A Numerical Assessment of Enhanced Microwave Hyperthermia Using Au Nanoparticles

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***Abstract*— Microwave hyperthermia has emerged as an increasingly recognised therapeutic approach for addressing various challenging medical conditions. This study conducts acomparative analysis between a three-layered phantom with and without the inclusion of gold nanoparticles in the tumor region. The investigation explores the use of nanoparticles for enhancing hyperthermia generation, their activation source, characteristics and implementation from an electromagnetic numerical analysis perspective.**

***Index Terms*—Microwave, hyperthermia, dielectric properties, gold nanoparticles.**

I. INTRODUCTION

Hyperthermia (HT) involves elevating the temperature of a specific tissue region for a designated period (typically 30-60 minutes) without affecting the temperature of the surrounding tissues [1]. The target temperature in HT is between 40 °C and 45 °C. Studies on HT have confirmed that elevating tissue temperatures can result in the destruction and reduction of cancerous cells, with limited adverse effects on healthy tissues [2]. Furthermore, HT enhances the susceptibility of specific tumour cells to radiation therapy and chemotherapy [3]. To this end, HT has been applied in conjunction with various other forms of cancer therapy, such as chemotherapy as well as radiation therapy [1]. Presently HT can be administered using three distinct modalities, these are ultrasound, thermal conduction and microwave (MW) radiation. Depending on the locationand tissue on which hyperthermia is applied its effects will vary [4]. One of the situations where HT has shown potential is in breast cancer treatment [5]. However, the main obstacle lies in heating the cancerous tissue to the optimal temperatue while avioding damage to the surrounding healthy tissues. Recently, nanoparticle (GNP) technology has found increasing application in HT [6], as it allows for precise control of the thermal energy delievered to the tumor region [7, 8]. This advancement helps to enhance treatment efficacy while minimising harm to nearby healthy tissue.

In this research, a three-layered phantom adopted and modeled using the CST-Microwave (MW) Studio software for EM simulations. The tissue mimics parameters used in this model are derived from the ones described in [9, 10]. The simplicity of the breast model used in this numerical analysis enables the replication of the phantom in real-world scenarios in future studies, facilitating the construction and simulation of practical applications. The aim of this study is to investigate the use of GNPs agent in boosting the focusing capability of the proposed HT system, which consists of eight antenna elements. The focus will be on examining the distinctions between a three-layered with and without GNPs agent localised in the tumore region of the breast phantom mimic. Two methods were employed to maximize SAR in the tumor region. The first involved 2D analysis over the surface area by post-processing the electromagnetic field data extracted from CST in MATLAB, using swarm particle optimization. The second method utilised a fully 3D analysis directly implemented in CST over the volume, leveraging the built-in optimisation tools.

A brief introduction which explains the motivation to the work is provided above. This is followed by the methodology of the numerical work as the main results obtained in this work.

II. METHEDOLOGY

A. Simulation of the problem

The initial phase of this research centred on the creation of the CST HT simulated system consisting of eight FORA dipole antennas [11] operating at 2.45 GHz, as depicted in Figure 1. The antennas were placed into a circular orientation around the breast phantom with 25 degree angular separation. The numerical breast phntom consists of two layers: a gibro-glandular layer and a fat layer, with the tumor inclusion located within the gibro-glandular layer, as shown in Figure 2.

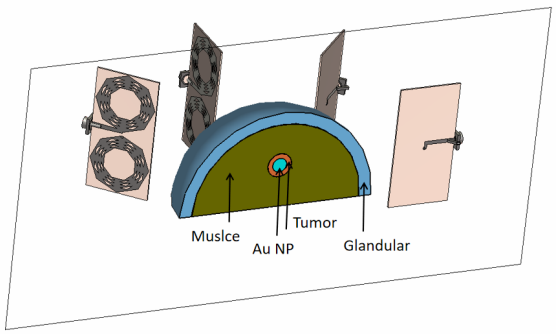

Figure 1 cross section of the proposed CST hyperthermia system, showing the FORA array is show surrounding the 3-layered breast phantom.

The tumor was positioned at the center, located 17.5 mm beneath the top flat side of the mimic, with a radius of 6 mm. The fibro-glandular layer had a radius of 35 mm, while the outer fat tissue extended to a radius of 40 mm. The dielectric properties of these mimics and formulation recipes are detailed in [8] and [9]. Table 1 presents the dielectric properties of the different mimicking layers, which were imported into CST MW Studio material library for use in the simulations.

Table 1. Dielectric characteristics of breast layer[10].

