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Enhancing the focusing properties of an ellipsoidal beamformer based imaging system: a simulation study

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Abstract— **Aim of this study is the improvement of the focusing properties of a microwave radiometry tomography system, used for the imaging of the product of temperature and conductivity in biological tissues via contactless measurements. The operation principle of the device in question is based on an ellipsoidal conductive wall cavity, which provides the required beamforming and focusing. The biological tissue under measurement is placed on one of the two focal points whereas on the other one, a dipole antenna measures the black body type radiation emitted from the head's tissue. In the framework of the present research several approaches are followed in order to improve and optimize the system's focusing properties on the tissue area of interest. Extensive simulations using a commercial FEM tool are performed in a wide range of operation frequencies. Dielectric spheres of various electromagnetic characteristics are placed either around the source (human head model) or the receiver (dipole antenna) in order to improve the matching on the head-air interface. The ability of focusing the electromagnetic energy in specific areas inside the human head is herein investigated in detail and further discussed.**

I. INTRODUCTION

FOCUSED Microwave Radiometry is a measurement technique which detects the natural-thermal radiation emitted by matter. The human brain being at a temperature *T* and having specific electromagnetic properties emits chaotic radiation throughout the whole electromagnetic spectrum. A novel Microwave Radiometry Imaging System (MiRaIS) based on the above Quantum Physics theory, has been used the past six years in various validation experiments as a potential intracranial imaging device [1]-[7]. The system mainly comprises an ellipsoidal conductive wall cavity and a sensitive radiometric receiver, operating at low microwave frequencies [1]-[7]. Both phantom and animal experiments as well as initial human experimentation show promising results regarding the system's potential diagnostic capabilities [1]-[7].

In the framework of this research in order to validate such a biomedical device, two are the main theoretical issues that have to be tackled; on one hand the system's focusing abilities on the tissue area of interest and on the other, the relation between the measured radiometric signal and the properties of the tissue under measurement. Regarding the latter, as it has been theoretically shown in the past and verified through experimentation, the system provides measurements of the variation of the product of temperature and conductivity of the medium under measurement [3]. These measurements are also proportional to a field factor which is a strong function of spatial coordinates and is defined by the system's focusing properties [1]-[3]. These are ensured by the use of the ellipsoidal reflector which possesses the well-known geometrical property of beamforming and focusing every ray originating from one focus to the other [8].

Since though the present problem is an electromagnetic one, it should be investigated how and in what extent the above geometrical model applies. Thus, in order to solve and analyze the second theoretical issue that is of concern as mentioned above, two theoretical electromagnetic analyses have been carried out; the electric field distribution inside the ellipsoidal conductive wall cavity in the presence of a spherical human head model has been calculated by developing a semi- analytical technique based on the Green's Function Theory [1], [2], [5], [7] and using a simulation FEM tool [1], [4]-[7]. From the simulation and numerical results it is concluded that in the range 1.3-3.5GHz imaging of the head model areas placed at the ellipsoid's focus is feasible with a variety of detection depths and change of the spatial resolution, depending on the frequency used. According to the numerical results the detection depth varies from 1.8cm to 5cm while the spatial resolution (3dB focusing region) from 1cm to over 3cm. [1]-[7].

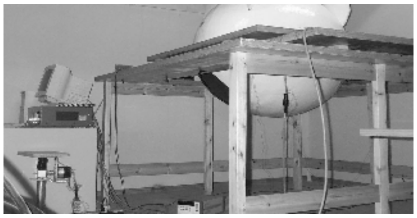

Fig. 1. Photo of the **M**icrowave **Ra**diometry **I**maging **S**ystem

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Following the above research, optimization of the system's focusing properties is being attempted. Both spatial resolution and sensitivity to the change of the human head center localization in respect to the ellipsoid's focus are investigated at various operation frequencies.

Hence, two novel approaches for the problem of the focusing on different head regions are analyzed in this paper. Initially, the dipole antenna is covered by dielectric spherical layers and following, the human head model is placed in a dielectric sphere. The electric field distribution is calculated in both cases while compared to each other as well as to the scenario of not using any matching dielectric material. Following, numerical results are presented in order to evaluate the significance of each proposed solution. The study concludes with a discussion section including commenting over the results of the two approaches. Finally, overall conclusions are presented.

