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FACULTY OF BIOMEDICAL ENGINEERING
Department of Biomedical Technology

Comparison of antenna elements by using a virtual model of a real patient

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Bachelor thesis supervisor: doc. Ing. David Vrba, Ph.D.

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Studijní program: **Biomedical and Clinical Technology**
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II. ÚDAJE K BAKALÁŘSKÉ PRÁCI

Název bakalářské práce:

Porovnání anténních elementů s použitím virtuálního modelu reálného pacienta

Název bakalářské práce anglicky:

Comparison of antenna elements by using a virtual model of a real patient

Pokyny pro vypracování:

In the COMSOL Multiphysics, create three numeric models of the hyperthermic (HT) applicator. The applicators will consist of 4 antenna elements (AE) operating at a frequency of 70 MHz. The first will use dipole AE, the second waveguide and the third metamaterial. Next, insert a virtual patient model created in Materialize Mimics from CT images into the system. Create a mesh of the entire model in the Materialize 3-matic program and then import it back into COMSOL Multiphysics. Compare the properties of a dipole, waveguide and metamaterial applicator in terms of electrical efficiency, sensitivity of adaptation to changes in the dielectric properties of the patient model and the ability to focus electromagnetic power to the treated area.

Seznam doporučené literatury:

- [1] C. A. Balanis, Advanced Engineering Electromagnetics, ed. Solution Manual, Wiley, 1989, Chapter 2, ISBN 0471621943
- [2] C. CALOZ, and T. ITOH, Electromagnetic metamaterials: transmission line theory and microwave applications, ed. 1st, John Wiley & Sons, 2006, ISBN 0471669857
- [3] Hana Dobšíček Trefná, Jan Vrba, Mikael Persson, Time-reversal focusing in microwave hyperthermia for deep-seated tumors, Physics in Medicine and Biology, ročník 55, číslo 8, 2010, Duben

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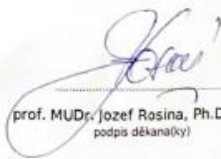
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DECLARATION

I hereby declare that I have completed this thesis having the topic “3D bioprinted collagen I with incorporated stem cells” independently, and that I have attached an exhaustive list of citations of the employed sources.

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Tamerlan Yusifov

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Abstract

In this bachelor work, a virtual model of a real patient which was previously created by Materilize Mimetics software was used to compare different hyperthermic applicators (Dipole, wave guide and metamaterial) in terms of electrical efficiency, sensitivity of adaptation to changes in the dielectric properties and ability to focus electromagnetic power to the treated area. All the simulations were made with an aid of COMSOL Multiphysics software, where the models of the applicators were made. The first task was done by changing relative permittivity of muscle layer of the model and comparing S_{11} parameter values and the second one was done by applying 1400 W to the model and measuring resulting specific absorption rate (SAR) value. The result of the experiment showed us that tumor cell absorbed the highest energy in the simulation with wave guide and metamaterial applicators, the resulting SAR values were the highest. The difference in between these two applicators is barely noticeable. Whereas the relative permittivity did not have much of an impact on S_{11} parameter value in any of simulations of applicators.

Key words; Hyperthermia applicators, Numeric models, Regional Hyperthermia, dielectric properties of applicators

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List of symbols and abbreviations

List of Symbols

Symbol	Units	Meaning
m	kg	mass
SAR	W/kg	Specific absorption rate
S_{11}	dB	Reflection coefficient
V	M^3	volume
P	W	Power
f	Hz	frequency
ρ	Kg/m^3	density
σ	S/m	Electrical conductivity
ε		Relative Permittivity

List of abbreviations

Abbreviation	Meaning
CT	Computed tomography
DNA	Deoxyribonucleic acid
RNA	Ribonucleic acid
HT	Hyperthermia
DRL	Distance related losses
ML	Mismatch losses

1. Introduction

Nowadays, despite numerous of scientific research in the field of medicine and technology, humanity faces a lot of incurable diseases, one of which is a cancer. Cancer is a disease that begins with a mutation, when a cell of the body (a somatic cell, i.e., not a reproductive cell) begins to divide/grow uncontrollably. Normal body cells work according to their internal clock with a working mechanism. These internal clocks regulate, for example, at what moment a cell divides, grows and matures, ages and/or dies, that is, all those natural processes that make up the cell's life cycle - the so-called cell cycle. In a cancer cell, this regulatory mechanism is damaged [1]. Cancer is very dangerous and deadly disease. According to statistics, in 2016 it was responsible for 30 % of all deaths in the country [2]. This can be seen on a pie chart figure 1.1

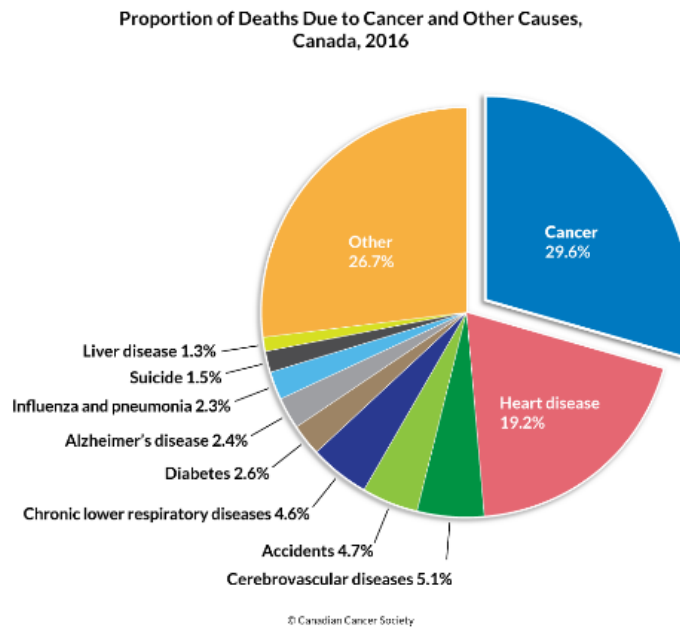


Figure 1.1- Proportion of Deaths to Cancer

One of the most abundant types of cancer is a stomach cancer. Based on the figure provided (figure 1.2), we can derive that men suffers from stomach more than a woman. [3] One of the most leading U.S universities -MIT, suggests that that women are more protected from stomach cancer than a man due to hormone estrogen. Previously, scientists have had linked higher rate in males with their diet and lifestyle, for instance- smoking. However, recent

scientific research and experiment on mice suggest that the main reason is a natural biological factor, mice that were treated with an additional estrogen dramatically lowered rates of stomach cancer. [4].

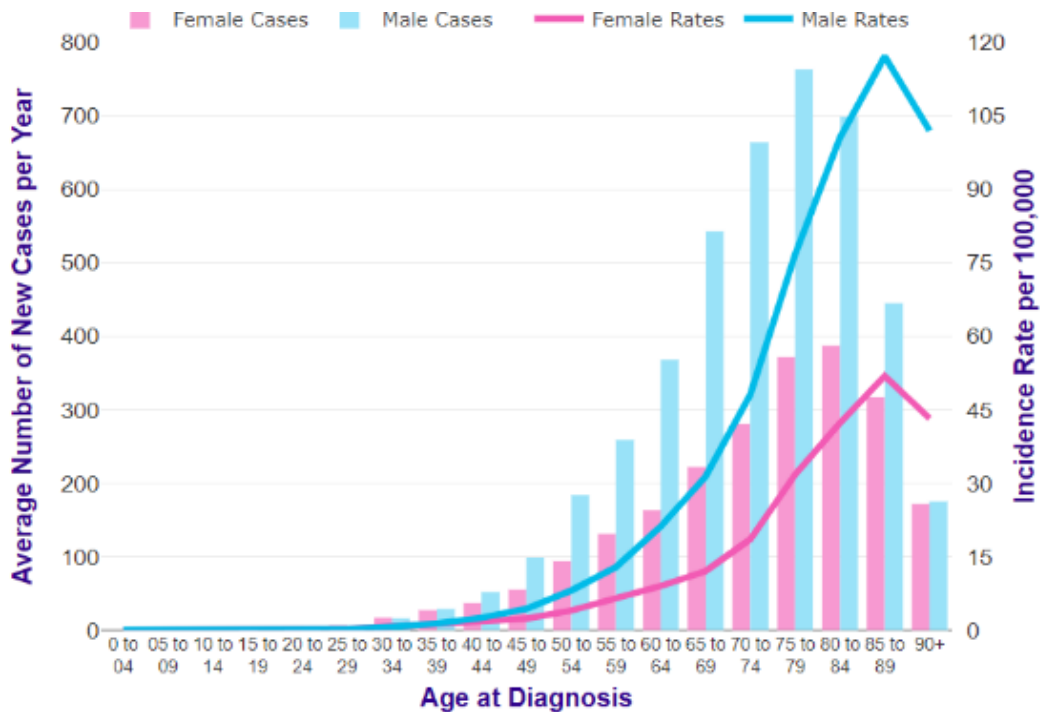


Figure 1.2- distribution of cases in years

Currently, we have a lot of ways in which we can treat cancer. The following treatments are major examples: chemotherapy, radiation therapy, surgical intervention, biorhythms. However, it is known that application of solely one treatment is sometimes insufficient, thus the most common way of beating cancer is combing two therapies together. Apart from this, these conventional treatments of cancer treatment usually cause unwanted side effect. Now, the most promising merge of therapies that scientist mostly work on now is hyperthermia and chemotherapy [5]. Figure 1.3 shows that average positive response rate of patient that have had combined hyperthermia [6] with other cancer treatments is higher.