Tissue Type	Conductivity (Sm^{-1})	Mass Density (kgm^{-3})	Permittivity
Tumor	4	1040	50
Fibro glandular	0.45	1040	14
Fat	0.0339	935	3.9095

In investigating the effect of nanoparticles on enhancing HT treatment, the nanoparticles were introduced into the tumor as a spherical inclusion with a radius of 3 mm. The dielectric properties of the nanoparticles were assigned using the built-in material library in CST MW Studio. At this stage, no thermal properties were assigned to any of the materials constituting the breast phantom, focusing solely on the electromagnetic properties. The hyperthermia applicator, which also serves as the activation source for the GNPs agent, consists of fractal octagonal ring antenna (FORA) elements. The suitability of such an antennas was investigated and demonstrated significant potential as an effective HT applicator in [11]. FORA represents a versatile, printable antenna adaptable to a diverse array of applications [10]. Its abilityto operate in both flat and curved configurations holds significance for HT therapy systems, allowing them to conform to the contours of the patient's body. Further details on the antennas can be found in [11].

B. Gold nanoparticles

The GNPs were prepared as described in [13], with a size of 21 nm confirmed via DLS, UV-Visible spectrophotometry, and Transmission Electron Microscopy TEM analysis. Their dielectric properties were measured and imported into CST Microwave Studio for inclusion in the tumor region during simulation.

C. 2-D SAR Analysis and Data Generation

The proposed hyperthermia applicators were tested on a hemispherical phantom, both with and without the inclusion of a GNP agent in the tumor region. Electromagnetic (EM) wave focusing on the tumor was achieved through optimization of the electric field distribution, which was extracted from CST MW Studio and processed in MATLAB. To generate the electric field data, a finite element method (FEM)-based approach in CST MW Studio was employed in the frequency domain, where each antenna was excited individually while the remaining antennas were kept in the model to account for their influence. This setup enabled the simulation of electric field () and electrical conductivity () distributions at the central axial slice of the phantom. These distributions were then imported into MATLAB for post-processing and optimisation to maximise the specific absorption rate (SAR) in the tumor region. It should be noted that both the applicator and the phantom were placed in free space, and the antennas were excited using uniform lumped ports with a 50 Ω impedance. This method offers a more efficient and computationally feasible approach for analyzing all possible electric field vectors and heating potential distributions, allowing for a comprehensive comparison between scenarios with and without the GNP agent in the tumor region. Further details on the SAR distribution calculations are provided in [11].

D. 3-D SAR Analysis Using CST MW Studio

In this computational analysis, three GNPs inclusions were introduced to evaluate their effect on enhancing microwave hyperthermia treatment. Each GNP inclusion had a radius of 0.5 mm and was strategically positioned around the outer boundary of the tumor, in close proximity to its surface. The high-frequency time-domain solver in CST Microwave Studio was employed to simulate the proposed hyperthermia system. The SAR distribution was calculated as point SAR within CST, optimising the energy focus on the tumor while minimising energy absorption in the surrounding healthy tissues. This analysis involved calculating the SAR distribution throughout the entire volume of the biological model, and the tumor volume, to ensure effective and localized treatment. Several automated optimisation methods are included in CST MW Studio. For optimal SAR localisation at the tumor, a sophisticated local optimiser, specifically the genetic algorithm, was employed in our study due to its effectiveness in exploring a wide range of parameter spaces and ensuring the best focus of energy on the tumor region.

III. RESULTS

Figure 2 shows a localised region of the highest SAR value, which consides with the position of the inserted tumor, indicated by the black inner circle, in the absence of GNP agent.

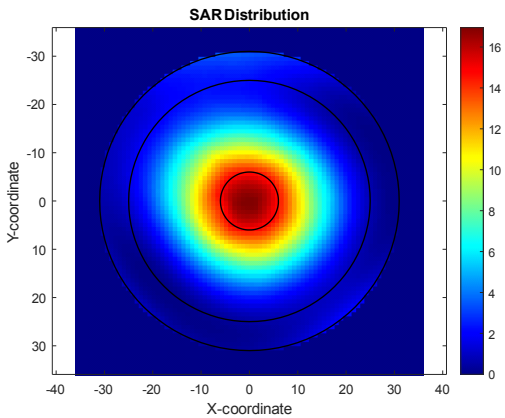

Figure 2 SAR distribution for the 3-layered phantom focused at the center at 17.5 mm depth.

On the other hand, Figure 3 illustrates that the presence of GNP significantly localises and increases the SAR value within the tumor region. This can potentially lead to mimise the hotspots that arise in the surrounding healthy tissue region.

