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Optimization of Antenna Excitations for Non-Invasive Microwave Hyperthermia for Breast Cancer Treatment

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ABSTRACT

This research demonstrates an effective focused microwave hyperthermia for non-invasive breast cancer treatment at early stages where the tumour size is small and has not spread to nearby tissues. First, a three-dimensional (3-D) Micro-Strip Patch (MSP) antenna array consisting of four elements and operating at 2.45GHz is used. Second, two evolutionary optimization techniques, particle swarm optimization (PSO) and genetic algorithm (GA), are compared in terms of optimization speed in order to select the algorithm which will be used in this study to calculate the ideal phase and amplitude excitations for each MSPA. The fitness function of the used algorithm aims to increase the specific absorption rate (SAR) and power density (Q) at the tumour site while keeping these values at minimum levels in healthy positions. The focusing technique is used to collect a data of accurate antenna excitations of a tumour having a radius of 2.5 mm (less than 1 cm^3 volume), embedded in every possible position in the glandular tissues in the antenna array's central plane. Using MRI results from a real patient (age 40) in the prone position, a realistic breast model was produced. In order to demonstrate the efficiency of the suggested 3D microwave focusing technology, the temperature distribution at the tumour centre position was measured and compared with other healthy locations. The data gathered are then used to create a non-invasive hyperthermia GUI system for the treatment of breast cancer.

1. Introduction

According to the International Agency for Cancer Research's (IARC) most recent global cancer statistics [1], female breast cancer has become the most commonly diagnosed form of cancer in the world, with 2.3 million cases diagnosed in 2020, exceeding the number of new cases of lung cancer for the first time. It has also become the most common cause of cancer death if not detected and treated at early stages where the tumour has not yet spread to nearby tissue [2].

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The stage of breast cancer is a critical factor in determining potential treatments. It is a way to explain where the cancer is, how much the cancer has grown, and whether or not it has spread to nearby tissues. There are five stages ranging from stage 0 to stage 4. The higher the stage number, the larger and more widespread the cancer [3].

A promising cancer treatment that can be used alone or in conjunction with other treatments like radiotherapy or chemotherapy is microwave hyperthermia [4-6]. Compared to the existing therapeutic treatments it is non-ionized and non-invasive. The objective of hyperthermia is to maintain healthy tissues at their usual temperature while raising the tumour's temperature to a moderate level (over 42°C) for a considerable amount of time [7,8]. Choosing a suitable antenna element and optimization technique lead to effective focusing of EM power at the tumour position.

Microstrip patch antenna (MSPA) has more advantages compared to traditional antennas. They are lighter in weight, have a low volume, and a low profile. They are ideal for mass production due to their low fabrication costs and ease of manufacture. The dimensions of the printed patch and the material properties of the substrate onto which the antenna is printed determine the MSPA performance. Using the MSPA in array configuration is a good way to improve the gain, increase the bandwidth, and the microwave energy is considered to be the most powerful way to cause hyperthermia noninvasively in the treatment of malignant tumours [9-11].

PSO and GA are evolutionary optimization techniques that has drawn the attention of many researchers and has shown to be efficient in optimizing multidimensional problems in a variety of fields such as antenna design [12-21]. John Holland introduced the concept of GA at the University of Michigan in the 1970 [22], and it is based on natural genetics and natural selection mechanisms. PSO was first introduced by Kennedy and Eberhart in 1995 [23]. The technique uses a basic mechanism that mimics the swarm behaviour of birds flocking to direct the particles to find the optimal global solutions. The GA and the PSO flow charts are shown in Figure 1 and Figure 2 respectively.

Different techniques are used in these studies to concentrate the microwave energy at the site of the tumour. Time reversal technique is used in [24,25] to target tumour that is situated in the antenna array's centre using basic point sources and a two-dimensional (2D) breast model. A beam forming technique is used in [26]. However, The model disregards both the antenna radiation characteristics and the impact of a preexisting tumour.

