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A Microwave Diagnostic Technique for Early-Stage Brain Stroke Characterization

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Abstract

An early diagnosis of brain stroke diseases is crucial to identify the recommended medical treatment in the first hours after the accident. In this contribution, the early-stage characterization of brain strokes is tackled by a microwave imaging technique which exploits the benefits of a combined qualitative/quantitative data inversion. A first qualitative image of the stroke is exploited to build the map of the Lebesgue-space exponent function adopted by the inner solving step of a Newton-type reconstruction approach. Numerical results are presented as an initial assessment of the proposed strategy.

1 Introduction

The possibility of detecting brain injuries and strokes with the aid of microwave diagnostic systems has attracted the attention of several research groups in the last years [1]–[6]. Radar-based, approximate qualitative techniques, and full-wave methods have been proposed to accomplish this challenging task, with the final goal of supporting the early-stage diagnostic process (which has notably a key importance, in particular in the first hours) or the post-event monitoring. One of the major potential benefits of microwave-based diagnostic techniques is related to the possibility of realizing portable devices, usable when traditional methods cannot be applied (e.g., inside ambulance or close to patient's bed). In the framework of quantitative full-wave methods, an important role is played by Newton-type procedures, which have also been applied to stroke diagnostics in [7], [8]. In particular, [8] reports the initial validation of a method based on a regularization approach in Lebesgue spaces with variable-exponent $L^{p(\cdot)}$, where the exponent $p(\cdot)$ is a function of the point inside the investigation domain. In previous works, this function was adaptively defined on the basis of the inversion results achieved iteration-by-iteration, but in the first step it was initialized to a fixed value.

In this paper, a diagnostic system in which the variable-exponent inversion is combined with a qualitative technique, which provides the initial map of the exponent function without resorting to significant a-priori knowledge about the target under test, is proposed.

The paper is organized as follows. Section 2 presents the imaging system prototype and the adopted hybrid inversion approach. Some results in a simulated environment are discussed in Section 3. Finally, Section 4 draws some concluding remarks.

2 Microwave diagnostic technique

The proposed microwave diagnostic technique includes an ad-hoc measurement system (which takes care of scattered-field data collection) and a hybrid inversion approach, adopted for characterizing the dielectric properties of the body under test. Both these aspects are summarized in the following paragraphs. A simplified schematic diagram of the system is shown in Figure 1.

2.1 Measurement system

In order to acquire measurements of the electric field in a set of points around patient's head, a system composed by $N = 21$ cavity-backed bowtie-like antennas [7] located on an 3-D printed elliptical support structure with uniform angular distribution has been developed. Between each antenna and the head, a plastic bag filled with a 70% glycerin/water mixture is used as matching medium. The antennas are connected to a custom switch matrix that allows to acquire multistatic-multiview data. Measurements are done by a vector network analyzer (VNA), which adopts a frequency-stepped strategy in order to collect multifrequency data.

All the parts of the measurement system are connected to a personal computer, which synchronizes RF switch operations, reads VNA measurements and processes the acquired data by means of the inversion method.

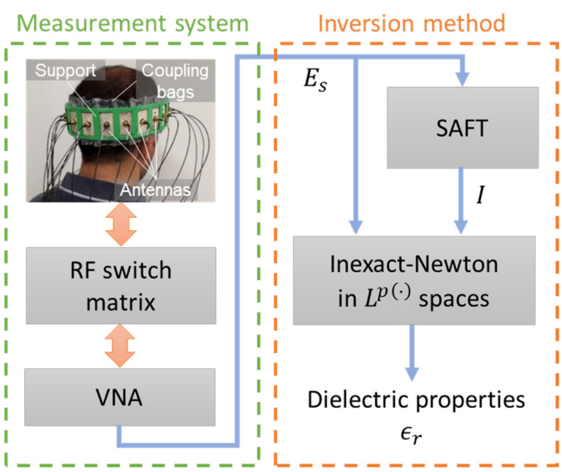

Figure 1. Schematic diagram of the proposed microwave diagnostic system for brain stroke characterization.