II. MATERIALS AND METHODS

The study presented here is the solution of the reciprocal problem in order to reduce the computational intensity and the significant memory demands imposed by the solution of the initial "forward" problem. According to the reciprocity theorem, a response of a system to a source is unchanged when source and measurer are interchanged. Hence, instead of placing the source in the head model, the response of the double-layered sphere, placed on one focal point of an ellipsoidal cavity, to the excitation generated by a dipole antenna, positioned on the other focus, is calculated.

The analysis of the electromagnetic problem is approached numerically using commercial simulation software (**H**igh **F**requency **S**tructure **S**imulator, **HFSS**, Ansoft Corporation) [9]. HFSS solves Maxwell's equations using a finite element method, in which the solution domain is divided into a set of tetrahedral elements, termed as "mesh." The characteristics of the generated mesh are crucial to obtaining a reliable, well-converged solution.

The aim of the performed simulation tests is to focus on an arbitrary but specific area inside a human head model at various frequencies. Therefore the human head is simulated by a double layered sphere (i.e. brain and skull). Dielectric permittivity and conductivity values are those of the respective human head tissues at the corresponding frequencies. Specifically the inner sphere simulates the brain. The brain is consisted of grey and white matter, each having different permittivity e_r and conductivity σ values [10]. The mean values are obtained for this case. The outer spherical layer represents the skull and has also the corresponding e_r and σ values [10].

Theoretically, as mentioned above, every ray originating from one focal point inside the ellipsoid merges on the other focal point with the same path length [8]. In the present case the microwave radiometry "rays" are electromagnetic waves and originate not just from a simple point but from a dipole antenna having specific dimensions. However, both numerical as well as experimental results [1]-[7] have shown that with the MiRaIS setup electromagnetic energy focuses on an area around the opposite focal point. Hence, if a region of the head is placed at the focal point the energy emitted by the antenna will converge on this area but presenting a variety of penetration depths, spatial resolution and shift from focus center that are frequency depended [1]-[7]. It has been shown in the past, as theoretically expected, that electromagnetic waves attenuate in large depths, especially at higher frequencies. This means that areas deep into the brain are hard to examine.

In order to use a diagnostic device such as the MiRaIS, it is of great importance to have the ability to image any arbitrary area inside the human head, placed on the ellipsoid's focal point where maximum peak of radiation is achieved [1]-[3]. Although the system at its present state seems to exhibit spatial sensitivity in the case when the area of interest is moved away from the geometrical focus, energy still has the tendency to focus in the head center, when the frequency used ensures such a penetration depth [1]-[3].

In order to overcome this and towards the improvement of the system's focusing properties at higher and lower operating frequencies, two approaches were investigated. Initially, the antenna is placed inside two dielectric spherical layers both being lossless materials but having the same permittivity constant as the relevant human head tissues. The dimensions of these spheres are the same as the spheres representing average brain and skull respectively. This scenario is based on the idea that the problem is reciprocal so both focal areas could exhibit similar focusing characteristics.

The second setup proposes that the head is placed inside a larger sphere of a dielectric material with the same permittivity value as the head model's inner sphere (brain). The center of this larger sphere is placed on the ellipsoid's focus. The head model may be placed at any point inside this dielectric material. The idea is that the whole head-dielectric volume is almost homogenous so that electromagnetic wave scattering due to different refraction index is minimized. Furthermore, having almost the same refraction index means that the waves coming from different directions are not significantly bended inside this area, so they may converge to the ellipsoid's focal point. In order to perform the desirable focusing the head's area of interest is placed on the ellipsoid's focal point which coincides with the large sphere's center. The material of the sphere could be foam based or liquid, so that the head would be able to move inside it. The radius of the sphere is almost double of that of the human head so that the latter can be moved in a way that every area can be placed on the focal point.

III. SIMULATION RESULTS

In this section simulations at various frequencies are presented with the view to evaluate the performance of the system in each of the above mentioned cases. In order to minimize the computational intensity, a quarter of the ellipsoid was used for the calculations, exploiting in this way the electrical symmetry of the model in two planes. The ellipsoid is a structure created by revolution of an ellipsis around its major axis. The initial mesh and the following mesh adaptations are carried out by the program. The initial mesh in the present setup usually contained 15,000-20,000 tetrahedrals. After some iterations, the final mesh typically contained 60,000~100,000 tetrahedrals depending on the frequency and the complexity of the model simulated. Convergence is assessed by monitoring the convergence of the S-parameters (*i.e.*, transmission and reflection) from iteration to iteration.