Local and global optimization techniques are used [27-30] to maximize Specific Absorption Rate (SAR), as well as the power density near the tumour. Trust Region Framework is used in [27,28], which is a local optimization algorithm, for microwave focusing only at the array's centre plane. In [28,29], by increasing the power density at the tumour volume ($1cm^3$), the 3D antenna array's excitation parameters are optimised using the global algorithm PSO.

In [30], GA is used to find the optimum antenna parameters to focus the energy inside the tumour location using antenna phased array. Although the effect of the optimization on the maximum value of the SAR inside the model was shown, the simulations were performed on a layered cylindrical model of human tissue with a tumour of 10 mm radius.

In [31], a comparison of five different optimization techniques for hyperthermia treatment of breast cancer. In terms of hotspot reduction and confined SAR focusing in the tumour position, both GA and PSO techniques outperformed other algorithms. The algorithms were applied to 3D patient breast models derived from their respective MRI data.

Previous studied were conducted using different types of antennas. While most of the previous work on focused microwave hyperthermia use linearly polarized antenna arrays. In [32], a study of using circularly polarized antenna arrays to focus microwave hyperthermia for breast cancer treatment is presented. Two types of circularly polarized patch antennas are applied. Although the

simulation results show that proposed antennas are suitable for focused microwave hyperthermia, the simulation was conducted using a simple breast model with a tumour of 1cm diameter, and the temperature distributions was not considered.

In [33], an investigation of using a slotted circular patch antenna at 2.45 GHz for breast tumour microwave hyperthermia treatment is presented. where purpose of the study is to realize efficient and high gain slotted circular antenna array, the research used only a single antenna, and the simulations were performed on a simple breast model with a tumour of 20mm diameter.

A new prototype applicator was developed in [34], and the power density distribution was analysed and compared with that obtained from a wave guide applicator. Although the primary results show that with the new prototype applicator is capable to focus the EM energy, the study was tested using single applicator on a 3D simple breast model with a cube tumour of 0.8cm (wide, high, and large) inserted on four different position inside the breast fat tissue.

2. Methodology

In order to achieve the aforementioned goal, the central plane of the breast glandular tissue is divided into 12 virtual lines with 120 possible tumour locations in the glandular tissue. First, a comparison between PSO and GA is performed. A tumour of 2.5 mm radius is inserted and the antenna excitation parameters are obtained by reaching the goal function after a maximum number of 15 iterations are reached. The amplitudes of the antenna range from [0 to 2 Volts] and the phases range from [-180° to 180°].

The simulation tool CST is utilised to calculate the distributions of power used in thermal simulations utilising the EM solver and thermal solver, and it is used to study microwave hyperthermia, and to find the optimum antenna excitations using the built-in global optimization algorithms. CST contains several optimization algorithms, both local and global. The process to achieve the hyperthermia goal is shown in the Figure 1. The thermal solver is used to calculate the temperature distribution, while the EM solver is utilised to calculate the power distributions and SAR inside the breast model.

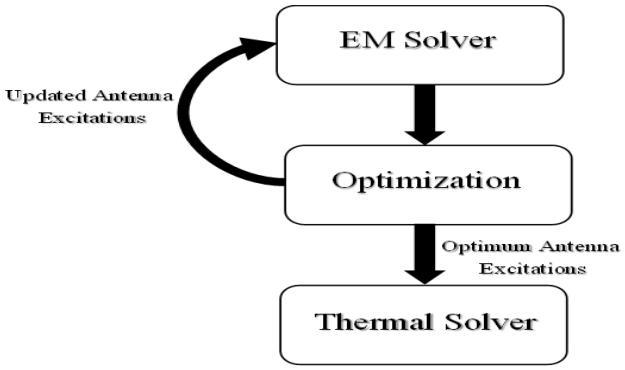


Fig. 1. The proposed microwave hyperthermia process

The rate at which energy is absorbed per unit mass by the breast tissues when exposed by EM field is given by:

$$SAR=\frac{\sigma|E|^2}{2\rho} \quad (W/Kg) \tag{1}$$

where σ and ρ are electric conductivity and density of the breast tissue, respectively, |E| is the maximal value of the electric field induced in the breast tissue.

