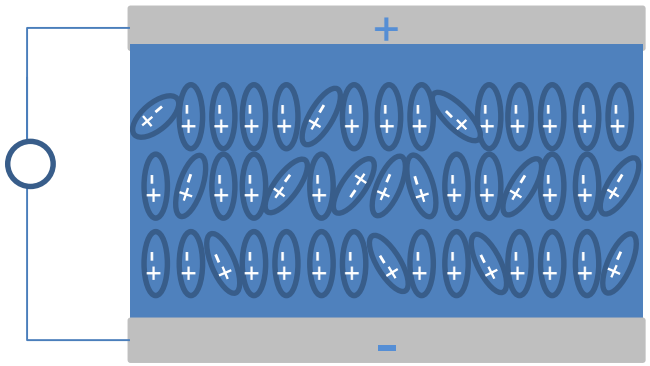


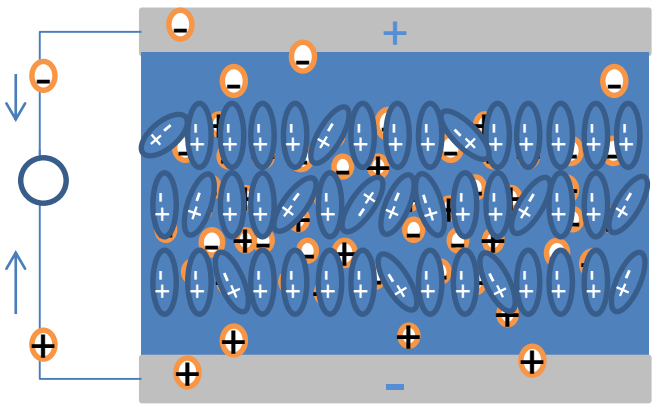


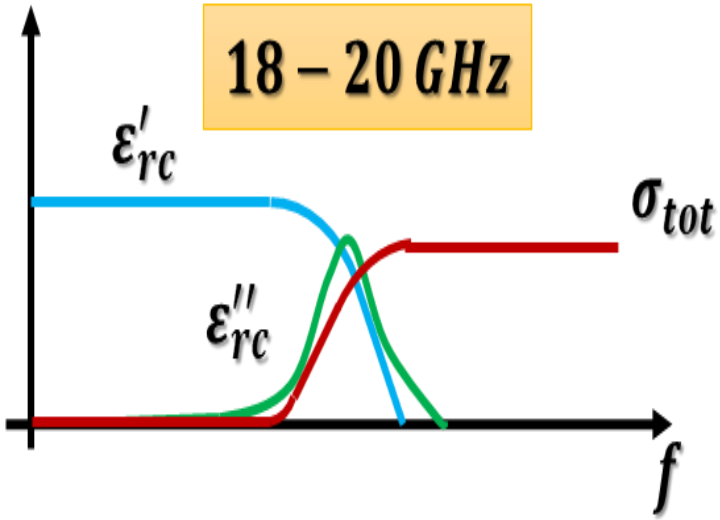
$$Y = j\omega\varepsilon_0 \frac{A}{d}\left(\varepsilon'_{rd} - j\frac{\sigma_{tot}}{\omega\varepsilon_0}\right)$$

