Towards Optimal Patient-Specific Hyperthermia Treatment-Planning via Constrained Power Focusing

Domenica A. M. Iero[1*], Lorenzo Crocco[2], and Tommaso Isernia[1,2]
[1]Dipartimento di Ingegneria dell'Informazione, delle Infrastrutture e dell'Energia Sostenibile (DIIES) Università Mediterranea di Reggio Calabria, Italy, [2]Istituto per il Rilevamento Elettromagnetico dell'Ambiente (IREA) Consiglio Nazionale delle Ricerche (CNR), Napoli, Italy
[*]domenica.iero@unirc.it

INTRODUCTION

The effectiveness of a hyperthermia treatment depends on the proper shaping of the electromagnetic power deposited in the target region. As a matter of fact, by relying on a Green's function approach to the solution of the Bioheat equation, the correspondence between thermal and electromagnetic power focusing can be rigorously proved [1].

Therefore, to achieve the goal of a selective heating of the tumor, patient-specific treatment planning is mandatory and this task corresponds to the *synthesis* of the excitations of the applicator. Typically, this latter is a fixed geometry array, as such radiating systems allow enough degrees of freedom to accommodate the challenging application's requirements.

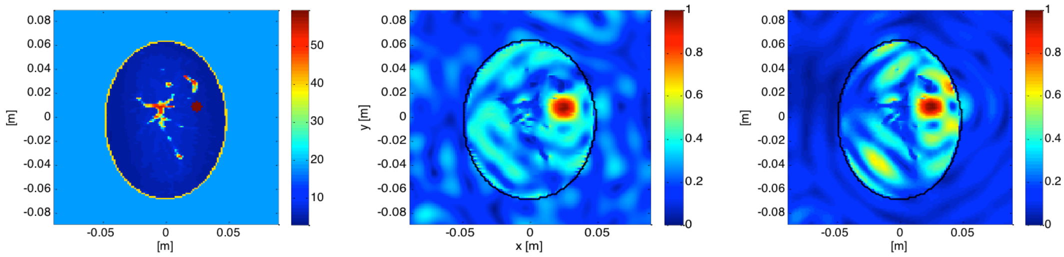
In this contribution, we present an innovative Optimal Constrained Power Focusing (OCPF) method [1,2] capable of achieving the optimal patient-specific punctual power shaping of a time-harmonic electromagnetic wave. In particular, to show the capabilities of the optimal design of the hyperthermia applicator and the importance of controlling the deposited power distribution in the whole treated region, we compare the OCPF with an optimized Time Reversal focusing technique [3] that provides the lowest side-lobes time-reversed field in a given target region by properly choosing the test source polarization.

OPTIMAL CONSTRAINED FOCUSING OF ELECTROMAGNETIC FIELDS

The OCPF approach allows to achieve the optimal excitations set for a hyperthermia applicator exploiting array antennas. As a matter of fact, the so-designed applicator guarantees the maximum power deposition in a given (tumor) target position, while keeping it below predetermined levels in healthy tissues, preserving them from undesired heating. Such a remarkable feature is achieved by turning the focusing problem into the solution of a set of convex programming (CP) problems. As well known, CP problems admit just one maximum, which is globally optimal. Therefore, the optimal excitations set is achieved by exploiting local search algorithms and no global optimization procedures are necessary, thus avoiding their computational burden and intrinsic limitations [4].

It is worth to note that while the transposition of the constrained power focusing problem into a CP problem is straightforward in case of scalar fields [1], when dealing with vector fields a nondeterministic polynomial-time hard (NP-hard) problem has to be solved. This issue, deriving from the vector nature of the field, can be effectively dealt with by applying the proper equality constraints method [5]. In particular, as shown in [2], the problem can be formulated in terms of a multi-objective (MO) optimization, which is solved by decomposition into several single-objective (SO) CP problems. Finally, the globally optimal solution of the problem is simply identified as the maximum energy point of the achieved Pareto front.

Notably, the excitation set designed with OCPF is patient-specific, since the underlying optimization is customized to the features of the treated region. In particular, the tissue properties are exploited to impose suitable constraints on the power distribution, which allows



(a) (b) (c)

Fig.1 Focusing of vector fields (TE polarization) in a slice of fatty breast: (a) permittivity profile, (c) OCPF [3] focused field intensity, (c) optimized TR [4] focused field intensity.

to avoid the occurrence of undesired hot spots. It is worth noting that an extended numerical analysis has shown that the procedure is robust against (a certain degree of) uncertainty on the available patient specific information [1].

RESULTS AND DISCUSSION

To provide an example of the performance that can be achieved with the OCPF, we report the result of a simulation concerned with the hyperthermia treatment of an early stage breast cancer, see Fig.1(a). The example is run in the ideal case of a 2D scenario (invariant along the z axis), but the TE polarization of the electric field is considered. Therefore, as in the actual clinical practice, the vector nature of the fields has to be taken into account. The applicator is a circular array of filamentary magnetic currents. Fig.1(b) shows the normalized power distribution achieved by exploiting the OCPF [2] designed applicator. As can be seen, the method not only allows to focus the field in the target, but also allows to keep the field intensity below the prescribed level elsewhere. Hence, one gains a complete control over the achievable power deposition, which is especially important in glandular tissue and skin, where conductivity is larger. For the sake of comparison, we have reported in Fig. 1(c) the result obtained with the applicator designed using the optimized TR [4], which provides a sub-optimal result being the maximum side lobe amplitude 15% larger than the OCPF. This is due to the fact that, different from OCPF approaches, TR, even in its optimized version, cannot keep under control the power deposition around the target point or guarantee the global optimality of their solution. Clearly, similar comments apply as well to other unconstrained optimization methods.

A complete numerical validation of the above reasoning and more details about the adopted focusing procedures will be given at the workshop.

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