# Internal Homogenization of Biological Tissues for Electromagnetic Dosimetry

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***Abstract*** ─ In this paper, the internal homogenization method is introduced to determine the effective physical properties (permittivity and conductivity) of biological tissues. This method is performed on a 2D child head model obtained from MRI data. An original procedure where the complex 2D head model is represented as a multilayered circular structure is employed to retrieve the effective medium parameters. Results obtained with the proposed internal homogenization concept are compared with those obtained from the original heterogeneous model (with 4 tissues) and effective medium theories such as Maxwell-Garnett and Polder van Santen.

## I. INTRODUCTION

Nowadays, mobile phones and wireless handy computers are widely used and there have been public concerns about their possible hazardous effects due to the emitted electromagnetic radiation. To quantify these effects, the most widely used quantity is the specific absorption rate (SAR) [1]. Dosimetry based on computer simulations is usually preferred because the SAR measurement on a living human body is difficult to perform [2]. In numerical dosimetry, the finite difference – time domain (FDTD) method is a well-known method to solve Maxwell's equations, but its cubic meshing scheme reduces the accuracy when complex geometries with curvature are simulated [3].

In this paper, the finite element method (FEM) is used. However, the FEM is a time consuming technique. Furthermore, human head is a complex structure composed of several biological tissues with different thicknesses and physical properties. This complex and fine structure is very difficult to simulate even with high computing systems. Therefore, homogenization plays an important role to simplify the structure and then reducing the time required for the simulation. Homogenization consists of replacing the entire complex structure with a simplified model having effective physical properties. In literature, different approaches were proposed to homogenize composite materials such as metamaterials, periodic structures, etc. [4]. In [5], to homogenize a multilayered structure, authors proposed to use FDTD grid with a coarser mesh which allows to reduce the computation. In [6], authors developed the adjoint method combined with the FDTD method for the homogenization of human body's models. The retrieval method based on S parameters is a classical method to determine the effective medium constitutive parameters [7]. This method has been successfully applied to metamaterials in [8] and [9]. The field averaging technique has been applied to homogenize periodic structures with unit cells having inclusions much smaller than the electromagnetic wavelength [10, 11]. In the present work, the "internal homogenization" method, introduced by [12], is used and the obtained results are compared with those of the heterogeneous medium and results given from Maxwell-Garnett and Polder van Santen theories. Moreover, a new effective parameters extracting procedure based on the representation of the complex heterogeneous head as a simplified circular model is also presented.

## II. HOMOGENIZATION

Homogenization is a term given to the treatment of inhomogeneous medium where physical properties are dependent of the space coordinates. Its aim is to find an effective medium model where physical properties do not vary within the model. In case of an external excitation, such a medium should exhibit similar behavior to the equivalent inhomogeneous medium. To calculate the effective material parameters of a heterogeneous medium, effective medium theories (EMT) are often used. In subsequent sections, the internal homogenization based on a layered circular structure and some of widely used EMT such as Maxwell-Garnett and Polder van Santen mixing theories will be presented.

### A. Internal homogenization procedure

Although, the concept of "internal homogenization" was introduced to assign an effective permittivity for a single inclusion contained in a bulk material, we applied it to attribute an effective medium parameter to a simplified child head. As opposed to the internal homogenization, the external homogenization consists

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of assigning an effective permittivity to a distribution of inclusions in a matrix.

For simplicity, the child head model is considered to have subwavelength structure so that the quasi-static approximation can be applied. The simplified model is assumed to have multi-layered circular geometry that is composed of 4 different tissues: skin, muscle, skull and brain.

The internal homogenization procedure is as follows: the 2D heterogeneous model is replaced by an equivalent multi-layered circular structure (Fig. 1). The radius of each tissue is calculated in accordance to its total area given by MRI data (Table 1). The homogenization is then applied to the multi-layered circular structure. Thereafter, in order to calculate its response to an external electromagnetic excitation, the calculated effective medium parameters are presented to the 2D model of the head.