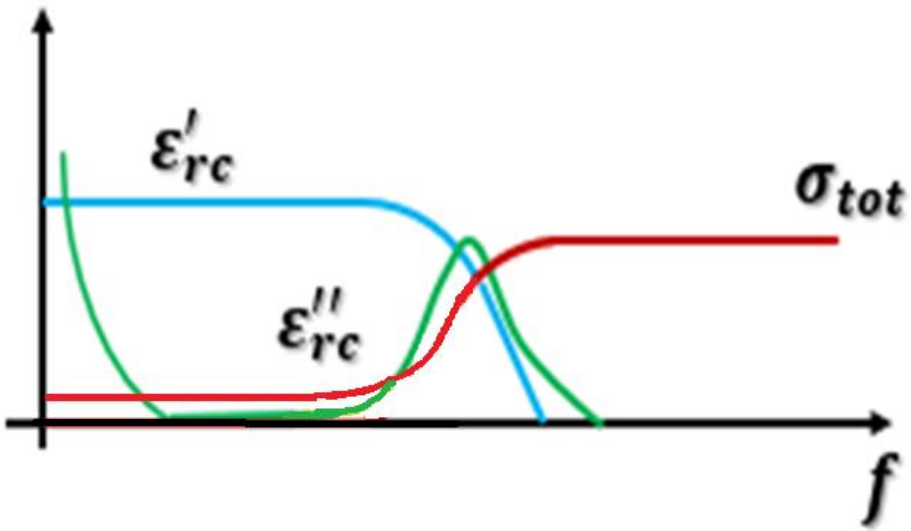


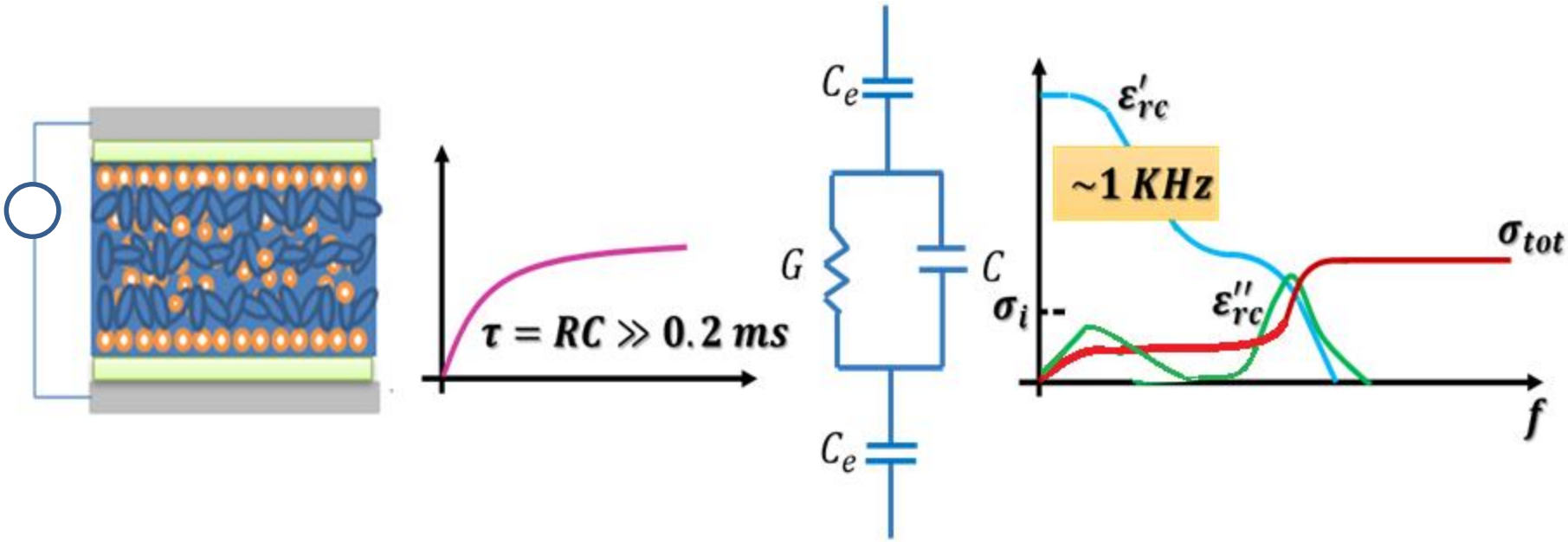


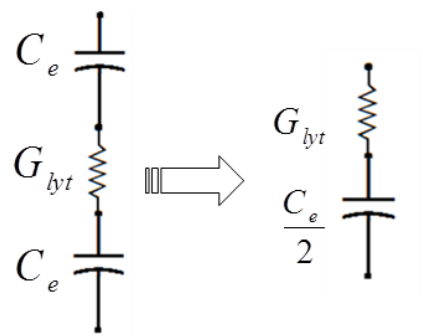

+
-


+
-


18 – 20 GHz
ε'_{rc}
σ_{tot}
ε''_{rc}
f


ε'_{rc}
σ_{tot}
ε''_{rc}
f



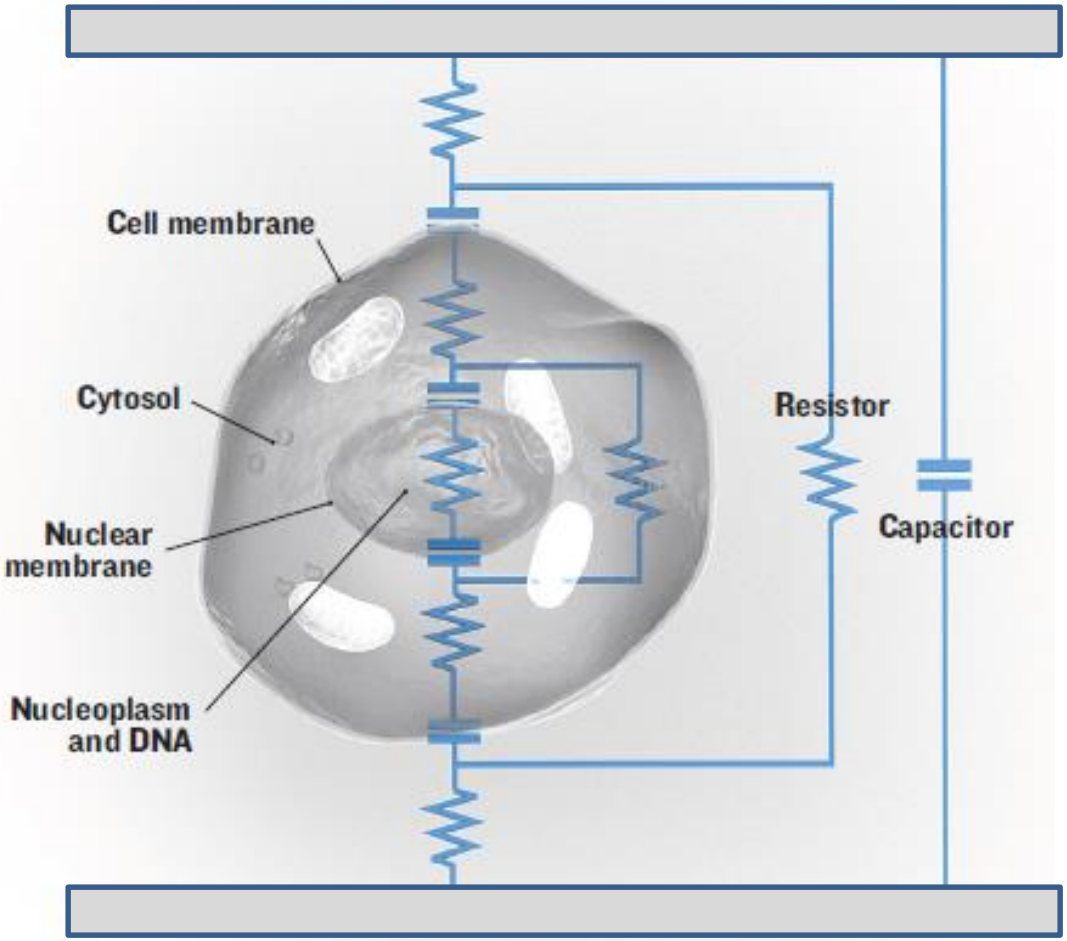


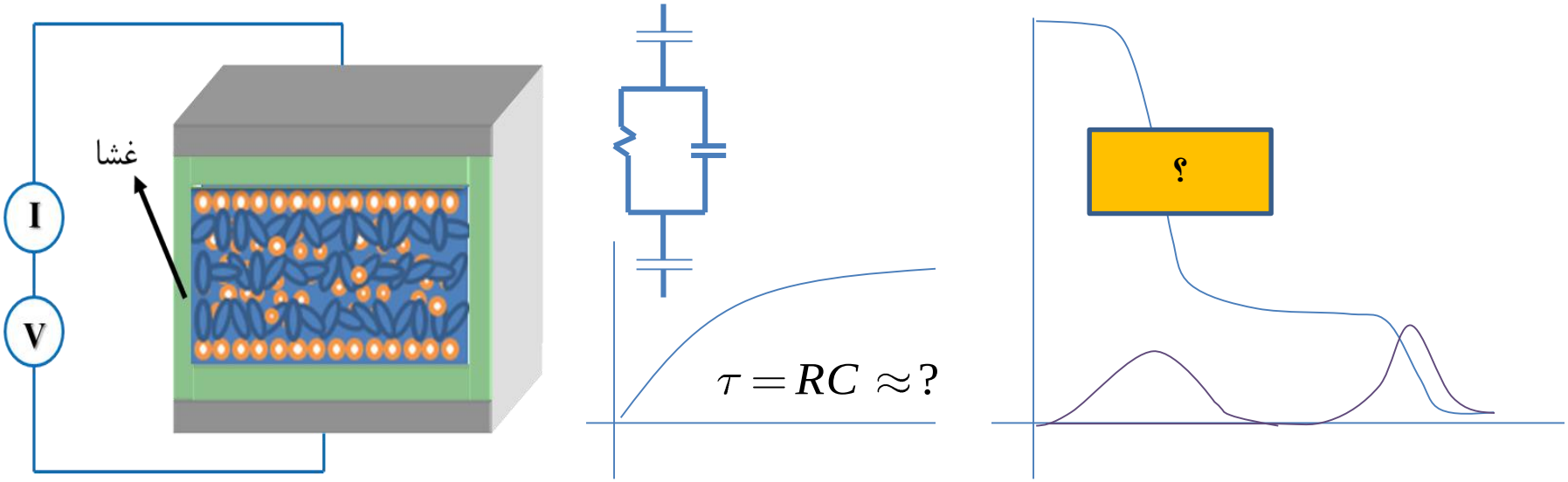
$$R_{lyt} = \frac{1}{\sigma_{lyt}} \frac{d}{A} \quad , \quad C_e = \varepsilon_0 \frac{A}{\delta}$$

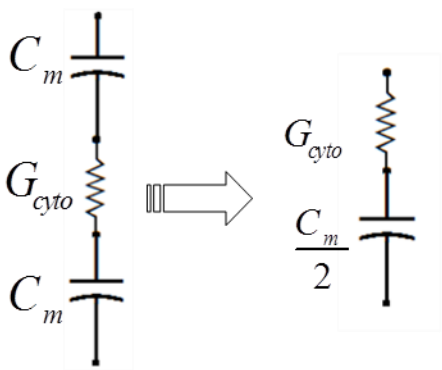
$$\tau = R_{lyt} \frac{C_e}{2} = \frac{8.85 \times 10^{-12}}{1 \times 2} \frac{10^{-2}}{10^{-9}} \approx 4 \times 10^{-5}\ \mathrm{s} = 40\ \mu s$$

$$\omega_{relax} = \tau^{-1}$$

درک رفتار فرکانسی محیط سلّولی





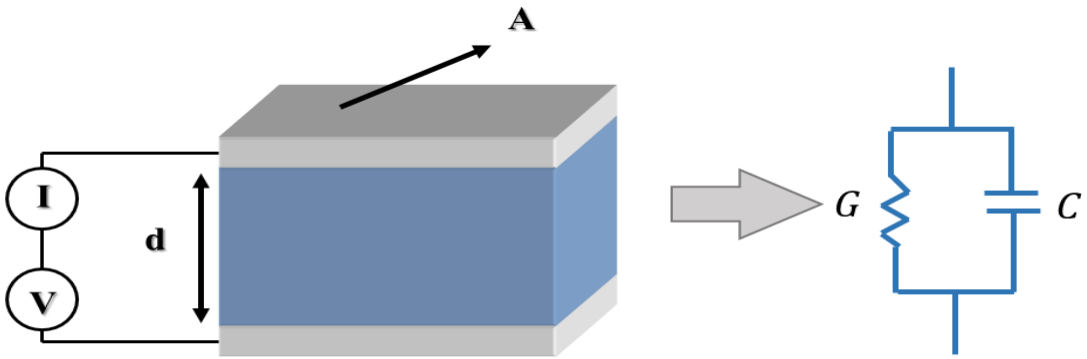


$$R_{cyto} = \frac{1}{\sigma_{cyto}} \frac{d_{cyto}}{A} \quad , \quad C_m = \varepsilon_0 \varepsilon_m \frac{A}{d_m}$$

