2nd URSI AT-RASC, Gran Canaria, 28 May – 1 June 2018

New In-vivo Mapping of Human Tissues via Inverse Scattering

Martina T. Bevacqua[1], Gennaro G. Bellizzi[1,2], Lorenzo Crocco[1,2], Tommaso Isernia[1,2]
1 DIIES, Univ. Mediterranea of Reggio Calabria, Italy, (martina.bevacqua, gennaro.bellizzi, tommaso.isernia)@unirc.it
2 CNR-IREA, National Research Council of Italy, Naples, Italy, crocco.l@irea.cnr.it

Abstract

This contribution introduces a novel approach for in-vivo estimation of electrical properties of biological tissues based on the solution of an inverse scattering problem and on an innovative use of morphological maps derived by magnetic resonance imaging or other medical imaging techniques. This issue is relevant in different medical applications, especially in hyperthermia treatment planning, where the expected performances are evaluated on the basis of the adopted electrical model of the patients. A preliminary numerical example of the proposed mapping is given dealing with a realistic head model.

1. Introduction

The predication of the performances of medical treatments, such as hyperthermia (HT) [1-3], is generally pursued on the basis of the knowledge of conductivity and permittivity of the biological tissues and thermal patient model. The accuracy of the assumed electrical and thermal model plays a key role on actual in-vivo success of the resulting therapy.

Usually, in HT treatment planning the electrical properties (EPs) model of the patient is built according to the morphological information derived by the segmentation of medical images, e.g. obtained through magnetic resonance imaging (MRI) or computed tomography (CT), and by associating to each tissue of the images the electromagnetic parameters measured in ex-vivo condition [4]. Several ex-vivo EPs databases exist in literature, which are also on-line available, but unfortunately there is no certainty about their reliability with respect to the EPs exhibited by tissues in-vivo conditions [5].

For this reason, this contribution aims at introducing an innovative and low-cost approach for the in-vivo estimation of patients' EPs aimed at HT planning. The proposed technique can be relevant in HT treatments as it exploits the antennas in the HT system not only to provide the power needed to heat the tumor but also to probe the region of interest. In particular, the mapping is pursued by performing a microwave (MW) tomography and by solving the related inverse scattering problem. In order to partially overcome the well-known difficulties corresponding to such a problem as well as the reduced spatial resolution of MW imaging, the approach benefits from the patient specific morphological information extracted from MRI or CT, as briefly explained in the following.

Throughout the paper we consider the canonical 2D scalar problem (TM polarized fields) and we assume and drop the time harmonic factor $exp\{j\omega t\}$.

2. In-vivo Estimation via Inverse Scattering Problem and MRI-based projection

In inverse scattering problem one aims at recovering the EPs of unknown targets, located in a region under test Ω, starting from the knowledge of the incident fields and the measurements of the corresponding scattered fields.

The EPs of the targets are encoded in the contrast function $\chi(r) = \epsilon_s(r)/\epsilon_b - 1$, wherein ϵ_s and ϵ_b are respectively the complex permittivities of the scatterers and the background medium, and $\boldsymbol{r} = (x, y)$ identifies a point belonging to Ω. The region of interest is probed by means of a set of antennas located in $\boldsymbol{r_t}$ in a closed curve Γ, while the resulting scattered fields are measured by receiver antennas also located in $\boldsymbol{r_r}$ on Γ.

The equations describing the scattering problem for the generic transmitter/receiver positions are [7]:

$$E_s(\boldsymbol{r_r}, \boldsymbol{r_t}) = \mathcal{A}_e[W(\boldsymbol{r}, \boldsymbol{r_t})] \tag{1}$$

$$W(\boldsymbol{r}, \boldsymbol{r_t}) = \chi E_i(\boldsymbol{r}, \boldsymbol{r_t}) + \chi \mathcal{A}_i[W(\boldsymbol{r}, \boldsymbol{r_t})] \tag{2}$$

where $E_i(\cdot)$, $E_s(\cdot)$ and $W(\cdot)$ are the incident field, scattered field and contrast source induced in the scatterer, respectively, and $\mathcal{A}_\mathrm{e}$ and $\mathcal{A}_\mathrm{i}$ are a short notation for the integral radiation operators. As well-known, the problem is non-linear and it is also ill-posed due to the properties of the involved operator $\mathcal{A}_e$ [7].