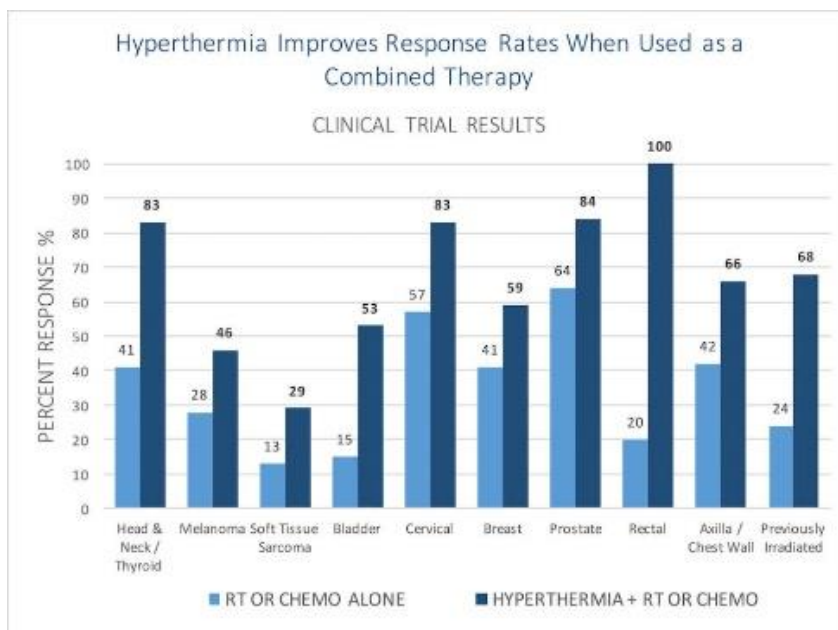


Figure 1.3- responses of patients

While the impacts of heat on the body have been researched for a long time, there has been a surge of interest in using "new" microwave hyperthermia for tumor treatment since the 1970s. The first numerous manufacturing facilities were produced hyperthermia at the time as a result of growth. New trends and innovations have turned hyperthermia into a valuable treatment for some forms of cancer in recent times.

Before going into depth of the field, we have to understand key points. Hyperthermia is a therapeutical application of the heat which is used in a controlled manner to a specific region of the body. Generally, we have three ways of applying hyperthermia. Local, regional and whole-body hyperthermia. The most advanced and the most precise method is a local hyperthymia. Depending on area of interest, heat is applied in three ways: externally, endocavitary and interstitially. The temperature that is usually applied to the region of interest (cancer cells region) is ranging from 41 to 45 degrees of Celsius. The main idea of this application of heat is to slow down the growth of the tumor, this is done due to fact that hyperthermia in tumor tissues leads to thermal damage and destruction of defective cells, while healthy cells remain intact. Heating tumors does enhance the effect of chemotherapy and radiotherapy [7] [8].

Nowadays, researchers have adopted local hyperthermia method to make it more efficient. Scientists of IIT-H university in India have found a special way to deliver the light-absorbing agent drug into the body, this is done via liposomes or lipid nanoparticles. Moreover, these liposomes are absolutely harmless and according to the researchers do naturally degrade in the body after transformation of its content. Apart from that these liposomes are not toxic, thus there is no risk of side effects [9].

This bachelor thesis deals with comparison of antenna elements by using a virtual model of a real patient which was previous made from numerous of CT scans with an aid of Materialize Mimics application. COMSOL Multiphysics will be the primary tool used in this project. It will be used to construct three numerical models of hyperthermia applicators. The system will have four antenna components that will operate at frequency of 70 MHz. Dipole antenna components will be used in the first system, waveguide will be used in the second, and metamaterial will be used in the third. Following the development of these systems, the virtual will be placed inside the system. Finally, after all of the preceding steps have been completed, the applicators can be compared in terms of electrical efficiency, sensitivity of adaptation to changes in the dielectric properties of the patient model, and ability to focus electromagnetic power to the treated region.

In order to compare the applicators in terms of electrical efficiency and sensitivity, electrical permittivity will be altered from 60 to 80 and S_{11} values will be measured. This procedure will be done for all three systems so that compares can be made in between them. This is a vital variable that has to be analyzed, as based on the theory the permittivity of a muscle has an impact on energy absorption, this leads to the fact that hyperthermia treatment may be different for different people with different body structure [10].

Furthermore, for comparison in ability to focus electromagnetic power to the treated region of different antennas, a total power of 1400 W will be delivered from four ports in different way, in order to discover which combination of four powers results in best SAR and Electromagnetic power loss density values.

Hyperthermia

Hyperthermia, also known as thermotherapy, is a relatively modern technique of treating cancer under which the tumor tissue is heated to a temperature in the range of 40-44 °C, over a set amount of time (approximately 60-90 minutes), causing tumor cells to die or be damaged. Over the past years, a lot of clinical experiments proved a huge potential for this type of a treatment. Positive data was obtained from treatment of melanoma, esophageal cancer, breast cancer, neck cancer, cervix cancer and many more [11]. This method has been developed on the fact that tumor cells are far more sensitive to high temperatures than normal cells, this can be partially explained by hypoxia, nutrient deficiency, and acidosis of tumor cells [12]. This type of treatment is not used solely, but in combination with chemotherapy or radio therapy. Research studies suggest that combination of those treatments may significantly enhance the cancer treatment, because of the fact that exposing cancer cells to high temperature may damage DNA and proteins, cause several protein accretion, induce oxidative damage on cell and mitochondrial membrane, inhibit DNA repair and more [13]. Although this is very promising type of treatment, nowadays hyperthermia is only used in very developed countries such as Germany and Netherlands as a part of a standard cancer treatment. Although, there are numerous ways of heating the tissue, the most frequently one used nowadays in oncology is electromagnetic. This is attributed to high frequency electromagnetic energy's ability to infiltrate biological tissues, allowing for uniform heating of a greater volume.

Types of Hyperthermia

Depending on the volume and the location of the tissue, hyperthermia can be applied in variety of ways. Hyperthermia is split in three main parts: Local Hyperthermia, regional Hyperthermia and the whole-body hyperthermia [14].

The main idea behind local hyperthermia method of treating the cancer is that the heat is delivered to small area like a tumor. Heat can be applied in different forms of energy: microwave, radio frequency and ultrasound. Application of local hyperthermia enables us to directly destroy the cancerous cell [15].

When it comes to the regional hyperthermia, we have to understand that this type of treatment is used to target tumors that are deeper in the body, thus the whole procedure of the regional hyperthermia application is far more difficult than the local hyperthermia. The main reason for this is that this type of hyperthermia does apply energy to deep-seated tumors which means that the energy may also be supplied to neighboring unwanted tissues. Regional hyperthermia is usually applied to larger regions, for instance abdominal cavity. Doctors may apply this type of hyperthermia in three main ways, which are: “Deep tissue”, “Regional perfusion” and “Continuous hyperthermic peritoneal perfusion” (which is also known as CHPP) [16]. This bachelor thesis is concentrated on regional hyperthermia treatment.

Whole-body hyperthermia usually is using low heat in order to elevate the body temperature up to 42°C. This type of hyperthermia treatment is used for the patient that suffer from last stage of the cancer, so the whole-body hyperthermia is applied to treat metastatic cancer. Mainly, this is done by hot water blankets or a thermal chambers [17]. The main difference in comparison to other types of the treatments is that the whole-body hyperthermia does not target any specific tissue, or a body. It can also be used to prevent cancer relapse.

Working principle of the hyperthermia

The disparity in between healthy cells and tumor cells in terms of physiological behavior is responsible for hyperthermia treatment of cancer. Tumor cell lacks in oxygen and in nutrient level. This is the key point in understanding the mechanism of this type of treatment of oncological disease. As was previously mentioned cancer cells lack in oxygen, this makes chemotherapy sometimes insufficient in tumor treatment, however when hyperthermia is applied, the blood flow increases, and vasodilation occurs [18]. When this happens, the cancer cells become more vulnerable to rise in temperature and thus applied heat may destroy cancer cells directly or it can be used as a “helping tool” for other cancer treatments, such as chemotherapy or radiotherapy, making overall success in cancer treatment. In general, healthy cells may withstand the rise in temperature, whereas cancer cells cannot.

As was mentioned before, hypothermia seems to also have many other biological effects, for instance damaging DNA, inhibiting DNA repair following chemotherapy or radiotherapy, increasing drug release in situ and many more. The processes during which new

replicons are assembled and creation of DNA is reorganized into mature chromatin have shown to be the most heat sensitive. It has been discovered that heat cytotoxicity occurs in a rapid mode rather than the more normal sluggish mode during the G1 process. The rapid mode is characterized by cell detachment and slowed rates of protein, RNA, and DNA synthesis within the first few days after heating with an aid of hyperthermia. In terms of another effects, it has been scientifically proven that hyperthermia has an effect on mitochondria. Hyperthermia does oxidative damage to the membrane system and mitochondria of tumor cells. Because of their metabolic characteristics, tumor cells are far more vulnerable to this type of damage due to their reductive efficiency is limited [19].

More about antennas and hyperthermic applicators

When taking into consideration different types of the applicators one has to consider several factors that influence the choice of applicator. These two factors are DRL which is also known as distance related losses, and ML which is also known as mismatch losses. For high-performing purposes the applicator has to be placed quite closely to the tissue however, we have to optimize the dimensions so that overheating does not occur. Apart from this applicator has to provide highest amount of energy to the treated area in our case- tumor. Dipole, waveguide and metamaterials are common applicators in hyperthermia treatment.

A dipole antenna is relatively low cost and lightweight, it only consists a conductive wire which if half the length of the wavelength the antenna may generate [20]. This wire is separated in the middle, leaving us with two sections (antenna arms) which are split by insulator. Each end of this arm is connected to a coaxial cable (usual impedance of which is about 50Ω) for receiving the signal. In terms of radiation, the maximum radiation which is produced by dipole antenna is when dipole antenna is perpendicular to the conductor, and zero in the axial direction [21].