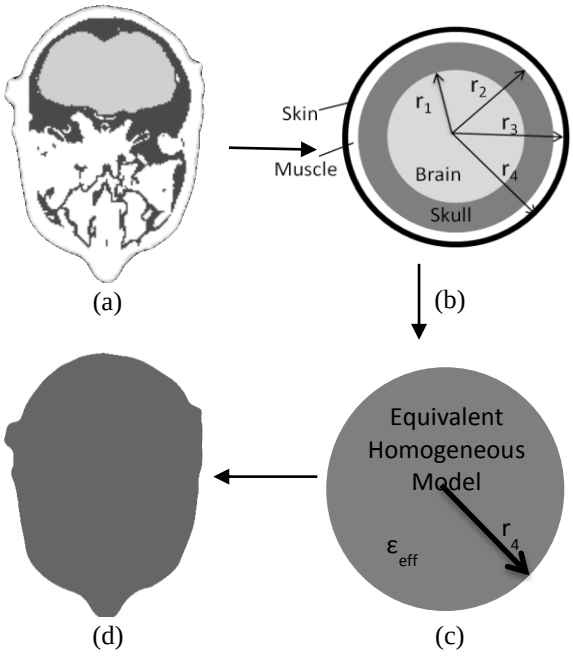


Fig. 1. Effective parameters extracting scheme: (a) heterogeneous head model, (b) simplified circular multi-layered model, (c) equivalent homogeneous model with effective permittivity $\varepsilon_{eff}$ and radius $r_4$, and (d) homogeneous head model.

Table 1: Approximated thickness for each tissue

| Tissues | Skin | Muscle | Skull | Brain |
|---|---|---|---|---|
| Radius (meter) | 0.1286 ($r_4$) | 0.1139 ($r_3$) | 0.0686 ($r_2$) | 0.0324 ($r_1$) |

The internal homogenization method is based on the equivalence of the polarizability of the multi-layered model and the equivalent homogeneous model. The derivations of the polarizability expressions are long and out of the scope of this paper. The interested readers are invited to refer to [13], [14] and [15]. The homogenization procedure begins with the first two inner layers, i.e., the brain and the skull tissues. The polarizability is expressed as $\alpha_1$ and $\alpha_2$ for the two layered sphere (brain + skull) (1) and the equivalent homogeneous sphere (2), respectively:

$$\alpha_1 = -4\pi\varepsilon_0 \left( \frac{r_2^3(\varepsilon_1+2\varepsilon_2)(\varepsilon_2-\varepsilon_0)+r_1^3(\varepsilon_1-\varepsilon_2)(2\varepsilon_2+\varepsilon_0)}{2r_1^3(\varepsilon_1-\varepsilon_2)(\varepsilon_2-\varepsilon_0)+r_2^3(\varepsilon_1+2\varepsilon_2)(\varepsilon_2+2\varepsilon_0)} \right) r_2^3, \quad (1)$$

$$\alpha_2 = 4\pi\varepsilon_0 \left( \frac{\varepsilon_{12}-\varepsilon_0}{\varepsilon_{12}+2\varepsilon_0} \right) r_2^3, \quad (2)$$

where $\varepsilon_1$ and $\varepsilon_2$ are the permittivities of the brain and the skull respectively, and $r_1$, $r_2$ are the approximated radius of each tissue. By equating these two polarizabilities, the effective permittivity $\varepsilon_{12}$ (for the brain and the skull) of the equivalent sphere is given by (3):

$$\varepsilon_{12} = \varepsilon_2 \frac{r_2^3(\varepsilon_1+2\varepsilon_2)+2r_1^3(\varepsilon_1-\varepsilon_2)}{r_2^3(\varepsilon_1+2\varepsilon_2)-r_1^3(\varepsilon_1-\varepsilon_2)}. \quad (3)$$

This calculation is repeated in an iterative manner until the effective permittivity $\varepsilon_{eff}$ of the whole model (4 layers structure) is determined.