Very many different approaches have been developed in literature in order to partially take on such difficulties. In the following we consider the contrast source inversion (CSI) method [8], in particular the formulation introduced in [9], where the unknowns W and χ are simultaneously estimated by minimizing a non-linear functional, i.e.

$$\Phi(W,\chi)=\sum_t \frac{\|W(\boldsymbol{r_t})-\chi E_i(\boldsymbol{r_t})-\chi\mathcal{A}_i[W(\boldsymbol{r_t})]\|_{l_2}^2}{\|E_i(\boldsymbol{r_t})\|_{l_2}^2} + \sum_t \frac{\|E_s(\boldsymbol{r_t})-\mathcal{A}_e[W(\boldsymbol{r_t})]\|_{l_2}^2}{\|E_s(\boldsymbol{r_t})\|_{l_2}^2} \quad (3)$$

wherein only the dependence from the illumination condition is highlighted.

Due to the non-linear nature of the problem, the functional (3) is non-quadratic. Moreover, due to the huge number of the involved unknowns, gradient-based minimization schemes could be trapped in local minima [10].

In order to avoid the occurrence of *false* solutions (where the adjective *false* denotes solutions different from the actual solution) and simplify the complexity of the inverse scattering problem, some priori information on χ can be exploited in the minimization of (3). In particular, one could represent the unknowns of the problem by means of a convenient representation basis, in such a way to restrict the dimensionality of the unknown space [11] and to fall into the right attraction basin.

To this end, in the following we adopt a representation basis conveniently derived from the segmentation of the (pre-treatment) MRI or CT images. Accordingly, the contrast function χ is projected into a 'tissue space', wherein each basis assumes non-zero values only in those pixels belonging to the considered tissue. The inverse scattering problem is hence turned into a parameter estimation problem, wherein only a single (complex) parameter is looked for in each different tissue.

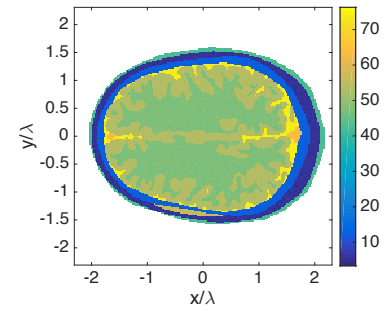
3. A preliminary numerical example

In order to assess the capability of the proposed in-vivo EPs estimation, a preliminary numerical example dealing with a transversal slice of an anthropomorphic head model is provided. The model is derived from the repository available in [12] and by associating to each tissue the complex permittivity value in [13] (see figure 1(a)). Moreover, in order to consider a more realistic scenario, a random variation of 20% is superimposed to in each pixel of model.

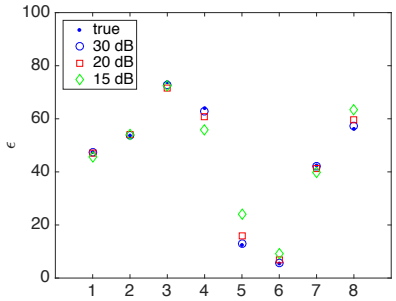
The data have been simulated by using a full wave forward simulator based on the method of moments and corrupted with a random Gaussian noise with a given SNR. In particular, a set of incident fields radiated by 32 line sources evenly spaced on a circumference with radius of 0.18 m has been considered. The working frequency is f=1GHz, while the matching medium has permittivity 40 and conductivity 0.01 S/m. The subdomain has been discretized in 200 × 200 cells of size 0.22 m.