Waveguide is another type of antenna that is widely used for medical purposes as well. In short, waveguide is a device that is responsible for the transport of the electromagnetic energy from one area to another. Most of the times, waveguides are nothing more than just a hollow metal tube. They are able to direct power to the wanted region directly. They work as a high pass filter, allowing only certain frequencies to pass through it, whereas the energies that have low frequency will be just [22]. Waveguide type of applicator is based on rectangular waveguide. The main advantage of waveguide applicator with respect to the hyperthermia is that it is able to transfer maximum energy without loss of energy and without the irradiation to the surrounding area. A huge advantage of this applicator is that it is able to provide a large depth of penetration due to the fact that it works on low operational frequency [23].

Another type of antenna that is widely used, and indeed utilizes in my work is a metamaterial antenna. In short, metamaterial antenna is using metamaterials in order to increase its performance. Metamaterial can be described as an artificial material whose property is commonly found in nature. [24]. Metamaterials are used in antenna in order to obtain better bandwidth and the power gain of the antenna.

Analysis of effectiveness of the antenna

SAR, which is also known as a specific absorption rate is a very useful technique with an aid of which one can measure the rate at which energy is absorbed per unit mass by a human body when it is exposed to a radio frequency electromagnetic field. The value of SAR is highly depending up on frequency and the intensity of the applied magnetic field, thus it can be used in analysis of effectiveness of the antennas in the project. Mathematic representation of SAR may be found in equations 1 and 2 [25].

$$SAR = \frac{d}{dt} \frac{dW}{dM} = \frac{d}{dt} \frac{dW}{\rho dV} \quad \left[\frac{W}{Kg} \right] \quad \text{or} \quad \left[\frac{W}{g} \right] \quad (1)$$

dW= infinitesimal energy

dM= infinitesimal portion of mass of tissue

ρ= mass density of the human tissue

v= volume of the sample

However, in practice a simplified equation for SAR calculation is being used:

$$\text{SAR} = \frac{\sigma E^2}{\rho} \quad (2)$$

σ is the sample electrical conductivity

E= RMS electric field

ρ =Density

V=volume

SAR will be further used in discussion and conclusion section in order to compare different types of antennas and to make a final statement with respect to the most suitable type of antenna for hyperthermia application.

S_{11} parameter will also be used further in the experiment for analytical purposes. S_{11} is a parameter that demonstrates how much of a power is reflected from the antenna. This quantity is measured in dB, if the value of S_{11} equals to 0dB, this shows that all power is reflected from the antenna and thus nothing is radiated [26].

2.Methods

Fast majority of the work was performed in the software “COMSOL Multiphysics”. This software was used to create a numeric model of hyperthermia applicators consisting of different antenna elements: dipole, waveguide and metamaterial antennas operating at 70MHz. The first system of antennas that was created was with four dipole antennas, as this type of antennas are the easiest to model using the relevant software. The model itself consists of several layers: Plexiglass, dielectric substrate, water layer and the antenna elements. In terms of dimensions of all the layers, the height of plexiglass layer is **0.01m**, **0,001m** for substrate layer, **0,0250m** for phantom and **0.08m** for the water layer respectively. The most complicated part of the model was to design dipole antenna. The main difficulty was the shape optimization and designing this type of antennas in a way to minimize the reflection. The actual dipole antenna model consists of several parts: two antenna arms and a port. As was previously mentioned, dipole antenna has to have a port for a coaxial cable. This was placed in the middle of the model (in between two antenna’s arms), sketch of the dipole antenna can be seen on figure 2.1.

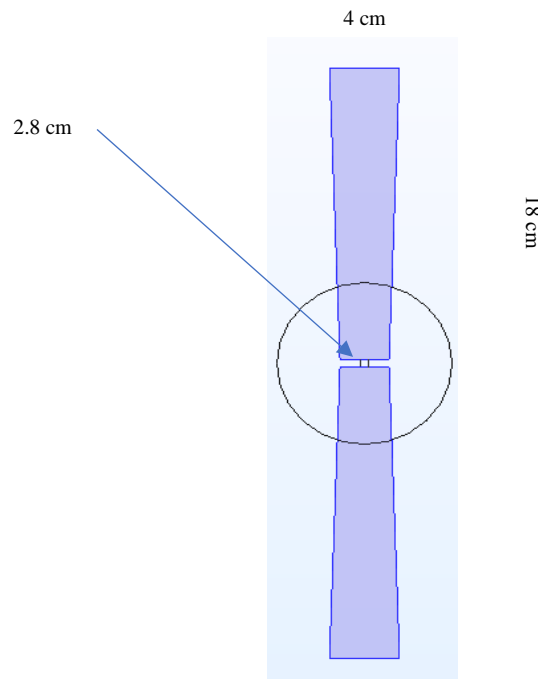


Figure 2.1- Dipole antenna sketch from COMSOL Multiphysics

More specifically, in COMSOL Multiphysics, in **geometry toolbar**, four blocks of different height and width were created. These 3D blocks represent plexiglass, substrate, water and phantom layer respectively. On top of the dielectric substrate a dipole antenna with port was modeled. In order to optimize the dimensions of the dipole antenna, **work plane** mode was used. The sketch of the model from two different perspectives can be seen on figure 2.2 and 2.3 respectively.

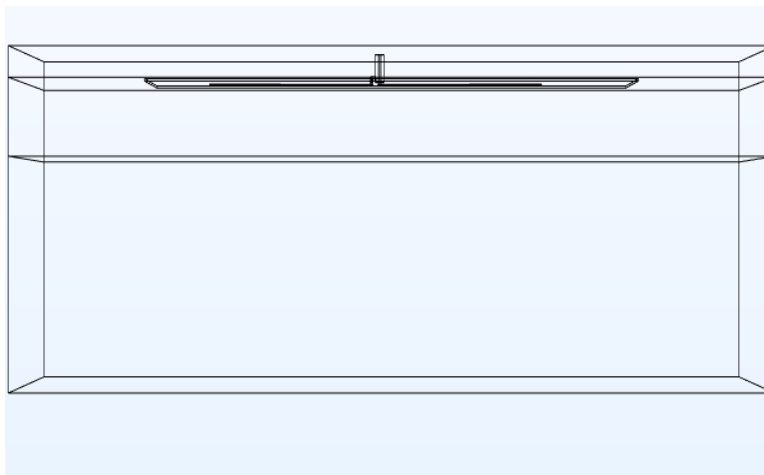


Figure 2.2 – dipole applicator layers

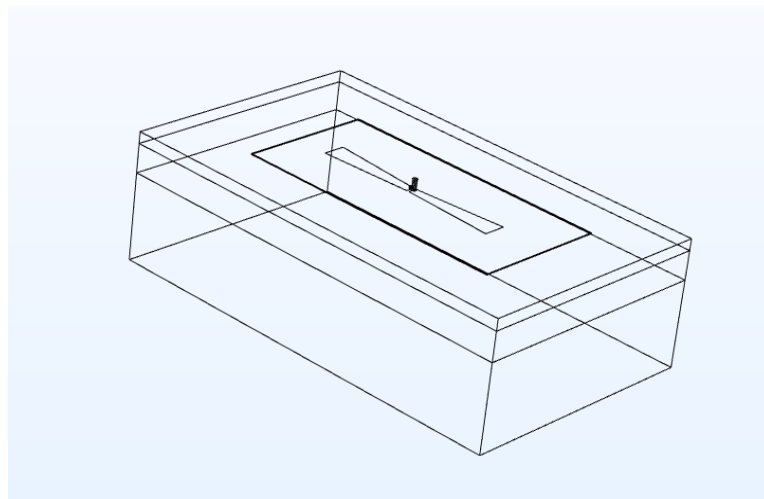


Figure 2.3- dipole applicator layers

After that, a hexagonal shaped hyperthermia system was modeled in the same software. Four dipole antennas were placed on sides. The system consists of a several layers whose properties may be seen on table 2.1. Four dipole antennas were placed on top of substrate layer. The overall annotated sketch of the system may be seen on figure 2.4.

Table 2.1- electrical properties of the different layers

	Relative Permittivity	Relative Permeability	Electrical conductivity
Plexi	2.6	1	0.003
Distilled water	80.2	1	0
Air	1	1	0
Dielectric substrate	4.5	1	0.025
Phantom			0.7

[27]

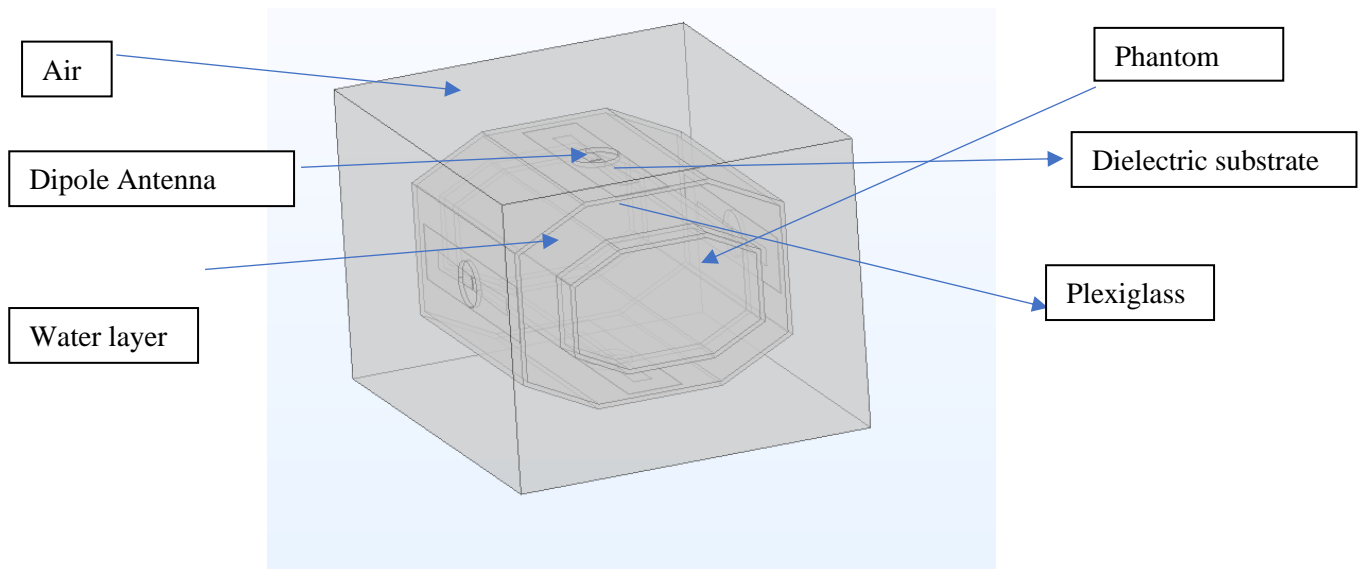


Figure 2.4- shows the overall structure of the system

The same procedure was conducted for the waveguide antenna. Figure 2.5 shows the arrangement of the layers and table 2.2 shows the dimensions.

