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Experimental Validation of a Microwave Scanner for Brain Stroke Monitoring in Realistic Head Models

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***Abstract*—This work addresses brain stroke evolution assessment in mimicked clinical conditions using a low-complexity microwave imaging (MWI) scanner and realistic anthropomorphic head models. In particular, the MWI prototype employs a wearable 22-element flexible-antenna array, keeping a simple architecture and demanding low-computing power. It allows a real-time follow-up of the stroke-affected areas, providing 3-D maps of the dielectric variation through a differential linear imaging approach based on the Truncated Singular Value Decomposition (TSVD), the distorted Born approximation, and artifact removal procedure. The system includes a digital twin that emulates high-fidelity scenarios via EM full-wave simulations performed in an in-house Finite Element Method (FEM) solver. Finally, the assessment examines the system's monitoring capabilities involving custom-made and lifelike phantoms representing a dynamic stroke evolution.**

I. Introduction

Brain stroke is a fast-evolving life-threatening medical condition with a higher incidence in the aged population [1], which occurs when the oxygen-rich blood supply to the brain is affected by an artery blockage or the burst of a vessel, inducing, respectively, an ischemic (IS) or hemorrhagic stroke (HEM). Due to the nature of the stroke, a prompt medical response is crucial to mitigate brain damage and its repercussions, such as death and post-event short and long-term disabilities. Thus, the physicians diagnose and intervene in it supported by gold-standard image-based tools like Magnetic Resonance Imaging (MRI) and Computed Tomography (CT). However, these are expensive, bulky, and time-consuming and use ionizing radiation in the CT case, limiting their portability and continuous monitoring capabilities.

The unmet medical demands open the door to complementary technologies such as microwave-based ones, reflected in the recent appearance of devices in development or even prototypes in patient trials for stroke classification and imaging [2], [3],which own portability, safeness, non-invasiveness, and cost-effectiveness features. These exploit the penetration of the microwaves and the dielectric contrast between the stroke-affected areas and the healthy surrounding to retrieve dielectric maps, i.e., images, by means of inversion algorithms whose input is the backscattered signal.

This paper concentrates on the extension of the microwave imaging (MWI) scanner validation presented in [4] towards real-life use, exploring and exploiting its capabilities to perform in-time monitoring of complex mimicked scenarios while using realistic head models.

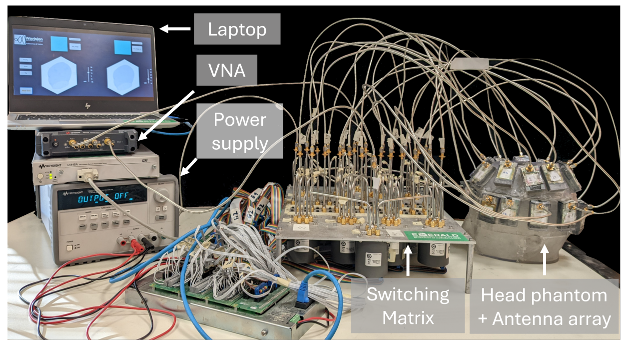


Fig. 1. Scheme of the MWI system prototype.

II. Microwave Brain Scanner

The multi-view MWI prototype consists of a head-conformal helmet-shaped array with twenty-two printed monopole antennas that work around 1 GHz and interface the head through a flexible graphite-rubber matching medium [4]. The acquisition system includes a 2-port Vector Network Analyzer (VNA, Keysight P9375A) and an ad-hoc electromechanical switching matrix (see Fig. 1). Additionally, a laptop controls the switching, collecting the full 22×22 scattering matrix, and runs the imaging algorithm. The scanning time is about 5 minutes, mainly limited by the switching time.

The imaging task is approached by inverting the difference between the scattering matrices gathered at two times, ΔS, to obtain the output 3D map of the dielectric contrast variation within the head, $\Delta\chi$. More details on the imaging algorithm are given in [4], [5]. Hence, the problem is linearized relying on the distorted Born approximation, considering the weakness and local variation of the stroke. Thus, the total field can be assumed equal to the reference field [6], [7]. The truncated singular value decomposition (TSVD) scheme applied to the linear imaging operator leads to the final inversion formula:

$$\Delta\chi = \sum_{n=1}^{L_t} \frac{1}{\sigma_n} \langle \Delta S, [u_n] \rangle \, [v_n], \tag{1}$$

where σ_n is the $n-$th singular value, and $[u_n]$ $[v_n]$ are right and left singular vectors of the discretized operator, respectively, while L_t is the truncation index acting as a regularization parameter. The latter is set equal to -30 dB, to mitigate the effects of noise on the inversion.

