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Microwave Thermal Ablation: focusing energy in target tissue using fat layer

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Abstract—**Microwave thermal ablation therapy is a minimally invasive technique introduced in the interventional oncology practice to treat a range of cancerous pathologies. Whereas satisfying results are obtained with the treatment of large and relatively homogeneous areas (e.g. hepatic tumours), treatments of small and inhomogeneous targets are currently under investigation. Minimizing the transversal dimension of applicators represents a crucial aspect in the case of sensitive structures (e.g. blood vessels) surrounding target area. Despite several improvements being proposed, a minimal invasive applicator suitable for small targets adjacent to crucial structures remains an unsolved issue, so far. A proposal to achieve a compromise between a minimally-invasive applicator geometry and a focused thermal pattern is presented in this work. The idea concerns exploiting insulator properties of fat layer, which normally coats the organs in the abdominal cavity. In this scenario, fat tissue is used to focus the heating pattern in the target tissue. Low effective conductivity of fat tissue induces a low absorbed power of the tissue and a consequent low heating of the area. Based on these evaluations, fat layer is also used to avoid unnecessary and potentially dangerous overheating of surrounding healthy structures.**

Index Terms—**Microwave ablation, antenna, insulator tissue, minimally invasive technique**

I. INTRODUCTION

Over last ten years, thermal ablation therapies were introduced in medical practice to treat a range of cardiovascular pathologies (e.g. arrythmias) and cancerous diseases (e.g. liver, lung, kidney tumours) [1], [2]. The ablation effect induces cell death by coagulation necrosis at temperature above 55-60°C [3]. Recently, promising results were reached in the treatment of solid tumours, like hepatic tumours, by Microwave Thermal Ablation (MTA) [4], [5]. In MTA, the electromagnetic field (EM) is induced in the target tissue by an antenna connected to a microwave generator and excited by an alternate current at a frequency of 2.45 GHz or 915 MHz. The thermal effect is generated by the interaction between water dipoles of biological tissues and the alternating electric field. Particularly, the heat is produced by friction effects of adjacent water dipoles and consequent displacement currents [1], [6]. As the EM field can propagate in healthy tissues as well as in diseased tissues, large and relatively homogeneous areas (30-40 mm) can be successfully treated in few minutes (3-5 min) by MTA [1]. The effectiveness of the ablation treatment is strictly dependent on the power and time settings chosen to excite the antenna, as well as on the antenna design [5], [7], [8]. The monopole and dipole antennas have been extensively used in the designs of MTA applicator [8], [9], [10]. However, directively addressing EM field energy in target area using a omnidirectional antenna like monopole and dipole, can be challenging as these antennas have essentially a nondirectional pattern in a given plane. Therefore, optimizations and improvements in antenna designs were introduced in [11] and [12]. Directional MTA antenna designs with a modified monopole radiating element and shaped reflectors (i.e. hemicylindrical, elliptical, parabolic) were proposed. These studies reported improved MTA applicators with the objective of creating directional heating patterns. However, the transversal enlargement caused by the integrated reflective element in the MTA applicator is not suitable for the treatment of targets in close proximity to critical biological structures.

In human anatomy, a layer of viseral fat surrounds each abdominal organ, including the liver, kidney, glands (for example adrenal gland), or lymph nodes. Based on this observation, this study proposes the strategic placement of the MTA applicator between target tissue and the surrounding fat layer, exploiting the fat layer as a reflector. This placement of the MTA applicator within this fat layer has the effect of focusing the EM power in the target area, while sparing adjacent sensitive structures [13].

This study was designed to demonstrate proof of concept by evaluating the feasibility of the proposed method using numerical simulations. In Section II the MTA applicator model and the "tissue" geometries in the numerical model are described. Moreover, the work flow conducted for each simulation is described. In Section III results related to each performed simulations are shown and discussed in terms of Specific Absorption Rate (SAR) (W/kg) distribution and localised temperature profile. A summary of the objective pursued and the results obtained during this preliminary study, are described in Section IV.