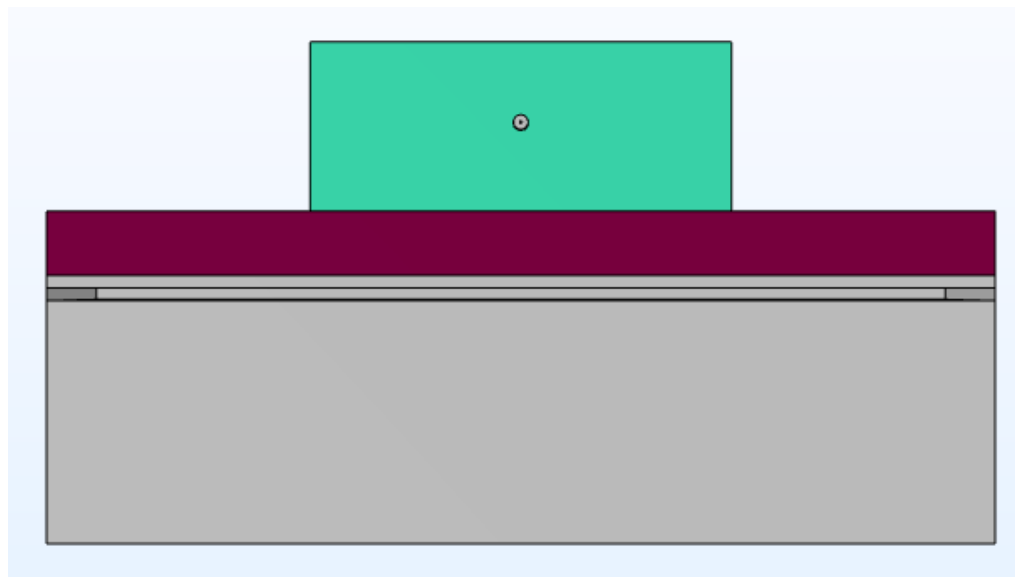


Figure 2.5-arragenemetn of layers of the model with waveguide type antenna

Table 2- electric properties of the layers in the model with the waveguide antenna

	Relative Permittivity	Relative Permeability	Electrical conductivity
Muscle	70	1	0.55
Water	85	1	0
Fat	13	1	0.06
Dielectric substrate	2	1	0
Air	1	1	0

As was mentioned previously, the system of metamaterial applicators will also be analyzed, however the model was not created in the COMSOL Multiphysics as a part of the project, instead the model was obtained from the source, figures 2.5 and 2.6 represent the model [28].

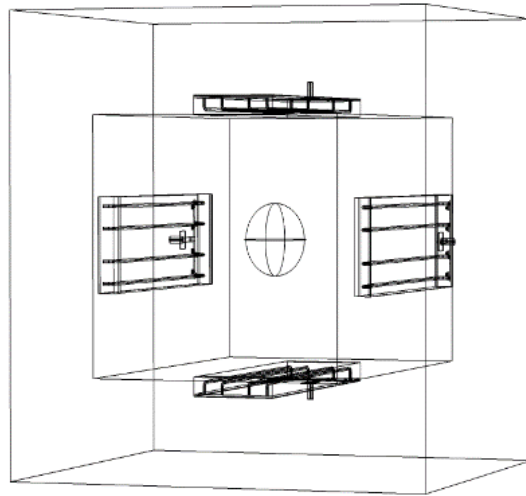


Figure 2.5- system of metamaterial applicators

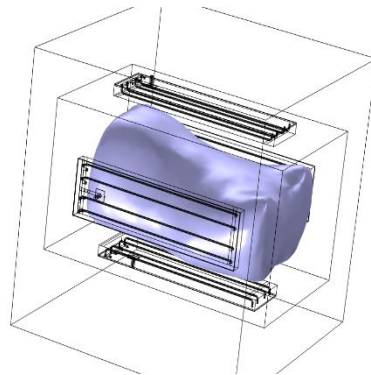


Figure 2.6- system of metamaterial applicators with anatomical body

Materialise 3-matic

In order to optimize the geometry of the model that was premade with an aid of the application “Mimics Materialism”, “3D-matic” software was used. In this application, we enabled mode- Filled with triangle edges. This was done in order to see the mesh of the current model. The meshed obtain was not sufficient in terms of geometry, so remesh function was used to obtain a better model that will be used later in the work. Remesh is a special technique that is widely used to rebuild the geometry of the model with a more uniform topology. Figure 2.7 shows the final model of the torso after remeshing procedure in 3D matic software [29].

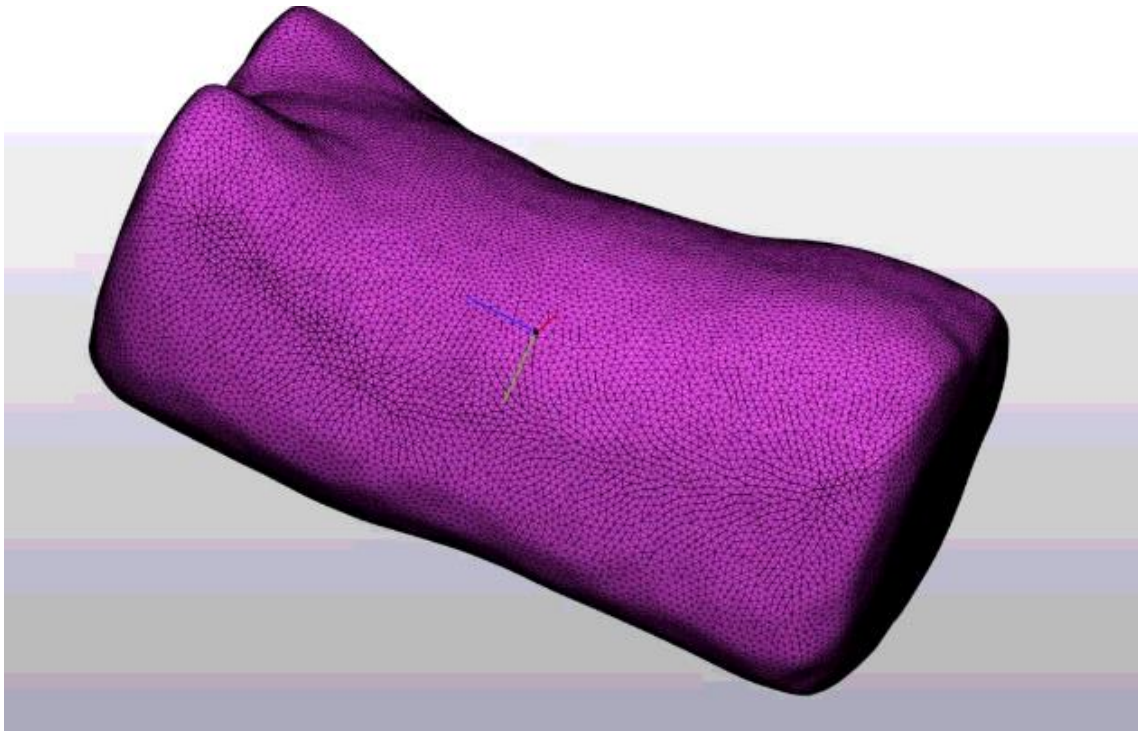


Figure 2.7- remeshed model of the torso

After the successful remeshing of the anatomical structure with an aid of 3D Matic materialise few changes were made before importing the model into the COMSOL. First, in the toolbar of 3D matic, option “Create volume mesh” was chosen, the maximum edge length of triangles was set up as 10 mm, after option “export volume mesh into COMSOL Multiphysics” was chosen. By following these steps, one is able to work with volume mesh in the COMSOL.

COMSOL Multiphysics

In COMSOL Multiphysics, we are working with previously made applicator that consists of four antennas of different kind (Dipole and Waveguide). After running a working file with the applicator, one had to choose “**Global definition**” from the “Model builder”, after mesh part and choose **3D part**. This enables to import a 3D mesh into the COMSOL Multiphysics. After this step, in geometry toolbar, function “import file” was chosen in order to place a 3D model in the premade applicator with antennas. COMSOL Multiphysics does place the model right in the middle of our geometry, hence does require any further manipulations with the dimensions.

Moreover, in “Model Builder” few other minor changes were made, one work plane was hidden, and an object was extruded from the model in order to place the anatomical structure into the system.

In order to make the model is constructed as accurate as possible and thus to have an effective result, which one can rely on, in materials sections, few minor changes were made. Material “**Phantom**” was chosen and further in domain the anatomical structure with tumor inside was chosen as a phantom.

Finally, in “Model Builder”, function Mesh was chosen in order to build a final mesh of the system with the anatomical structure, the mesh of the system is shown in results section. In order to extract relevant data and hence compare dielectric properties of different systems, study branch was chosen in the “Model Builder” and function “compute” was enabled. The graphs obtained are shown in section “results” and further analyzed and compared in discussion section.

