COST-STSM-TD1301-151016-081173 Scientific Report

STSM Topic: Development of new inversion strategies for MRI based Electrical Properties Tomography

STSM Applicant: Martina Teresa Bevacqua, Università Mediterranea di Reggio Calabria, Reggio Calabria (IT).

Host: Rob Remis, Delft University of Technology, Delft (NL)

Period: 13/11/2016 to 14/12/2016

Abstract

The knowledge of electric properties (EPs) of biological tissues is a fundamental issue to address medical applications of MWI. In the last decades the possibility of reconstructing the electric conductivity and permittivity inside the human body based on field maps acquired by a magnetic resonance imaging (MRI) system has received great attention. In particular, researchers at TU Delft recently have developed a novel approach to tissue parameter retrieval based on the Contrast Source Inversion (CSI) method. On the other hand, at Università Mediterranea, the LEMMA group has a consolidated expertise in inverse scattering and quantitative imaging especially in solution techniques based on CSI. In particular, they have introduced a new inversion model, which can exhibit in some cases better performances with respect to the standard CSI. In this respect, this STSM has been mainly aimed at adapting and testing this new model in the framework of the CSI-EPT. Besides this specific goal of the STM, the overall activities have set the ground for fruitful synergic cooperation between the two institutions on this topic, which is expected to bring results that hopefully will be relevant for the whole MiMed network.

1 Purpose of the STSM

The proposed STSM has aimed at exploring and improving a novel, non invasive, methodology for mapping the dielectric properties of human tissue *in vivo* by combining the expertise of two different groups of research: the group of Prof. Rob Remis at TUDelft and the Lab for E.M. Methods and Applications (LEMMA) group at Università Mediterranea.

At Università Mediterranea, the LEMMA group has developed new reliable and effective solution algorithms for the solution of inverse scattering problems at microwave frequencies [1,2] and has a consolidated expertise in inverse scattering and quantitative imaging also in case of phaseless data [3]. On the other hand, at TUDelft, the Prof. Rob Remis and his research group have recently produced new interesting developments in MRI based Electrical Properties Tomography (MRI-EPT)[4,5] with direct applications to clinical trials.

In this respect, during the STSM a preliminary analysis of the performances of the new inversion model proposed in [1,2] for MRI-EPT has been performed by taking advantage from the knowledge and experience of LEMMA group in inverse scattering and of Prof. Rob Remis and his research group in MRI-EPT.

2 Description of the work carried out during the STSM

The work carried out during this STSM has involved different aspects, which are described in the following two paragraphs.

2.1 Preliminary study of the MRI-based Electric Properties Tomography

The first two weeks have been aimed at getting an insight in the general topic of the MRI-EPT and in the techniques developed by the Host Institution.

The knowledge of electric properties (EPs) of biological tissues is a fundamental issue to address medical applications of MWI. For instance, the capability of obtaining high accuracy maps is essential to determine the specific absorption rate and for imaging based personalized hyperthermia treatment planning. More in general, EPs may also provide diagnostic information related to physiological and pathological conditions of tumors and healthy tissues.

In the last decades the possibility of reconstructing the electric conductivity and permittivity inside the human body based on field maps acquired by a MRI system has received great attention. Nowadays it is possible to use this technique to achieve in vivo maps of the dielectric properties of tissues in the lower part of the microwave spectrum, thanks to the availability of clinical scanners at 7 T and the ongoing development of high field whole-body scanners.

Various studies have shown that using an MRI system is feasible to retrieve the electric tissue parameters from measurable so-called transmit B_1^+ field. This latter is the magnetic field component emitted by the radiofrequency (RF) coil that effectively rotates spins. Rotation of the spins results in a measurable NMR signal. In 1991, Haacke has proposed the idea of extracting the tissue parameters from MR data [6]. More recently, Katscher et al. [7] has introduced Electric Property Tomography (EPT) as a means of retrieving the conductivity and permittivity of different tissue types. Van Lier et al. [8] has demonstrated the feasibility of EPT using phase only information and Sodickson et al. [9] has developed the so-called Local Maxwell Tomography (LMT) technique. All these methods are based on the local field equations (Maxwell's equations or Helmholtz's equation), which are used as a basis for tissue parameter retrieval. The electromagnetic boundary conditions are not taken into account, so, unreliable results may be produced especially near interfaces between different tissue types. Moreover, these methods are also sensitive to noise, since spatial differentiation operators act on generally noisy measured B_1^+ data.