II. MATERIALS AND METHODS

An omnidirectional monopole antenna was modelled in a commercial full wave electromagnetic simulation software (CST-MW Studio Suite), extracting 6 mm of the inner conductor from a modelled UT-047 coaxial cable (outer conductor diameter: 1.2 mm; inner conductor diameter: 0.4

mm). A concentric polyimide cylinder (outer diameter: 4.0 mm) filled by water was added around the outer conductor of the coaxial cable. The water temperature was fixed at 18 °C for the duration of each simulation, in order to simulate an integrated refrigerating/cooling system. The purpose of the cooling system in a clinical MTA is to prevent damages to the surrounded healthy tissues from overheating along the cable of the applicator.

Two different biological scenarios (where the applicator was inserted in different tissues) were modeled as follows:

a) Liver scenario model: A parallelepiped (80 mm side) composed of "liver" was realised to represent a homogeneous scenario. In this configuration, the antenna was placed in the middle of the parallelepiped.

b) Fat-muscle scenario model: Two adjacent parallelepipeds composed, respectively, of "muscle" (40 mm side) and "fat" were created to schematize the interface between two dielectrically different biological tissues. In the fat-muscle scenario, the impact of the fat, i.e. the less conductive layer, was investigated for different fat layer thicknesses: 30, 20, 10, 5 mm. The antenna was placed at the boundary between the fat and muscle parallelepiped.

For each biological material, the dielectric properties of tissue taken from the literature within the frequency range 0-3 GHz were used [14]. Overall, five simulations were conducted as described in Table I. EM and thermal simulations were consecutively run in the time domain for each scenario, using the CST-Multiphysics toolbox and the related Thermal-Transient Solver, at fixed power and time settings of 60 W and 60 s, respectively. From the electromagnetic simulations, the resulting SAR was calculated considering: the electric field excited by 60 W input power, the effective conductivity and the density of the materials involved, as required from the SAR definition [15]. SAR values calculated in the EM simulation are automatically inserted in the thermal simulation solver, in addition to thermal conductivity and thermal diffusivity, in order to calculate the temperature variation over the time according to Penne's transfer bioheat equation [16]. Moreover, concerning the thermal simulations, different temperature monitors were selected in order to analyse localised temperature increases during the 60 s of ablation and for 60 s after the end of the ablation, at different distances from the antenna feed. Temperature monitors were placed from 3 mm to 10 mm at 1 mm step, both positive and negative, along one of the two directions transversal to the antenna axis (x-axis), exploiting the cylindrical symmetry of the EM antenna pattern. It must be noted here that whereas the dielectric properties were obtained from experimental measurements, the thermal properties implemented are those available within the commercial software used. Moreover, the variation of the thermal and dielectric properties within the increasing temperature has not been considered within this study.

III. RESULTS AND DISCUSSION

First, the influence of the interface between muscle and fat, on the ablation has been investigated both in terms of SAR distribution as well as temperature increase. Fig. 1 compares the SAR distributions obtained in the homogeneous scenario, i.e. in liver, and in the heterogeneous scenario, composed by muscle and fat. A symmetrical ablation zone along the x-axis is illustrated in the liver scenario. In the case of fat-muscle interface, a smaller SAR distribution is shown in fat with respect to the muscle. Trends of localised temperature over 120 s time in the context of both the homogeneous (i.e. liver) and heterogeneous (i.e. muscle-fat interface) scenarios are depicted in the Fig.2. In liver case, the superposition of temperature curves extracted for positive and negative x-axis directions, indicates the same temperature increase according to the homogeneity of the scenario (Fig. 2a).