As was previously mentioned, S_{11} , SAR and electromagnetic power loss computations are needed to make a comparison in between the antennas. In order to analyze

the sensitivity of adaptation to changes in the dielectric properties of antenna, permittivity has to be changed. To do so, in the “**Model builder**”, we have to choose materials node and find phantom there. The phantom has to include two domains “anatomical structure that was previously created” and “tumor with radius of 5cm”. After choosing these two domains, under section “material contents, relative permittivity has to be changed. Following relative permittivity has to be set up: 60,65,70,75,80. For each of the permittivity, we have to recompute the model and after under results section, in “**S-parameter (emw)**” node, S_{11} plot can be obtained.

3. Results

After inserting a model into the system of four dipole antennas and creating a mesh, the following results were obtained, see figure 3.1. The mesh was performed on the system of antennas with included anatomical structure and inserted tumor (spherical object with radius of 5 cm that was placed right in the middle of the model).

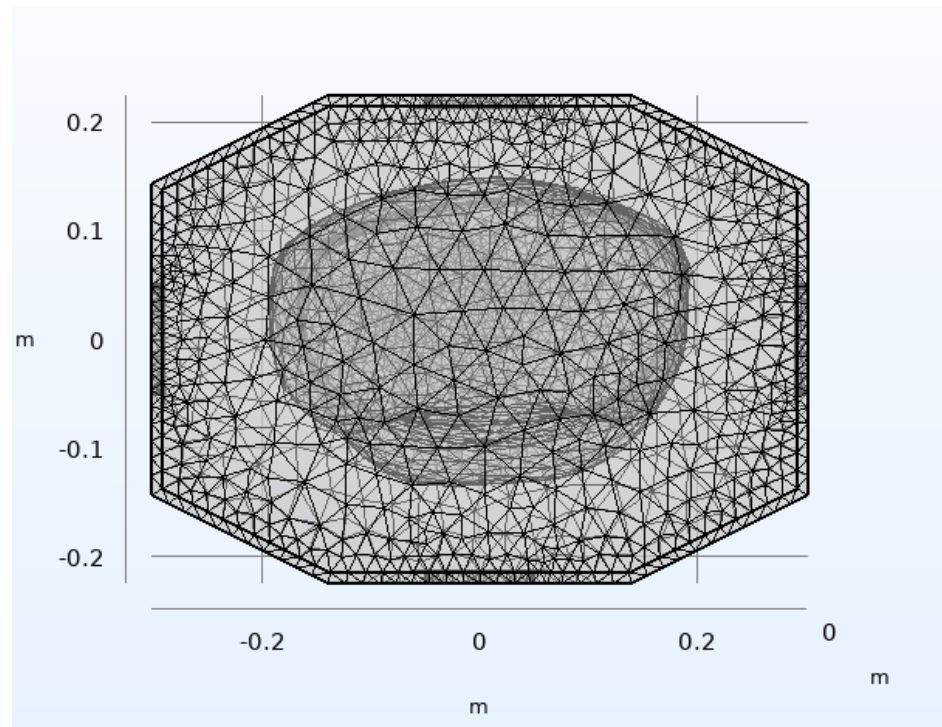


Figure 3.1-showing the mesh of the system with dipole antennas

After that, in results section, a 3D plot of electric field was extracted from the model. Figures 3.2 and 3.3 represent electromagnetic power loss density and SAR respectively.

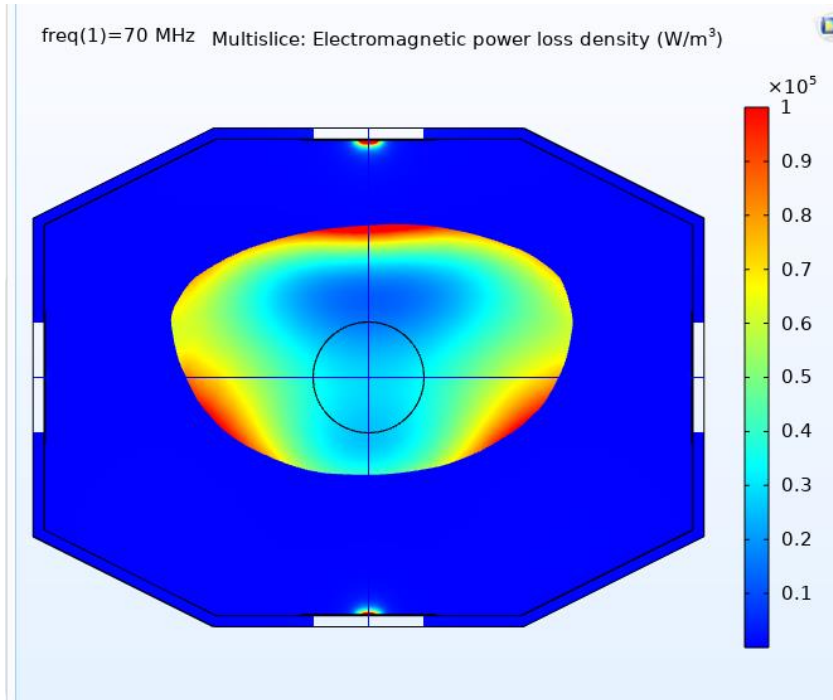


Figure 3.2 – shows the electromagnetic power loss density in W/m³

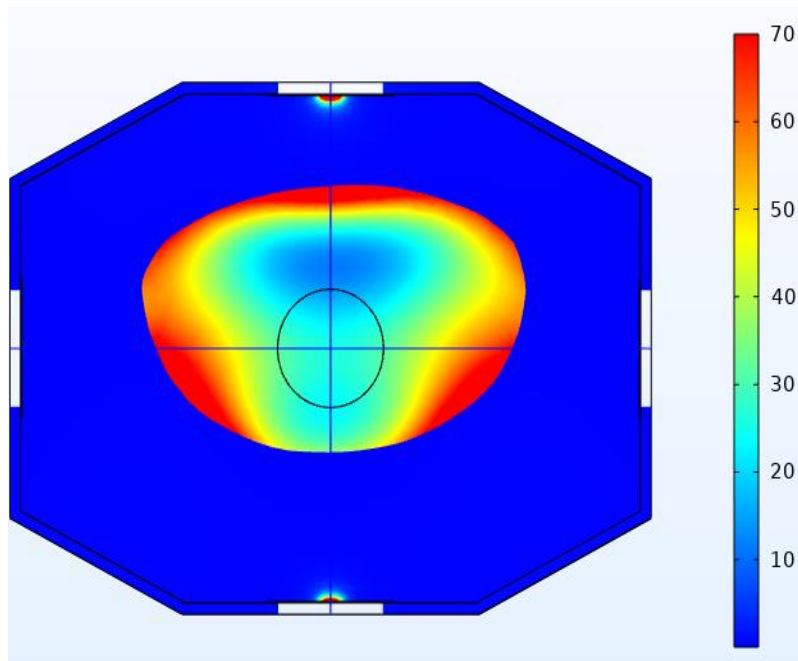


Figure 3.3- SAR in W/kg

After that, similar procedure was performed for the wave guide antenna system. Figure 3.4 shows the mesh of the system. Figure 3.5 demonstrate electromagnetic power loss density (W/m^3) and figure 3.6 shows SAR plot respectively.

