Analysis of Matching Media Effect on Microwave Brain Stroke Imaging via a Spherically Symmetrical Head Model

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Abstract— The effect of using a matching medium in the brain imaging via the microwave tomography technique has been investigated using a three-dimensional multi-layered sphere as a head model. By modelling the human head as a spherically symmetrical piecewise homogeneous sphere, the related scattering problem can be transformed into a one-dimensional form. As a result, the computational complexity of the problem can be significantly reduced. This scattering problem is then solved via the discretization of the one-dimensional integral equations, and through the dyadic Green's function related to the layered spherical structures. In order to test the effect of the matching medium for the brain stroke detection, the scattered electric fields for the healthy brain model and the stroke-affected one have been compared. The results show that in the absence of a matching medium the variation in the scattered field between two cases is too small to enable a successful stroke detection mechanism based on microwave imaging. On the other hand, in the presence of the matching medium, a noticeable difference in the scattered field has been observed. However, further tests employing more realistic models must be used to evaluate the applicability of the microwave tomography in the brain stroke detection.

1. INTRODUCTION

Microwave tomography can represent an alternative to commonly used imaging techniques such as computerized tomography or magnetic resonance imaging [1]. The researches on the subject are motivated by the need to make continuous control of the patient's state possible [2]. Since non-hazardous and portable imaging systems can be designed using microwave technology, an imaging tool operating on microwave frequency would be suitable for long term monitoring [1, 2].

Microwave imaging techniques rely on the difference in the electromagnetic properties between healthy tissues and stroke areas in the brain [1]. This difference results in a variation in the scattered field when the head region is excited by an external source operating in the microwave frequencies. Therefore, it is of crucial importance to maximize the penetration of the electromagnetic field into the inner parts of the human brain where the strokes occur. To this end, a matching medium with suitable electromagnetic parameters can be used to minimize the reflection by matching the impedances, in the interface between the surrounding medium and the skin [3]. The optimal parameters for the matching medium depends on the electromagnetic properties of the healthy and malignant tissues under examination, and determining those parameters is a very important step in the design of a successful microwave imaging system [4]. The effect of the matching medium can be best assessed by using a 3-D head model, which can provide a relatively realistic structure to test both the relevancy of using a matching medium, and the effectiveness of microwave imaging techniques in general.

In this work, a four layered piecewise homogeneous sphere has been used as a head model. In order to assess the effect of the matching medium, the related three dimensional scattering problem must be solved. However, given the high contrast values of the brain tissues, the solution of the 3-D scattering problem by classical techniques, such as method of moments, is a computationally expensive procedure. Therefore, in this study the problem has been transformed into a one dimensional form by taking advantage of the spherical symmetry [5]. As an alternative method, the dyadic Green's function related to the layered spherical structures has been used to verify the results [6]. After solving the scattering problem, the effect of the matching medium on the scattered field has been analysed by comparing the results for the cases with and without a stroke-affected brain area. The comparisons show that the presence of the matching medium increases the effect of the stroke region on the scattered electric field. This effect forms the basis for a possible application of the microwave imaging techniques for brain stroke monitoring.

2. FORMULATION OF THE PROBLEM

In order to analyse the effect of matching medium two different configurations have been considered. First, as a theoretical case, the sphere of radius a, which is assumed to represent the spherically symmetrical head model, has been assumed to be located in an open region of the matching medium, as presented in Fig. 1. The incoming electric field has been excited by an infinitesimal horizontal electric dipole with a current moment C_0 pointed in the x-direction, situated at the point $x = 0$, $y = 0$, $z = z_d$, $(z_d > a)$ on the z-axis. The region outside the sphere is characterized by a constant wave number of $k = \omega\sqrt{\epsilon_0\mu_0\epsilon_m}$, ϵ_m being the complex dielectric constant of the matching medium.

As a second configuration, a more realistic case given in Fig. 2 has been analysed. In this geometry, the layered sphere is assumed to be coated by a concentric layer of matching medium. The infinitesimal dipole is located inside the matching medium layer. The region outside this layer is considered to be free-space, characterized by the wave number $k_0 = \omega\sqrt{\epsilon_0\mu_0}$.