To compute the reference electric fields, a detailed digital twin is full-wave simulated via an in-house EM solver based on the finite element method (FEM) [8]. Moreover, it is used to forecast and analyze complex scenarios.

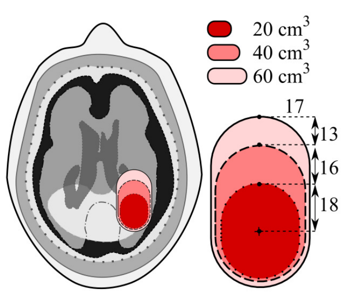
III. Monitoring Assessment

This section summarizes the study of the capabilities of the MWI scanner via its use in a mimicked evolving hemorrhagic condition growing from a volume of 20 to 60 cm^3 in the brain's right hemisphere and working with single-frequency acquisitions at 1 GHz. First, a numerical scenario is developed including a faithful human head model, with each tissue characterized by specific dielectric properties as shown in Fig. 2. Thereafter, the prototype system is tested with a lifelike experimental setup, exploiting human phantoms, with a hemorrhagic growing similar to the numerical model, within a simplified head model. The head is realized with a 3D-printed container filled with water-alcohol-salt mixture having average properties of white and gray matter, as detailed in [4]. A balloon tied to a tube is inserted, positioned in a controlled location, and progressively filled with stoke-mimicking liquids. The properties of the materials are measured via the coaxial probe method aided by Keysight software suite [9]. Figure 3 reports the transverse view of the normalized retrieved contrast cut at the middle of the stroke for both the numerical (first row) and experimental (second row) testing; it can be notice a correct tracking and locating of the stroke variations, with centrimetric resolution.

IV. Conclusion and Perspectives

This contribution outlines a novel low-complexity MWI prototype, demonstrating its potential in brain stroke monitoring by means of representative experiments on a homogeneous phantom. Furthermore, numerical results evidence the possibility of fairly extending the analysis to a more realistic anatomy.

Ongoing work is evaluating the system applied to custom multi-tissue complex phantoms. An example is given in [10], where the authors designed a custom manufacturing process using 3D printed molds and specific safe mixtures of urethane rubber and graphite powder.



	ε_r/σ (S/m)
Skin	40.94/0.890
Fat	5.470/0.053
Bone (skull)	12.36/0.156
CSF	68.44/2.455
Gray matter	52.28/0.985
White matter	38.58/0.622
Ventricle	68.44/2.455
Cerebellum	48.86/1.308
Blood (HEM)	63.41/1.576

Fig. 2. Left: Scheme of the monitored condition (dimension in mm); right: dielectric properties of the tissues at 1 GHz.

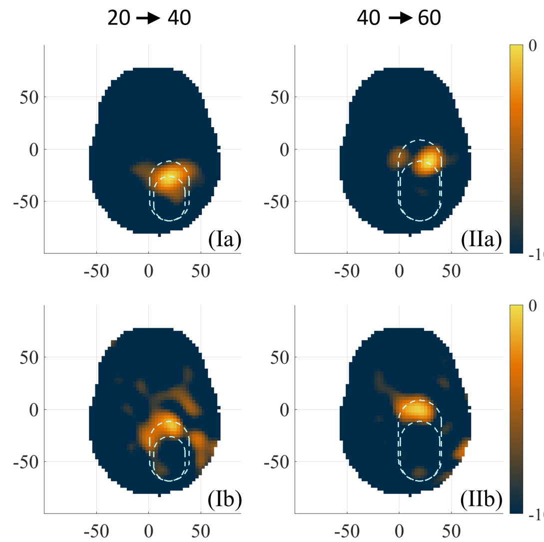


Fig. 3. Normalized contrast in [dB]. (a): numerical case using a multi-tissue head. (b): experimental case using a homogeneous phantom. (I): 20 to 40 cm^3 stroke. (II): 40 cm^3 to 60 cm^3 stroke. Dimensions in mm.

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