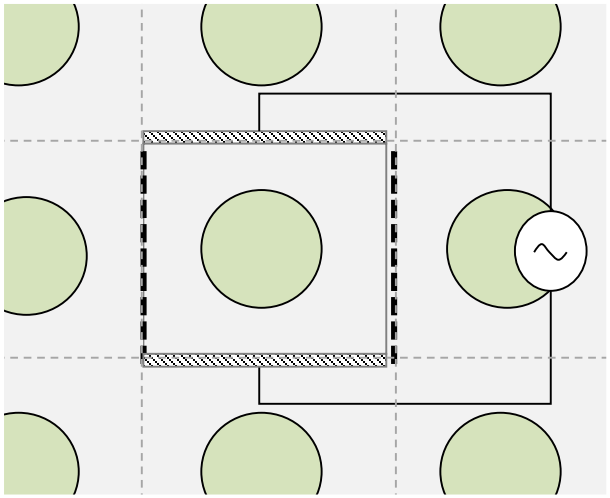
$$\tau = R_{cyto} \frac{C_m}{2} = \frac{8.85\times10^{-12}\times9}{0.2\times2} \frac{10^{-5}}{5.5\times10^{-9}} \approx 4\times10^{-7}\,\mathrm{s} = 0.4\,\mu s$$

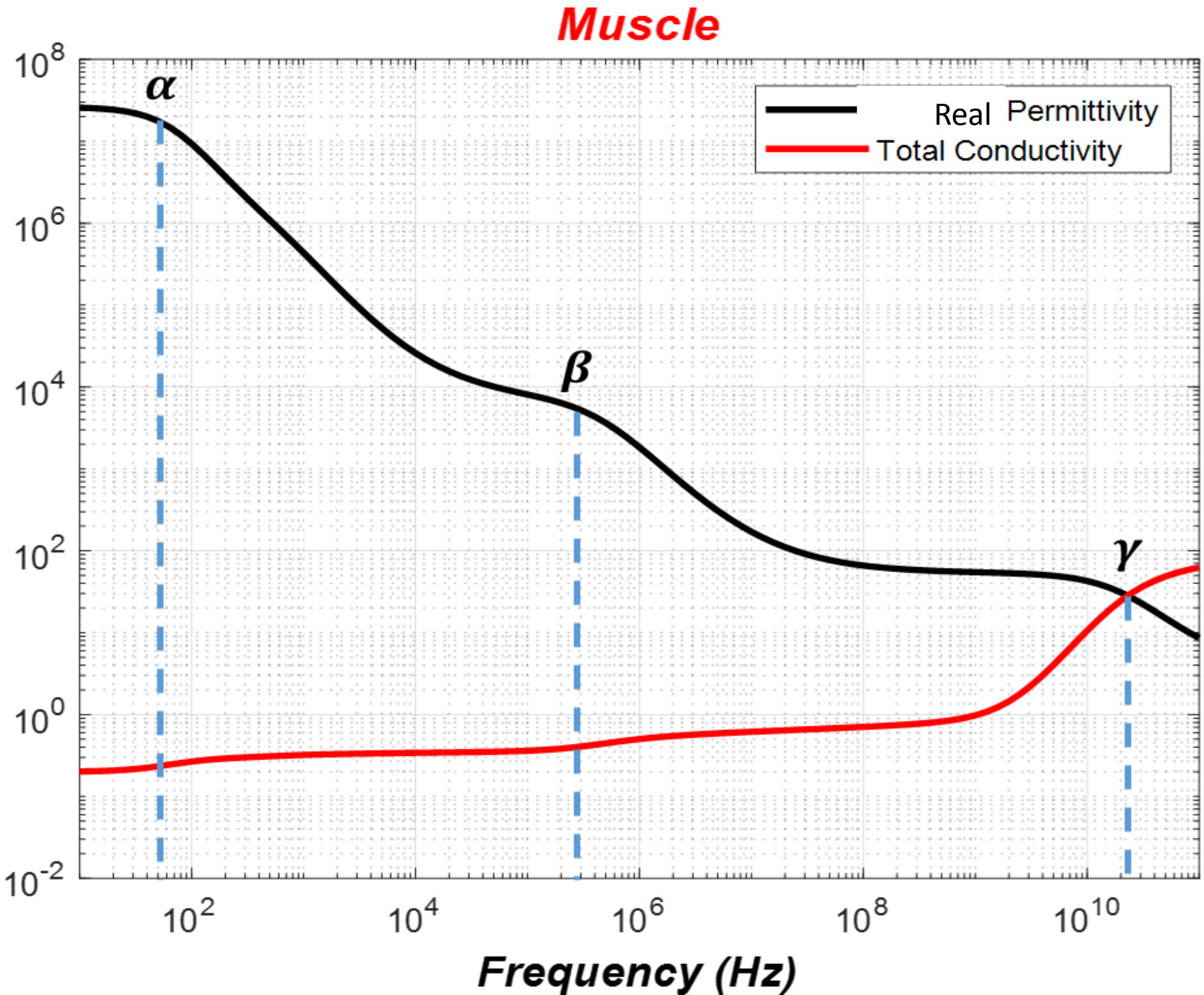
$$\omega_{relax} = \tau^{-1} = 2\pi f_{\beta}$$

استخراج خواص بر مبنای دوره تناوب



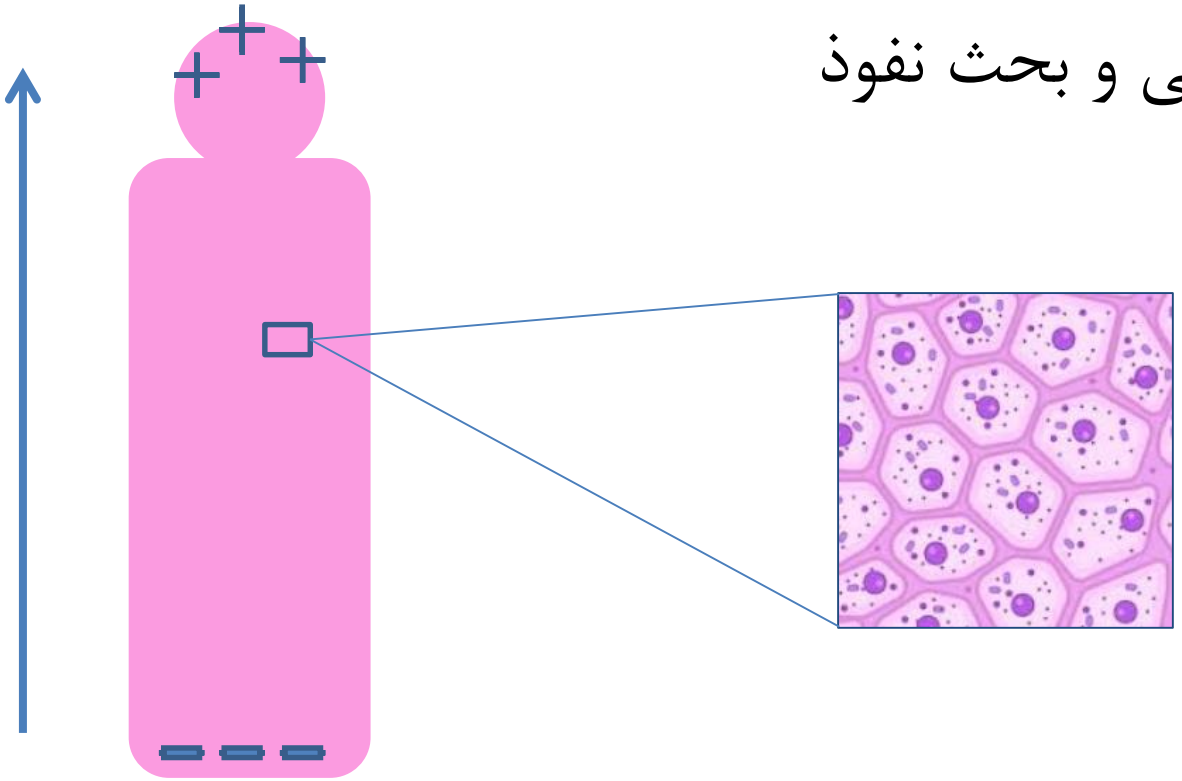
$$Y_{means} = \frac{I}{V} = G_{means} + j\omega C_{means}$$



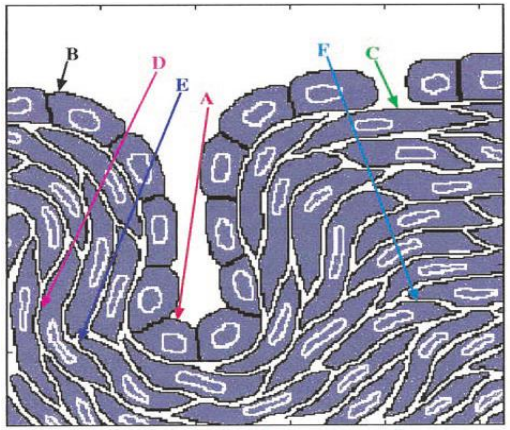

Muscle
Real Permittivity
Total Conductivity
α
β
γ
10^8
10^6
10^4
10^2
10^0
10^{-2}
10^2
10^4
10^6
10^8
10^{10}
Frequency (Hz)