The power density Q produced by the incident microwave signal is determined by [24,35] as:

$$Q_r(\theta)=0.5\sigma|E_r(\theta)|^2 \quad (W/m^3) \tag{2}$$

where $Q_r(\theta)$ is the power density at location r brought about by the phases of the input excitation, σ is conductivity, and E_r is the electric field at r. Next, solve Pennes bio-heat equation using Q as the thermal source [36]:

$$C_p(r)\rho(r)\frac{\partial T(r)}{\partial t}=\nabla.(K(r)\nabla T(r))+A_0(r)+Q(r)-B(r)(T(r)-T_B) \quad (W/m^3) \tag{3}$$

Where C_p denotes the specific heat, ρ denotes density, K denotes thermal conductivity, A_0 denotes metabolic heat generation, B denotes the capillary blood perfusion coefficient, T_B denotes blood temperature, and Q denotes power density.

By maximising the amplitudes and phases of each antenna element, the microwave hyperthermia may be focused. When the electric field profile is known, the power density, which can be calculated, may be utilised to calculate the temperature distribution.

The fitness functions for both optimization techniques are given by:

$$\text{Min } f(\alpha,\phi)=\{f_1(\alpha,\phi),f_2(\alpha,\phi)\} \tag{4}$$

Where α and ϕ are the antenna excitations (amplitudes and phases respectively). f_1, f_2 are given by:

$$f_1=\frac{\text{Q\_healthy}}{\text{Q\_tumour}} \tag{5}$$

$$f_2=\frac{\text{SAR\_healthy}}{\text{SAR\_tumour}} \tag{6}$$

The performance curve of the fitness function is compared with GA for the same number of 15 iterations as shown in Figure 2. While both optimization techniques reach the minimum fitness value, PSO computation time is lower than GA, where a single iteration in PSO takes 25 minutes, while in GA it takes 50 minutes using CORE i5, 16GB RAM, and 8GB SSD hard.

PSO has been increasingly used because of its many advantages, such as reliability, simplicity, and need for less computational effort when compared to GA [37-39], and it has shown its ability in many aspects to solve various optimization problems. PSO will be used in this study to find the optimum antenna excitations to reach the hyperthermia goal of treatment. A tumour with a 2.5 mm radius is placed in each of the 120 positions in the antenna phased array's centre plane and the antenna excitation parameters are obtained using PSO to reach the goal function after a maximum number of 50 iterations.

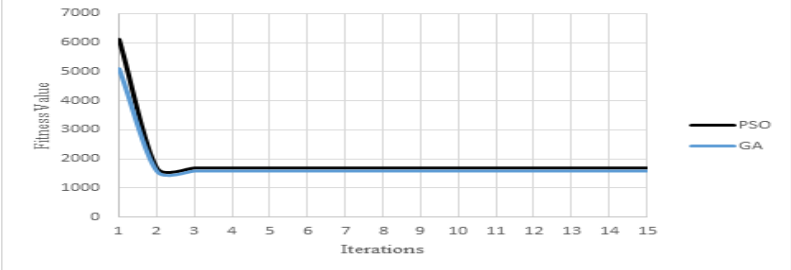
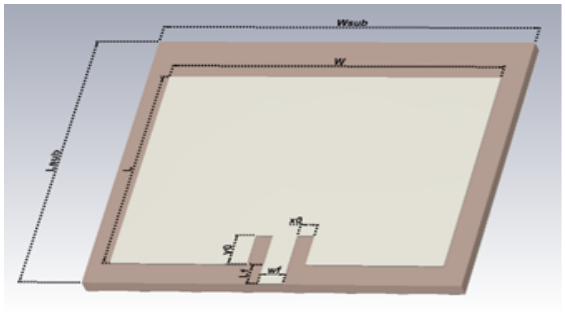