The ellipsoid has a major axis of 150cm and the interfocal distance is 90cm. The head model consists of an inner sphere (brain) of 8cm diameter and a layer (skull) of 1cm thickness around it. The values of permittivity and conductivity of brain and skull at various frequencies are listed in Table I. For the case of brain tissue, a mean value of grey and white matter is considered for the simulations.

TABLE I
PERMITTIVITY AND CONDUCTIVITY VALUES OF HEAD TISSUES AT VARIOUS FREQUENCIES

Freq. (GHz)	permitivity		conductivity	
	brain	skull	brain	skull
0.8	46.25	16.78	0.73	0.22
1	45.42	16.47	0.80	0.25
1.2	44.81	16.21	0.88	0.29

In the following simulation results, the center of the head model is placed at an arbitrary point, i.e. 4 cm off the ellipsoid's focal point towards the antenna. Two different approaches are presented and compared to the simple case (no "matching" dielectric materials used).

In Fig. 2 a simulation comprising the ellipsoidal cavity setup excited by a dipole antenna in the presence of the human head is presented. On the left focal point the dipole antenna is located, whereas on the other the center of the head model. The right mark under the head (Fig 2b) appearing in the figures of this paper indicates the ellipsoid's focal point and the left, the head's geometrical center.

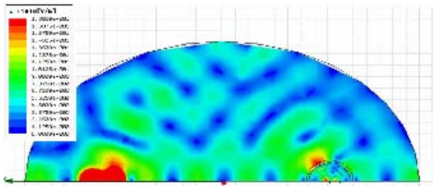


Figure 2a Field distribution at 1GHz

According to the ellipsoid's geometrical property, all of the radiated energy should merge on the focal point (left marker of Fig. 2b). It is observed though, that electromagnetic energy converges also towards the center of the head. However, the change of the field distribution inside and outside the head model compared to the field calculated when the head center is placed on the focus, indicates the system's focusing sensitivity to the head's movements. This is the solution of the simple case of the problem and the results are in agreement with previous studies [1]-[7].

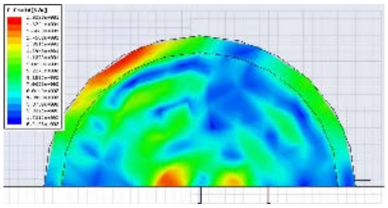
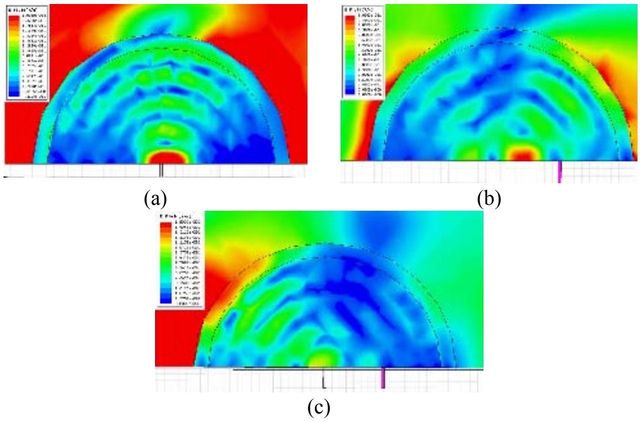


Figure 2b Head placed 4cm towards the antenna (zoom)

In a first attempt to improve the focusing on the desired area and to minimize the energy merged towards the head center, lossless dielectrics were placed around the dipole antenna. They consist of an inner sphere and a thin layer around it with the same dimensions and permittivity value as the head model dielectrics. The inner sphere has a diameter of 8cm and the outer layer, 1cm of thickness. The permittivity values at the correspondent frequency are given in Table I.

The configuration is examined at three operating frequencies: at 0.8GHz, 1GHz and 1.2GHz. At the frequency of 0.8GHz (Fig. 3a), the focal area of the electromagnetic energy is at the head center (left mark). At the frequency of 1GHz (Fig. 3b) the focal area seems to move slightly to the focal point but still is near the center of the head.