Recently, a novel approach, called Contrast Source Inversion-Electric Properties Tomography (CSI-EPT), to tissue parameter retrieval, based on the Contrast Source Inversion (CSI) method [10, 11], has been developed at TU Delft by Prof. Remis and his group. As opposed to the above-mentioned local methods, CSI-EPT takes the global integral representations for the electromagnetic field quantities as a starting point. The boundary conditions are then automatically taken into account and the method is less sensitive to noise since integral operators (instead of differential operators) act on the measured field data. In addition, in an MRI system one is able to measure the B_1^+ fields inside the object of interest whereby each voxel represents a receiving antenna. Consequently, the ill-posedness of the inverse problem is strongly reduced and, so, the method has the potential to achieve high-accuracy permittivity and conductivity tissue maps of interior parts of the human body.

The basic equations describing the CSI-EPT can be derived from Maxwell equations. In order to get an insight in the math, the canonical 2-D scalar problem (TM polarized fields) is considered in the following and the time harmonic factor $exp\{j\omega t\}$ is assumed and dropped. Let us consider the RF field, denoted as $\{E_i, H_\mathrm{i}\}$, that is present within an MRI scanner in absence of a dielectric background object or body. The medium parameters of the background are given by conductivity σ_b, permittivity ε_b and permeability $\mu_b = \mu_0$. Let us consider inside the scanner a dielectric object, which occupies a bounded subdomain D of the scanner, characterized by a conductivity σ_x, permittivity ε_x and permeability $\mu_x = \mu_0$. Under the above, the basic equations describing the phenomenon are:

$$B_{1\ scat}^{+}(r) = -\frac{k_b^2}{2j\omega}\left(\partial_y - j\partial_x\right)\int_D G(r,r')W(r')dr' = \mathcal{A}_m(W)$$

(1)

$$W(r) = \chi(r)E_i(r) + \chi(r)k_b^2\int_D G(r,r')W(r')dr' = \chi E_{inc} + \chi\mathcal{A}_e(W)$$

(2)

where:

- $r = (x, y)$ belongs to the investigation domain;
- $k_b = \omega\sqrt{\mu_b \varepsilon_b}$ is the wavenumber in the host medium, with $\omega = 2\pi f$ and f the working frequency ;
- $B^+_{1\,scat}$ is the magnetic scattered field measured in an MRI scanner;
- W is the contrast source induced inside the body;
- χ is the contrast function which relates the electromagnetic properties of the object to the one of the background;
- G is the Green's function pertaining to the background medium. If the background is the free space $G(r, r') = -j/4\, H_0^2(k_b|\boldsymbol{r} - \boldsymbol{r}'|)$, being H_0^2 the zero order and second kind Hankel function.
- $\mathcal{A}_m$ and $\mathcal{A}_e$ are a short notation for the integral radiation operators which relate the magnetic field and electric field to the electric currents, respectively.

Note that the scattering problem involved in the problem at hand is non linear as the contrast source W depends from the dielectric properties of the object and is also unknown.

