PASSIVE TEMPERATURE MONITORING IN REALISTIC ANATOMICAL HEAD MODELS USING MICROWAVE RADIOMETRY

MARIA KOUTSOUPIDOU, EVANGELOS GROUMPAS, IRENE KARANASIOU, MARIA CHRISTOPOULOU, Konstantinos Karathanasis, Stavros Koulouridis, Konstantina Nikita

Maria Koutsoupidou, Dr., National Technical University of Athens, Evangelos Groumpas, Mr., National Technical University of Athens, Irene Karanasiou, Dr., National Technical University of Athens, Maria Christopoulou, Dr., National Technical University of Athens, Konstantinos Karathanasis, Dr., National Technical University of Athens, Stavros Koulouridis, Prof., University of Patras, Konstantina Nikita, Prof., National Technical University of Athens

Abstract
Focused microwave radiometry, mainly used in clinical applications to measure in-depth temperature distributions inside the human body, may provide the capability of detecting local variations of temperature and/or conductivity at microwave frequencies of excitable cell clusters, such as in the case of brain tissues. In this paper, new aspects of our ongoing research regarding the use of focused microwave radiometry for brain intracranial applications are presented. More specifically, the beneficial use of lossless dielectric matching materials placed around anatomically detailed head models to improve focusing and detection is studied both theoretically and experimentally. The results show complete agreement of theoretical and experimental data; the system is able to sense thermal sources in human brain mimicking tissue with pre-specified detection depth and spatial resolution based on the operation frequency used. The results once again exhibit the system’s potential as a complementary brain imaging tool for in-depth passive temperature monitoring which could be clinically useful during hyperthermia sessions as well as to study the potential biological effects of mobile telephony.

Introduction
Microwave radiometry is a passive monitoring technique which provides information about temperature distribution inside the human body. An imaging system based on focused microwave radiometry able to provide local changes of temperature and/or conductivity in brain tissues has been developed by our group and used in experiments for the past 8 years. Both changes of temperature and conductivity in the human brain have been associated with brain activity.

Theoretical and experimental results conclude that with the appropriate combination of operation frequencies and dielectric layers, it is possible to monitor areas of interest inside phantoms with a frequency-dependent variety of detection depths and spatial resolutions. Previous experimental studies of our group demonstrate the system performance and focusing properties in phantom as well as human experiments. Moreover, numerous studies have also
demonstrated the improvement of the system focusing properties attributed to the use of dielectric and left handed matching layers.

Based on the above mentioned, the scope of our present study is to use more realistic head models both in theoretical and experimental analysis aiming to achieve a more accurate modeling of the system’s future actual operation capabilities. More specifically, an anatomically detailed head model was used to passively measure the temperature of specific points inside the brain phantom in real-time at 2.1 GHz. A thin dielectric cap covered the head model, in order to reduce the reflections at the air-phantom interface. The effectiveness of the dielectric matching medium was previously tested with a simple water phantom. The experimental results were validated by theoretical analysis, where the field distribution inside the head model was calculated.

Materials and Methods

System Description
The proposed imaging configuration, Microwave Radiometry Imaging System (MiRaIS), comprises an ellipsoidal conductive wall cavity to achieve beamforming and focusing, in conjunction with sensitive multiband receivers and a broadband discone antenna for detection (Gouzouasis et al., 2010; I. S. Karanasiou et al., 2004; Karathanasis et al., 2012, 2010). The geometrical configurations of the ellipsoidal beam-former and the system setup are depicted in Figure 1.

Figure 1. Block diagram of the system and

According to previous theoretical studies (I. Karanasiou et al., 2004; I. S. Karanasiou et al., 2004; Karanasiou and Uzunoglu, 2004), the measured voltage at the output of the radiometric receiver is proportional to

\[
I = \left(\frac{\omega_0^2 \mu_0 k}{\pi}\right) \Delta \omega \iiint \Gamma_A(\mathbf{r}^*) T(\mathbf{r}^*) \sigma(\mathbf{r}^*) d\mathbf{r}^* (1)
\]

where \(k\) is the Boltzmann’s constant, \(\omega_0\) is the center frequency of the bandwidth of the observed microwave spectrum, \(\mu_0\) is the free space magnetic permeability, \(V\) is the volume of the focusing area, \(T(\mathbf{r}^*)\) is the temperature spatial distribution within the medium of interest, \(\sigma(\mathbf{r}^*)\) is the spatial distribution within the medium of interest for the electric conductivity, and \(\Gamma_A(\mathbf{r}^*)\) is the Kernel function related to the observed medium Green’s function, taking into account the electromagnetic properties of the receiving antenna.
The temperature resolution of this system has been found to be approximately 0.1 mV/°C at 2.4 GHz in previous studies (Karathanasis et al., 2010).

2.1 Matching Medium

A dielectric material in powder form with electrical permittivity $\varepsilon_r = 9$ and dielectric loss tangent $\tan\delta = 0.0007$ ($K = 9$, Emerson and Cuming, Randolph, MA, ECCOSTOCK® HiK Powder), was tested as matching medium for brain temperature passive imaging. To this end, the following experiment was performed. Two cylindrical containers were filled with distilled water of approximately 40°C. The first container (container A) had 4 cm radius and 7 cm height and the second one (container B) had the same dimensions, but it was surrounded by a 1 cm thick layer of the dielectric matching medium. From time $t = 0$ s until time $t = 25$ s, the system measured the background noise. Container A was placed at the ellipsoidal beam-former’s focal point until $t = 50$ s when it was removed. Container B was then centered at the focal point from time $t = 75$ s until time $t = 100$ s, and again from time $t = 125$ s until time $t = 150$ s.