(a) (b) (c)
Figure 3 Field distribution of head at a) 0.8GHz , b) 1GHz and c) 1.2GHz

At the third frequency of 1.2GHz (Fig. 3c) there seems to be a difference in contrast to 1GHz. The main area of focusing is almost at the center. However, the frequency is high enough so that high attenuation is observed. Overall, by observation of the simulation results, the scenario of placing dielectrics around the antenna does not seem to improve the focusing compared to the simple case (e.g. see Figs 2b , 3b).

Proceeding to the second attempt of the optimization of the focusing properties, the head model is placed inside a larger lossless dielectric sphere. The center of the sphere is placed at the focus whereas the center of the human head has been moved 4cm off this exact point, as in the previous simulations. The permittivity value of the dielectric is that of the head model's inner sphere (brain). In this way the pair head-dielectric sphere can be assumed as a more homogenous structure in which the wave can propagate without being scattered due to different index of refraction. The results are depicted in Fig. 4a,b,c and d.

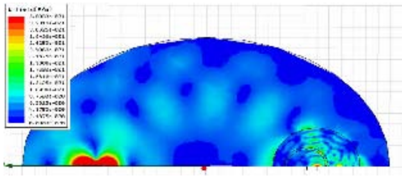


Figure 4a Field distribution of the whole ellipsoid at 0.8GHz

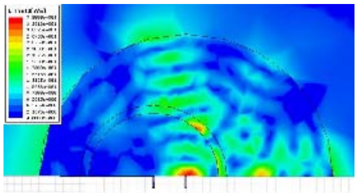


Figure 4b Field distribution of head and dielectric sphere at 0.8GHz

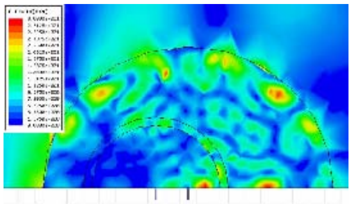


Figure 4c Field distribution of head and dielectric sphere at 1GHz

At the frequency of 0.8GHz (Fig. 4b) the focusing of the energy seems to be at the ellipsoid's focal point (right mark). At the higher frequencies of 1 and 1.2GHz (Fig. 4c and 4d), the area is shifted from its expected position but still clear away from the head center. The field distribution appears to have peak values in the area outside the head and inside the sphere. However, this would not pose a problem because this area is out of interest and exhibiting also constant material temperature and conductivity.

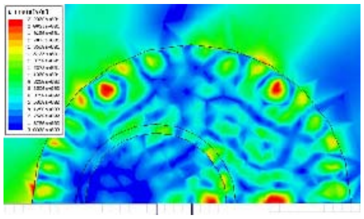


Figure 4d Field distribution of head and dielectric sphere at 1.2GHz

IV. DISCUSSION AND CONCLUSION

Two novel approaches in order to optimize the focusing properties of the MiRaIS, a 3D radiometry passive imaging system, are presented in this paper. Electromagnetic analysis has been performed using a Finite Element simulation methodology at various operating frequencies. Initially, the simulation scenario comprised the configuration of an ellipsoidal cavity excited by a dipole antenna in the presence of a human head model, placed at an arbitrary point in respect to the ellipsoid's focal point. The electric field distribution was calculated and compared to the first optimization scenario with the use of lossless spherical dielectric spheres placed around the radiating antenna. The simulation results do not exhibit any obvious improvements with regard to the simple case. In the second approach, the head is placed inside a larger sphere of dielectric material. In this case, and especially at the low frequency of 0.8GHz, the convergence of the energy is very close to the desirable focal point. Moreover, the field distribution around the head-sphere and air interface is not as intense as in the previous cases. The dielectric sphere has almost the same permittivity as the head tissue. In this way, better matching is performed, allowing more energy to be guided inside the head and less energy scattered.

Future research, including mainly phantom and human experiments, implementing the above focusing optimization techniques, will illustrate the value of the present simulation study. This further investigation could result in potentially creating a complementary totally non-invasive diagnostic brain imaging tool.

ACKNOWLEDGMENT

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