### B. Maxwell-Garnett EMT

One of the most popular and widely used effective medium theories is the so called Maxwell-Garnett EMT [16]. It dates from the beginning of the last century. It is expressed as (4):

$$\varepsilon_{eff} = \varepsilon_e + 3f\varepsilon_e \frac{\varepsilon_i-\varepsilon_e}{\varepsilon_i+2\varepsilon_e-f(\varepsilon_i-\varepsilon_e)}. \quad (4)$$

The Maxwell-Garnett formula is based on the fact that the heterogeneous medium is composed of isotropic spherical inclusion with $\varepsilon_i$ diluted in isotropic host material of permittivity $\varepsilon_e$. The volume fraction occupied by the inclusion is $f$. The formula is valid for very low concentration inclusions ($f$<<1). As for the internal homogenization described above, this theory implies the quasi-static approximation. It has been applied for several material types including microwave absorbing material containing conducting particles [17], composite dielectric medium [18], conducting polymers [19], etc.

### C. Polder van Santen EMT

A derivation of the Maxwell-Garnett mixing expression is Polder van Santen formula (also called Böttcher formula) that can treat a variety of mixtures [16], [20]. Especially, it is valid for ellipsoid inclusion and for all volume fractions. For spherical inclusion the formula takes the form given below (5):

$$\frac{\varepsilon_{eff}-\varepsilon_e}{3\varepsilon_{eff}} = f\frac{\varepsilon_i-\varepsilon_e}{\varepsilon_i+2\varepsilon_e}. \quad (5)$$

For dilute materials, Maxwell-Garnett and Polder van Santen formulas should give similar effective medium parameters [16].

## III. RESULTS

The homogenization procedures described above is applied to a 2D child head model obtained from MRI data. The physical properties of the head tissues from 10 MHz to 3 GHz are given below (Fig. 2 and Fig. 3) [21].

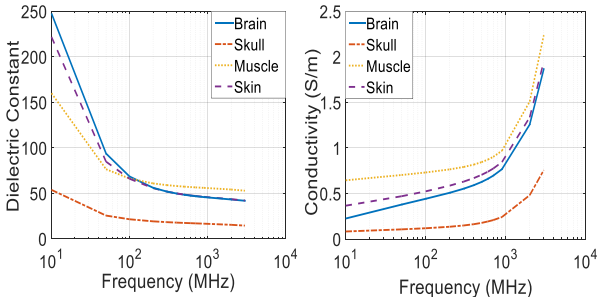


Fig. 2. Tissues parameters (10 MHz to 3 GHz): (a) dielectric constant, and (b) conductivity [11].

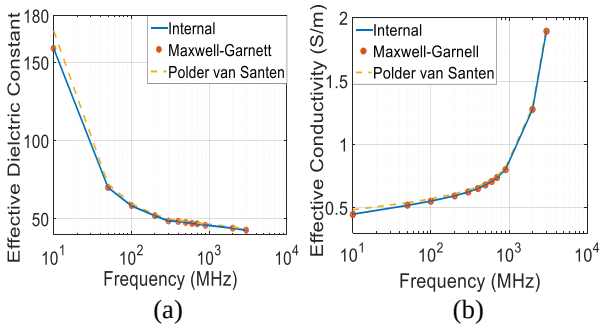


Fig. 3. Effective parameters of the homogeneous head model obtained with the three EMTs (10 MHz to 3 GHz): (a) effective dielectric constant, and (b) effective conductivity.

The same procedure described in 2.1 (Fig. 1) is used to obtain the effective parameters with the three different EMTs. These are given in Fig. 3. As the multilayered structure is composed of the core materials embedded in a medium of the shell material, and the same process is applied for both methods, the internal homogenization and Maxwell-Garnett EMT are expected to give the same effective parameters independently of the frequency of the excitation [12], [16]. This is confirmed by the Fig. 3. However, as the filling fraction for each tissue layer is not negligible, especially for the skin, the muscle and the skull (Table 2), Polder van Santen EMT give slightly different results compared to the two other methods.

