CYLINDRICAL PHASED DIPOLES ARRAY FOR HYPERTHERMIA OF DEEP-SITUATED TUMORS

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Abstract

The treatment of deep-situated malignant tumors is often a difficult problem in which the purpose is to reduce the size of completely remove a tumor by using one or more modalities. The traditional methods are: radiation therapy, chemotherapy and surgery. Hyperthermia is another method which is used alone or coupled with other methods of cancer treatment. Hyperthermia is a heating of the tumor that makes it more sensitive to chemotherapy or radiation therapy and leads to it thermal damage. Temperature range for hyperthermia treatment is from 42.5 °C to 45 °C. It is important to prevent heating of healthy tissues and to produce sufficient heating at the site of a deep-situated tumor. This kind of hyperthermia is called the local hyperthermia. The electromagnetic field in 100-200 MHz frequency range is optimal for heating of deep-situated tumors. The system for local hyperthermia of cancer was simulated. This system is based on cylindrical phased array consisting of multiple dipole antennas with operating frequency 150 MHz. The electric fields and specific absorption rate distributions are calculated in cut of tissue-equivalent phantom. Shown that electric field can be focused in desirable region by means of varying of amplitudes and phases of each dipole. The advantages of using combined therapy of common hyperthermia with chemotherapy or radiation therapy are discussed.

INTRODUCTION

Hyperthermia is a good adjuvant for the common modalities such as surgery, radiation and chemotherapy. It is proved that cancer cells are dying under the heating and the main goal is to deliver heat into source of disease without damaging of nearby healthy tissues [1-3]. Also suitability of using hyperthermia combined with radiation and chemotherapy is proved [4, 5]. Efficiency required that temperature within tumor remain above 43 °C for 30 to 60 minutes, while limit temperatures in normal tissues has to be lower than 43 °C. Noninvasive heating of deep-situated malignancy is a difficult technical challenge. Electromagnetic field is more prior for creating higher level temperature in desirable volume than other methods of physical effect. High penetration ability of radiofrequency EM field into human body in comparison with other frequencies ranges makes using of radiofrequency promising for distance hyperthermia. As temperature increase occurs not at the expense of heat transfer from surface to inwards, but because of electromagnetic field absorption, danger of skin burns is decreasing. This fact makes fields in 100-200 MHz frequency range is optimal because wave length in human body is proportional with body's sizes. The thermal effect lead to lysosome activation, tissue breathing and protein synthesis inhibition, tissues pH decreasing, kariokynetic cycle modification, trans membrane transfer improvement, sensitization tumor cells to chemotherapy and growing up immunity. Moreover basic advantages of electromagnetic hyperthermia occurs on radio resistance tumors, in other words on cells with high reparation effect from radiation. First of all hyperthermia decelerates cell's reparation and secondly induces strong heat damage of zone with bad thermal sink, hypoxia zone.

PHASED DIPOLE ARRAY

Cylindrical phased dipole array is proposed for creating high level temperature inside patient body. In this paper we assume that phased array consists of eight dipole antennas arranged on an inner side of a cylindrical plastic shell. Dipoles are surrounding the patient body and the amplitude and phase of each antenna is under control of the operator as shown in Figure 1. The space between patient's body and dipoles is filled with deionized water (conductivity σ≈0). Hereby dipole antennas are squeezed between the high-permittivity medium inside the tank (ε≈80 for water) and the low-permittivity medium outside the tank. We assume to use flowing deionized water not for cooling only. Due to the electric field energy density ($1/2 \cdot ED$) inside the tank is higher by a factor ε (the relative dielectric constant of the medium) the E-field energy is extremely concentrated in the inner side of a tank. The frequency of operation is chosen to be 150 MHz.

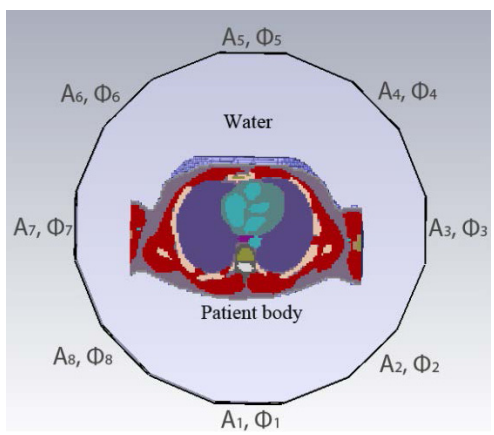

Figure 1: Patient body surrounded by phased dipoles array. Dipole antennas have amplitudes $A_1 \ldots A_8$ and phases $\Phi_1 \ldots \Phi_8$ respectively.

