

3D-1D modelling for electromagnetic dosimetry assessment of magnetic hyperthermia in presence of metallic cranial plates

Alessandro Arduino¹, Oriano Bottauscio¹, Denise Grappein², Stefano Scialò²,
Fabio Vicini², Umberto Zanovello¹, Luca Zilberti¹

¹Istituto Nazionale di Ricerca Metrologica (INRiM), Torino, 10135 Italy, a.arduino@inrim.it

²Dipartimento di Scienze Matematiche, Politecnico di Torino, Torino, 10129 Italy

This work presents a 3D-1D mathematical and numerical model for electromagnetic dosimetry at low and medium frequency in presence of filamentary implants. As a test case, the model is applied to the assessment of magnetic hyperthermia for neck tumour treatment in presence of a metallic cranial plate, leading to a correction of almost 13 % with respect to approximated models.

***Index Terms*—Bioheat equation, cranial plate, electromagnetic dosimetry, finite element method, magnetic hyperthermia.**

I. INTRODUCTION

Magnetic hyperthermia (MH) is a promising emerging technology for cancer treatment [1]. Based on the observed positive effect of the exposure of cancer cells to temperatures in the range from 41 °C to 46 °C, MH heats up the tissues taking advantage of the magnetic losses induced by a RF magnetic field in magnetic nanoparticles (MNPs) preliminarily injected in the tumoural region.

The definition of regulations for a safe application of MH is still ongoing, distinguishing between the biocompatibility of the MNPs and the safety of the magnetic applicator [2]. A rule of thumb to guarantee the latter is provided by the Atkinson–Brezovich limit, which forces the product between the maximum intensity of the magnetic field H and its frequency f (typically ranging from 100 kHz to 300 kHz) to be lower than $5 \times 10^9 \text{ A m}^{-1} \text{ s}^{-1}$ [3].

Unfortunately, the Atkinson–Brezovich limit does not provide a reliable safety condition if metallic implants are present in the body of the patient. Therefore, to avoid unquantified risks, the presence of metallic implants is an exclusion criterion for MH treatment [2]. The risk arises from the Joule losses due to the eddy currents induced by the time-varying magnetic field within the metallic components of the implant. The deposited heat diffuses towards the biological tissues surrounding the implant, leading to undesired temperature increases.

Simulations for assessing the safety of bulk orthopaedic and dental implants exposed to MH fields had already been conducted [4]. The mathematical model was extended to estimate the eddy currents induced in implants with a one-dimensional structure, like stents [5] and grids for cranial plates [6]. Here, a further extension of the model according to a coupled 3D-1D approach [7], [8] for the numerical approximation of the bioheat equation is presented.

II. MATHEMATICAL MODELLING

The heating of a filamentary metallic implant induced by a time-varying magnetic field involves two physical problems solved in cascade. The first is the electromagnetic problem of computing the electrical currents induced within the implant.

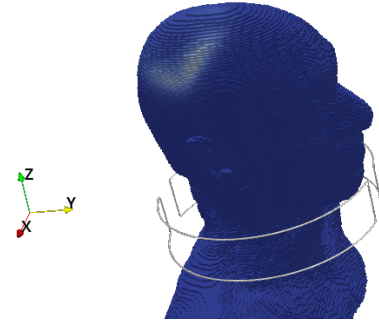


Fig. 1. Model of Glenn with collar-type coil for neck tumour treatment.

Then, the resulting Joule losses are used as forcing term of the thermal problem described by the bioheat equation.

A. Electromagnetic problem

The eddy currents are assumed to be confined within the implant. So, the computational domain is limited to the one-dimensional model of the filamentary implant, which can be described through an electrical network. Each branch represents a metallic wire with its own resistance in series with self and mutual inductances with all other branches in the network. The electromotive forces are the line integrals of the source magnetic vector potential along the branches [6].

B. Thermal problem

The heat due to the Joule losses in the implant diffuses by conduction towards the biological tissues, where heat transfer is modelled according to Pennes' bioheat equation [9]. A simple approximated way to handle this problem is based on thermal seeds. It consists in neglecting the implant metal and in distributing the power dissipated in each implant branch among the mesh elements discretizing the computational domain and containing a portion of the branch [6].

