Microwave Interstitial Tumor Ablation: New Modality for Treatment of Liver Cancer

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Abstract:

Hyperthermia is newly back in the interest of both, clinical and research oncologists, because of its properties to directly produce permanent damages of the treated tumors and to elicit important immunological responses against cancer cells by changing their immunogenicity.
Microwave ablation is used in the treatment of primary and secondary tumors of the liver.

Microwave antennas suitable for hyperthermia needs to be properly designed in order to deliver electromagnetic energy into the tumor tissue with minimal irradiation of healthy tissue Interstitial antennas are used to elevate the temperature of cancer tissues located deep inside of patient's body. A microwave generator produces microwaves, typically around 2.45 GHz, with 60 W power. Under anesthesia, thin needle electrodes are inserted into the body, usually under ultrasound guidance. A typical treatment cycle takes 60 s, where full power is applied. This produces a lesion of about 2 cm diameter. Treatment is repeated typically three times a week, until the entire tumor is ablated.
To obtain the solution for equations of EM deposition inside biological systems, it is required to choose a calculation method. Because human body models have complex geometry, with region of different characteristics, and for this a numerical method has to be employed.

In this paper it has been discussed how advanced electromagnetic numerical techniques can be utilized to design the interstitial antennas for realistic human body environment. To characterize and design interstitial antennas to be inserted inside the human body for microwave ablation different methodologies-Quasi-static Impedance method – Methods of Moments (MoM) – Finite Difference Time Domain (FDTD) – Finite Element Method (FEM) are utilized.

Keywords: Hyperthermia., MCT, Ablation, FEM, FDTD, MoM

1. Introduction

Talking about diseases, it is very rare not to hear the word “cancer" in daily conversation. The reason is that there are more than 10 million cases every year and it has become one of the most devastating diseases in the world, especially in developed countries [1].

With development in new technology, we have reached the question: why haven't we found a cure for cancer yet?

The main problem is that there are many kinds of cancers, so it is very difficult to find a general cure, since the treatments vary with type of cancer and location. The most known therapies for treating cancer diseases nowadays are radiotherapy and chemotherapy. However these treatments have many negative side effects, so it is very important to find alternatives which allow the patient to fight the illness without any other consequences or symptoms than the ones from the cancer itself. For example, radiation therapy side effects are hair loss, fatigue/malaise, low blood count, skin desquamation or mucosity development. For chemotherapy the most common side effects are nausea and vomiting, hair loss, and bone-marrow depression [2] [3].

A possible complementary treatment that is under development is denoted hyperthermia. The basic idea behind this treatment is to create an artificial “fever" of 41-45°C in the body of the patient without damaging the benign tissue. It is also denoted thermal therapy or thermotherapy, and is a type of cancer treatment in which it is tried to reach cytotoxic temperatures (> 42°C) during approximately 60 minutes. Different studies have shown that moderate temperatures can damage and kill cancer cells, usually with minimal injury to normal tissues. By killing cancer cells and damaging proteins and structures within cells, hyperthermia may contract the tumors. . Most of the research work being done on designing of microwave antennas for biomedical applications has focused on producing tumor ablation for medical treatments. Antennas may be used to provide heating by non invasive applicators and interstitial applicators. Internal and external heating hyperthermia techniques are shown in figure 1.

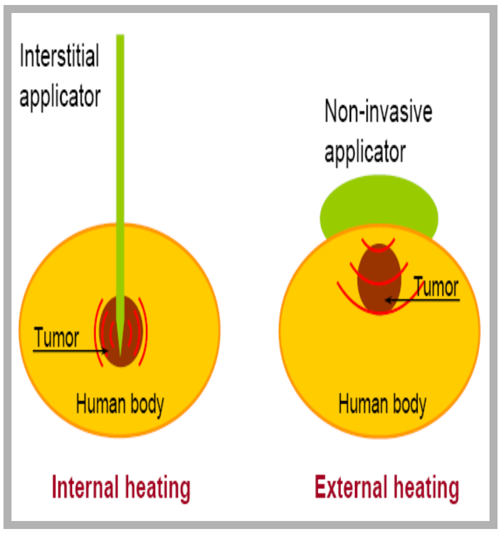

Figure 1. Internal and External heating techniques

2. Liver Cancer

The liver is the largest organ in the body and is located in the right upper quadrant of the abdomen. The liver creates, regulates, stores a variety of substances used by the gastrointestinal system and it serves a number of important digestive functions, formation of certain blood proteins, and the metabolism of carbohydrates, fats, and proteins.