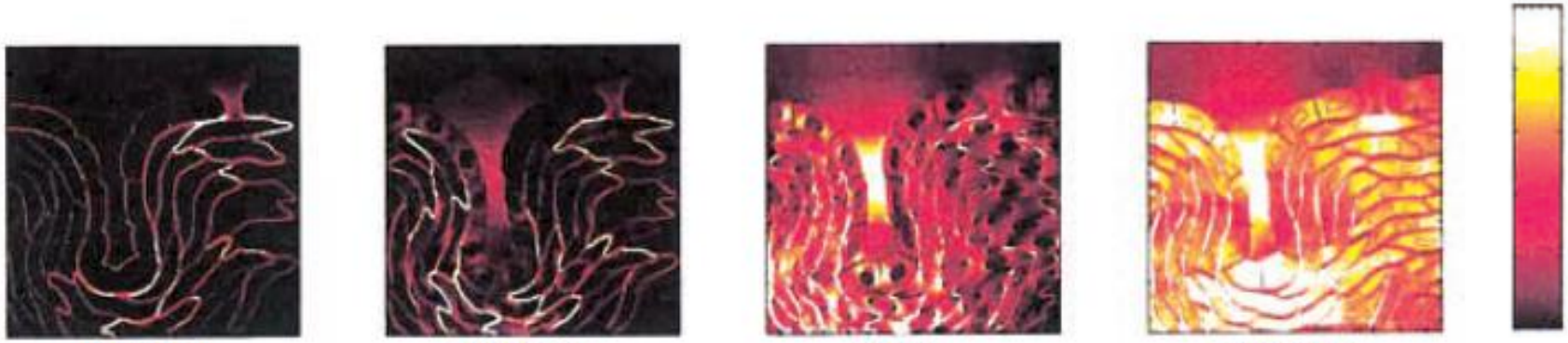
تامل: از دید تعریف گذردهی ε_{rc}

- تقریب بافت متراکم
- کاهش میدان در حجم
- فضای بین سلولی و بحث نفوذ



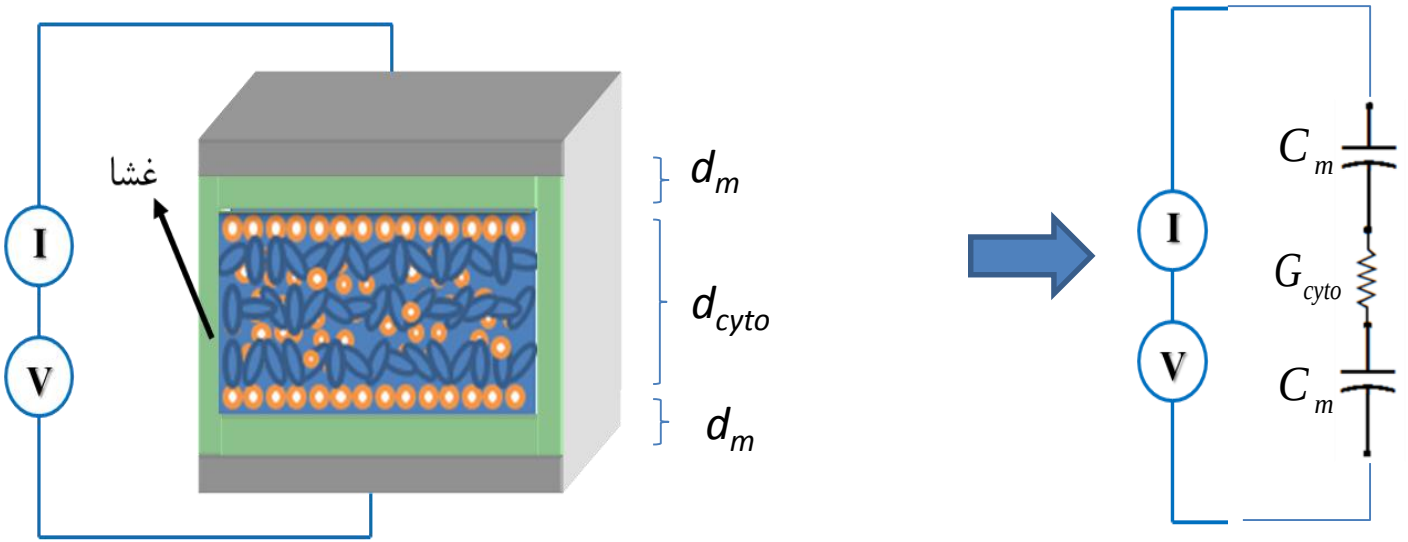
در مقیاس میکرو: تقویت غشایی (بهره غشا)





100 Hz 100 kHz 1MHz 10 MHz

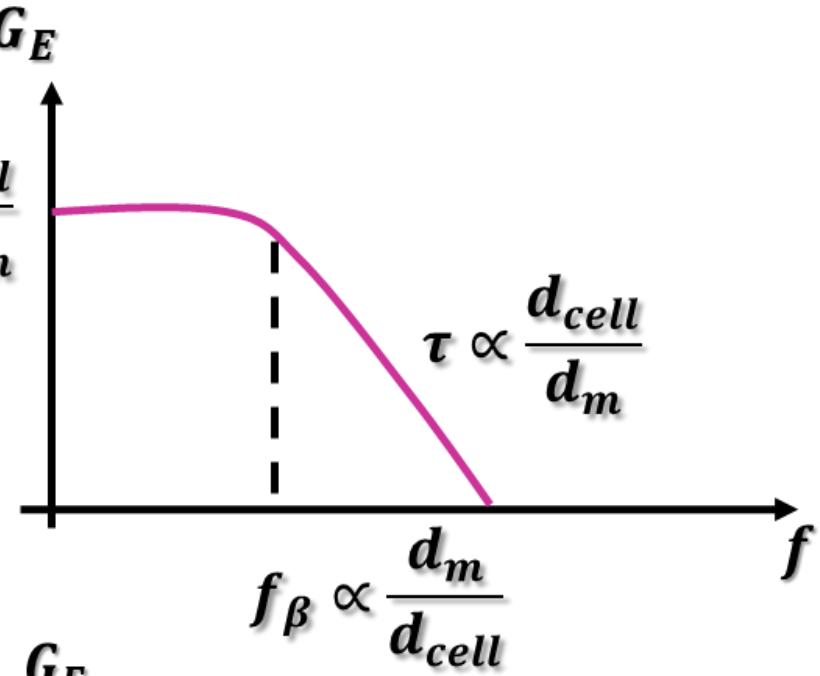
محاسبه بهره غشا



$$G_E = \frac{\dfrac{Z_m I}{d_m}}{\dfrac{(2Z_m + Z_{cyto})I}{2d_m + d_{cyto}}} = \frac{\dfrac{d_m}{\varepsilon_{rm}}}{\dfrac{2d_m}{\varepsilon_{rm}} + \dfrac{d_{cyto}}{\varepsilon_{rcyto}}} \frac{2d_m + d_{cyto}}{d_m} = \frac{\left(\dfrac{d_{cyto}}{2d_m}\right)}{1 + \left(\dfrac{d_{cyto}}{2d_m}\right)\left(\dfrac{\varepsilon_{rm}}{\varepsilon_{rcyto}}\right)}$$