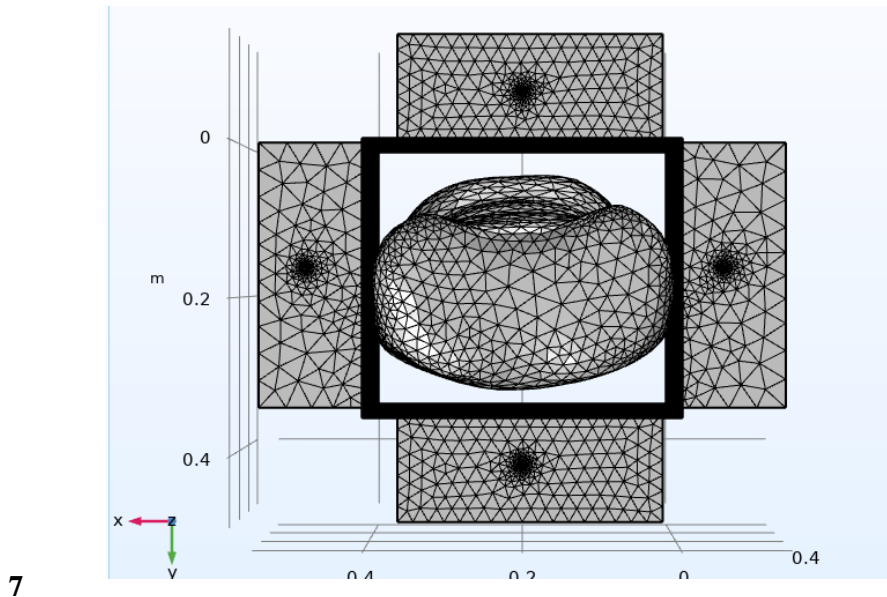


Figure 3.4-showing the mesh of the system with wave guide antennas

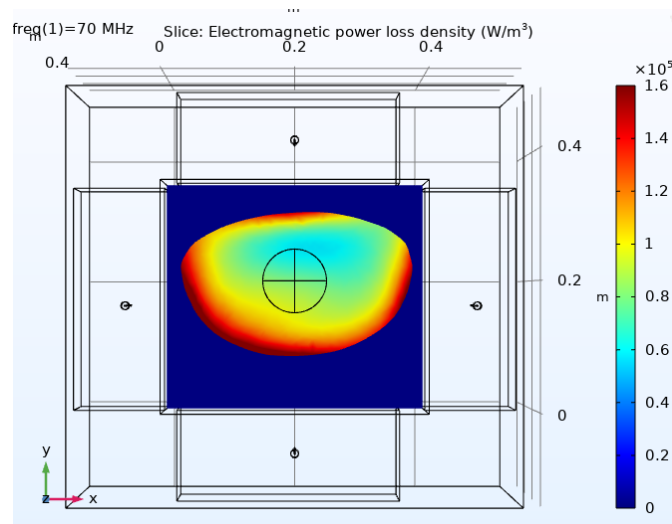


Figure 3.5- Electromagnetic power loss density W/m^3

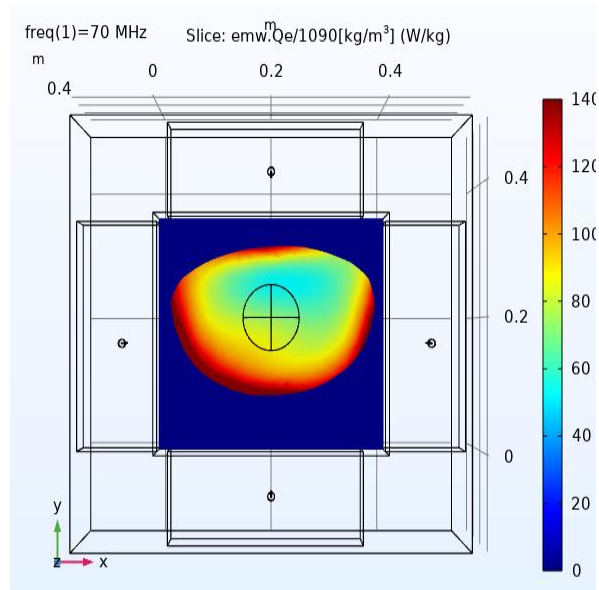


Figure 3.6- SAR

Apart from this, a parametric test on dipole system of antennas was conducted, it was performed in order to analyze the relationship between the width of antenna and the S_{11} parameter value, figure 3.7 demonstrated S_{11} plot obtained from this system.

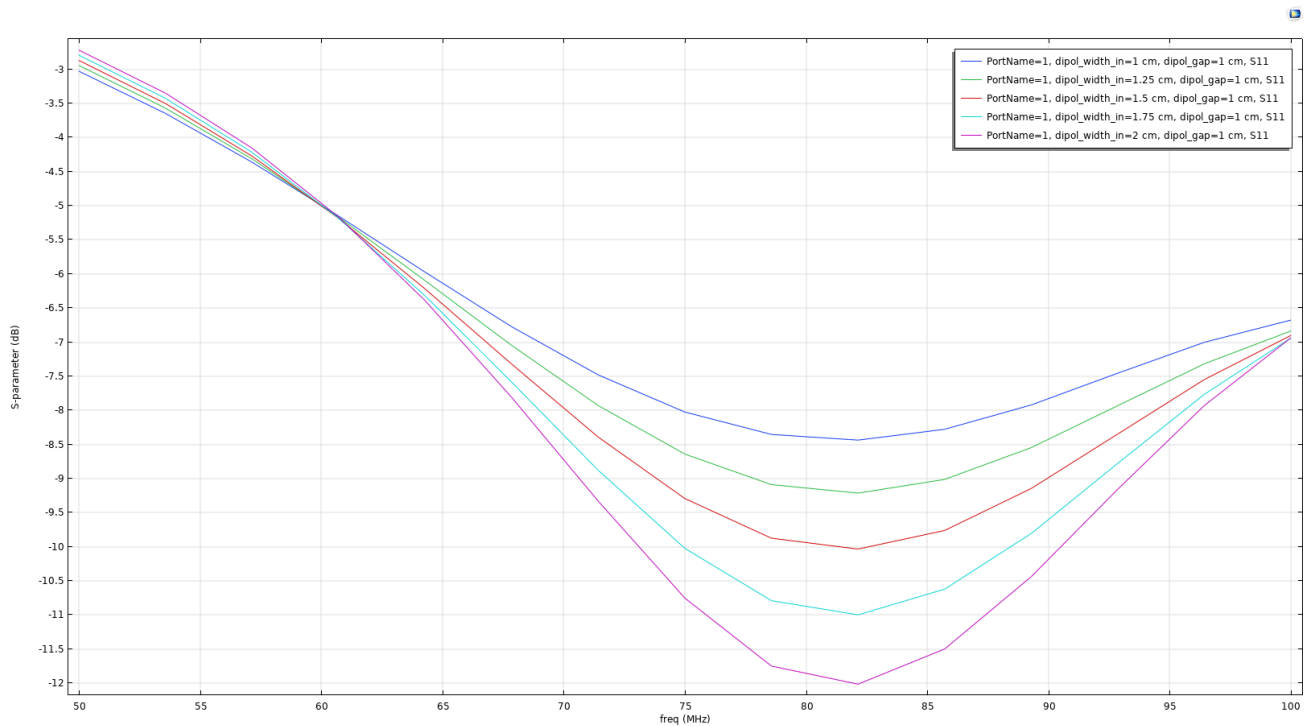


Figure 3.7 – Showing S_{11} plot of dipole antenna with different width

As was previously mentioned, one of the aims of the experiment is a comparison of antennas in terms of electrical efficiency and sensitivity of adaptation to changes in the dielectric properties of the patient model. Results of conducted experiment on relative permittivity and S_{11} values of dipole and wave guide antennas are shown in table 3.1 and 3.2 respectively.

Table 3.1-Effect of permittivity on S_{11} parameter of wave guide system of antennas

		Relative Permittivity (-)				
		60	65	70	75	80
Frequency (MHz)	60	-4.9712	-4.953	-4.9342	-4.9148	-4.8948
	65	-6.711	-6.6747	-6.6379	-6.6005	-6.5628
	70	-8.8059	-8.7424	-8.6789	-8.6154	-8.5523
	75	-10.875	-10.78	-10.686	-10.593	-10.502
	80	-12.095	-11.981	-11.868	-11.759	-11.652

Table 3.2-Effect of permittivity on S_{11} parameter of dipole system of antennas

		Relative Permittivity (-)				
		60	65	70	75	80
Frequency (MHz)	60	-9.7958	-9.9318	-10.056	-10.168	-10.267
	65	-11.796	-11.841	-11.861	-11.865	-11.828
	70	-10.596	-10.621	-10.625	-10.609	-10.574
	75	-7.7249	-7.7027	-7.6695	-7.6268	-7.5762
	80	-5.7698	-5.7106	-5.6485	-5.5847	-5.5204

Table 3.3-Effect of permittivity on S_{11} parameter of metamaterial system of antennas

		Relative Permittivity (-)				
		60	65	70	75	80
Frequency (MHz)	60	0.53250	0.52921	0.52680	0.52242	0.51893
	65	-0.67098	-0.69123	0.70558	-0.73231	-0.75308
	70	-12.099	-12.166	-12.329	-12.297	-12.361
	75	-0.34744	-0.36487	-0.38649	-0.40080	-0.41921
	80	0.40774	0.39993	0.39115	0.38422	0.37638

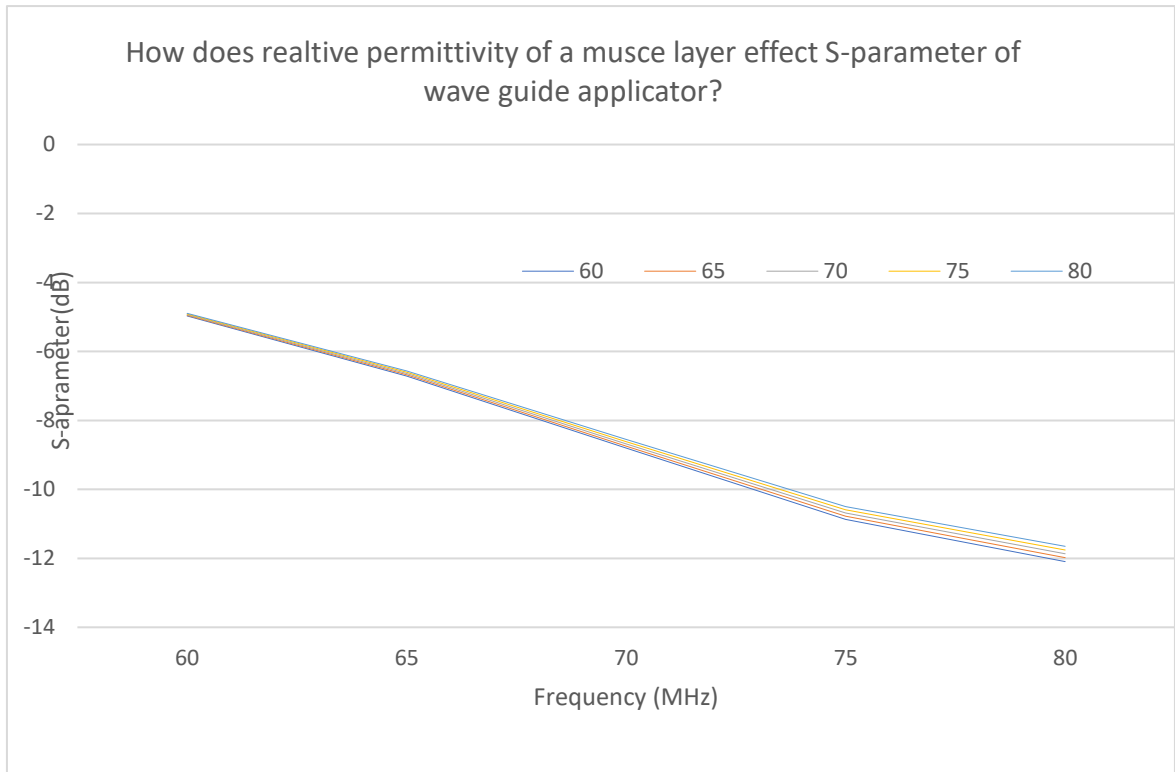


Figure 3.8- effect of relative muscle permittivity on S-parameter of wave guide applicator