The liver also plays an important role in blood circulation with approximately 25-30% of the resting cardiac output going to the liver. The liver receives oxygen-rich blood from the aorta through the hepatic artery, which accounts for 25% of the blood flow into the liver. The remaining 75% of the blood comes to the liver through the portal vein which carries nutrient-rich blood from the small intestine. Blood is removed from the liver through the hepatic vein.

Hepatocellular carcinoma (HCC), or primary liver cancer, accounts for 80-90 percent of all liver cancer. It occurs more often in men than women, and occurs mostly in people 50 to 60 years old. The disease has historically been more prevalent in parts of Africa and Asia, but becoming more common in the west recently due to an increase in hepatitis cases there [4],[5]. The cause of liver cancer is unknown, but contributing factor includes chronic liver disease, viral hepatitis, carcinogens, and food toxins. The worldwide incidence is 4 out of 10,000 people[5].

Figure 2. shows the blood supply to the liver and hepatic tumor [6]. The tumor receives 95% of its blood supply from the hepatic artery, while the normal liver tissue receives 75% of its blood from the portal vein and the rest from the hepatic artery.

HCC tumors usually grow in one or more focal nodules with typical doubling time of 30-200 days. The neovasculature that stems from the hepatic artery and surrounds the tumor is abnormal, and the endothelial lining of the newly formed vessels is fine and easily damaged [7] .

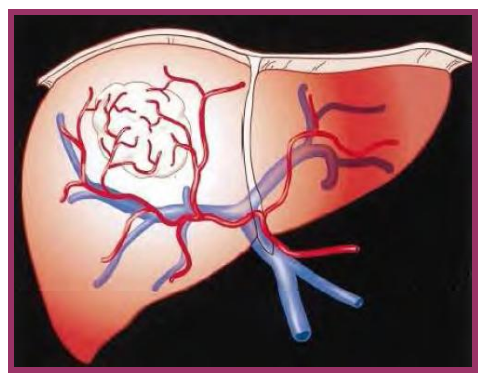

Figure 2. Blood supply to the liver and hepatic tumor. The large, vessel is the portal vein, and the thin red vessel is the hepatic artery which feeds the tumor[6]

3. Thermal Ablation

The methods of tumor ablation most commonly used in current practice is Thermal Ablation. Irreversible cell injury occurs when cells are heated to 46^{0}C for 60 minutes [8]. With increasing temperatures the time necessary to induce cell death is shortened and at 60-100^{0}C cell death is immediate and irreversible. Coagulation necrosis denotes irreversible thermal damage to cells. Temperatures greater than 105^0C result in tissue boiling, vaporization and carbonization, which may retard optimal ablation [9].

Ablative treatments have started to become viable alternative methods to treat patients who cannot be treated by surgery. Such ablative treatments include cryoablation, radiofrequency ablation (RFA), microwave ablation (MWA) or also called microwave coagulation therapy (MCT), and ethanol ablation, etc.[10],[11]. According to Simon et al [12] the main advantages of microwave technology, when compared with existing thermo ablative technologies, include consistently higher intratumoral temperature, larger tumor ablation volume, faster ablation times and improved convection profile.

The basic principle of microwave hepatic ablation is to apply microwave power to the liver tissue through the microwave applicator (the antenna). The power of the EM wave is absorbed by the liver tissue and heats the tissue. Liver tissue is destroyed after the tissue is heated to a high enough for a long enough time. Figure 3 shows the basic devices to perform a MWA consist of a microwave generator, a microwave applicator (the antenna), and a section of flexible coaxial cable to connect the antenna to the microwave generator. Ultrasound scanners are often used in the MWA procedures to guide the placement of the applicator.

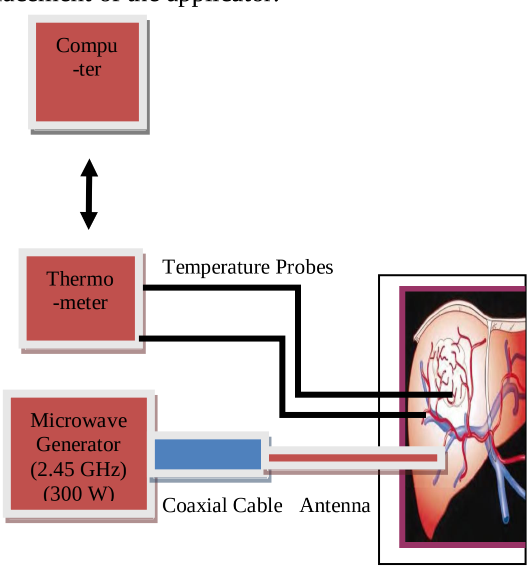

Figure 3. Schematic experimental setup of microwave liver tissue ablation.