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We have Maxvell's equations:

$$\nabla \boldsymbol{E} = i\omega\mu \boldsymbol{H}, \quad (1)$$
$$\nabla \boldsymbol{H} = -i\omega\varepsilon_c \boldsymbol{E}, \quad (2)$$

where to $\boldsymbol{E}$ and $\boldsymbol{H}$ is the complex amplitude of the electric and magnetic field correspondingly, μ is the magnetic permeability, $\varepsilon_c = \varepsilon + i\sigma/\omega$ is the complex permittivity, σ is the electric conductivity. Isolating $\boldsymbol{E}$ in (1) and (2) we have:

$$\nabla(\nabla \boldsymbol{E}) - k^2 \boldsymbol{E} = 0, \quad (3)$$

where k is the complex wavenumber $k^2 = \omega^2\mu\varepsilon + i\omega\mu\sigma$. E_j is the solution of E-field for antenna j scaled by the amplitude and phase take into account:

$$E_j = A_j E_{j0}(x,y) e^{i\Phi_j}, \quad (4)$$

where E_{j0} is the complex field for $A_j = 1, \Phi_j = 0$, and $A_k = 0$ for $j \neq k$. A time variation of the form $\exp(-i\omega t)$ is dissembled.

The specific absorption rate (SAR) or absorbed power per unit mass (W/kg) is given by:

$$SAR(x,y) = \frac{\sigma E E^*}{2\rho}, \quad (5)$$

where E is the total electric field at the point (x,y), E^* is the complex conjugate of E, σ is the electrical conductivity of tissue and ρ is the density of tissue.

E is the sum of the electric fields from each of the dipoles and the absorbed power per unit mass becomes:

$$SAR = \frac{\sigma}{2\rho} \sum_{j=1}^{8} \sum_{k=1}^{8} A_j A_k E_j E_k^* e^{i(\Phi_j - \Phi_k)} \quad (6)$$

Due to varying amplitudes and phases of dipole antennas necessary distribution of SAR is produced, in other words we can focus electromagnetic field in desirable volume (tumor) and to minimize energy absorption in healthy tissues.

RESULTS

Simulation of SAR patterns in horizontal plane with phantom filled with water is shown on Fig. 2. Four different combinations of relative phases are used. Here higher energy absorption is shown in red. As seen the maximum SAR peak moves either in horizontal or in vertical directions (amplitudes stays constant). High level of SAR around outer edge (not shown on the picture) is appeared because of the high near field neighboring with each dipole, which has little influence on heating process inside of the phantom. This temperature rise can be decreased by flowing water without any effect on heating inside the phantom. As seen, the SAR peak moves away from antenna with higher phase shift. The value of SAR is maximized when all antennas are in phase.

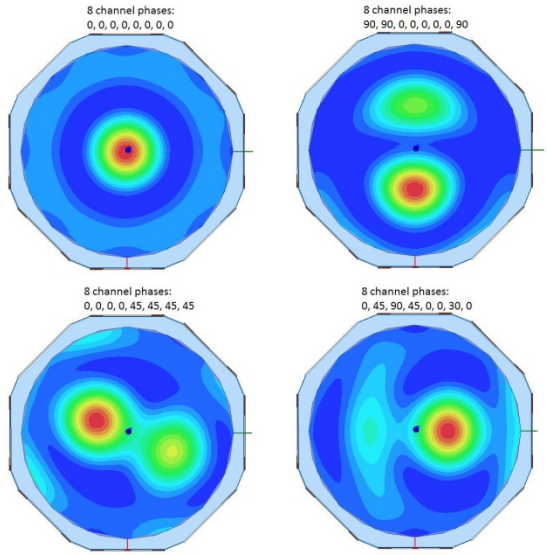

Figure 2: Results of simulation in the transverse cut for four combinations of phases. Combinations are provides movement of the SAR peak in both horizontal and vertical.

Fig. 3 shows SAR pattern in x-y plane of tissue equivalent phantom. This phantom is a primitive model of human leg with diameter 24 cm. Tumor size is 30 mm. All tissues are labeled on the picture. RMS feed power of each dipole is 0.5W. Dielectric properties of body tissues used in simulation are presented in Table 1 [6]. Phases are adjusted to focus heat onto tumor. If bottom antenna would be first and to keep count counter-clockwise, relative phases will be: $\Phi_1 = -5°, \Phi_2 = 30°, \Phi_3 = 50°, \Phi_4 = 65°, \Phi_5 = 50°, \Phi_6 = 30°, \Phi_7 = -5°, \Phi_8 = -5°$. All amplitudes still stay constant. As seen, the SAR peak is moved away from antenna 5 (relative phase 65°) as we noted above. The SAR minimum is located in bone due to low conductivity and high density in comparison with muscle tissue. Also we can decrease power absorption in outer side of phantom by using flowing water with constant cooling temperature.