Table 2: Filling fraction for each layer

| | |
|---|---|
| $r_1^3/r_2^3$ | 0.1052 |
| $r_2^3/r_3^3$ | 0.2184 |
| $r_3^3/r_4^3$ | 0.6948 |

These effective properties are then used in the 2D head model where only the external boundary exists and all internal boundaries are suppressed. Thus, due to a lower cell number, the computation time will be reduced consequently. In fact, the number of cells when the heterogeneous model is considered is 85490, whereas after the homogenization only 6146 cells remain due to the removal of all internal boundaries. The FEM computation is about ten times faster after the homogenization.

Validation of the internal homogenization method is carried out by computing the electric field distribution inside the original heterogeneous and the homogeneous models using a commercial FEM software. The computational resource used for this work is a computer equipped with Intel® Core™ Quad CPU Q8400 @ 2.66 GHz processor with 4 GB of memory. The source of radiation is an infinitesimal dipole placed at 1 cm from the boundary of the skin. Figure 4 and Fig. 5 show the electric field distribution at two frequencies, 100 MHz and 900 MHz, for heterogeneous and homogeneous models, respectively.

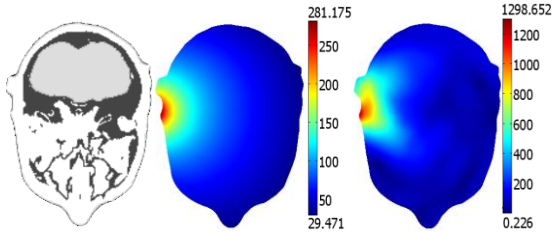


Fig. 4. Heterogeneous model (left), the electric field distribution at 100 MHz (center) and 900 MHz (right).

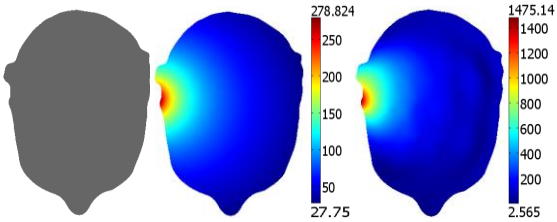


Fig. 5. Homogeneous model (left), the electric field distribution at 100 MHz (center) and 900 MHz (right).

It is clearly shown that at low frequency (100 MHz) the electric field distribution is similar for both models. However, at higher frequency (900 MHz), there is a net difference between them. To quantify this difference, the

relative error induced by each EMTs, i.e., internal homogenization, Maxwell-Garnett and Polder van Santen are computed. This is achieved by plotting the induced electric field magnitude along a horizontal line crossing the head at the level of the source point (Fig. 6).

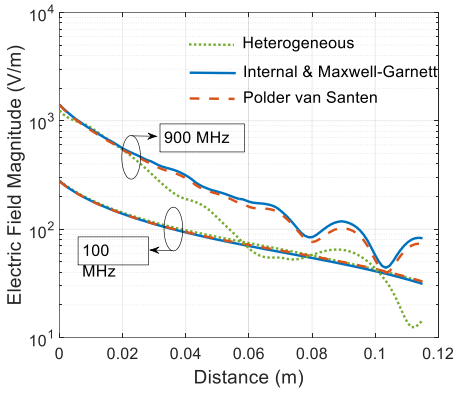


Fig. 6: Electric field magnitude along a line in the the head at 100 MHz and 900 MHz.

The plots in Fig. 7 are based on the data presented in Fig. 6, where the relative errors are calculated between the electric field distribution in the heterogeneous model and each presented EMTs.

