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***Abstract*—Towards a preclinical prototype for diagnostic and monitoring of cerebral pathologies, here we present the 3D electromagnetic (EM) virtual prototyping of different clinical scenarios as an instrument for studying the interaction of biological tissues with EM waves, for designing a microwave brain imaging scanner and for generating a set EM fields usually required by imaging algorithms. We employ a full-wave modelling, which uses a Method of Moment (MoM) solver with high order basis functions and includes frequency variable electrical parameters for each component. The model of the microwave imaging system consists of 24-element conformal antennas, an anthropomorphic adult human head, and a spherical shape blood-filled as stroke. Here, the simulated system and data are tested applying an imaging algorithm based on Truncated Singular Value Decomposition (TSVD) and Born approximation, but they can be combined with other microwave imaging algorithms.**

***Index Terms*—microwave imaging, full-wave simulation, stroke monitoring.**

I. Introduction

The brain stroke is a disease that restricts or stopped the regular supply of oxygen-rich blood and nutrients to part of the brain, causing the death of brain cells. A stroke occurs when a blood vessel of the brain is either blocked by a clot or bursts (or ruptures), then leading to brain injury, disability and possibly death [1]. Strokes are a medical emergency, and urgent treatment is essential. The sooner a patient receives adequate treatment, it reduces the damages, probability of death, latter disabilities, or a second stroke [2]. Worldwide, the figures show the stroke as the second on the rank of the most common cause of death, reaching 33 million cases per year, and third as a cause of disabilities, becoming the stroke in an essential social and economic issue [3]. In this context, the medical and academic community have identified the need for technologies that support an early diagnosis able to detect, localize, and follow-up the progression of the stroke during the treatment.

Currently, to diagnosis, it is used well-established technologies such as magnetic resonance imaging (MRI) and computerized X-ray tomography (CT), which deliver highly reliable diagnostic information. However, these have intrinsic limitations as time-consuming (not applicable in real-time monitoring), not portability, high cost, and harmful due to ionizing radiations (in the CT case), that let space for novel complementary technologies.

One of the upcoming technologies that have been gaining interest in brain imaging in the last years is microwave imaging (MWI) [4-10]. It is an attractive solution that exploits the fact that the healthy tissues of the brain and the stroke-affected zones present high electric contrast under applied microwave radiation to produce medical images. MWI overcomes the main drawbacks of traditional imaging techniques. First, MWI is a low-power approach; i.e., it is non-ionizing technology applicable to continuous monitoring. Second, MWI works similar technologies to telecommunications ones; then, it can take advantage of miniaturization and cost reduction of microwave technologies to deal with portability and cost issues of current methods.

In general, an MWI system for brain imaging is a low-intensity and cost-effective system that consists of an antenna array, a vector analyzer, a switching matrix, and dedicated hardware. The antenna acts as a permittivity sensor and determines the maximum resolution of the reconstructed image. As the antenna work on a high frequency, better spatial resolution attains an image. However, due to the low penetration of high-frequency waves in biological tissues, the antenna must find the best trade-off between resolution and penetration [10]. The VNA and the switching matrix transmit and receive all possible combinations of signals impinged towards the brain [7]. Then, the dedicated hardware processes the data and generates the image using an inverse algorithm [11][12].

This paper aims to provide a realistic 3-D simulation framework that mimics a lifelike microwave monitoring prototype in order to pre-assessment experimental clinical scenarios and laboratory setups. The proposed virtual prototyping is an essential step in the realization of the microwave imaging system that, thanks to including all the system details, allows us to mimic the real experimental scenario accurately and to easily optimize the system as well as changing the case under test.

Moreover, the full-wave numerical simulation generates EM fields and scattering data, which are valuable insets for stroke classification and image reconstruction algorithms [13][14]. A simulation framework can be an essential tool to evaluate and collect large samples of simulated clinical data required to train machine learning algorithms or refine the reconstructed images based on iterative reconstruction algorithms.

In the following sections, the paper presents a general description of the simulated MWI prototype for stroke follow-up, the simulation parameters, and data validation using an imaging algorithm.

II. 3-D Virtual Prototyping

The computational model used for the simulation consist of an optimized set of 24 discrete “brick” antennas placed conformal to a realistic anthropomorphic adult head as shown in Fig.1. In a laboratory setup, the bricks can be supported by a plastic helmet and then connected to a vector network analyzer (VNA) through a switching matrix [7]. The designed brick antennas are printed monopoles on FR4 dielectric slab immerse in a solid matching dielectric block made of polyurethane-rubber and graphite. The antennas work over the band of 0.8-1.2 GHz, are back feeding by a coaxial cable, and their substrate has an $\varepsilon_r = 4.3$, while the matching brick $\varepsilon_r = 18.5$ and $\sigma = 0.21$ S/m at 1GHz. A single antenna has a thickness equal to 0.16 cm, and the rigid coaxial a length of around 7 cm. Fig. 2 shows the additional geometrical data of the simulated brick-antenna.

