Advancements in the Experimental Validation of a Wearable Microwave Imaging System for Brain Stroke Monitoring

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***Abstract*—Stroke is a disease that negatively affect brain oxygenation, so impacting short- and long-term people living conditions or, in the worst case, provoking the death. Brain stroke causes physiological variations in the affected tissues, which in turn produce relevant changes in the permittivity and conductivity of the involved tissues. Such changes can be detected and imaged by processing the scattering response at microwaves of the brain. This work advances the experimental validation of a microwave-based scanner to generate 3-D contrast dielectric maps, using low-complexity microwave hardware and a real-time standalone linear inversion algorithm based on the distorted Born approximation. The validation herein presented faces non-trivial conditions using anthropomorphic multi-tissue head and stroke phantoms, so replicating a laboratory set-up very close to the clinical scenario.**

***Index Terms*—Biomedical microwave imaging, brain stroke monitoring, inverse scattering.**

I. Introduction

A stroke is a medical condition that leads to the deterioration of brain tissue due to an insufficient supply of oxygen and nutrients. This shortage is typically caused by a disruption in blood flow within the brain, which can result from a ruptured brain artery, a leak in the blood vessels, or the presence of a blood clot. Stroke induces changes in the normal physiological characteristics of the affected brain tissues, including alterations in their dielectric properties. In the case of a hemorrhage (HS), the permittivity of the tissue affected by the stroke increases owing to the presence of bleeding, while in the case of ischemia (IS), the permittivity decreases as a result of reduced oxygen supply.

Microwave imaging (MWI) technologies aim at providing information on the physiological conditions of the body, by relying on the electric contrast existing between healthy and unhealthy tissues. In particular, from the processing of the back scattered response of the region of interest when exposed to an EM field at microwaves radiated by an array of transmitting-receiving antennas, a spatial distribution of the electric contrast is obtained [1]–[6]. This technology is intended to serve as a complementary solution to current standards such as Magnetic Resonance Imaging (MRI) or X-ray-based Computerized Tomography (CT). MWI offers the advantage of being non-ionizing, utilizing low-power intensities, and remaining cost-effective despite its resolution limitations.

In this context, this work extends the capabilities validation of a low-complexity MWI prototype for monitoring in real-time the after-onset stroke evolution presented in [7], including experimental tests on the non-trivial scenario of an anthropomorphic multi-tissue head. Hence, we approach the problem of unknowing the actual morphology of the studied patient, and the stand-alone imaging retrieval with a low-computing demand. The results presented are a meaningful step towards the clinical testing of the device.

II. Imaging Algorithm

The imaging of a brain stroke condition starting from its response when exposed to microwaves is an inverse problem, which aims to recover the spatial dielectric distribution within a domain of interest (DoI) from a limited number of field samples measured outside it.

Such an imaging problem is an ill-possed and non-linear one, whose solution is not trivial. Hence, in the application herein presented, we narrow down the non-linearity issue by referring to a monitoring scenario, where the goal is to retrieve a temporal contrast variation caused by the stroke evolution.

In this case, the problem recasts to a simplified version considering a "weak" and localized perturbation, which allows us to rely on the Born approximation while building the imaging kernel, as shown in the forward statement in [8]. Following this approach, it is possible to tackle the problem via linear inversion strategies, for instance, using the truncated singular value decomposition (TSVD) algorithm [9] (applied in this work as in [7]), giving the possibility of providing instantaneous feedback, which is an unsolved medical need. The differential scattering matrix, known-input data, can be written as:

$$\Delta S(t_1, t_0) = -\frac{j\,\omega\,\varepsilon_b}{2\,a_p\,a_q}\int_{\mathrm{DoI}} \mathbf{E}_p^{ref}(\mathbf{r}, t_0)\cdot\mathbf{E}_q^{ref}(\mathbf{r}, t_1)\,\Delta\chi\,d\mathbf{r}, \tag{1}$$

where a_p and a_q are the incoming and outgoing power waves, given at the p-th and q-th antenna ports, respectively, ε_b stands for the permittivity of the background medium, j is the imaginary unit, and $\omega = 2\pi f$ is the angular frequency. The symbol "$\cdot$" denotes the dot product, $\mathbf{E}_p^{ref}$, $\mathbf{E}_q^{ref}$ are the field distributions radiated by the p-th and q-th antennas, at the time instants t_0 and t_1 respectively, in a reference scenario, and $\Delta\chi$ is dielectric contrast within DoI, being then the target of the inversion.