In the fat-muscle case, relevant differences in terms of temperature values between fat (positive x-axis direction) and muscle (negative x-axis direction) are observed (Fig. 2b). After 60 s, the temperature in fat is below 60 °C at each considered distance from the antenna. At 3 mm distance, the considerable temperature increase is related to the position of the observation point adjacent to the applicator. At furthest distances from the applicator, the maximum temperature reached in fat and muscle layers are 53°C and 70°C, respectively. At 5 mm away from the antenna, in fat layer a thermal increase of about 45°C is observed, while at 5 mm from the antenna both in muscle and in liver temperatures around 55-60 °C are observed.

Table 1: For each simulation, material type and fat thickness (where required), are reported.

Simulation #	Material	Fat Thickness (mm)	Power (W)	Time (s)
Sim. 1	Liver	-	60	60
Sim. 2	Fat-Muscle	30	60	60
Sim. 3	Fat-Muscle	20	60	60
Sim. 4	Fat-Muscle	10	60	60
Sim. 5	Fat-Muscle	5	60	60

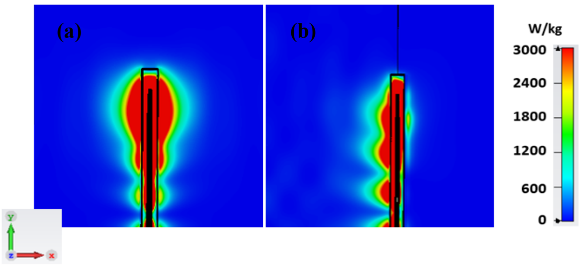

Fig.1.Simulated SAR distribution (a) in liver and (b) at the interface between muscle (on the left) and fat (on the right).

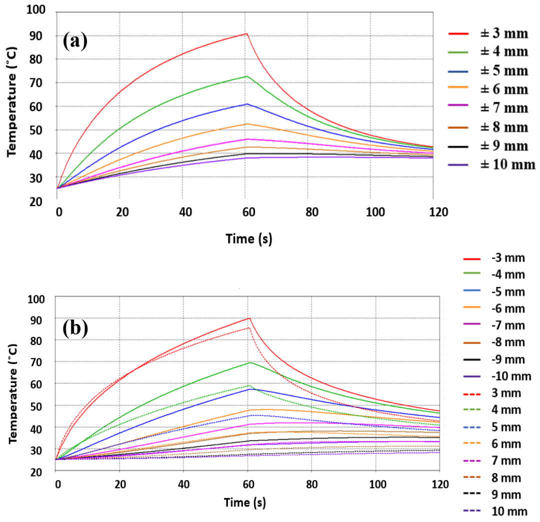

Fig.2. Temperature trends over 120 s obtained from simulation both in (a) "liver" scenario and (b) "muscle-fat" interface scenario. Different distances were considered (from 3 to 10 mm spaced by 1 mm step) from antenna feed along negative x-axis (dashed line) and positive x-axis (solid line). In (b) positive x-axis (solid line) is related to fat; negative x-axis (dashed line) is related to muscle.

Fig.3 shows SAR distributions obtained in a two layer tissue model containing both fat and muscle with different fat layer sizes: 30, 20, 10, 5 mm. Comparable SAR distributions in radial and longitudinal directions both in muscle and fat, are obtained in the cases of 30, 20, 10, 5 mm of fat layer thickness (Fig.3a-d). Trends of localised temperature over 120 s time were investigated for the different fat thickness scenarios considered. No difference was observed in the temperature increase between the 30, 20 and 10 mm cases. However, in the configuration of 5 mm of thickness the electromagnetic field flow is confined to the small (5 mm) fat layer, generating an "oven" effect that results in a considerable modification of the temperature distribution in fat and partially in muscle regions.