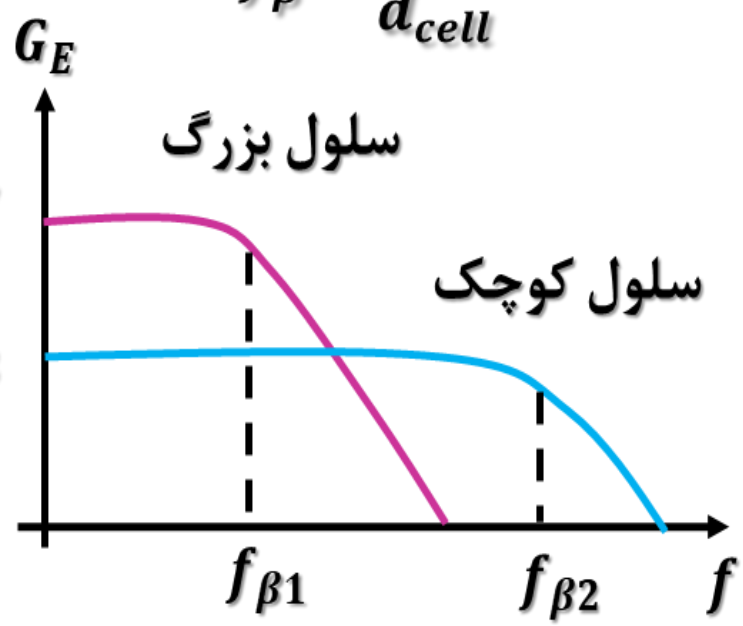
$$G_E = \frac{G_0}{1 + j\omega\tau}$$

$$\frac{G_0}{\sqrt{1+\omega^2\tau^2}} \propto \frac{d_{cell}}{2d_m}$$

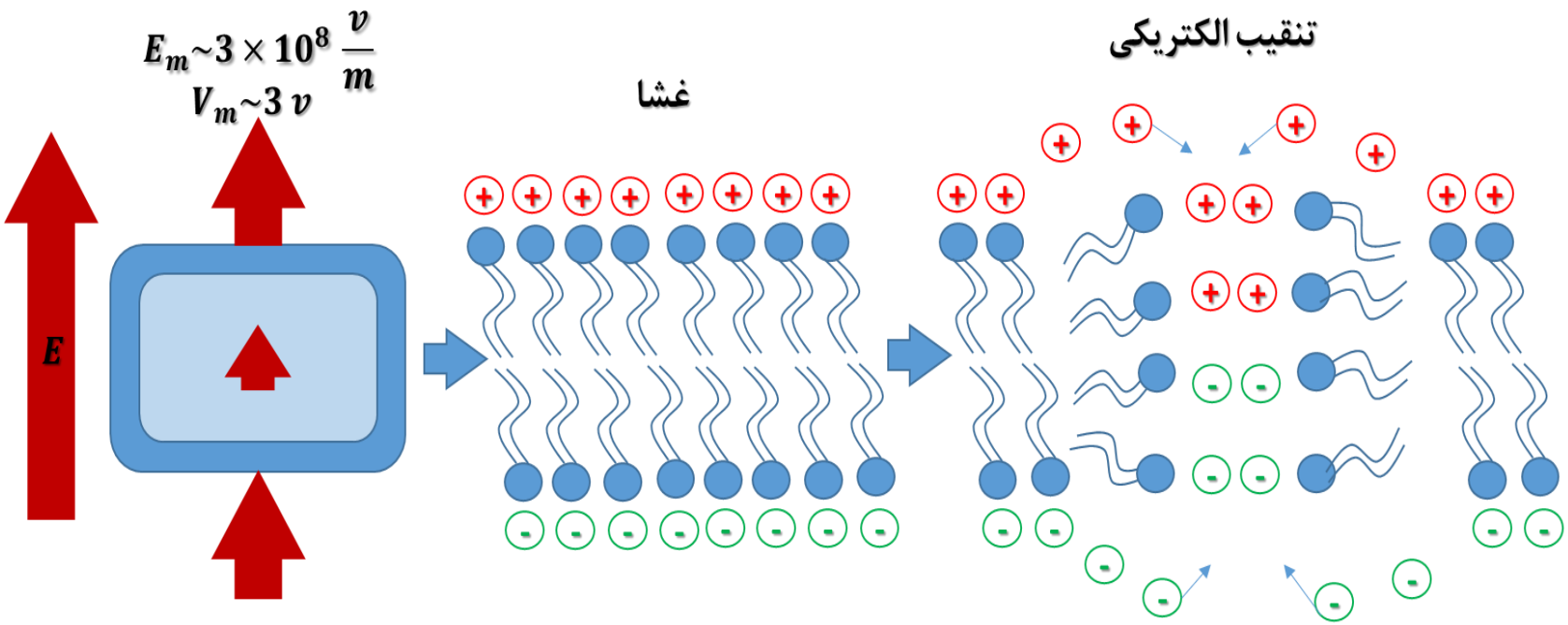


$$\propto \frac{1\,m}{2\times10^{-8}m} \sim 5\times10^{7}$$

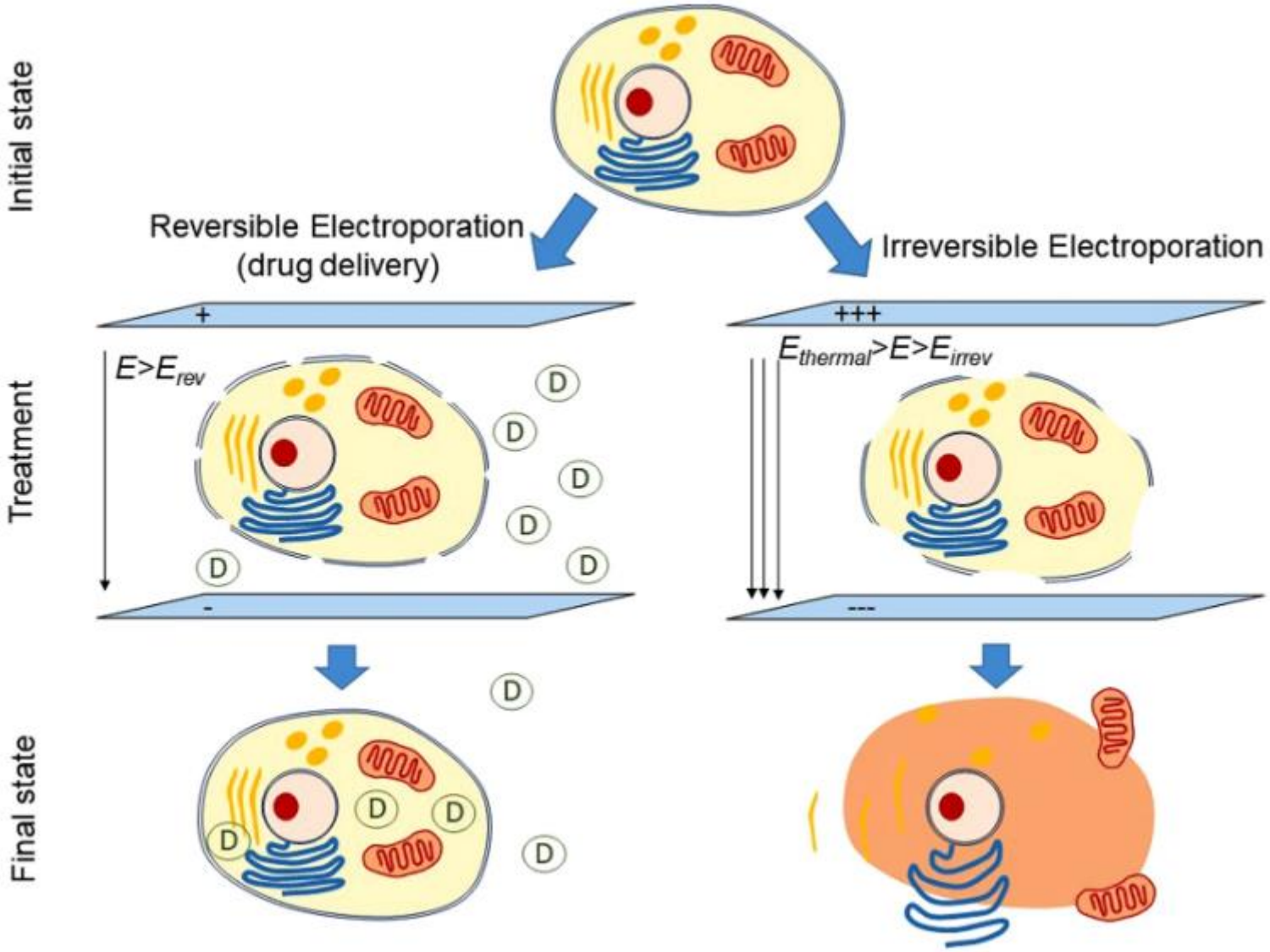
$$\propto \frac{10^{-5}\,m}{2\times10^{-8}m} \sim 5\times10^{2}$$