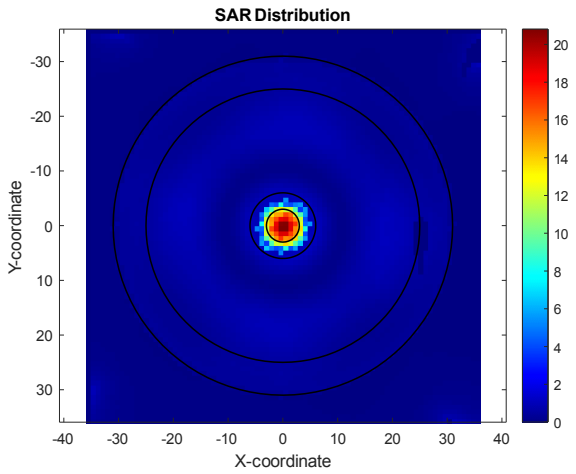

Figure 3 SAR distribution focused on the tumor located at the center at 17.5 mm depth from the flat surface in the presence of GNP.

This size of the phantom used facilitates a more realistic and comprehensive evaluation of the applicators performs across a substantial volume. This provides valuable insights into its effectiveness in energy distribution and its ability to address various anatomical features of the breast phantom. When comparing the two SAR scenarios, it is evident that the three-layered phantom, particularly with the inclusion of GNP significantly enhances the SAT within the localised area. This enhances energy absorption within the tumor, which will significantly raise the temperature to levels suitable for hyperthermia therapy, allowing for the destruction of cancer cells in a shorter duration. This is crucial, as tissue damage is closely related to the time-temperature history.

In Figures 4 and 5, the results show a localised region of the highest SAR value, which aligns with the position of the tumor in both the absence and presence of GNPs. The inclusion of GNPs significantly enhances the localised SAR value, with GNPs demonstrating the most substantial increase, leading to the highest energy concentration and the most focused energy distribution in the tumor region of 206.57 *W/Kg* and it is *150 W/Kg* at the center of the tumor. However, the maximum SAR in the absence of GNPs reached 118 *W/kg* at the core of the tumor region, as illustrated in Figure 5.

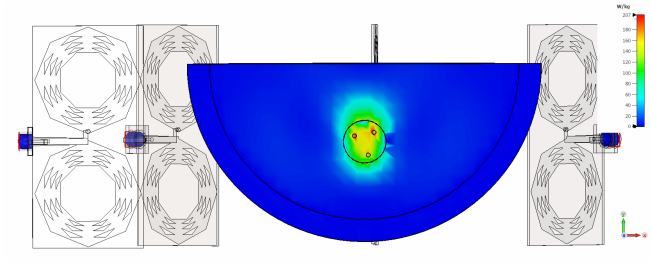

Figure 4 CST SAR distribution in the presence of 3 GNPs, originating from CST 3D analysis over the volume.

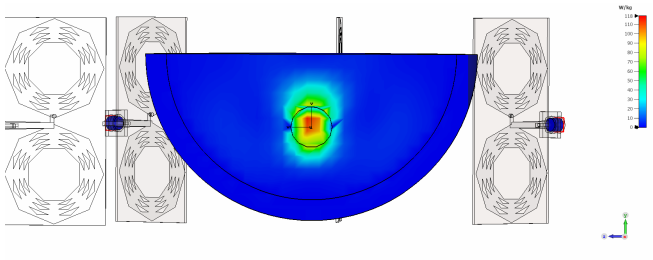

Figure 5 CST SAR distribution in the absenses of the 3 GNPs, originating from CST 3D analysis over the volume.

IV. CONCLUSIONS

The findings from this study underscore the significant benefits of utilising GNPs within a three-layered breast phantom to enhance HT therapy. Two scenarios were investigated: the first involved agglomerating gold nanoparticles (GGNPs) into a 3 mm radius, using 2D post-processing swarm particle optimization to achieve the best SAR distribution over the tumor surface. The second scenario involved the inclusion of three individual GGNPs, each with a 0.5 mm radius, and employed CST's built-in genetic algorithm to optimize SAR across the entire tumor volume. The incorporation of GNPs agent not only improves the localisation of the SAR within the tumor region but also facilitates more efficient energy absorption. This efficiency allows for effective temperature increases, which are crucial for damaging cancer cells in a shorter timeframe. CST MW Studio was employed to construct and simulate a noninvasive hyperthermia system capable of effectively heating breast tumors. The first method, involving 2D analysis with post-processing in MATLAB, proved to be effective, efficient, and time-saving. In contrast, the second method, which employed 3D analysis fully within CST, was more time-consuming due to the increased complexity and computational demands of volumetric optimization.

In forthcoming research, the system will be replicated in a real-world context, where a comparative evaluation will be conducted between the targeted hotspots obtained through in-silico modeling and those observed in the laboratory setting.

Overall, this study offers valuable insights into the performance of the proposed hyperthermia applicator and lays the groundwork for future research focused on enhancing therapeutic outcomes in cancer treatment, potentially leading to the development of a clinical prototype

ACKNOWLEDGMENT

This work has received funding and support from two key sources: the Evolve program and the Malta Council for Science and Technology (MCST)

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