The CSI-EPT method [4,5] aims at recovering the contrast function χ by tackles the problem in its full non-linearity by minimizing a cost functional, which takes into account the data-to-unknown relationship and the physical model [1,2,10,11], i.e.:

$$\Phi(\chi, W) = \Phi_{\mathrm{E}}(\chi, W) + \Phi_{\mathrm{M}}(W) \tag{3}$$

with:

$$\Phi_{\mathrm{E}}(\chi, W) = \eta_{\mathrm{E}} \|W - \chi E_i - \chi \mathcal{A}_e[W]\|^2_{\mathrm{D}} \quad \text{and} \quad \Phi_{\mathrm{M}}(W) = \eta_{\mathrm{M}} \left\|B^+_{1\,scat} - \mathcal{A}_m[W]\right\|^2_{\mathrm{D}}$$

where $\|\cdot\|$ is the ℓ_2 norm and $\eta_{\mathrm{E}} = \|\chi E_i\|^{-2}_{\mathrm{D}}$ and $\eta_{\mathrm{M}} = \|E_s\|^{-2}_{\mathrm{D}}$ are normalization coefficients.

2.2 Contrast Source Extended Born Model for MRI-EPT

The last two weeks have been aimed at adapting the new scattering model proposed in [1,2] to the case of interest and at implementing it in the code developed by Prof. Remis and his group.

The aforementioned new model, called contrast source extended Born (CS–EB), can be obtained by means of a simple rewriting of (2), i.e. [1,2]:

$$W(r) = p(r)E_{inc} + p(r)\mathcal{A}_{eMOD}(W(r)) \tag{4}$$

wherein:

$$\mathcal{A}_{eMOD}(W) = \mathcal{A}_e(W) - f_D(r)W(r)$$

$$p(r) = \frac{\chi(r)}{1-\chi(r)f_D(r)} \qquad f_D(r) = \int_D G(r,r')dr'$$

Together with (1), the object equation (4) identifies the CS-EB model, where the fundamental quantities are the W and the auxiliary function p, which now embeds the contrast function. Note that the function f_D(r) can be evaluated in a closed form in many cases of practical interest. For example, if R denotes the radius of the circular cylinder D, one shows that [1,2]:

$$f_D(r) = -j\frac{\pi k_b R}{2} H_1^{(2)}(k_b R) J_0(k_b r) - 1 \tag{5}$$

where $H(\cdot)$ is the Hankel function of first order and second kind while $J_0(\cdot)$ is the Bessel function of zeroth order. Moreover, note that by assuming R as a parameter, the CS-EB (2) and (4) can be interpreted as a family of equivalent equations, which also means that a proper choice of R could be eventually exploited in order to optimize performances of inversion procedures.

The CS scattering model (2) and the CS-EB one (4) have two different degrees of non linearity (DNL), related to $\|\chi\mathcal{A}_e\|$ and $\|p\mathcal{A}_{eMOD}\|$, respectively. The quantity $\|\chi\mathcal{A}_e\|$, or equivalently $\|p\mathcal{A}_{eMOD}\|$, is a measure of the difficulty of the inverse problem. This represents a fundamental advantage of using the CS-EB model. In fact, it results that the CS-EB model has a reduced DNL with respect to CS one when $|p(r)| < |\chi(r)|$ [2]. As the larger the DNL, the larger the possible number of local minima and the more the possibility of being trapped into a false solution. In order to avoid false solutions, it is always convenient to deal with equations having a DNL as low as possible.

By implementing the new model in the CSI-EPT code and by considering a parametric analysis of the parameter R in (5), the use of CS-EB model is resulted more favorable in term of convergence and saving of iterations than the classical CSI model. This preliminary result has encouraged a future collaboration with the Host institution and further investigations of the potentiality of the CS-EB for MRI-EPT, as described in the following.

3 Description of the main results obtained

In this STSM, an accurate understanding of the physical phenomenon and the analytic model on the basis of the MRI-based EPT has been acquired. Moreover, an accurate study of the literature and the different proposed methods has been performed, with particular interest in the techniques developed by the Host Institution.

Starting from this framework, the CS-EB model, developed at University Mediterranea in collaboration with CNR-IREA, has been adapting to the problem at hand and then implemented in the code. A preliminary analysis has been performed thus demonstrating the potentiality of the CS-EB model for MRI-EPT in term of convergence and numbers of iterations.

