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On the effective medium theory to study the dielectric response of the cancerous biological tissue

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ABSTRACT

Herein, we are making a step forward by treating cancerous tissues as the highly disordered anisotropic media. The classical Maxwell-Garnett technique is utilized. The former stands for as a perfect tool allowing to evaluate an effective medium of the sample analytically with no needs of human intervention by performing an experimental analysis to measure the parameters of the sample. It should be noted, that laboratory measurements of the effective properties are not needed in this case as well. In this relation, the presented technique allows for the creation of the phantom tissue models for the further usage in clinical applications.

Keywords: Times Roman, image area, acronyms, references

1. INTRODUCTION

This work aims to refine fundamental ideas used in electrodynamics and some optical problems and to apply them for biological systems. We aim to correct a common practice if effective medium models for biological systems. An analytical approach to calculate the macroscopic complex dielectric properties of materials is possible due to the effective medium theory (EMT) models. The former is performed by employing the dielectric properties of their constituents and their volume fractions [1]. Precise calculation of the effective properties is the key factor aiming to design the electromagnetic behaviour of the composite and analyze the features of the electromagnetic scattering. A large variety of the mathematical tools had been taken on board seeking to calculate the effective properties of compounds [2-4]. The former phenomenon takes place due to the fact that J. C. Maxwell firstly analyzed the conductivity of compounds combined of conducting particles and non-conducting matrix medium. The most classic formulas are the Maxwell Garnett and the Bruggeman equations [5]. Most of other mathematical expressions were suggested on the basis of them. Though, the precise calculation of the effective properties of compounds is a complex task by utilizing the mentioned formalism. The main problem is that these expressions are obtained under certain assumptions. These include low particle concentration. Moreover, some essential factors having a great impact on the obtained results cannot be directly attained including the dielectric properties of particles, particle geometric and morphological distributions, etc. [6].
Cancer, a leading causes to death, is a significant burden of disease worldwide. It is well-known that early cancer detection is of substantial importance to increase the chances of survival. To address this grand societal challenges, this work aims at introducing a paradigm shift in the study of the dielectric response of the cancerous biological tissues. Herein, we consider a cancerous biological tissue as an anisotropic composite. It should be mentioned that machine learning techniques can be widely applied aiming to automate the process of modelling of the phantom tissues.

2. THEORETICAL BACKGROUND

Effective medium theories stand for as a perfect toll aiming to identify an effective dielectric function for a composite material taking into account the dielectric function of its components and their geometrical distribution [7-10]. Let us now assume that inclusions are embedded into the host medium. Moreover, the implants are prepared by utilizing different materials with permittivities ε_n (n=1, 2, … , N). Then Maxwell-Garnett equation is generalized as

$$\frac{\varepsilon_{MG}-\varepsilon_h}{\varepsilon_{MG}+2\varepsilon_h}=\sum_{n=1}^{N} f_n \frac{\varepsilon_n-\varepsilon_h}{\varepsilon_n+2\varepsilon_h}, \quad (1)$$

where f_n is the volume fraction of the n-th component.

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The random sequential addition (RSA) method can be used aiming to generate the random point distribution for low filling fractions. In the frame of this methodology, random particle positions are generated sequentially. Moreover, new random particle (satisfying uniform distribution) is accepted if does not overlap with already occurring instances. It will become more challenging to obtain a new area for a new particle because of the continuation of the acceptation and rejection process. In this relation, there is a critical limit (for equal-sized circular particle, 55% filling fraction). It is impossible to add additional particles above the mentioned limit. In case of higher filling fractions, random particle distributions can be generated using the molecular dynamic hard sphere packing method. Additional limitations on particle distribution pattern are needed if the filling fraction increases. Doing so, the compound becomes wavy crystalline and then crystalline from disordered. In this relation, herein, the highest filling fraction for random composites is 80% [11].

$$\frac{\varepsilon_{MG}-\varepsilon_h}{\varepsilon_{MG}+2\varepsilon_h}=f_1\frac{\varepsilon_1-\varepsilon_h}{\varepsilon_1+2\varepsilon_h}+f_2\frac{\varepsilon_2-\varepsilon_h}{\varepsilon_2+2\varepsilon_h}+f_3\frac{\varepsilon_3-\varepsilon_h}{\varepsilon_3+2(1)\varepsilon_h} \tag{2}$$