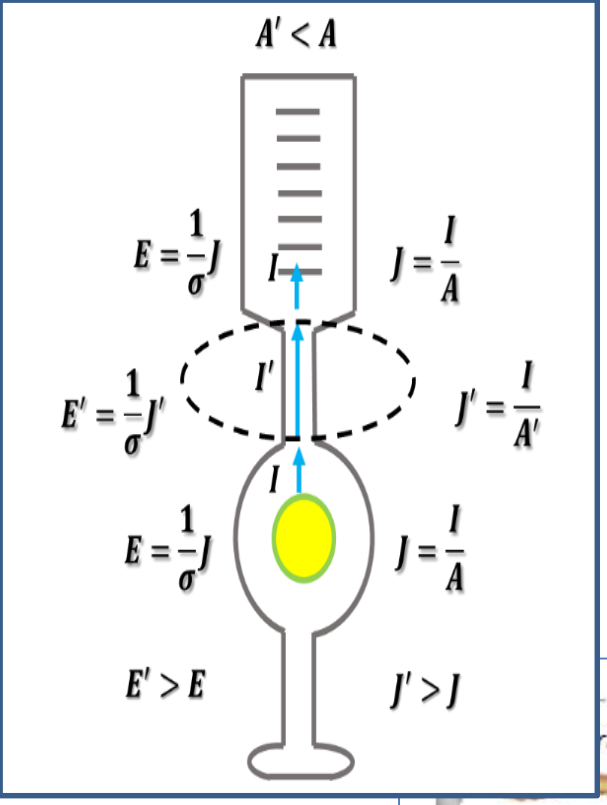
کاربرد تهاجمی: تنقیب الکتریکی
Electroporation