2.2 Hybrid inversion approach

The measured scattered-field data are denoted as $E_s(\mathbf{r}, \omega)$, where $\mathbf{r} \in M$ (M being the measurement domain) and $\omega \in \Omega$ is the corresponding angular frequency inside the considered frequency band Ω. First of all, a qualitative synthetic aperture focusing technique (SAFT) is applied to retrieve an indicator function $I(\mathbf{r}), \mathbf{r} \in D$ (D being the investigation domain, i.e., a 2-D region on the xy plane). The obtained qualitative indicator $I(\mathbf{r})$ gives a first estimation of the location of the inclusion inside the body under test, and is calculated as [9]

$$I(\mathbf{r}) = \int_M \int_\Omega E_s(\mathbf{r}', \omega) e^{j\frac{2\omega}{v}\|\mathbf{r}-\mathbf{r}'\|} d\omega d\mathbf{r}', \qquad \mathbf{r} \in D \tag{1}$$

where v is the velocity of the electromagnetic wave in the propagation medium.

After this step, a quantitative method derived from [8] is used to find the dielectric permittivity ϵ_r inside the region D by inverting the well-known nonlinear relationship

$$E_s(\mathbf{r}, \omega) = \mathcal{F}_\omega(\epsilon_r)(\mathbf{r}), \qquad \mathbf{r} \in M \tag{2}$$

where $\mathcal{F}_\omega$ is the nonlinear operator which describes the scattering phenomena at the angular frequency ω [9]. This technique is based on a frequency-hopping inexact-Newton method and exploits the regularization properties of variable-exponents Lebesgue spaces $L^{p(\cdot)}$ inside the inner Landweber solver [10], where $p(\cdot) = p(\mathbf{r}), \mathbf{r} \in D$ is a function of the point inside the investigation domain D. In the first inexact-Newton iteration, the exponent function $p(\mathbf{r})$ is chosen (between the minimum and a maximum values p_{min} and p_{max}, respectively) based on the results of the qualitative step. In particular, $p_0(\mathbf{r})$ is computed as

$$p_0(\mathbf{r}) = p_{min} + (p_{max} - p_{min}) I_N(\mathbf{r}), \qquad \mathbf{r} \in D \tag{3}$$

where $I_N(\mathbf{r}) = |I(\mathbf{r})| / \max_{\mathbf{r} \in D} |I(\mathbf{r})|$ is the normalized indicator function obtained by the SAFT qualitative method. In this way, instead of fixing a single value of p_0 in the first iteration, it is possible to take into account the available information about the target and to assign higher values (close to p_{max}) where the SAFT method detected a significant discontinuity with respect to the background properties, and lower values (close to p_{min}) elsewhere.

3 Results

The proposed inversion strategy has been initially assessed in a numerically simulated environment. A realistic head phantom is taken from the upper part of the *AustinWoman* voxel-based model [13], whose biological tissues are described by Debye models. Inside this model, a hemorrhagic brain stroke is simulated by inserting an inclusion with ellipsoidal shape, characterized by the dielectric properties of blood. This inclusion is centered at $\mathbf{r}_{stroke} = (0.117, 0.172, 0.175)$ m and has x, y, z semi-axes of length 0.02 m, 0.05 m, and 0.05 m, respectively. Like in the measurement system described in Figure 1, $N = 21$ measurement points are located around the head on a horizontal ellipse at $z = 0.175$ m with x, y semi-axes of length 0.092 mand 0.11 m. The multistatic-multiview setup has been simulated by performing N forward simulations, where each measurement location is in turn occupied by an Hertzian dipole, and the remaining points are used to sample the electric field. The forward electromagnetic problem has been solved by the numerical code *gprMax* [11], which is an open-source finite-difference time-domain (FDTD) solver [12]. A simulation region of $0.284 \text{ m} \times 0.32 \text{ m} \times 0.30 \text{ m}$ discretized with cubic voxels of 2-mm side has been considered, where the head model is surrounded by a 70% glycerin/water mixture. The resulting number of cells for the FDTD simulation is equal to 3.408×10^6. Absorbing boundary conditions are implemented by a perfectly matched layer (PML) with 10-cell thickness. The time window simulated by the FDTD has a duration of 30 ns and the adopted time step is equal to 3.85167 ps.