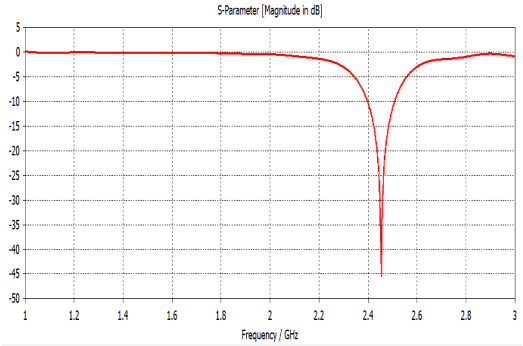
Fig. 2. PSO and GA fitness function performance curve

3. Simulation Environment

To fulfil the planned study's objective. The four elements of a 3D phased array are completely grounded MSP antennas operating at 2.45GHz, with a half wavelength separation between each element. Figure 3 depicts the MSPA element design, the return loss in the absence of breasts and in the vacant area.



(a)



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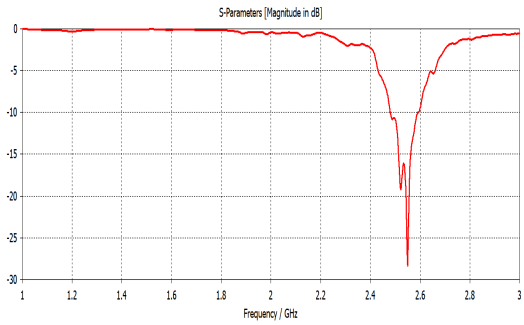


(c)

Fig. 3. (a) Single element MSPA, The return loss in dB (b) In free space (c) with breast tissue present

The measurements of each element needed to reach the necessary operation frequency are shown in Table 1. The substrate material is FR-4 (εr=4.3).

Table 1
Dimensions of MSPA

Parameter	Value (mm)
y_0	4.06
x_0	1.88
w_f	2.99
w_p	38.86
Thickness of patch	0.2
Thickness of ground	0.035
h	1.6
L_{Sub}	35.81
W_{sub}	44.67
L	27.64

A 40-year-old real patient's MRI results from the prone position were used to produce the realistic breast model. To separate the various breast tissues, the MRI picture is then run via 3D Slicer software [40]. Each tissue is given accurate thermal and electrical properties, and a 2 cm chest muscle is included to the model in CST before the model is exported [41,42]. Figure 4 shows the breast model and antenna array submerged in a bolus of water for cooling and matching purposes.

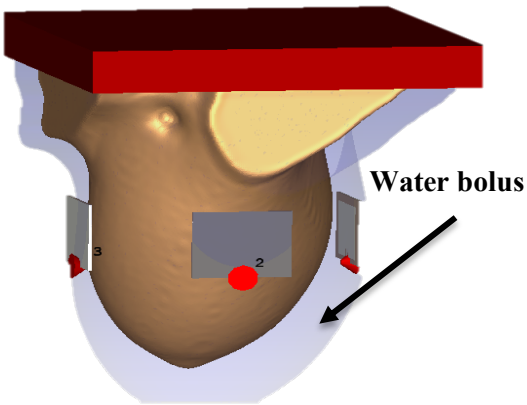


Fig. 4. The simulation environment

The thermal and electrical properties for each tissue are listed in Table 2.

Table 2
Breast tissue thermal and electrical characteristics at 2.45GHz [41,42]

Tissue	C_p KJ/Kg K	ρ Kg/m^3	K W/m K	A_0 W/m^3	B W/m^{3}K	ε_r	σ S/m
Fat	2.77	930	0.2	400	800	5.28	0.104
Glands	3.77	1020	0.42	6400	2400	35	0.137
Tumour	3.852	1050	0.5	5000	4800	57	3.00
Muscle	3.546	1041	0.53	480	2700	52.75	1.77

Since MRI data initially shows a breast in good health, a 2.5 mm-diameter tumour [43] that depicts the early stages of breast cancer is placed inside the glandular tissue for each point at the plane of the antenna array's centre. At w = 0 mm, the array's central plane is located.