Fiber-optic thermometers can be used to measure tissue temperature. MRI scanners can be used to examine lesion size after the procedures. In a clinical MWA procedure, position of the tumor is determined in advance with medical imaging devices, including MRI, CT or ultrasound devices. A MWA probe is placed into the tumor with an open surgery or a percutaneous procedure, guided by ultrasound or other medical imaging device as shown in figure 4.

The probe is connected to the microwave power generator. Microwave power level and heating duration are selected in advance according to the shape and size of the tumor. Microwave power is then applied for the selected duration. A thermal lesion of predicted volume is created by the applied microwave heat to cover the entire tumor with 1 cm margin.

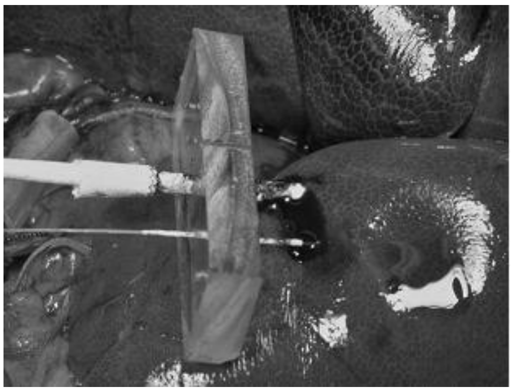

Figure 4. MWA probe placed into the tumor with surgery

The MWA probe is then safely retrieved. Before the clinical procedure finished entirely, imaging devices can be used to verify the lesion size and shape the ultimate goal of ablation technology, including MWA, to kill the liver tumor while preserving healthy liver tissue effectively.

4. NUMERICAL METHODS

The numerical methods used to predict the induced fields in biological bodies of realistic shape and composition are enlisted below:

Quasi-Static Impedance Method
Methods of Moments (MoM)
Finite Difference Time Domain Method (FDTD)

Finite Element Method (FEM)

The quasi-static impedance method is restricted to lower frequencies, but the MoM, the FDTD and the FEM methods may be used for any frequency of interest. In addition, both the Finite Difference Time Domain Method and Finite Element Methods involve solving Maxwell's equations in the differential form for the computation of induced fields.

4.1 Quasi-Static Impedance Method

The impedance method was introduced in 1984 by Gandhi et al. [13] as a simulation method suitable for quasi-static electromagnetic radiation problems that arise in the field of bioelectromagnetics. For low frequency situations, where the dimensions of the biological body are small compared to the wavelength, the impedance method has been found to be highly efficient as a numerical procedure for calculating internal current densities and induced electrical fields. In this method, the biological body or the exposed part thereof is represented by three dimensional (3-D) networks of impedances whose individual values are obtained from complex conductivities for various location of the body. The impedance method has been used for calculating SAR distribution for operator exposure to spatially variable fields of induction heater, linearly or circularly polarized RF magnetic fields representative of magnetic resonance imagers, due to capacitive type electrodes used for hyperthermia and for interstitial RF needle applicators for hyperthermia. The main limitation of this method is that it is restricted to frequencies (<30 to 40 MHz for human body)

4.2 Methods of Moments (MoM)

The MoM [14] is used in conjunction with either the volume integral equation method or the surface integral equation method for finding the solution to unknown fields inside the body, hence divided into two types

VMoM
SMoM

4.2.1 VMoM

The volume integral equation method (VMoM) requires determination of unknown fields through out the volume of the body using the volume equivalence principle and the MoM. In 1984, for the first time, were the volume integral equation were solved using a modern, (partially) [15] conforming approach i.e. MoM. The MoM is used to transform the integral equation into a matrix equation by subdividing the body into N simply shaped cells. The fundamental limitation of this method is the use of full or nearly full matrix which needs the extensive computer storage and long running time. Even with the availability of larger and faster computers, this difficulty is not completely resolved.