One may derive from Eq. (2), that

$$\varepsilon_{MG}=-\frac{\varepsilon_h+\varepsilon_h(C+B+A)2}{C+B+A-1}, \tag{3}$$

where $A=\frac{f_3(\varepsilon_3-\varepsilon_h)}{\varepsilon_3+2\varepsilon_h}$, $B=\frac{f_2(\varepsilon_2-\varepsilon_h)}{\varepsilon_2+2\varepsilon_h}$, $C=\frac{f_1(\varepsilon_1-\varepsilon_h)}{\varepsilon_1+2\varepsilon_h}$.

The spectrum of a tissue may be more appropriately described in terms of multiple Cole-Cole dispersion

$$\hat{\varepsilon}_h(\omega)=\varepsilon_\infty+\sum_n\frac{\Delta\varepsilon_n}{1+(j\omega\tau_n)^{(1-\alpha_n)}}+\frac{\sigma_i}{j\omega\varepsilon_0} \tag{4}$$

3. MODELLING OF THE PHANTOM TISSUE

The phantom tissue models are created based on the metamaterial formalism methodology. It is assumed, that brain (grey matter) forms the host medium and cancerous cells are implanted in it. Following the former approach one may construct an anisotropic metamaterial (Fig. 1) with the host material being grey matter of the brain and the nanocylinders embedded in it possessing permittivity of the cancerous cells. Based on the presented approach, the obtained metamaterial media stands for as the disordered structure with the effective permittivity calculated by Eq. 3. It is assumed, that the permittivity of the host medium is predicted employing the Cole-Cole model (Eq. 4). Fig. 2 demonstrates permittivity of the grey and white matter of the brain calculated employing the Cole Cole model (Eq. (4)) along with the effective of the cancerous affected tissue. It was assumed, that biological tissue is highly affected by the cancerous cells. Herein, we will deal with the example of the glioblastoma cells embedded into the sample. Doing so, filling ratio of the cancerous cells is f_g=0.95.

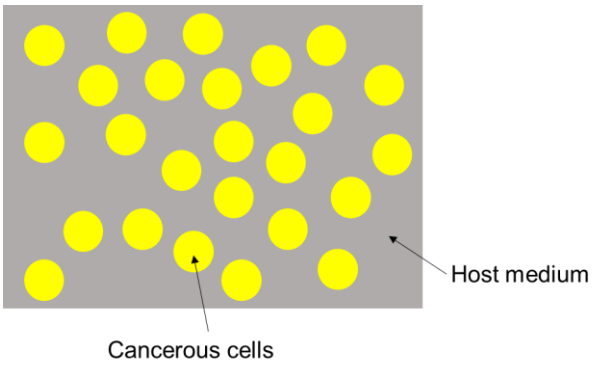
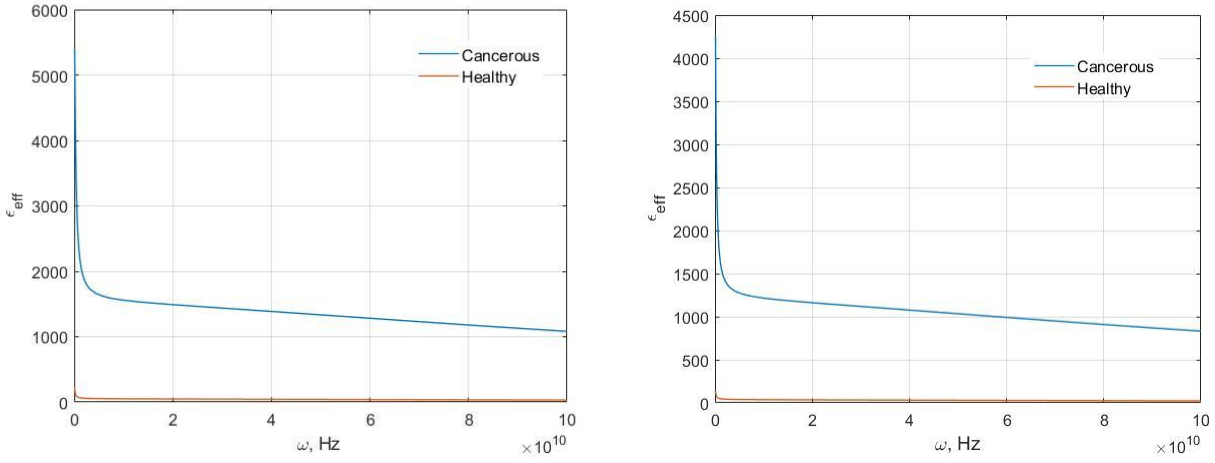