Table 1: Dielectric properties of human tissues used in simulation.

Tissue	Relative permittivity	Conductivity [S/m]	Density [kg/m^3]
Muscle	62.18	0.73	1047
Fat	5.84	0.04	955
Bone	14.41	0.07	1990
Tumor	74.5	0.9	1047

For accurate simulation we have to use real body model, which will be obtained after CT or MRI scanning. SAR distribution in longitudinal cut of voxel human leg is shown on Fig. 5. All antennas are in phase, amplitudes are

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equal. Maximum SAR is 1.63 W/kg with RMS feed power 0.5 W on each dipole. For hyperthermia in thorax or abdomen we have to use lower frequencies for deeper penetration of electromagnetic fields onto human body.

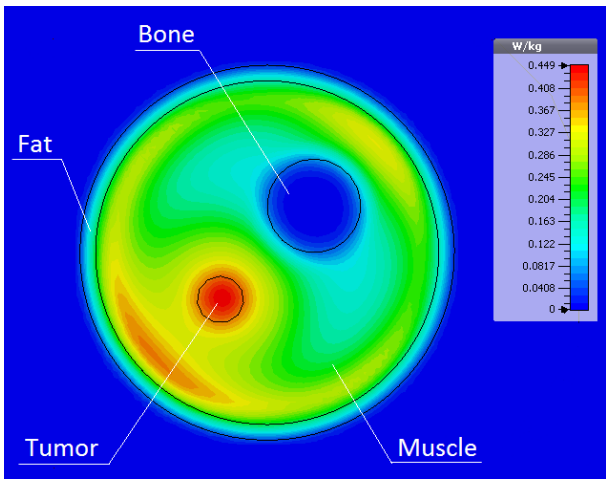

Figure 3: SAR distribution in transverse cut of phantom with adjusted relative phases. Tissues are labeled. RMS feed power of each dipole is 0.5W.

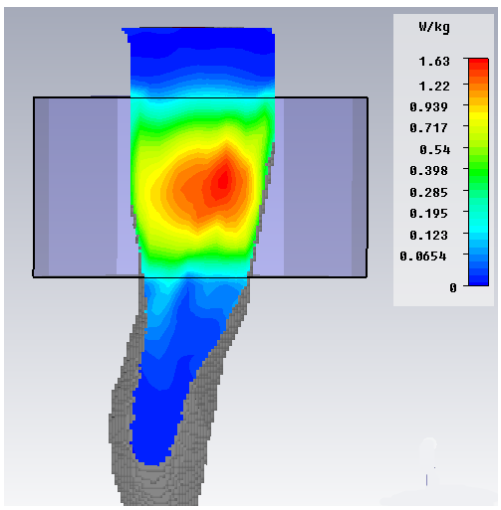

Figure 5: SAR distribution in longitudinal cut of voxel human leg. All antennas are in phase. RMS feed power of each dipole is 0.5W.

CONCLUSION

Combined therapy using the hyperthermia with the radiotherapy of the chemotherapy is very perspective methods of the cancer treatment. The efficiency of combined therapy is evaluated on practice. Cylindrical phase dipole array is proposed for electromagnetic hyperthermia of deep-situated malignancy.

As was noted above, using of voxel models is preferable for more accurate simulation. For these goals we develop software which able to produce voxel model of human body (or body parts). Further different tissues are separated and assigned to the relevant dielectric and thermal properties.

Also software for solving bio-heat transfer equation is under developing, where we have to take into account perfusion, thermal conductivity and tissue specific heat, which will be used for thermodynamic simulation, i.e. for planning of hyperthermia procedure. The bio-heat transfer equation is solved for changes in temperature [7]:

$$\rho c \frac{dT}{dt} = \kappa \cdot \nabla^2 T - \rho \rho_b c_b F (T - T_b) + \rho \cdot SAR \qquad (7)$$

where T is temperature, t is time, ρ is tissue density, κ is thermal conductivity, c is the tissue specific heat, F is the blood flow rate (perfusion), type “b” is for blood. This equation shows relate between temperature’s rise over the time in a desirable region to the heat inputs (SAR) and heat losses from thermal conduction and convection (blood flow rate).

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