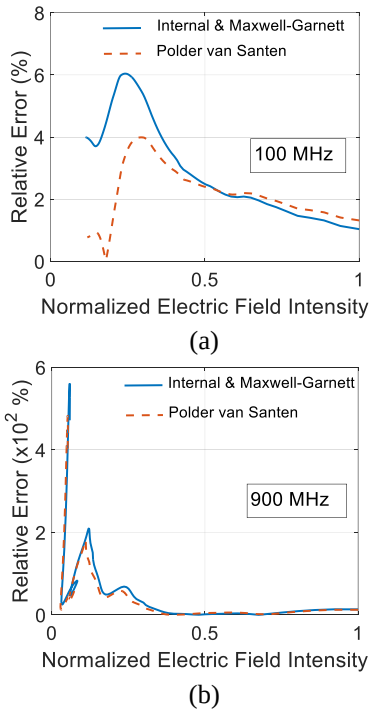


Fig. 7. Relative error vs. normalized electric field at: (a) 100 MHz and (b) 900 MHz.

Figure 7 shows that the overall error is more important at 900 MHz than at 100 MHz. Especially in the vicinity of the excitation (higher electric field magnitude), where the EM radiation is much likely to have damage on biological tissue, the error induced by the homogenization techniques are very low.

Furthermore, to confirm the validity of the employed internal homogenization method, the average relative error is plotted versus the frequency (Fig. 8). It is obtained by summing up the relative errors calculated at each point along the line and dividing it by the number of points. The average error remains acceptable up to 400 MHz (about 10%). Beyond this frequency, the homogenization gives inaccurate results. This important error is due on one hand to the fact that the quasi-static approximation is no more valid beyond this frequency. On the other hand, the circular multilayered structure is not fully representative of the complex 2D head structure. Furthermore, at high frequencies, the EM response is more dependent on fine details of the structure.

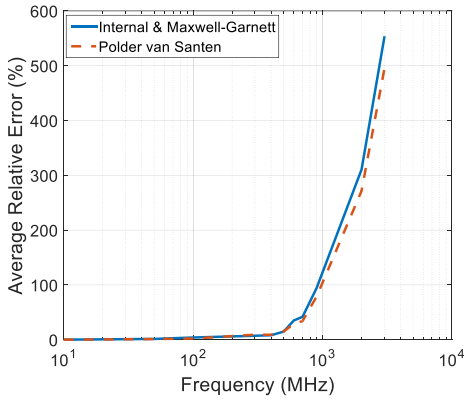


Fig. 8. Average relative error vs. frequency.

## IV. SENSITIVITY ANALYSIS

In this part, the influence of the head model parameters to the electric field distribution is studied. These parameters are the approximated thickness (radius) obtained for each tissue and the physical properties such as the dielectric constant and the electrical conductivity. The Monte Carlo (MC) method is used for this purpose.

First, the influence of both physical constants and the radius of each tissue is considered. The model parameters are considered to have 10% of uncertainty with a uniform distribution over the range of variation centered at the nominal values presented in the previous section. 100000-sample MC simulation based on the internal homogenization formula (3) presented in Section II is used to analyze the dispersion of the effective medium parameters, i.e., the average values and the standard deviation of the dielectric constant and the conductivity. For instance, results at 100 MHz are presented in Table 3. It is shown that 10% of uncertainty

of the model parameters induces about 5% of dispersion of the effective dielectric constant and about 7% of the effective conductivity when all model parameters are considered, i.e., physical constants (Δp, dielectric constants and conductivities) of each tissue and corresponding radius (Δr). The first two columns show the results corresponding to this case. In Table 3, the first row corresponds to the values obtained with the nominal values of the model parameters, without any uncertainties, and are given as a comparison.

Second, if one supposes that the physical constants of each tissue are fixed and only the radii of the tissues have uncertainties (Δr), the results presented in Table 3 (right two columns) are obtained. The uncertainties due to the approximated radii is about 62% (for the dielectric constant) and 78% (for the conductivity) of the previous results when all model parameters are considered. Thus, the radius has more effect on the effective medium parameters. However, the uncertainty induced remains reasonably low.