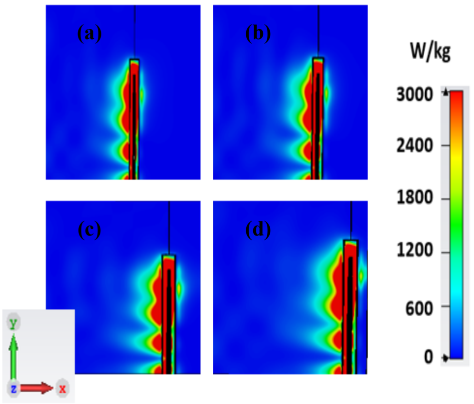

Fig. 3.Simulated SAR distribution in the case of an interface modelled by a muscle cube (negative x-axis) and fat cube (positive x-axis). Different fat layer thicknesses are considered: (a) 30 mm; (b) 20 mm; (c) 10 mm; (d) 5 mm.

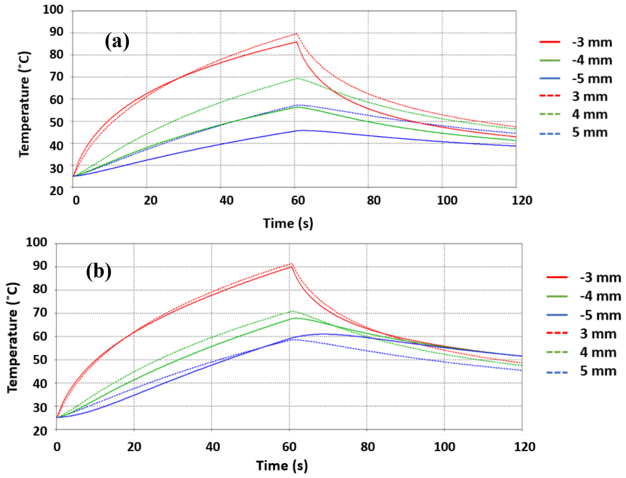

Fig. 4. Temperature trends over 120 s obtained from simulation in muscle-fat interface scenario, in cases of: (a) 10 mm fat layer thickness and (b) 5 mm fat layer thickness. Temperatures are recorded at different distances from antenna feed along negative x-axis related to muscle (dashed line) and positive x-axis related to fat (solid line). In both cases six different positions were considered in both directions: 3 mm, 4 mm and 5 mm.

This effect is notable in Fig.4 that compares localised temperature increases obtained in cases of both a 10 mm and 5 mm fat thickness. It is possible to observe the "oven" effect occurring in the scenario of 5 mm fat layer thickness (Fig. 4b) results in higher temperature levels in fat and, marginally, in muscle, compared to the scenario of 10 mm fat layer (Fig. 4a). After 60 s, temperatures at a distance of 5 mm from the antenna to fat area reach 45°C and 60°C, in case of a 10 mm and 5 mm fat layer thickness, respectively.

IV. CONCLUSIONS

In this work a proof of concept study was conducted to investigate the impact of biological tissues' interfaces, in particular fat layers, on the EM field distribution generated by an antenna for MTA application excited at 2.45 GHz. SAR distributions and localised temperature increases were analysed. A liver tissue scenario (considered homogenous and widely investigated in applications concerning MTA) was compared to a heterogeneous scenario involving a muscle-fat interface. Symmetric SAR and temperature distributions were noted in liver case, as would be expected in a homogeneous scenario. In the case of the fat-muscle interface, the SAR profile and temperature trends show different results according to the different dielectric properties of the two tissues (i.e. muscle and fat) involved. A smaller SAR profile and lower temperatures in fat region than in muscle region was observed. In more detail, the peak temperature in fat remains below the temperature range required to induce direct cell killing by coagulation necrosis (above 60°C). Therefore, exploiting the insulator property of a fat layer could represent a reasonable strategy in order to focus EM power into a target area, sparing healthy tissues of the surrounding area. In addition, the "oven effect" caused by the incapability of EM field to spread within a small fat layer thicknesses, was investigated. The results suggest that a fat layer of at least 5 mm is needed to account for this insulating effect, at the power and time considered.

In conclusion, the exploitation of biological interfaces involving fat tissue could be investigated as a potential solution in order to obtain an effective and well-focused ablation zone in MTA.

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