4. Results

Using PSO, the optimum amplitudes and phases are found using electromagnetic (EM) focusing. The optimisation parameters are the four MSP excitations of the antenna. During the simulations, all four ports were simultaneously energised. A sphere-shaped tumour has been placed into the glandular tissue with a 2.5 mm radius for each site. Maximising power loss density and SAR at the tumour centre while minimising both as much as possible at other healthy points is PSO's goal. Plotted through each virtual line is the power loss density Q for each of the 120 places. Each line is 5 mm away from the previous one with different lengths inside the fibro glandular tissue as shown in Figure 5 and Table 3.

Line 1 is 45 mm in length with eight possible tumour positions as shown in Table 3. Each position is separated by 5mm from the previous one. The tumour is initially put at position 1 of line 1 (u, v) = 0, 5 (mm), and then PSO evaluations are started to identify the ideal amplitudes and phases values where the fitness function is validated or the maximum iterations are reached. Up until the tumour is implanted at the final position of line 1 at (u, v) = 0, 40(mm), the operation is repeated.

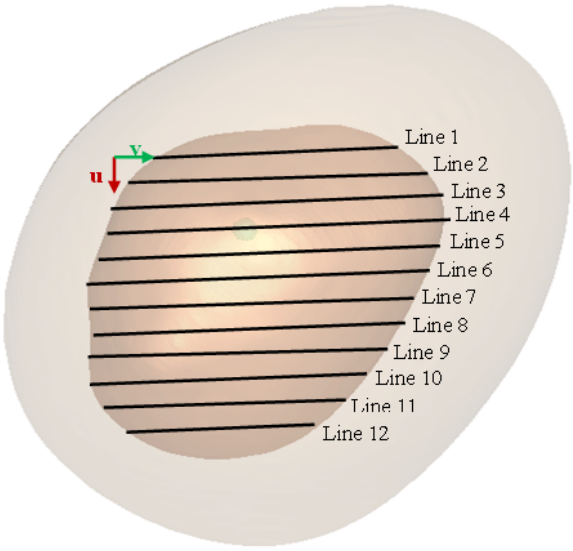


Fig. 5. The central plane of the breast with 12 virtual lines in the fibro glandular tissue

Table 3
The length for each virtual line inside the fibro glandular tissue and the number of positions per line

Line No.	Line length	No. of positions/line
1	45 mm	8
2	55 mm	10
3	60 mm	11
4	60 mm	11
5	70 mm	12
6	70 mm	12
7	60 mm	11
8	60 mm	11
9	55 mm	10
10	50 mm	9
11	45 mm	8
12	40 mm	7

Figure 6 shows the results of Q distributions of several lines for various tumour positions, with the tumour centre having the highest Q compared to other lines. The process is repeated for each position of the rest lines to obtain the optimized antenna excitations to achieve focusing at the inserted tumour position.