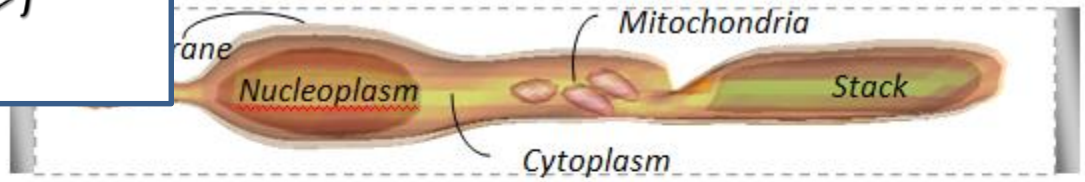


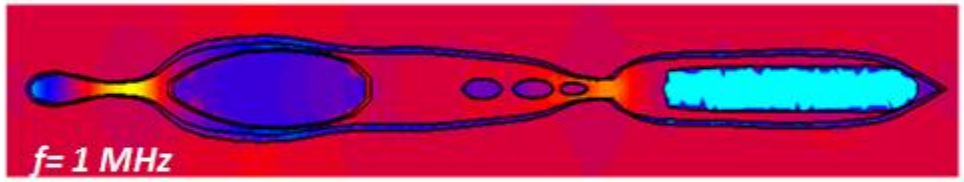
تنقیب الکتریکی

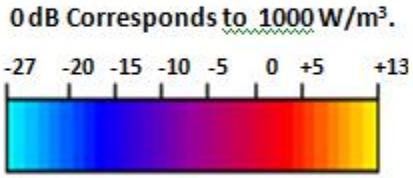


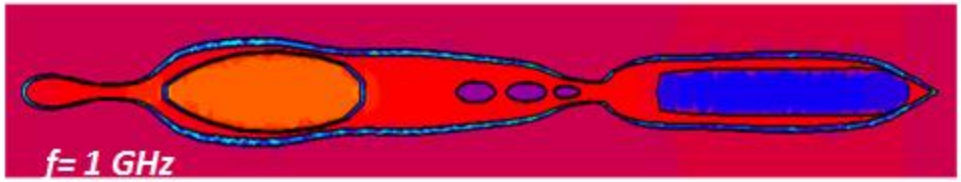
در مقیاس میکرو: تقویت گلوگاهی

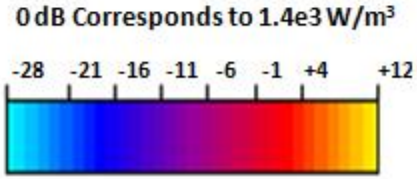




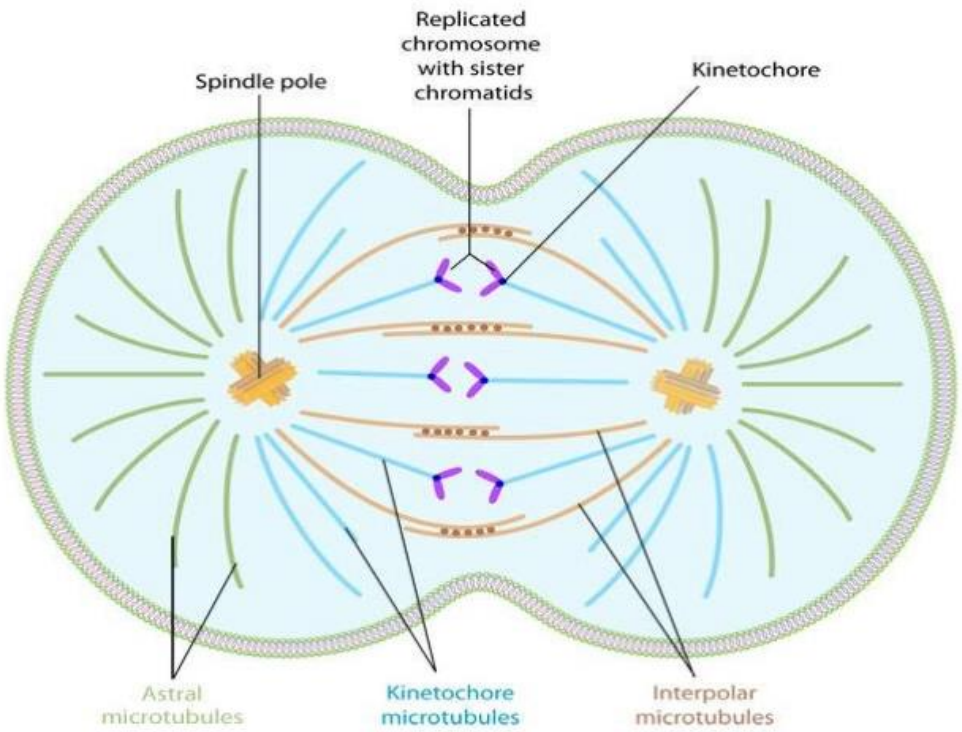


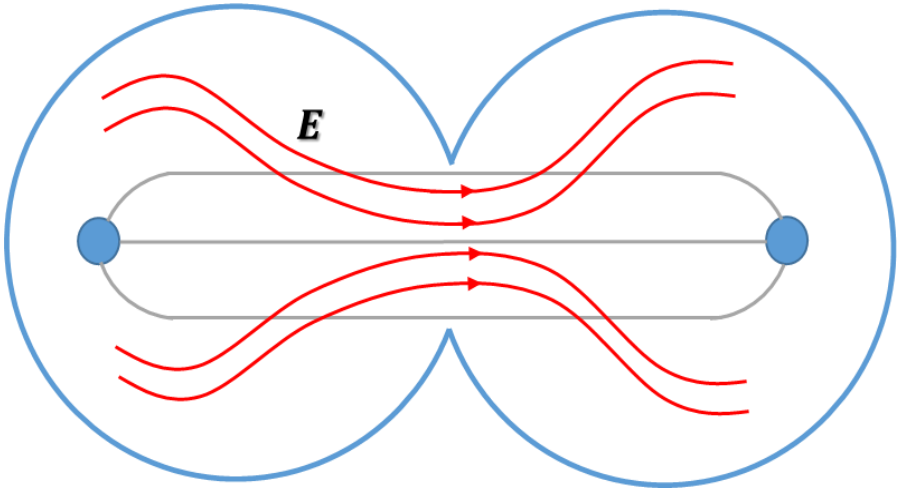






یک کاربرد: جلوگیری از تشکیل دوک میتوزی





خواص محلول‌های زیستی

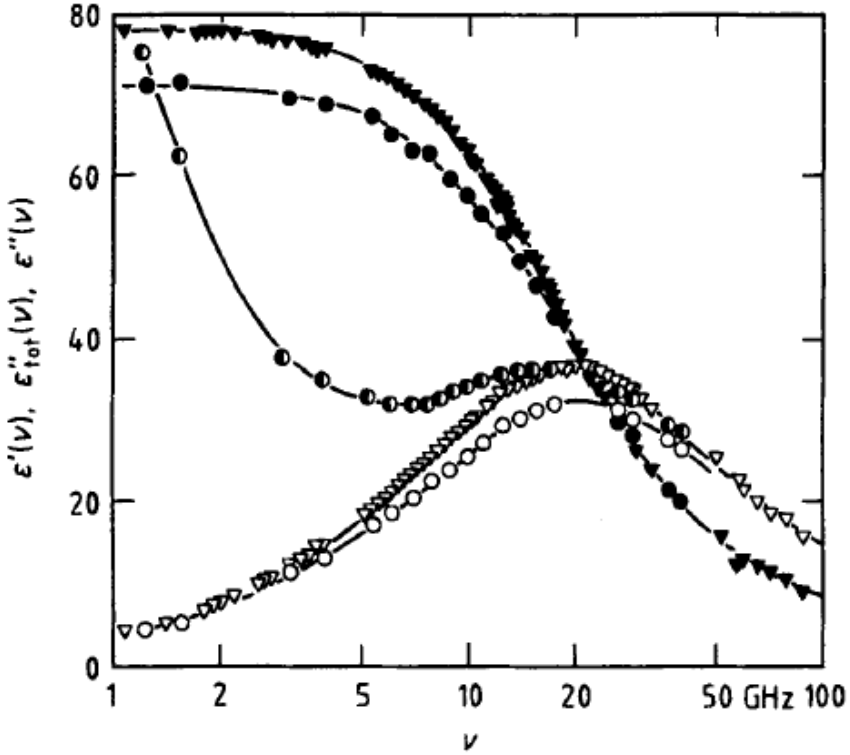
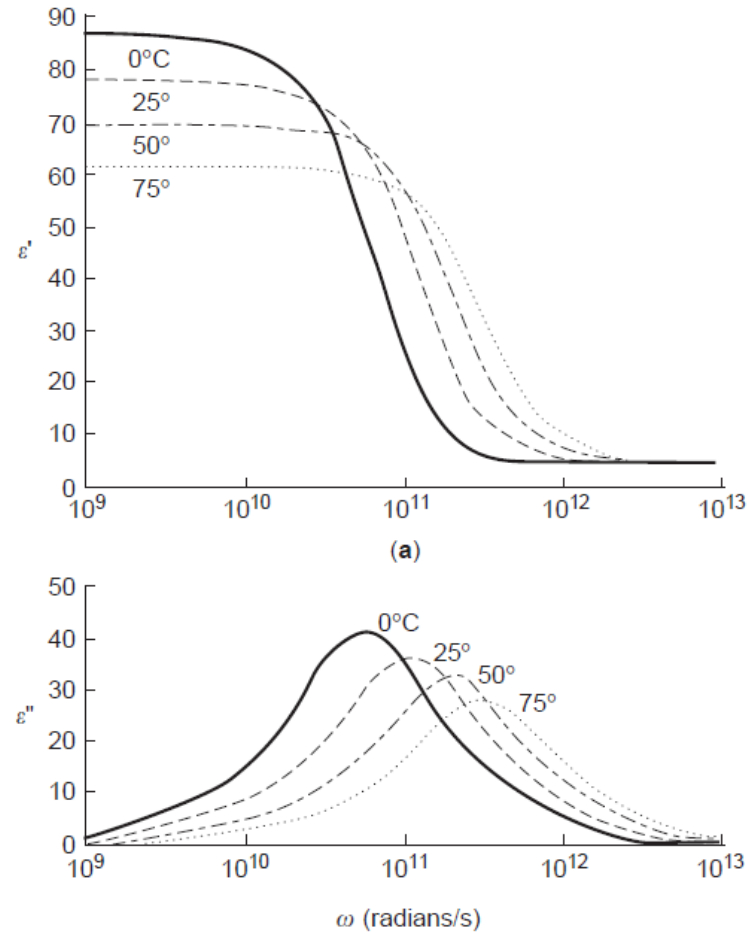
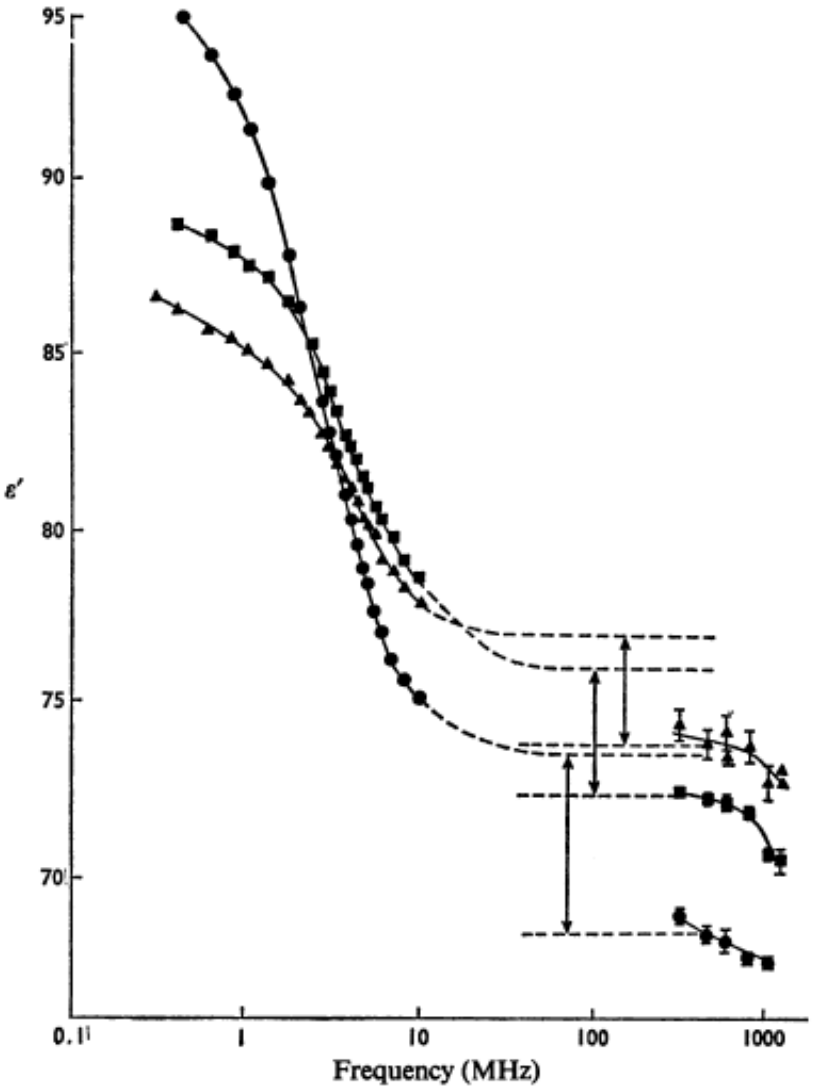


Fig. 23. Complex dielectric spectra for water (triangles) and for a 0.5 molar aqueous solution of sodium chloride (circles) at 25°C. Filled symbols refer to $\epsilon'(\nu)$, open symbols to $\epsilon''(\nu)$. Half-filled circles show the total loss $\epsilon''_{tot}(\nu)$ of electrolyte solution (Ref. 163).



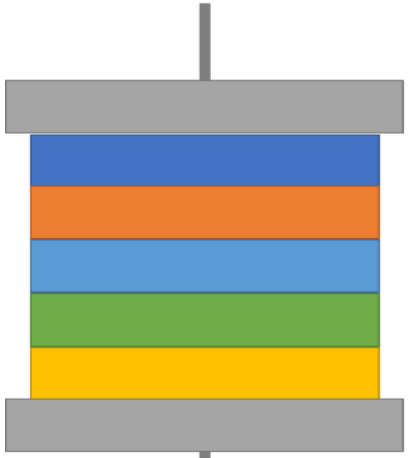
خواص محلول‌های زیستی

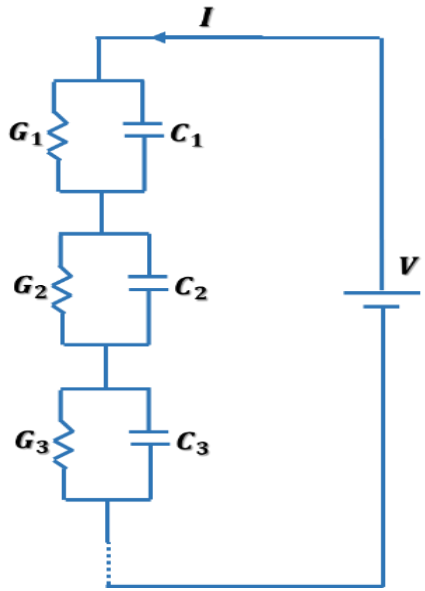


. *Experimental dispersion curve for myoglobin solutions of concentrations* 7.7% (▲), 9.9% (■) *and* 16.1% (●)
The points below 10 MHz were obtained by interpolation of previously published data (South, 1970).