Different electromagnetic parameters have been used in the formulation of the head model [1, 2]. The choice of operating frequency is also an important parameter which significantly affects the outcome of the microwave imaging procedure [1]. The frequency should be chosen as an optimum value that enables the penetration of the electric field into the brain region, while ensuring the necessary resolution for the microwave imaging [1]. In this study, the operating frequency has been chosen as $f = 1\,\mathrm{GHz}$. By taking the frequency dispersion into account, the electromagnetic parameters for each layer of the head model has been presented in [2] for $f = 1\,\mathrm{GHz}$. In Table 1, the thickness and the complex dielectric constant for each layer of the head model has been given. For the brain region, in order to preserve the spherical symmetry, the mean value of the grey matter and the white matter has been chosen as the complex dielectric constant. Accordingly, the complex constant for the matching medium has been chosen as $\epsilon_m = 40 + 13i$, as given in [2].

The scattering problem related to the four layered piecewise homogeneous head model, given in Fig. 1, is a three-dimensional one. However as explained in [5], by taking advantage of the spherically symmetrical geometry, one can reduce the problem into a one-dimensional form. This transformation is achieved by expressing the interior electric field and the free space dyadic Green's function as a series expansion in terms of vector spherical harmonics, which are orthogonal over a spherical surface. Using this orthogonality, the three dimensional electric field integral equation can be transformed into a system of one-dimensional integral equations [5]. An alternative solution for the scattering problem can be formed by using the dyadic Green's function related to the layered spheres constructed in [6]. The comparison and verification of the results obtained via both methods for the scattering problem has been given in the next section.

For the geometry given in Fig. 2, the dipole is located inside the matching medium layer. The

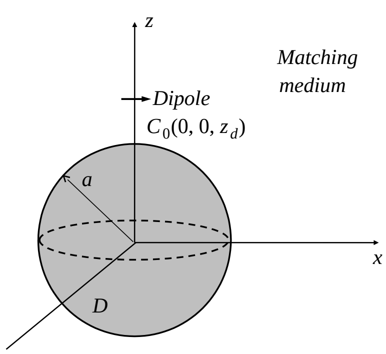

Figure 1: The geometry of the problem with an open matching medium region.

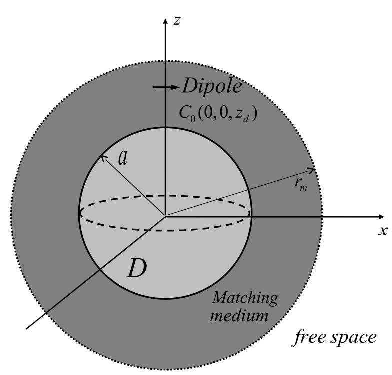

Figure 2: The geometry of the problem with a matching medium layer.

Table 1: The parameters for the layers of the head model.

Layer	Matter	ϵ_r	Thickness
1	Brain	$45 + 16.5i$	8.2 cm
2	CSF	$57 + 26i$	0.3 cm
3	Bone	$13 + 2i$	0.7 cm
4	Skin	$40 + 11i$	0.8 cm

field is also assumed to be measured within that layer. Therefore, this configuration involves a five layered sphere with an internal source. As demonstrated in [5], the presence of the internal source creates a singularity at the vicinity of the dipole, and the series for the total electric field inside the sphere fails to converge at that region. In order to avoid this problem, the thickness of the matching medium layer should be large enough to separate the source and the measurement region. The suitable values determined via numerical tests will be used in the simulations assessing the effect of the matching medium in the next section.

3. NUMERICAL RESULTS

In this section, in order to demonstrate the validity of the methods, the results obtained via both methods will be compared. First, the scattered field for the geometry given in Fig. 1 has been calculated via the one-dimensional integral equations, and the dyadic Green's function. The dipole is located at the point $z_d = 0.12\,\mathrm{m}$ on the z-axis. The scattered field is measured on a spherical surface of radius $r = 0.13\,\mathrm{m}$, in the H-plane ($\phi = \pi/2$) and in the E-plane ($\phi = 0$), for different values of θ, $\theta \in [0, \pi]$. For the method with integral equations, the integrals are discretized by 100 points to increase accuracy. The number of terms n involved in the series expansion for the field is determined as $N_{\max} = 30$ for both methods. The results presented in Fig. 3 show perfect agreement between the method with integral equations and the dyadic Green's function. In the comparison for the geometry with a matching medium layer, the thickness of the matching medium layer is chosen as 5 cm. The dipole is situated at the point $z_d = 0.11\,\mathrm{m}$, and the total electric field inside the matching medium layer is measured on the surface of the layer at $r_m = 0.15\,\mathrm{m}$. The integrals are discretized by 150 points, and the cut-off number for the series is chosen as $N_{\max} = 30$ for both methods. The agreement between the results given in Fig. 4 demonstrates that both methods are reliable in determining the total electric field inside the matching medium layer.