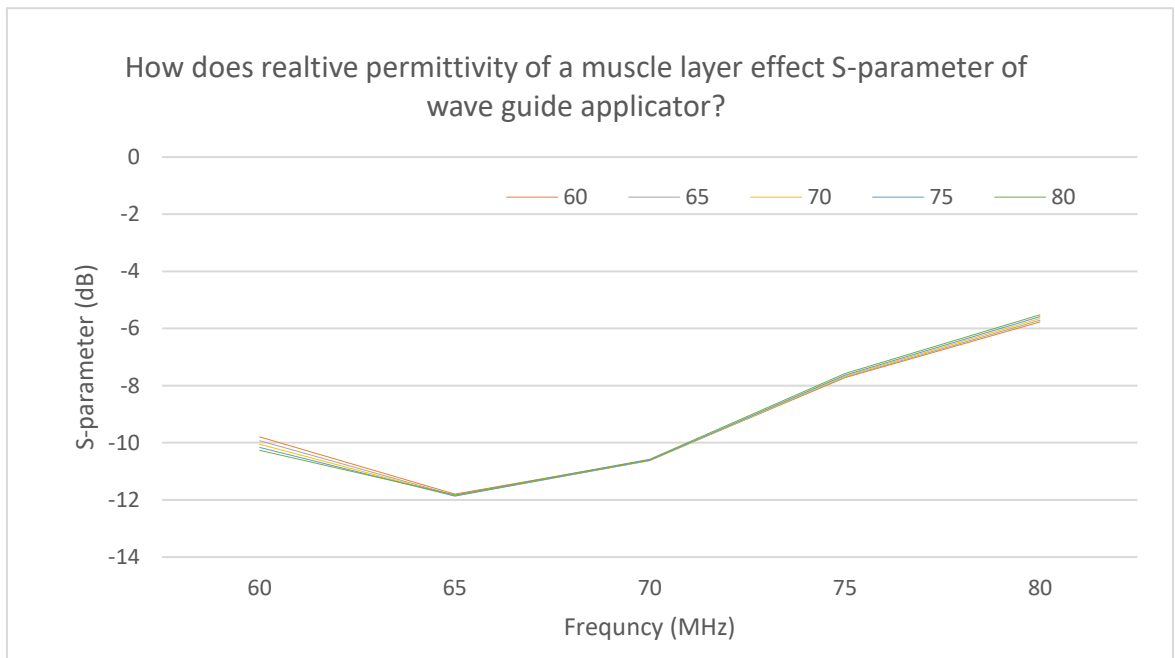


Figure 3.9-effect of relative muscle permittivity on S-parameter of dipole applicator

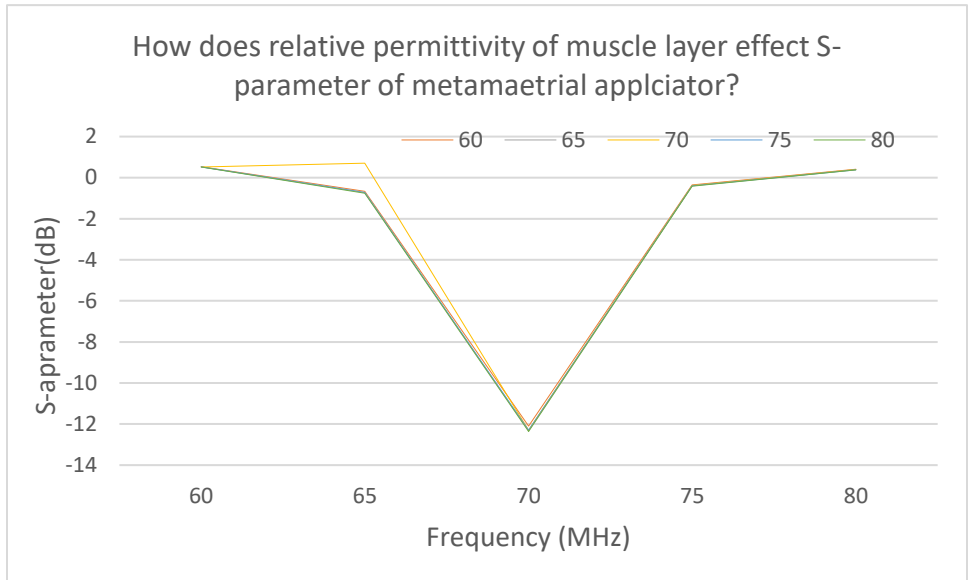


Figure 3.10-effect of relative muscle permittivity on S-parameter of dipole applicator

Table 3.3-comparison of different power delivery to the system of dipole antennas

Number of experiments					
1	2	3	4	5	6
Power (W)					
600	500	450	450	350	250
600	500	450	450	350	250
100	200	250	300	400	450
100	200	250	200	300	450
Electromagnetic power loss density (W/m ³)					
16.381	31.909	34.289	34.239	38.11	40.56
SAR (W/kg)					
0.015029	0.029275	0.031458	0.031412	0.034964	0.037211

Table 3.4- comparison of different power delivery to the system of dipole antennas

Number of experiments					
1	2	3	4	5	6
Power (W)					
600	500	450	450	350	250
600	500	450	450	350	250
100	200	250	300	400	450
100	200	250	200	300	450
Electromagnetic power loss density					
14.551	14.824	14.892	14.446	14.509	14.849
SAR (W/kg)					
0.013349	0.01360	0.013662	0.013253	0.13311	0.013623

Table 3.5- comparison of different power delivery to the system of metamaterial antennas

Number of experiments					
1	2	3	4	5	6
Power (W)					
600	500	450	450	350	250
600	500	450	450	350	250
100	200	250	300	400	450
100	200	250	200	300	450
Electromagnetic power loss density (W/m ³)					
22.882	30.163	33.972	34.212	38.082	40.265
SAR (W/kg)					
0.020992	0.027673	0.031167	0.031387	0.034919	0.036940

For visualization purposes, bar chart graphs were plotted, where Electromagnetic power loss density and SAR are displayed. The resulted charts may be seen on figures 3.9, 3.10, 3.11, 3.12, 3.13 and 3.14 respectively. X-axis plotted on both of the figures represent different experiment (six possible combinations of the same power (1400 W)), whereas y-axis on figure 3.9 represent Electromagnetic power loss density measured in W/m^3 and specific absorption rate (measured in W/kg) on the figure 3.10.