4.2.2 SMoM

The surface integral equation method (SMoM) makes use of two coupled integral equations, i.e. electric field and magnetic field integral equations for the tangential components of the field of the surface separating the biological body from the air. The unknown surface currents are found by Fourier decomposition and moment method. The fields inside the biological body are calculated using the previously computed surface currents, the reciprocity theorem and the concept of measurement matrix. The surface integral equation method is applicable to any arbitrarily shaped homogeneous body of revolution. This method is restricted to only homogeneous models, where model is inhomogeneous this method is not suitable.

4.3 Finite Difference Time Domain Method (FDTD)

The FDTD method was first proposed by K.S Yee in 1966 [16] and has proved to be very efficient numerical algorithm in computational electromagnetics for the solution of Maxwell's curl equations by directly propagation of waves into a volume of space containing the biological body. This method is based on the approximation of the derivative by central differences to evaluate the field components. The traditional FDTD algorithm generates regular grid in the

Cartesian co-ordinate system and uses staircase approximation to analyze structure on an underlying Cartesian grid.

FDTD can be used to solve many types of electromagnetic problems, as cost of computing keeps reducing. Computer memory and speed however limit the size of problems that can be solved. The method is applied to antenna design & analysis, microwave circuits, biological interaction with electromagnetic waves, optics and radar cross-section problems. The method handles the solution of interaction of antennas with the human body in a straight forward manner for prediction of biomedical applications, such as electromagnetic heating for cancer.

4.4 Finite Element Method (FEM)

The FE method originally used by P. Silvester [17] for electromagnetic field problems and has been preferred numerical algorithm in many fields of applications. However, its use and popularity in predicting field intensities in biological systems have been modest until recent progress in mesh generation, boundary conditioning and large matrix solvers. Aside from the low memory requirement (on the order of N), an inherent attraction of FEM is its adaptability in modeling inhomogeneities and complex geometries. The basic approach of FEM method for predicting EMF distributions inside the biological bodies starts by subdividing the physical space and biological body of interest into meshes of small volumes or cells of tetrahedral elements. Each cell element and node location will have to be systematically numbered and described. Once the volume has been subdivided, labeled, and appropriate property values ascribed, the unknown field with in each element is then approximated using linear extrapolation. A major step in FEM is the formulation of the system of linear equations with proper boundary conditions that can produce an approximate solution to unknown field intensity with a prescribed accuracy. The procedure of calculation of SAR distribution and temperature distribution using bioheat transfer equation is shown in figure 5.

5. Why FEM ?

The finite element method (FEM) is generally used to simulate hepatic microwave ablation, because it is a powerful tool to transform differential equations over a volume to algebraic equation at the points, called nodes. These represent the solution to the governing equations and the boundary conditions in an average sense by piece wise simple functions. The volume to be solved is divided into elements, if sufficient continuity conditions are met, solution converges to the exact solution as a number of element increases. By exact solution we mean the solution to the mathematical model which in turn often is an idealization of reality. COMSOL Multiphysics is an excellent tool for FEM solver. The COMSOL Multiphysics simulation environment facilitates all steps in the modeling process - defining the geometry, specifying the physics, meshing, solving and then post-processing the results.

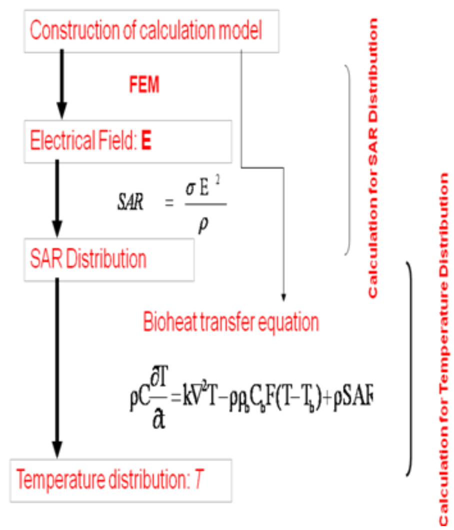

Figure 5. Procedure of calculations

6. Conclusions

The ultimate goal of the current research on microwave ablation technique is to develop technologies to increase the coagulation volume while reducing the treatment time and making the therapy more straight forward by reducing its complexity. To study, investigate, and develop new techniques and to improve those currently employed, research can make use of experimental studies, phantom and theoretical models. The later is the powerful tool in this kind of investigation, since they are rapidly economically provides an understanding of the electrical and thermal behavior involved in the microwave ablation. The COMSOL Multiphysics is the complete package to achieve the goals of the current research for the benefit of all the humanity.

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