![Graph showing radiometric voltage output of temperature measurements](image)

Figure 2. Radiometric voltage output of temperature measurements for testing dielectric material ($K = 9$, Emerson and Cuming, Randolph, MA, ECCOSTOCK® HiK Powder) as matching medium at 2.1 GHz.

The radiometric output at 2.1 GHz is presented in Figure 2. The placement of both containers resulted in a radiometric output increase from the baseline. However, the increase created by container B is significantly enhanced if compared to the effect created by container A. As it is observed, the proposed matching medium improves the sensitivity of the signal detection. During the following experiments with MiRaIS, the dielectric material will cover the external surface of the anatomic head model, in order to reduce the electromagnetic reflections at the air-phantom interface and increase the imaging sensitivity of the system.

Numerical Analysis

The simulations were performed using the commercial software SEMCAD X by SPEAG, [www.speag.com](http://www.speag.com) (SEMCAD, n.d.). Figure 3 shows the simulation setup: a radiating element was placed at the right focal point of the ellipsoidal cavity and the anatomically detailed head model was placed in the left one. The head phantom models the head of an adult woman; it is significantly detailed and consists of 44 tissues.
Figure 3. Simulation setup of the ellipsoidal cavity: the antenna is placed on the right focal point and the head model on the left focal point. The anatomically detailed head model covered by a cap with dielectric matching medium.

The analysis was initially performed with the bare head model and then, the simulation was repeated with the head model covered by a cap of a dielectric matching medium ($\varepsilon_r = 9$ and $\tan\delta = 0.0007$) with equal properties to $K = 9$ (Emerson and Cuming, Randolph, MA, ECCOSTOCK® HIK Powder). The focal point of the ellipsoidal cavity was aligned to the center of the head model, which is depicted as a black dot at Figure 3.

A monopole over ground plane antenna operating at 2.1 GHz was chosen as radiating element for the simulation setup. For computational reasons, in the simulations the reciprocal problem is solved, where the field created by the radiating element is calculated inside the ellipsoidal cavity and the head model.

Figure 4 shows the distribution of E-field magnitude inside and around the head model with a logarithmic scale with and without the dielectric cap. The colour maps were clamped at a common maximum field strength of 20 V/m. The analysis results reveals that the use of a dielectric layer increases significantly the penetration of the field inside the head model.

Figure 4. Electric field distribution inside the human head model with and without the presence of matching layers at 2.1GHz.

Experiment

Brain Phantom

For the temperature measurements with MiRaIS, an anatomically detailed head model was used. Inside the head model, a brain phantom comprising white and gray matter was placed (Figure 5). The grey matter phantom recipe consisted of 570 ml distilled water, 200.7 g cornflour, 12.4 g agar and the white matter phantom recipe of 400 ml distilled water, 203.3 g corn-
flour, 10.8 g gelatin (Mohammed et al., 2014). The dielectric matching medium covers the external surface of the head model forming a layer of 1 cm thickness.

Figure 5. a. Brain phantom comprising white matter (blue area) and grey matter (white area) inside anatomically detailed head model. The external surface of the model is covered by dielectric matching medium, 1 cm thick. The beam-former’s focal point is aligned firstly with point A and sequentially with point B. b. The head model placed on the wooden base of the conductive beam-former.

Experimental procedure
Previous studies examined the system’s ability to detect phantoms at different temperatures using microwave radiometry (I. Karanasiou et al., 2004; I. S. Karanasiou et al., 2004; Karanasiou and Uzunoglu, 2006, 2004). In this paper, the temperature of specific points inside an anatomically detailed head model is sensed using passive microwave radiometry in real time.

The anatomic head model is placed on a wooden base with the points A and B (Figure 5.a) of the brain phantom sequentially aligned to the beam-former’s focal point. Point A lies on the white matter – grey matter phantom border line and point B lies 1 cm deeper inside grey matter. A small cylindrical container with 30 ml distilled water at 38 °C is used as a thermal source to be detected by the radiometer.

The procedure of the experimental setup was as follows: Initially, the focal point of the beam-former matches point A. Until t = 40 s the radiometer measured the background noise. The small container is then inserted at point A inside the brain phantom and it is removed at t = 80 s. At t =120 s the small container is re-inserted inside point A and left until t = 160 s. Then, point B of the phantom is centered at the focal point of the beam-former and this procedure is repeated.

Figure 6 presents the radiometric voltage outputs during the experimental setup at 2.1 GHz for points A and B. At point A, the thermal source was detected with a clear voltage increase from the baseline. The detection of the thermal source at point B corresponded to a smaller voltage increase. In both cases the experiment was repeatable. Therefore, it is confirmed that MIRals can detect a warm area of small volume inside a cooler environment inside the anatomically detailed head model at least 2 cm deep inside the brain at 2.1 GHz, as the simulation results have already shown.
Conclusions

In this paper, passive microwave radiometry was used to detect temperature changes at various points inside an anatomically detailed head model at 2.1 GHz. MiRaIS can perform totally passive, real-time with enhanced sensitivity and resolution temperature monitoring of the brain. However, brain is the most complicated human organ presenting complex dielectric properties, and thus, it is still a challenge to image specific locations within this tissue.

Herein, the simulation analysis was performed using an anatomically detailed head model consisted of 44 different tissues. Also, the final experimental setup consisted of the head model filled with white and grey matter phantom measured. The results have shown that temperature changes can be detected at least 2 cm deep inside the brain phantom at 2.1GHz. A dielectric material was examined as matching medium through experiment and numerical analysis. The results have shown that this material significantly enhances the sensitivity of the imaging system.

Future work will focus on thermal analysis inside the anatomically detailed head model using software tools. Also, the resolution and sensitivity of the system will be further investigated with experiments on the anatomically detailed phantom.

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