Table 3: Uncertainty on the effective dielectric constant at 100 MHz

| | Δp and Δr | | Δr Only | |
|---|---|---|---|---|
| | ε | σ | ε | σ |
| Effective parameters for nominal values | 58.40 | 0.5528 | 58.40 | 0.5528 |
| Average effective parameters | 58.18 | 0.5540 | 58.20 | 0.5542 |
| Standard deviation | 3.12 | 0.0403 | 1.96 | 0.0318 |
| Variation (%) | 5.37% | 7.28% | 3.36% | 5.74% |

Finally, the variability of the electric field magnitude in a horizontal line due to the uncertainty of the effective dielectric constants and conductivities has been studied. For both frequencies, 100 MHz and 900 MHz, the average electric field magnitude and the standard deviation versus the horizontal distance from the feed point side of the head are estimated and plotted (dotted lines) in Fig. 9.

For this study, the first case where both physical constants and radii have uncertainties is considered (columns 1 and 2 in Table 3). It can be seen in Fig. 9 that, the variation in the effective parameters induces small changes in the electric field magnitude at 100 MHz. Depending on the distance, the uncertainty of the electric field varies between 2% and 7%. As expected, at 900 MHz the uncertainties of the effective parameters and radii have more effect on the electric field. The uncertainty can be as high as 17%.

The electric fields obtained when the homogeneous head model is made entirely out of the constituent tissues parameters are also shown in Fig. 9. One can observe that, there is a discrepancy between the results given by our method (dotted lines in Fig. 9) and those obtained if one were using one of the tissues parameters as effective medium parameter. The model made out of the skin seems to give the closest results because at those particular frequencies the effective parameters obtained are close to those of the skin.

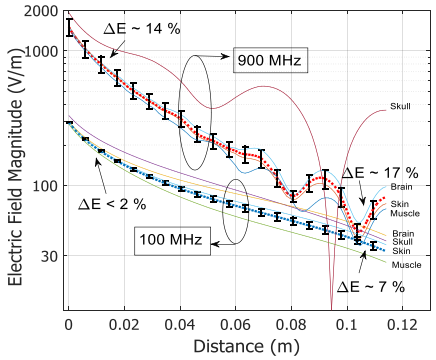


Fig. 9. The electric field magnitude variation in a horizontal line with the corresponding uncertainties due to the effective medium physical constants variations.

## V. CONCLUSIONS

In this paper, the concept of internal homogenization is presented and the results are compared with the heterogeneous model and Maxwell-Garnett and Polder van Santen effective medium theories. It has been shown that, up to a certain frequency where the quasi-static approximation is valid, the complex multi-layered structure can be replaced by its counterpart effective medium. The internal homogenization method gives similar results to those obtained from Maxwell-Garnett but slightly different results compared to Polder van Santen EMT. The use of a multilayered circular model to extract the effective parameters is also presented. This procedure highly simplifies the modeling of the complex head structure by removing boundaries between tissues and by replacing the space-depending physical parameters by a homogeneous effective parameter. For this 2D case, the simulation with the homogeneous model is about 10 times faster than for the heterogeneous one. The difference in terms of computation time will be even higher if a 3D model is considered.

Although, the employed method is limited in frequency, it is worth to note that, most of the error is far away from the excitation and is located where the electric field intensity is weak. Thus, one can propose to use the homogenization only in the vicinity of the radiation source, inside the head, a few centimeters from the skin. Homogenization allows to diminish the number of cells required to represent thin shells and consequently the simulation time is reduced considerably.

Finally, the sensitivity analysis showed that the possible uncertainty in the head model parameters might have impacts on the electric field magnitude. The level of the induced uncertainty depends on the distance to the source point and the frequency. Histerically

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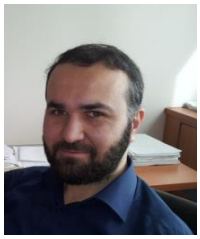

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