Moreover, it is worth noticing that the assumption of a reference scenario to build the kernel, which is a frequency-depend integral one and is computed via detailed full-wave simulations [10], relies on the fact that the patient's morphological specifics are unknown during an actual clinical situation. Hence, we assume a reference scenario with a homogeneous head to get the basis where the ΔS are projected during the imaging.

Finally, for the testing, we employ 1 GHz as frequency operation, which is determined as optimal for the application and considers the trade-off between resolution and penetration [11]. Moreover, to reduce the effects of noise propagating within the imaging kernel and provoking artifacts, we apply the mitigation scheme proposed in [7].

III. Experimental Validation

Regarding the hardware component, the MWI scanner consists of a multi-view architecture mainly made of a two-port vector network analyzer (VNA, Keysight P9375A), acting as a transceiver, twenty-two antenna array, and an electromechanical switching matrix multiplexing the signals [7].

To validate this prototype, we design a multi-tissue phantom to closely mimic a stroke patient's real-life conditions. The phantom is composed of two main parts: a solid one that represents all tissues except for the brain, which is made in liquid form. For the former, we employ either a mixture of urethane rubber and graphite powder or carbon-loaded plastic [12]. In contrast, the brain tissue simulation is achieved using a mixture of water, alcohol, and salt [13]. We use the Keysight "N1500a materials measurement suite" software to characterize the dielectric properties [14].

Figure 1(a) depicts the realistically shaped stroke and in (b) the multi-tissue head wearing on the antenna array as a helmet. Moreover, notice the head phantom has an upper cavity that allows it to fill the brain area up while facilitating the positioning of the stroke in different locations. Meanwhile, (c) presents the 3-D retrieved normalized contrast of an HS positioned at the rear-left side (occipital lobe), approximately 5 cm from the top of the head. It is reported as just a slice centered in the middle stroke variation, and the volumetric shaping is indicated at the top, considering the values below -3 dB of the maximum. We can verify that the stroke area is well-identified.

IV. Conclusion and Perspectives

This study showcases an experimental validation of a low-complexity MWI device consisting of twenty-two antennas. It is employed to conduct 3-D stroke imaging within a realistically simulated laboratory environment utilizing an anthropomorphic multi-tissue head phantom. The findings affirm the system's reliability with regard to pinpointing a stroke's location, even under the assumption of the linearized (homogeneous-based) imaging kernel. Moreover, it endorses stand-alone, low-computing, and real-time capabilities.

As the next steps, an extended measuring campaign is planned, including the use of machine learning algorithms for pathology discrimination [15] and a COTS-based customization of RF front-end systems [16].

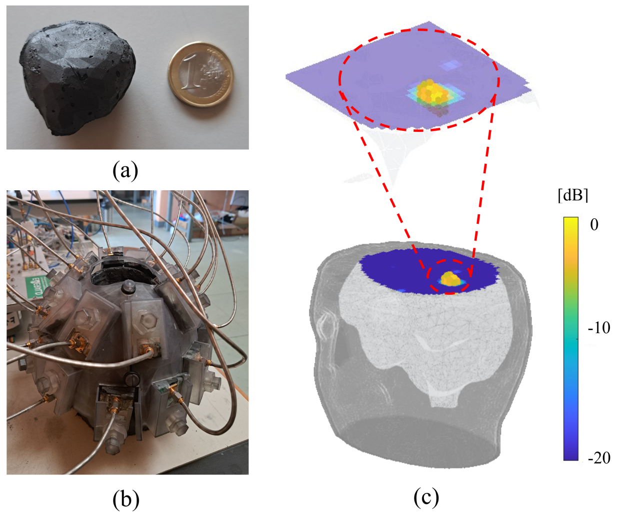

Fig. 1: Realistic stroke phantom (a); multi-tissue head phantom with the helmet in which antennas are placed (b) and 3-D normalized dielectric contrast sliced in the middle of the stroke region (c).

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