Scattered field data in frequency domain are extracted by performing a Fast Fourier Transform (FFT) operation. In particular, five frequencies with 50 MHz spacing in the band $\Omega = [500, 700]$ MHz have been considered. The same frequencies are adopted for both the qualitative and the quantitative procedures. In the inversion method, the region D is a chosen to be a horizontal cross section of the head, located at the same height of measurement points in the z axis and composed by 1485 4-mm square subdomains. In order to perform the initial SAFT reconstruction, a homogeneous medium with relative permittivity equal to 50 has been considered. The variable-exponent inversion algorithm has been run by using the healthy head as reference configuration and with the following parameters: $p_{min} = 1.4$ and $p_{max} = 2.0$, threshold on the relative residual variation equal to 1%, maximum number of iterations in both the inner and outer loop equal to 100. The normalized qualitative indicator obtained by the SAFT is reported in Figure 2, and the

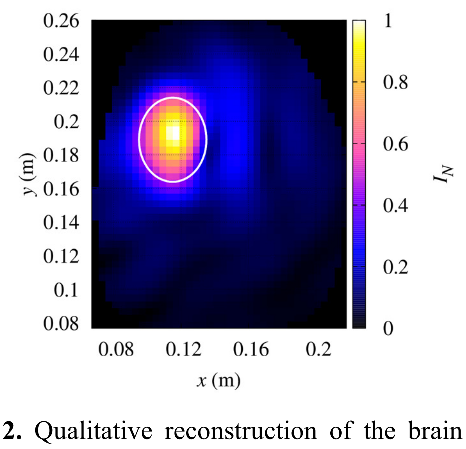

Figure 2. Qualitative reconstruction of the brain stroke obtained by means of the SAFT.

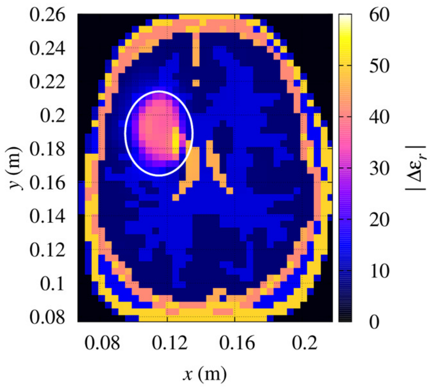

Figure 3. Reconstructed magnitude of $\boldsymbol{\Delta\epsilon_r}$ at 700 MHz obtained with the proposed hybrid inversion strategy.

reconstructed magnitude of $\Delta\epsilon_r = \epsilon_r - \epsilon_{r,b}$ ($\epsilon_{r,b}$ being the complex relative dielectric permittivity of the matching medium) retrieved by means of the inexact-Newton method is shown in Figure 3. As can be seen from these results, the brain stroke has been correctly localized and characterized by the hybrid technique, where the qualitative image has been used to define an initial map of the $p(\mathbf{r})$ function inside D, enhancing the full-wave reconstruction.

4 Conclusions

In the frame of early-stage brain stroke detection and monitoring, this contribution aimed at presenting a microwave diagnostic technique, which is able to localize and characterize the pathological tissues inside the head. A hybrid qualitative/quantitative method is adopted to process the scattered-field data obtained by a custom measurement system. A preliminary assessment of the proposed inversion technique is performed by means of numerical simulations with a realistic head model.

6 References

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