In general, Joule losses are not uniformly distributed within the implant. So, thermal conduction could, in principle, take place along the metal of the implant itself. This effect cannot

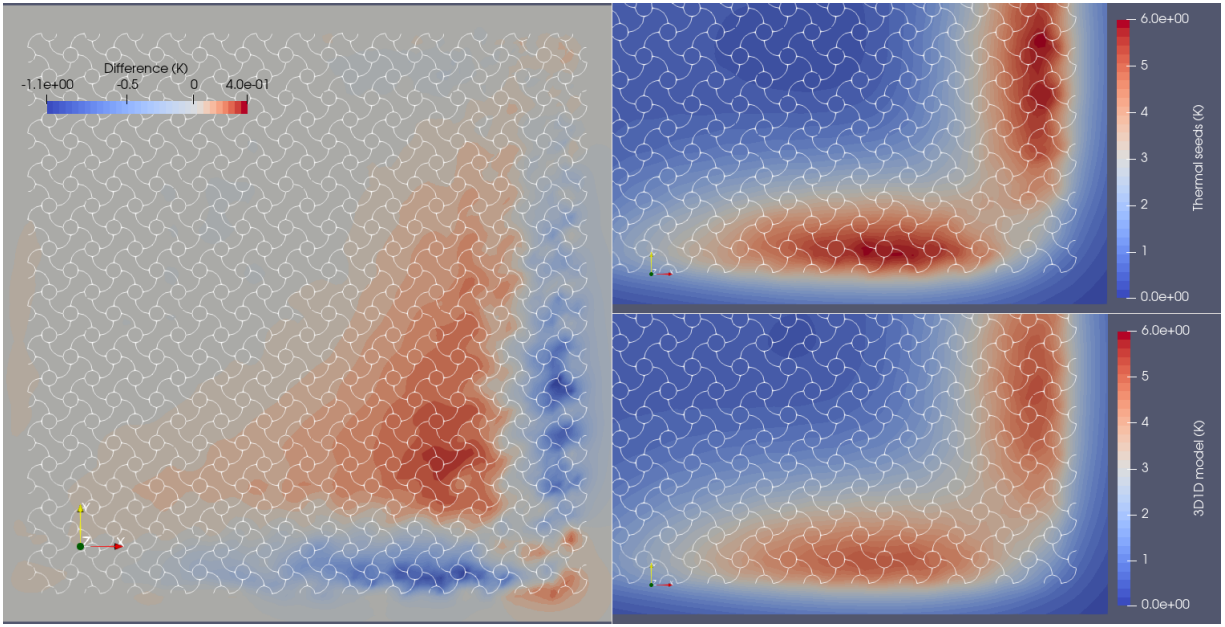


Fig. 2. Comparison of the temperature increase on the grid for cranial plate estimated using the thermal seeds (top right) or the coupled 3D-1D approach (bottom right). The difference (left) between the results obtained with the 3D-1D model and the thermal seeds is also reported.

be modelled with the thermal seeds and the resolution of the mesh able to capture the geometrical details of the thin implant structure for a complete solution of the bioheat equation would make the computational burden of the problem unmanageable.

In this work, to overcome this limitation, a coupled 3D-1D approach [7], [8] is used. The resulting numerical model is based on the finite element method, used to approximate independently the 3D (heat in the body) and the 1D (heat in the implant) models, which are coupled through a constrained optimization problem. This allows the 3D and the 1D meshes to be non-conforming one with respect to the other.

III. TEST CASE

The anatomical head model of Glenn from the Virtual Population [10] is equipped with a square grid for cranial plate with sides of 10 cm properly deformed to fit its skull. The model, illustrated in Fig. 1, is exposed continuously for 30 minutes to the magnetic field at 100 kHz generated by a simplified version of an open collar-type coil, used for neck tumour treatment [6]. The maximum intensity of the magnetic field generated within Glenn's body leads to $Hf = 1.3 \times 10^9 \text{ A m}^{-1} \text{ s}^{-1}$, satisfying the Atkinson-Brezovich limit.

The electromagnetic problem is solved assuming that the implant is made of titanium (ASTM F67) and its thickness is equal to 0.6 mm. The thermal problem is solved using both the approximated approach based on thermal seeds and the physically complete coupled 3D-1D model. In both cases, Glenn's head is discretized with uniform 1 mm voxels and the problem is solved with linear nodal shape functions. The thermal properties of the biological tissues are assigned from the IT'IS Foundation database [11].

The resulting temperature increase on a surface containing the cranial plate is reported in Fig. 2 for both the approaches, together with the difference between the two solutions. The

maximum temperature increase is estimated by the 3D-1D approach to about 5.2°C , whereas the thermal seeds overestimate it to about 6.0°C . Looking at the difference map, it is clear that the lower peak value in the 3D-1D approach is due to the heat conduction through the metal, that reduces the temperature where the thermal seeds predict the maximum increase and, at the same time, rises the temperature of the inner part of the plate up to further 0.4°C with respect to the thermal seeds.

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