Since previous examples demonstrated that both method can be used in the assessment of the effect of the matching medium, the method with the integral equations will be solely used for the remaining numerical tests. The success of the microwave imaging techniques depends on the amount of variation in the electric field caused by the stroke area in the brain region. Therefore, the difference between the fields, scattered by a healthy brain and by a stroke affected one, should increase in the presence of a matching medium. In order to test this assumption, first the field scattered by a healthy brain has been compared with the field scattered by a stroke affected brain, in the absence of the matching medium. The region outside the four layered sphere is assumed to be free-space vacuum. For the stroke affected brain, the ϵ_r of the brain region is replaced by the complex dielectric constant of the stroke area given in [2] as $\epsilon_s = 36 + 13i$. Although this is not a realistic case, it is suitable for the purpose of analysing the effect of matching medium. For the measurement of the scattered field, same parameters given for Fig. 3 have been used. In all the remaining cases, the values calculated for $\theta \in [0, \pi]$ in the H-plane ($\phi = \pi/2$), and in the E-plane ($\phi = 0$) are presented in the same figure. In each figure the top half represents the values measured in the E-plane ($\phi = 0$), and the bottom half represents the values measured in the H-

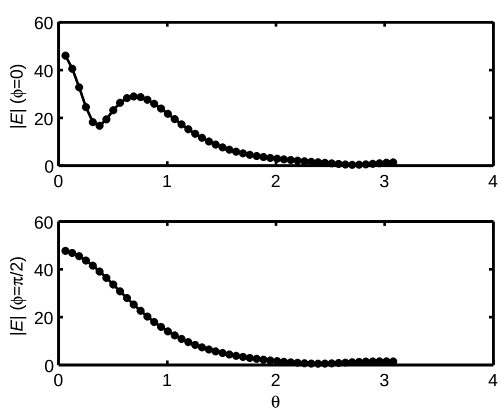

Figure 3: The magnitude of the field scattered by the four layered sphere; solid line corresponds to the solution with integral equation and dots to the dyadic Green's function.

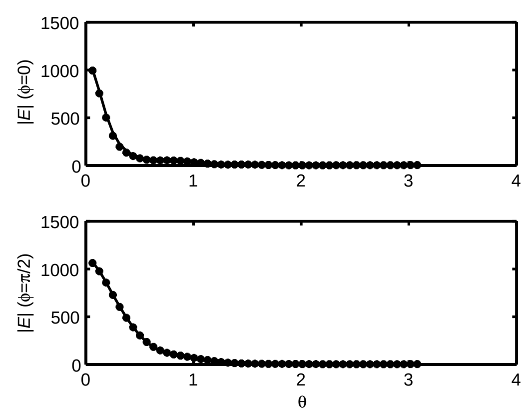

Figure 4: The magnitude of the total field inside the matching medium layer; solid line corresponds to the solution with integral equation and dots to the dyadic Green's function.

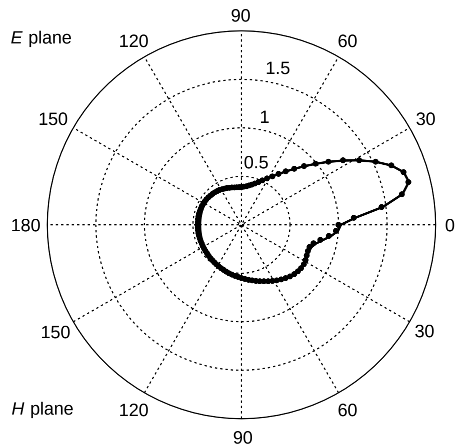

Figure 5: The magnitude of the field scattered in the absence of the matching medium; solid line corresponds to the stroke affected brain and dots to the healthy brain.