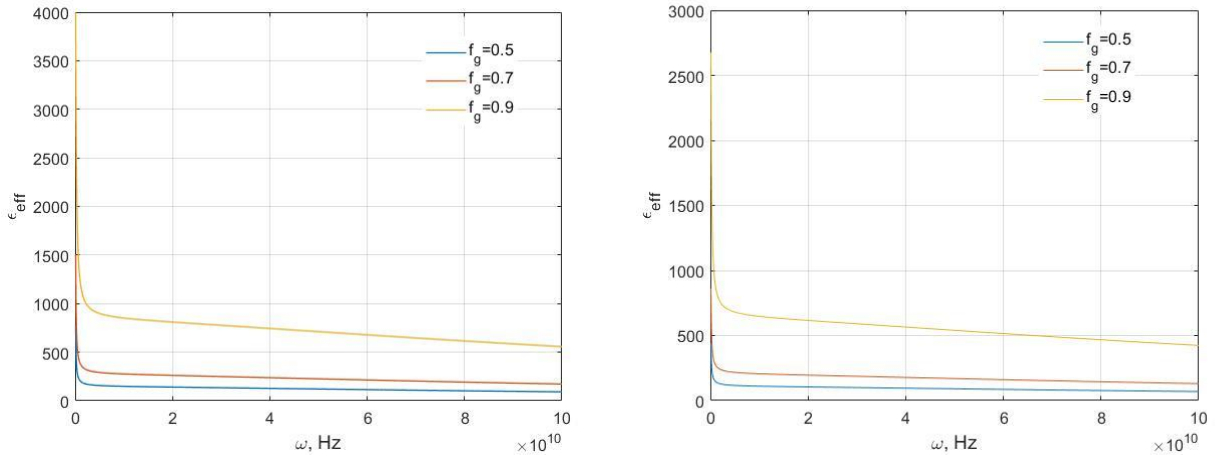
Fig. 1. Biological tissue with the embedded cancerous cells



(a) (b)

Fig. 2. Dependence of the effective permittivity versus frequency. f_g=0.95 (a) grey matter [12]; (b) white matter [12].

It can be observed in Fig. 2, that the effective permittivity of the cancerous media is larger than the values obtained for the healthy tissue case. It is of particular interest to examine the effect of the amount of the cancerous cells on the material properties. Thus, Fig. 3 depicts dependencies of the effective permittivities upon frequency for different filling ratios.



(a) (b)

Fig. 3. Dependence of the effective permittivity versus frequency for different filling factors of the cancerous cells. (a) grey matter [12]; (b) white matter [12].

As it can be observed in Fig. 3, presence of the cancerous cells in the sample makes a dramatic impact on the effective permittivity value. A significant increase in the permittivity is observed by increasing amount of the cancerous cells in the sample. The obtained results are in good agreement with those obtained in [12] for the cancerous tissue case. In this relation, one may conclude that presented metamaterial based formalism approach stands for as a good tool to create the phantom tissue models needed for clinical practice. By comparing results presented in Fig. 2 (a) and (b) one may conclude, that presence of the cancerous cells is making a more dramatic impact in case of the white matter rather than in case of the grey one.

4. CONCLUSIONS

It was concluded that cancerous tissues can be treated from the perspectives of the highly disordered metamaterial medium. In this relation, effective permittivity of the biological tissue under consideration can be considered. It has been shown that a cancerous composite with effective dielectric function described in the framework of classical effective medium theories provides larger values of the effective permittivity in comparison to the calculated properties of the healthy, undamaged medium case. The presented approach may serve as a perfect tool aiming to create phantom tissue models for the clinical applications.

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