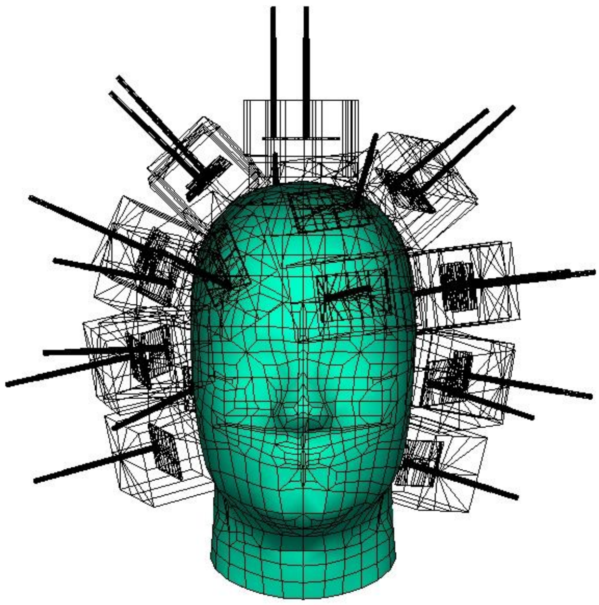
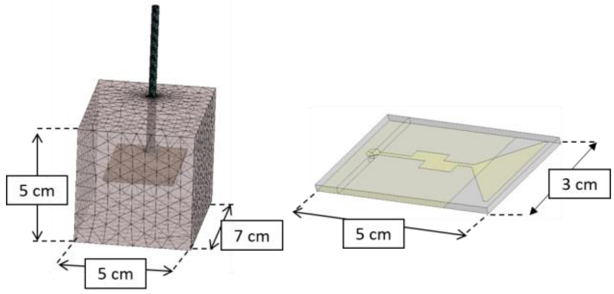


Fig. 1 Antenna array helmet and human head phantom

Then, as a first test case, we use a human phantom filled homogeneously by an average brain medium that mimics the dielectric properties of grey/white matter as reference scenario of a healthy subject. Meanwhile, the bleeding patient model (the one affected by a hemorrhagic stroke) adds to healthy model a 2cm spherical region filled uniformly with blood for play the stroke. The dielectric properties of brain and blood are $\varepsilon_r = 38.58$ and $\sigma = 0.62$ S/m, and $\varepsilon_r = 63.4$ and $\sigma = 1.58$ S/m at 1GHz respectively.

The reported choice of the working frequency band as well as the optimal antenna layout follow the rigorous procedure, based on the inspection of the spectral properties of the discretized scattering operator, described in [6][10].



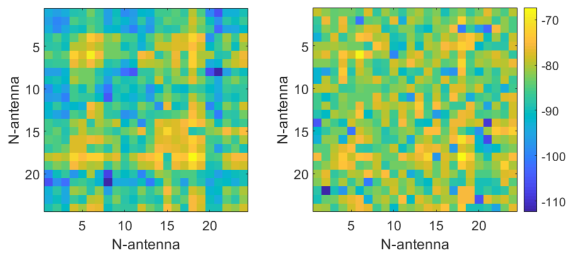
(a) (b)

Fig. 2 Brick antenna geometry. *(a)* Brick dimension, *(b)* Innet antenna dimension

In the following, we perform the numerical simulation on WIPL-D Pro software®, using a solver based on Method-of-Moments with high-order basis functions and GPU acceleration [15]. The complete model reaches above 200k unknows and generates simulated reception/transmission coefficients between all possible combinations of antenna pairs in healthy/non-healthy cases, and the EM field distribution within the human head.

III. Validation with TSVD Algorithm

The described 3-D modeling of a MWI system is here validated via an imaging reconstruction of an intracranial stroke affection. For the reconstruction, we implement the Born approximation and the Truncated Singular Value Decomposition (TSVD) algorithm [10]. From the 3-D simulated scenario, we gather the electric field in a volume surrounded the head to generate a discretized scattering operator, and the differential (between a healthy and unhealthy cases) scattering matrix at the antenna ports: these data are given in input to the TSVD algorithm to detect the position and size of the stroke area. Furthermore, we exploit the simulation framework to assess the reconstruction quality under a noise condition, which is a critical factor for real implementation.



