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Application of Magnetic Circuit and Multiple-Coils Array in Induction Heating for Improving Localized Hyperthermia

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Abstract— Aiming the application of localized hyperthermia, a magnetic induction system with new approaches is proposed. The techniques in this system for improving the effectiveness of localized hyperthermia are that using magnetic circuit and the multiple-coil array instead of a giant coil for generating magnetic field. Specially, amorphous metal is adopted as the material of magnetic circuit. Detail design parameters of hardware are well described. Simulation tool is employed for this work and experiment result is reported as well.

Keywords—cancer therapy, hyperthermia, Helmholtz coil, induction heating, magnetic circuit.

I. INTRODUCTION

LOCALIZED hyperthermia [1]-[3] has attracted attention in last decades because of its potential as a non-invasive cancer therapy, and as an alternative treatment of conventional modalities of X-radiation, chemotherapy and surgery.

Most of the announced systems of localized hyperthermia employing magnetic induction heating are using one single giant coil [4][5] being supplied with strong current with frequency not more than 50kHz. The reason of designing coil this way is because that, producing a localized hyperthermic dose to deep-seated tumors is still very difficult and the magnetic field decreases very quickly when apart from the current source [6]. On the other hand, either using nano-particles [7][8] or ferromagnetic needles [9] to be the implants inside the body is still of inefficiency due to the tiny conducting volume and insufficient permeability. These two factors make the progress of application of localized hyperthermia using magnetic induction heating very slow. Namely, problem still remains for obtaining satisfied penetration and focus of the applied magnetic field. Besides, giant coil system makes it impossible to have a potable design and causes consideration of electrical dangerousness when it is equipped in a hospital.

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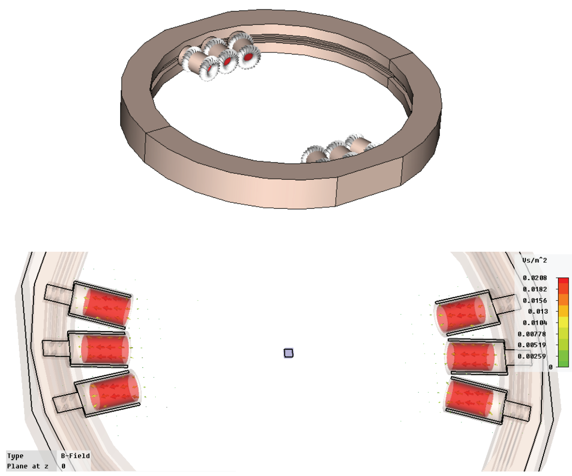

Fig. 1 The proposed coil system composed of several pairs of Helmholtz coil

As for the coil design, if only one coil set is used, the magnetic field flux density $\vec{B}$**(*Gauss*)** at the coil center is very difficult to have a sufficient level, especially when the diameter of coil is large. Supplying a large current seems the only way to enhance it. Even so, since the magnetic field varies very fast spatially, it is also not easy to establish a uniform area for treatment inside a single coil. The set of Helmholtz coil [6] was indeed used in [2] to produce the uniform field in terms of concept, but their orientation of field is to produce the longitudinal vector along the body, and that is supposed to be not helpful if needles are used, not mentioning its heavy power consumption. Contrarily, the coil system shown in Fig. 1 is proposed for the localized hyperthermia by magnetic induction heating. By a non-metal supporter, several pairs of Helmholtz coil are equipped. These coils are movable surrounding the body, such that the focused point can be adjusted depending on the position of cancer or tumor. The principle vector of resultant field $\vec{B}$ is transverse to the body, and is supposed to be more effective for the needle implements.

In this paper, a demonstrating system, in which the magnetic circuit making use of amorphous metal [10] in addition to multi-coils mentioned above, is reported. Both of computer simulation and temperature results are presented.

II. Basics of Induction Heating fot Localized Hyperthermia

The induction heating by magnetic field is based on the mechanism of eddy current [6], which in theory may be derived by the Faraday's Law [6]. However, local heating on conducting materials is involved in very complex physical microscopic material process, and it is even so when being investigated in the derivation of macroscopic circuit [1], not mentioning the heating process is happening in a bio-tissue. Usually, the external applied field is termed as the zeroth-order field, and the induced magnetic field is termed as the first-order field, which is caused by the eddy current on the conducting implants. If the zeroth-order one is far larger than the first-order one, the interaction between them can be ignored. For example, when the induction heating is applied on a conducting bar with a thickness $\boldsymbol{a}$ and a height $\boldsymbol{b}$, and with an applied magnetic flux density $\vec{\boldsymbol{B}}$ which is perpendicular to the bar surface, the spatially averaged power dissipation per unit length can be expressed as [11]:

$$P = \frac{ab\left(b\,{\partial \vec{B}}/{\partial t}\right)^2}{12\rho_e} \qquad (1)$$