قواعد ترکیب لایه‌ای

ترکیب سری



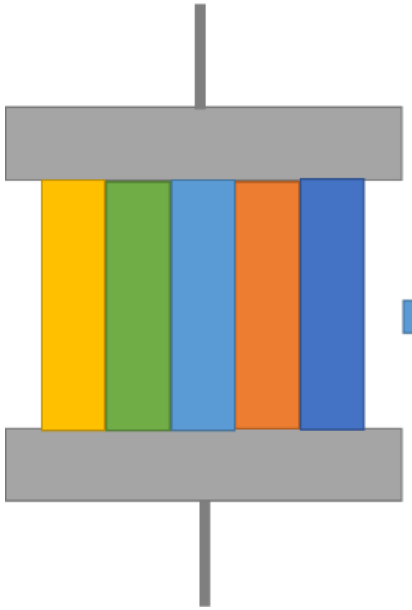


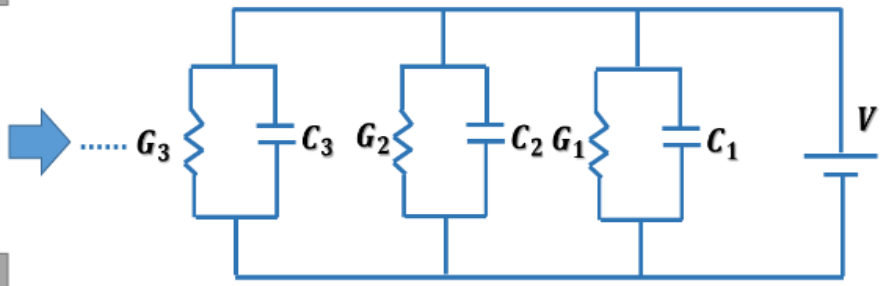
$$\frac{1}{y_{eq}} = \sum_i \frac{1}{y_i}$$

$$\frac{1}{y_{eq}} = \sum_i \frac{1}{y_i} \rightarrow \frac{d}{\varepsilon_{rc.eq}} = \sum \frac{d_i}{\varepsilon_{rc_i}}$$

$$\frac{1}{\varepsilon} = \sum_{n=1}^{N} \frac{v_n}{\varepsilon_n}.$$

ترکیب موازی



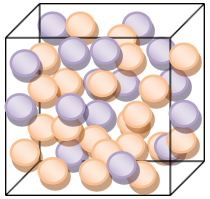


$$y_{eq} = \sum_i y_i$$

$$\varepsilon_{rc.eq} = \frac{1}{d} \sum \varepsilon_{rc_i} \times d_i$$

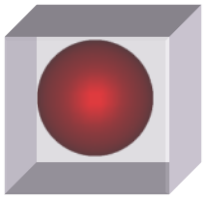
$$\varepsilon = \sum_{n=1}^{N} v_n \varepsilon_n.$$

ترکیب با ذرات محدود



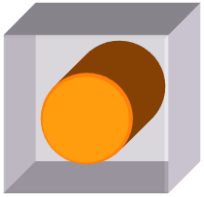
$$\sum_{n=1}^{N} v_n \left(\frac{\varepsilon - \varepsilon_n}{\varepsilon_n + 2\varepsilon} \right) = 0$$

قاعده بروگمان: Bruggeman($\varepsilon_1, \varepsilon_2, \ldots, \varepsilon_N$,v1,v2,..., vN)



MG3D

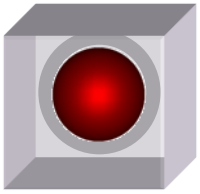
$$\varepsilon_{eff} = \varepsilon_b + 3v_i \varepsilon_b \frac{\varepsilon_i - \varepsilon_b}{\varepsilon_i + 2\varepsilon_b - v_i (\varepsilon_i - \varepsilon_b)}.$$



MG2D

$$\varepsilon_{eff} = \varepsilon_b + 2v_i \varepsilon_b \frac{\varepsilon_i - \varepsilon_b}{\varepsilon_i + \varepsilon_b - v_i (\varepsilon_i - \varepsilon_b)}.$$

قاعده ماکسول-گارنت: MG3d($\varepsilon_b, \varepsilon_i, v_i$) ;MG2d($\varepsilon_b, \varepsilon_i, v_i$)

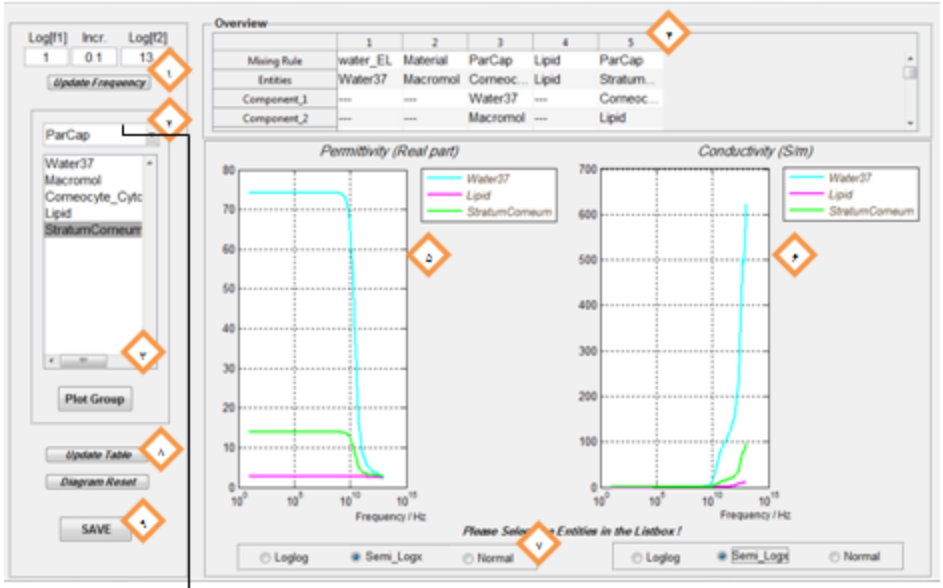


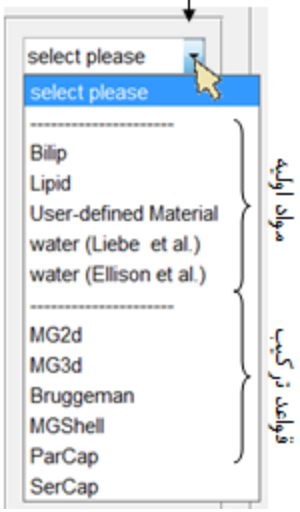
MGSHELL

$$\frac{\varepsilon_{eff} - \varepsilon_b}{\varepsilon_{eff} + \varepsilon_b} = v_i \frac{(\varepsilon_l - \varepsilon_b)(\varepsilon_c + 2\varepsilon_l) + w(\varepsilon_c - \varepsilon_l)(\varepsilon_b + 2\varepsilon_l)}{(\varepsilon_l + 2\varepsilon_b)(\varepsilon_c + 2\varepsilon_l) + 2w(\varepsilon_c - \varepsilon_l)(\varepsilon_l - \varepsilon_b)}.$$

MGShell($\varepsilon_b, \varepsilon_c, \varepsilon_l, v_i$,w)

قواعد ترکیب در زبان Matlab





۱ - تعریف بازه فرکانسی محاسبه
۲ - منوی تعریف ماده اولیه یا تعریف قاعده ترکیب
۳ - فهرست اسامی مواد اولیه یا ترکیبی ایجاد شده
۴ - تاریخچه ترکیبات، که برای هر ماده قاعده ترکیب و مواد اولیه دخیل در آن را نشان می‌دهد
۵ - صفحه رسم گذردهی حقیقی
۶ - صفحه رسم رسانایی موثر
۷ - تنظیمات نمایش:عادی، نیمه لگاریتمی، مقیاس لگاریتمی هر دو محور
۸ - دکمه‌های به‌روزرسانی جدول تاریخچه ترکیبات
۹ - ذخیره‌سازی نتایج پروژه : تاریخچه، ماتریس‌های خواص مواد، و تصویر گرافیکی (.jpg) از محتویات هر دو صفحه رسم

Water(f(Hz),T(°C),σ_{DC})

$$\sigma_{tot} = \omega \varepsilon_0 \varepsilon_r'' + \sigma_i$$

درباره اثبات فرمول‌های ترکیب در انتهای فصل آتی سخن خواهیم گفت.