(a) (b)

Fig. 3 Differential scattering matrix at the antenna ports scaled in dB. *(a)* Case without noise, *(b)* Case with high level of noise (white gaussian noise of 50dB)

Like the first scenario, we consider a noiseless case for imaging reconstruction. In this initial situation, the differential scattering matrix obtains a maximum value of -67.6 dB staying above the VNA levels. Then, like a second case, we add high levels of white gaussian noise (around 50dB) to simulated data to mimic an extreme noisy condition of measuring. Fig. 3 depicts both differential matrixes evidencing a dispersing effect due to the noise.

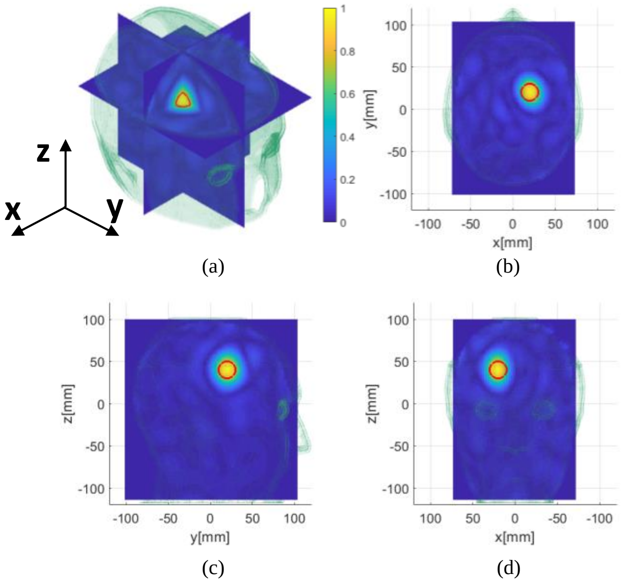


Fig. 4 Reconstructed imaging of a 2cm hemorrhagic stroke simulated scenario. *(a)* 3-D view with the three main slices on middle of the stoke area, *(b)* Transverse plane, *(c)* Sagittal plane, *(d)* Frontal plane

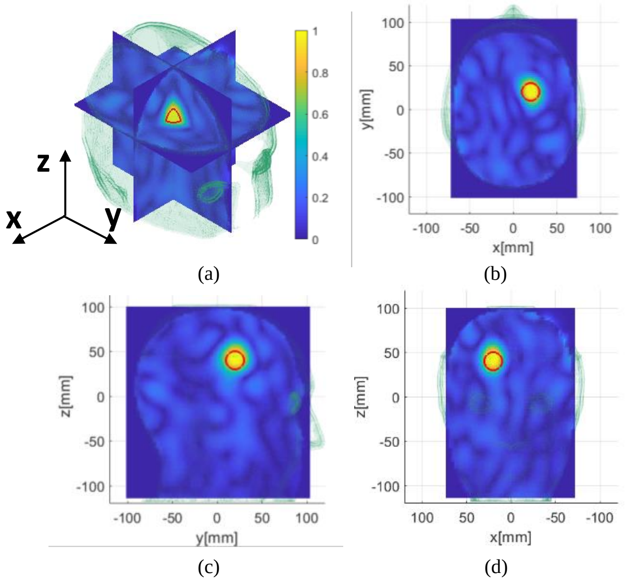


Fig. 5 Reconstructed imaging of a 2cm hemorrhagic stroke simulated scenario adding white gaussian noise of 50dB. *(a)* 3-D view with the three main slices on middle of the stoke area, *(b)* Transverse plane, *(c)* Sagittal plane, *(d)* Frontal plane

Finally, Figs. 4 and 5 depict the reconstructed images for the two cases mentioned above. Each figure represents the imaging of cases under test though a 3-D view and transverse, sagittal, and frontal planes on the stroke area. Here it is worth mention that despite the reconstruction figures are showing just tree planes, the imaging algorithm recovers a 3-D image, and any other plane could be displayed. In Figs. 4 and 5, the red circles indicate the actual size of the hemorrhagic stroke, while the lighter zones show the reconstructed stoke affected region.

For the noiseless case, we can notice an almost perfect match between the expected and reconstructed stroke volume. However, in the added noise case, the reconstructed result highlight the healthy area is more than in the noiseless one and distorts the stroke area slightly, although the stroke area is still differentiable from the background.

IV. Conclusions and Perspectives

We presented a description and validation of a full-wave numerical model of a brain stroke monitoring system generating 3-D imaging reconstruction of likely clinical condition or lab testing case. The model includes detailed realistic scenarios and has the potential to be extend to further and complex ones.

The next steps of the research include a more sophisticated head including different tissues, and the assessment of different cerebrovascular medical conditions.

Acknowledgment

This work was supported by the EMERALD project funded from the European Union’s Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No. 764479.

We thank to Prof. Branko Kolundzija and WIPL-D for providing the WIPL-D Pro software.

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