4 Future collaboration with host institution

The fruitful cooperative work promoted by the STSM will be hopefully of great interest to future collaboration with the Host institution.

Further tests and optimizations of the CS-EB model for the problem at hand will be performed. First of all, a further analysis on the role of R in the equation (5) will be performed in order to understand how selecting its optimal value [2]. Moreover, another interesting possibility involves the extension of CS-EB for EPT in case of partially known lossy scenario, obtained by taking advantage by the a priori knowledge of the support of the object under test and the average value of the dielectric properties of human tissues.

Finally, in the above-described analysis the uncertainties in the phase of B_1^+ are not taken into account. In practice, direct measurements of the phase are not available and they are usually based on the transceiver phase assumption [4,5]. In order to avoid the transceiver phase assumption, future work could be devoted to the extension of the approach developed by the collaboration between Università Mediterranea and CNR-IREA [3] to the problem at hand.

5 Confirmation of the host of the successful execution of the STSM

We confirm that MARTINA TERESA BEVACQUA from Università Mediterranea di Reggio Calabria worked in our laboratory at Delft University of Technology from 13/11/2016 to 13/12/2016. The visit has been successful and the results, which will promote further cooperation between the two involved institutions, are described in this report, which I confirm.

Rob F. Remis

6 References

[1] T. Isernia, L. Crocco and M. D'Urso, "New tools and series for forward and inverse scattering problems in lossy media," in *IEEE Geoscience and Remote Sensing Letters*, vol. 1, No. 4, pp. 327-331, Oct. 2004.

[2] M. D'Urso, T. Isernia and A. F. Morabito, "On the Solution of 2-D Inverse Scattering Problems via Source-Type Integral Equations," in *IEEE Transactions on Geoscience and Remote Sensing*, vol. 48, No. 3, pp. 1186-1198, March 2010.

[3] L. Crocco, M. D'Urso, and T. Isernia. "Inverse scattering from phaseless measurements of the total field on a closed curve," *JOSA A*, vol. 21, No. 4, pp. 622-631, 2004.

[4] E. Balidemaj et al., "CSI-EPT: A Contrast Source Inversion Approach for Improved MRI-Based Electric Properties Tomography, " *IEEE Trans. Medical Imaging*, vol. 34, No.9, pp.1788-1796, Sept. 2015.

[5] E. Balidemaj et al., "CSI-EPT: A novel contrast source inversion approach to EPT and patient-specific SAR based on B1+ maps," in Proc. 21th Annu. Meet. ISMRM, Salt Lake City, UT, 2013, p. 4178.

[6] E. M. Haacke, L. S. Petropoulos, E. .W. Nilges, and D. H. Wu, "Extraction of conductivity and permittivity using magnetic resonance imaging," Physics in Medicine and Biology , Vol. 36, No. 6, pp. 723-734, 1991.

[7] U. Katscher, T. Voigt, C. Findeklee, P. Vernickel, K. Nehrke, and O. D¨ossel, "Determination of electric conductivity and local SAR via B1 mapping," IEEE Trans Med Imag , Vol. 28, No. 9, 1365-75, 2009.

[8] A. L. Van Lier, D. O. Brunner, K. P. Pruessmann, D. W. Klomp, P. R. Luijten, J. J. Lagendijk, and C. A. T. van den Berg, "B+1 phase mapping at 7 T and its application for in vivo electrical conductivity mapping," Magnetic Resonance in Medicine , Vol. 67, No. 2, pp. 552-561, 2011.

[9] D. K. Sodickson et al. "Generalized local Maxwell tomography for mapping of electrical property gradients and tensors," Proc. ISMRM 2013 , 4175, 2013.

[10] P. M. Van den Berg and R. E. Kleinman, "A contrast source inversion method," Inverse Problems Vol. 13, pp. 1607 – 1620, 1997.

[11] P. M. Van den Berg and A. Abubakar, "Contrast source inversion method: state of art," Progress in Electromagnetics Research , Vol. 34, pp. 189 – 218, 2001.