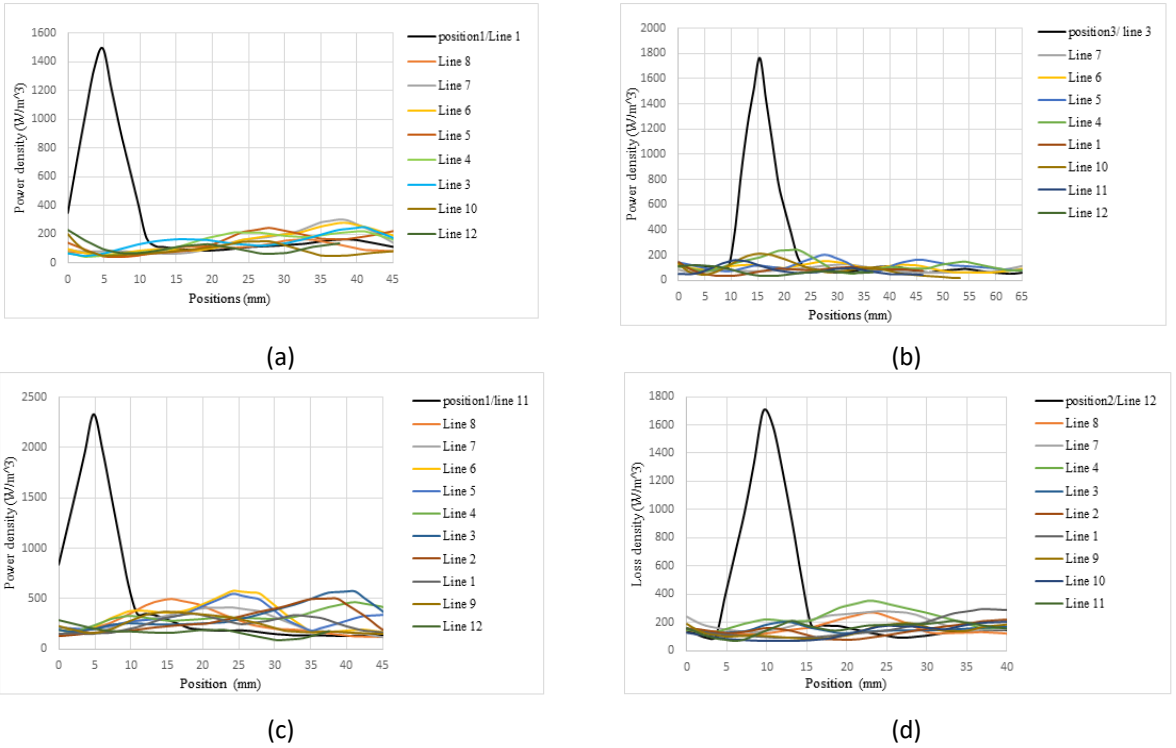


Fig .6. Comparison of the Q distributions for selected tumour positions along different lines

Four steps must be taken in order to determine the temperature distribution at the tumour sites. The first step is to apply the tumour (2.5mm radius) at the selected position, then use the values of the four MSPA's optimised amplitudes and phases. The final stage involves utilising Eq. (2) and the EM solver to calculate the power density Q that the incident MW signal produced. The thermal solver is then used to solve the Pennes bio-heat equation Eq. (3) using Q as thermal source.

After 1800 seconds (or 30 minutes) of heating, the necessary hyperthermia temperature (over 42°C) is reached. The tumour's temperature is above 42°C while healthy tissue is maintained safe to demonstrate the efficiency of the therapy, which involves reaching the hyperthermia temperature at the tumour centre position. In Figure 7, the temperature distribution inside the breast shows the success of the focused strategy in treating hyperthermia for breast tumours of 2.5 mm radius.

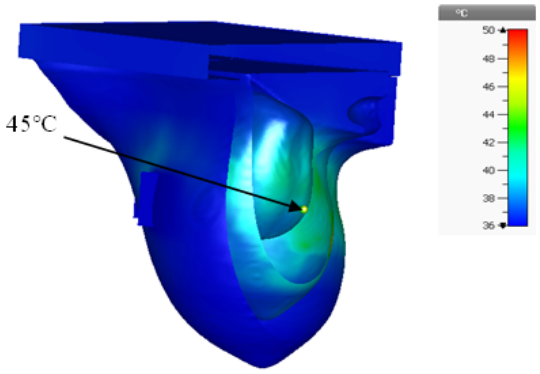
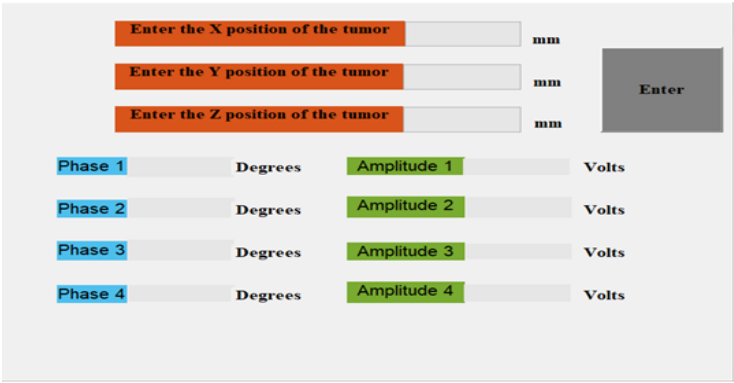
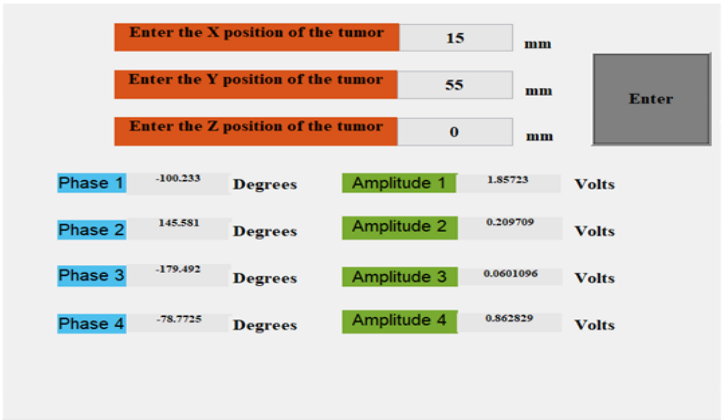