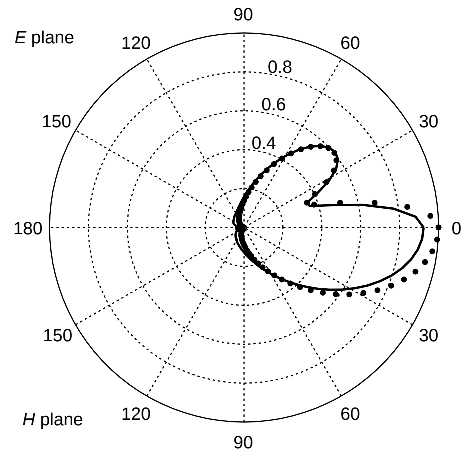

Figure 6: The magnitude of the field scattered in the presence of the matching medium; solid line corresponds to the stroke affected brain and dots to the healthy brain.

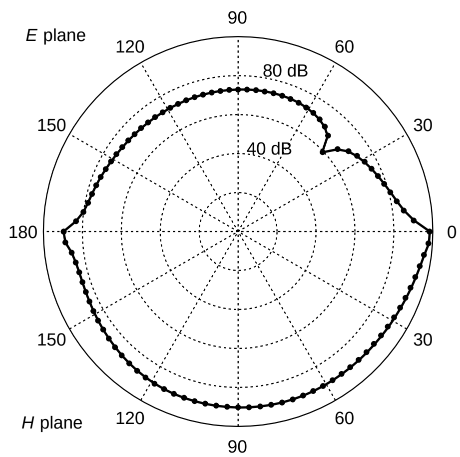

Figure 7: The ratio of $|E|/|E^i|$ in the absence of the matching medium layer; solid line corresponds the healthy brain, and dots to the stroke affected brain.

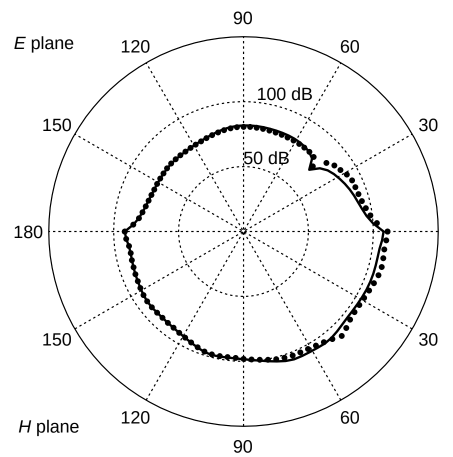

Figure 8: The ratio of $|E|/|E^i|$ in the presence of the matching medium layer; solid line corresponds the healthy brain, and dots to the stroke affected brain.

plane ($\phi = \pi/2$). The results for the normalized scattered fields, presented in Fig. 5, demonstrate that in the absence of a matching medium, no significant variation occurs in the scattered field when the brain is affected by a stroke. The results for the same case with the presence of the matching medium outside the four layered sphere is given in Fig. 6. Comparing these results with those presented in Fig. 5 shows that the matching medium causes a variation in the scattered field.

Next, the same test is performed for the geometry with a matching medium layer, previously analysed in Fig. 4. The parameters for the method and the measurement region are the same as that case. Since in this configuration the total field on the matching medium layer is calculated instead of the scattered field, the ratio of $|E|/|E^i|$, E^i being the incoming field, is plotted in the next figures. First in Fig. 7, the results in the absence of the matching medium is presented. Similar to the results in Fig. 5, there is no discernible variation in the outcome for the stroke affected case. On the other hand, in the presence of the matching medium layer, the existence of the stroke region alters the field values, as seen in Fig. 8.

4. CONCLUSION

The effect of the matching medium on the brain imaging has been tested by using a piecewise homogeneous layered sphere as a head model. Two different configurations has been used to compare the the field scattered by a healthy brain and by a brain with a stroke area. The simulations show that without a matching medium, the presence of the stroke area do not cause a significant change in the scattered field. Therefore, it can be concluded that the presence of an appropriate matching medium layer is a prerequisite for a working microwave imaging system. However, the effect of the matching medium as observed in the numerical simulations might be inadequate for a successful implementation of the microwave tomography for the brain stroke detection.

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