In figures 1(b)-(c) are reported the permittivity and conductivity values of the retrieved profiles corresponding to different SNR and the different tissues. As it can be seen the estimation of the EPs is extremely accurate, thanks to the basis representation (4) arising from the MRI segmentation and composed of just eight functions. The obtained mean square error with respect of the actual values are about 0.001, 0.009 and 0.07, respectively for SNR=30 dB, 20 dB and 15 dB.

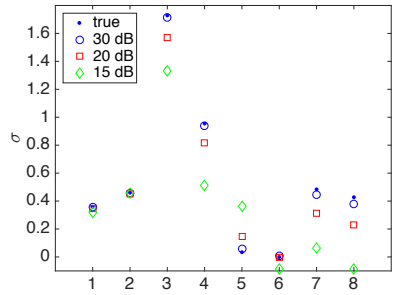
More details and other examples will be given at the conference, together with a fully assessment of a recently introduced hyperthermia treatment planning technique [3].



(a)



(b)



(c)

Figure 1. In-vivo estimation of EPs of brain tissues: (a) Permittivity distribution of the reference profile. (b) Permittivity and (c) conductivity values of the retrieved profile superimposed to the actual one for the different tissues and different SNR.

4. References

1. M. M. Paulides, G. M. Verduijn, and N. V. Holthe, "Status quo and directions in deep head and neck hyperthermia," Radiation Oncology vol. 11, 2016.

2. P. Takook, H. D. Trefna, X. Zeng, A. Fhager, and M. Persson, "A Computational Study Using Time Reversal Focusing for Hyperthermia Treatment Planning," Progress

In Electromagnetics Research B, vol. 73, pp. 117–130, 2017.
3. G. G. Bellizzi, L. Crocco and T. Isernia, SAR constrained focusing through multi-frequency array applicators, 2017 First IEEE MTT-S International Microwave Bio Conference (IMBIOC), Gothenburg, 2017, pp. 1-4.
4. V. Fortunati, R. Verhaart, F. van der Lijn, W. Niessen, J. Veenland, M. Paulides, and T. van Walsum, "Tissue segmentation of head and neck CT images for treatment planning: A multi-atlas approach combined with intensity modeling," Medical Physics, vol. 7, no. 40, 2013.
5. Ryan J Halter et al, The correlation of in-vivo and ex-vivo tissue dielectric properties to validate electromagnetic breast imaging: initial clinical experience, Physiol. Meas. 30(6):S121, 2009
6. U. Katscher, C. A. Berg, Electric properties tomography: Biochemical, physical and technical background, evaluation and clinical applications. NMR in Biomedicine, 2017.
7. D. Colton and R. Kress. Inverse Acoustic and Electromagnetic Scattering Theory", Springer-Verlag, Berlin, Germany, 1998.
8. P. M. van den Berg and R. E. Kleinman, A contrast source inversion method," Inv. Prob., 13:1607–1620, 1997.
9. I. Catapano, L. Di Donato, L. Crocco, O. M. Bucci, A. F. Morabito, T. Isernia, and R. Massa, "On quantitative microwave tomography of female breast," Prog. Electromagn. Res, PIER 97:75–93, 2009.
10. T. Isernia, V. Pascazio and R. Pierri, On the local minima in a tomographic imaging technique, in IEEE Trans. on Geosci. and Remote Sens., 39(7): 1596-1607, Jul 2001.
11. M. T. Bevacqua, L. Crocco, L. D. Donato and T. Isernia, "Non-Linear Inverse Scattering via Sparsity Regularized Contrast Source Inversion," in IEEE Transactions on Computational Imaging, vol. 3, no. 2, pp. 296-304, June 2017.
12. Zubal, I. G., C. R. Harrell, E. O. Smith, Z. Rattner, G. Gindi, and P. B. Hoffer, Computerized three-dimensional segmented human anatomy,Med. Phys., 21(2): 299–302, 1994.
13. Dielectric properties of body tissues in the frequency range 10 Hz–100 GHz, http://niremf.ifac.cnr.it/tissprop.