Fig. 7. Temperature distribution for 2.5 mm tumour radius

The collected data of antenna excitations with respect to the 120-tumour positions at the antenna phased array's central plane. is stored in a database, where medical professionals enter the coordinates of the tumour to determine the best antenna amplitudes and phases to fulfil the goal of hyperthermia treatment. The medical professionals can insert the x, y, and z position of the tumour using the MRI breast image. After that, the amplitudes and phases of each antenna are obtained for which the goal of the hyperthermia treatment is achieved as depicted in Figure 8.



(a)



(b)

Fig. 8. (a) The proposed GUI using MATLAB. (b) The amplitudes and phases of each antenna for a tumour at position 11 in line 4

5. Conclusions

Each MSP antenna array element's amplitudes and phases are calculated using PSO for every conceivable position of a tumour in fibro glandular tissue at the antenna array's centre plane, which is divided into 12 virtual lines with 120 potential tumour locations. The tumour radius is 2.5 mm for a more difficult scenario, and each tumour location is separated by 5 mm from the one next to it. To maximise power deposition (Q) and SAR at the tumour centre while minimising values in healthy tissue is the PSO target function for each position. The antenna's excitations are perfected after 50 iterations for each of the 120 potential tumour sites in fibro glandular tissue. The outcomes showed that the precise tumour volume may be targeted for heat treatment.

The temperature distribution is measured for specific tumour places at various lines at the antenna central plane in the breast fibro glandular tissue to assess the effectiveness of the focused hyperthermia treatment. After 1800 seconds (30 minutes) of heating, the necessary hyperthermia temperature (over 42°C) is reached. Also, the temperature distribution is compared with more healthy positions. A proposed GUI using MATLAB for clinical doctors to achieve non-invasive hyperthermia for breast cancer treatment is presented.

When compared to other research that employed simpler antenna configurations and breast models, the presence of a realistic environment in this work adds to the complexity of the experiment, even though the proposed focusing approaches demonstrate potential as a strategy for microwave hyperthermia. The current research may be constrained by this increased complexity.

6. Future Work

The power densities and temperature distributions inside the breast model are computed in the proposed method using electromagnetics calculations. The solution time is typically long and calls for a lot of hardware memory because of the realistic environment used, though. The optimization procedure used to determine the ideal amplitudes and phases of each antenna element consumes the majority of the computational time. Even though PSO has demonstrated its capacity to tackle a variety of optimization problems, solving a problem of this size still requires a lot of time. At certain tumour positions, the Q distributions were not the best, these results could be improved if larger number of iterations were calculated. It is fair to predict that these significant computational efforts will be reduced by utilizing more optimized software and hardware structures.

Artificial intelligence (AI), which has been brought to biomedical engineering and opened up new opportunities for medical investigation, could be used to further this effort. This could be accomplished by using large date of MRI breast images, for each breast image, the antennas excitations are obtained for each possible tumour positions using global optimization algorithm. With these large data, deep learning could be applied to train these data in order to estimate each antenna element's amplitudes and phases for new patients.

Acknowledgement

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