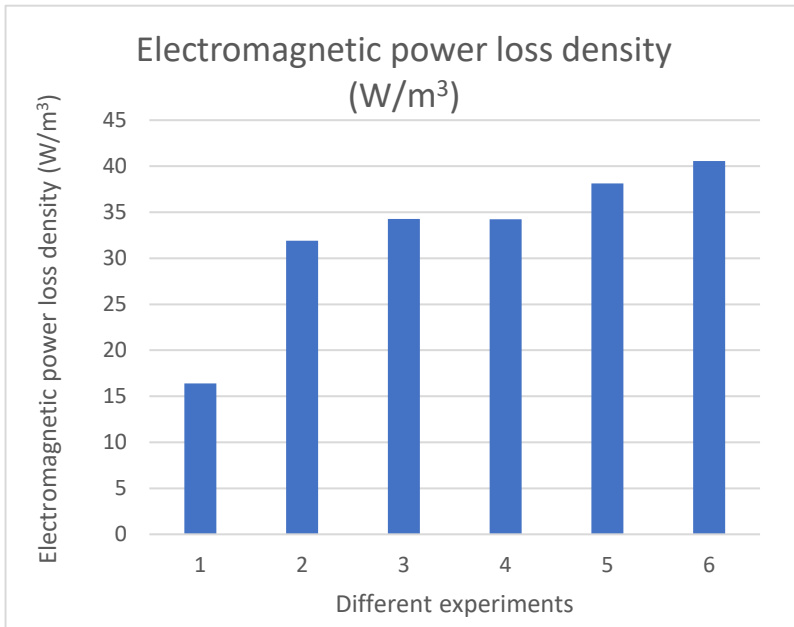


Figure 3.11- Electromagnetic power loss

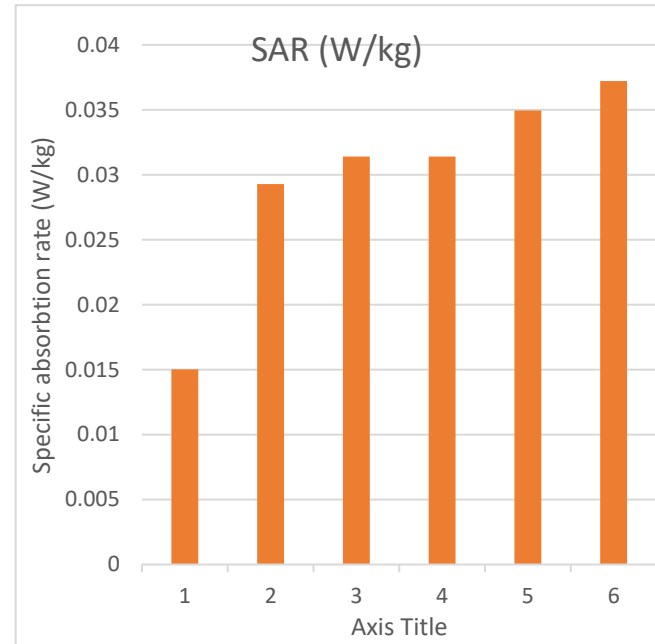


Figure 3.12-SAR

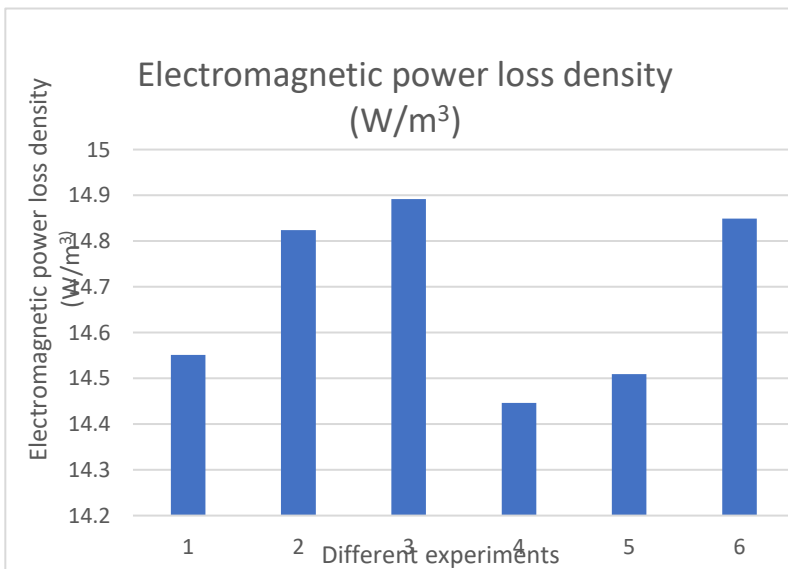


Figure 3.13- Electromagnetic power loss

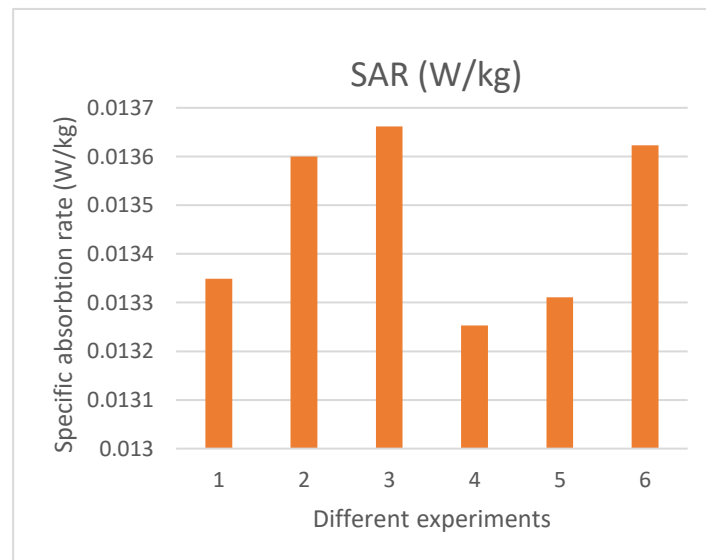


Figure 3.14-SAR

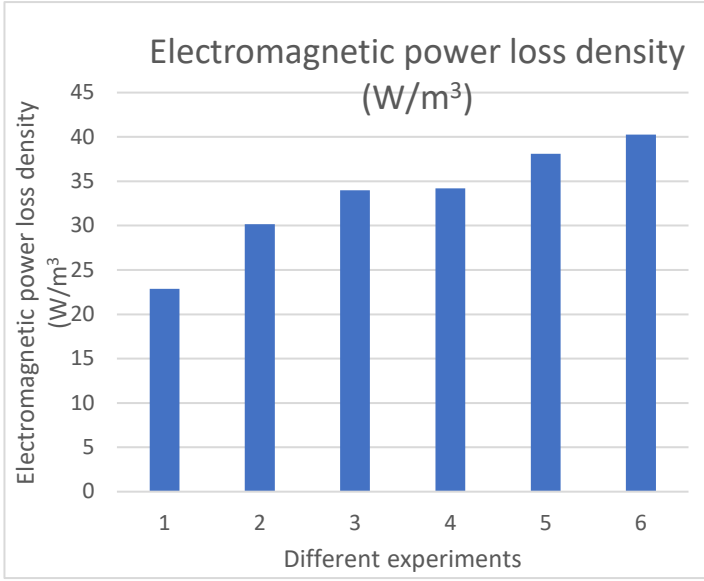


Figure 3.15- Electromagnetic power loss

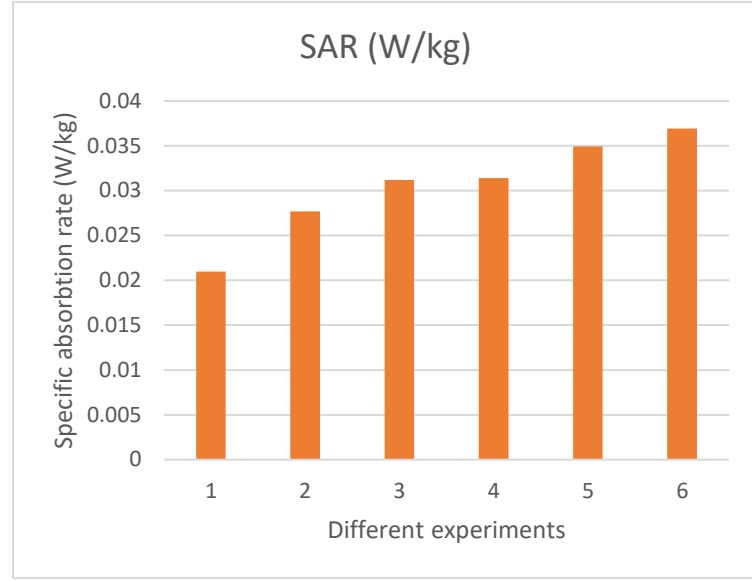


Figure 3.16-SAR

4. Discussion

Based on the results obtained from the experiments, we may state that the width of inner part of antenna has a significant impact on the S_{11} value, which is also known as reflection coefficient. According to the figure 3.7 that demonstrates S_{11} parameters of dipole antennas of different width, one may observe that dipole antenna with inner width of 2 cm has a value of -8.75 dB, whereas for dipole antenna with 1 cm as inner width, the value obtained is only -7.25dB.

In terms of best frequency for individual applicators, according to the results obtained (this can be seen on table 3.1), waveguide applicator gives the best S_{11} parameter value at 80 MHz, dipole applicator at 65 MHz, and metamaterial applicator radiates best at 70 MHz.

According to the results of conducted experiment where the relative permittivity of the muscle layer of anatomical structure was changed (from 60 to 80), the following trend may be observed for wave guide applicators system: as relative permittivity increases, we are obtaining lower S_{11} value. For instance, for permittivity of 60, the S_{11} value equals to -11.796 dB, whereas for permittivity of 75, the respected value is -11.865 dB. The following observation allows us to state that relative permittivity of 75 is ideal for maximizing the radiation of the wave guide antennas system. However, due to the fact the obtained difference is very small, this alternation in dB may be neglected. Moreover, the following trend was not observed for two other applicators.

In terms of ability to focus energy to the treated area, as was previously mentioned, the values of power radiated from four different ports were changed in order to obtain the optimal values for each individual port for all systems of applicators. Based on the observations (results of which may be seen on table 3.3), we may state that an ideal combination of power for wave guide applicator system is 450 W for upper and lower ports and 250 W for side ports. Setting up a system of wave guide antennas with the following configuration gave us highest SAR value (Specific absorption rate). As mentioned before, specific absorption rate may be defined as rate at which energy is absorbed per unit mass by a human body. Based on the fact that the tumor model of the system absorbs energy at highest at this configuration of the powers from the ports, we may conclude that these values are the best in targeting tumor cells. The same trends were obtained for two other applicators as well.

Taking into considerations SAR values obtained from system of dipole and wave guide and metamaterial applicators, one can observe that tumor model absorbs energy better in the system of wave guide and metamaterial. The difference in between SAR values obtained from these two systems is extremely small (40.56 and 40.256). The reason behind this phenomenon is in surface area of the antenna. The area of wave guide and metamaterial applicators that radiates is bigger than of dipole, this results in higher energy emission and thus resulting in higher SAR value. Theoretically, in order to obtain similar SAR values for the dipole system of applicators, the number of applicators has to be increased in the system, for example from four to six or eight, this will result in better SAR value.

In terms of accuracy of the results, during simulation of the systems, the electrical conductivity (σ) of water was set to 0 for simplification and faster simulation, however if the value of electrical conductivity will be changed to 0.001, this will result in more accurate results. However, as the main purpose of the project was to analyze and compare different antenna applicators in terms of electrical efficiency, sensitivity of adaptation to changes in the dietetic properties of the patient model and the ability to focus electromagnetic power to the treated area, the number of independent variables had to be minimized, thus electrical conductivity was set to 0.

5. Conclusion

Based on the results obtained from conducted experiments, we may state that the aims of the project were met. This experiment showed as that wave guide and metamaterial applicator systems are the best in terms S-parameter value and gives us the biggest SAR values (40.56 W/kg and 40.265 W/kg) in comparison to dipole applicator (only 14.849 W/kg). However, there has to be more research made in relation to relative permittivity experiment as the results obtained did not show significant difference in S-parameter value. Possibly, more relative permittivity values can be analyzed next time. Apart from this, the electrical conductivity was set to 0, even though it has to be 0.001, this was done to exclude electrical conductivity as a possible factor that may influence results. However, as this was only a simulation, for simplification purposes and faster computation of the model, it was set to 0. If the electrical conductivity of water layer would be increased to 0.001 in the project, it will result in lower SAR values for all the applicators. In the future experiment, it will be very beneficial to analyze different number of dipole applicators, possible 8 or even 16, as the results of this experiment indicate that the 4 dipole applicators in not enough to have a similar SAR value to wave guide or metamaterial system. Moreover, possibly even experimenting with position of these applicator in the system in may be analyzed to discover if these two applicators will have different results. Nevertheless, the aim of the project was met, and results obtained can be considered as relevant ones.

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