This equation is quite helpful to predict the effectiveness of induction heating when different configurations are equipped. By Eq. (1), the power dissipation is almost proportional to both of implant conducting volume and implant metal conductivity. As for the term,

$$\left({\partial \vec{B}}/{\partial t}\right)^2$$

stronger $\vec{\boldsymbol{B}}$ is definitely helpful, but it needs the implant to have higher relative permeability μ_r, say, that of ferromagnetic materials, to attract the zeroth-order applied magnetic field. It is noted too that, the spatially averaged power dissipation per unit length is square proportional to the frequency of the zeroth-order applied magnetic field, yet when the frequency is higher and higher, the "skin effect" [6] will decrease the volume for heating in metal. Therefore, the operating frequency of the applied magnetic field is one of the key engineering factors to optimize the heating process.

III. Coil Design

Very important parameter in winding the coil is to determine the coils' impedance. By circuit theory, the coils generating the magnetic field are the load of the current generator, and they establish a resonant condition together with a certain operating frequency. Anyway, the resonance is subject to a "complex conjugate matching" [6]. Namely, the impedance both of the external coil and capacitor inside the generator are purely imaginary, yet with opposite sign.

Fig. 2 Wound coil with multi-layer

Fig. 2 shows one example of realized coil which is wound by thin wires to avoid from skin effect in conducting wire, and is constructed in a form of multi-layer to provide sufficient magnetic field and have proper impedance. The layers are tired together in parallel. The dimension details of the coils used in the present work are shown in TABLE 1.

TABLE I
Dimension Details of the Coils

Diameter of the enameled wire	1 mm
inner/outer diameter of coil	15/30 mm
Layers of wound coil	15
Total no. of winding on one layer	15
Coil thickness	20mm

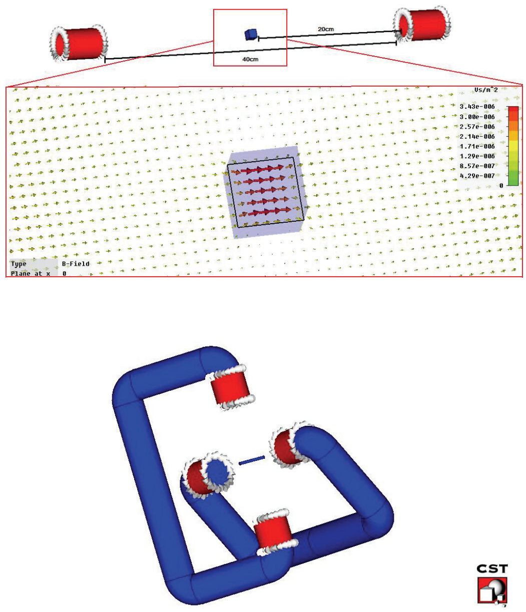

Fig. 3 Simulation of the magnetic field generated by a Helmholtz Coil

To predict the resultant magnetic field one or more sets of Helmholtz Coil are able to generate, a simulation model is also established in the work, see Fig. 3. Configuration of coil system can be varied in terms of supplied current, coil shape, coil distance, and the others, to evaluate the magnetic field strength and distribution. The tool used for this purpose is the electromagnetic package CST [12]. Such a simulation is able to clearly show that, it is very difficult to let magnetic field come to the middle way of a pair of Helmholtz coil if there are without any assistant means. Traditional method for this purpose is to add a magnetic circuit for the coils as shown in Fig. 4, where amorphous metal is used as the circuit materials.

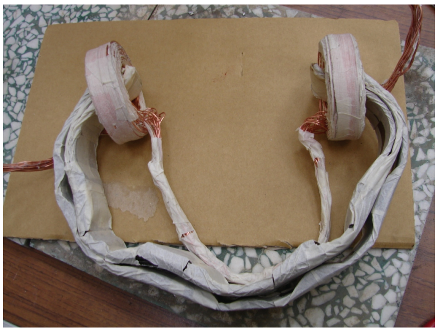

Fig. 4 Magnetic circuit of amorphous metal

The magnetic circuit in theory [13] is composed of materials with high relative permeability, such that the magnetic flux generated by coils can be guided to form a magnetic loop as shown in Fig. 4. In the present application of localized hyperthermia, the magnetic field is not possible to penetrate into the human body without such a magnetic flux loop. Ferromagnetic materials are often employed as the magnetic circuit in industry. However, the most important requirement for magnetic circuit is to have low power consumption caused by the eddy current in the ferromagnetic materials. Amorphous metal was invented to meet this aim, since it owns the characteristic of low power generated in it. Unfortunately, currently the amorphous metals are produced in the form of sheets only, and are not provided for arbitrary shapes. The thickness of the sheets used in Fig. 4 is 0.3mm. 220 stacked-strips with a width 3 cm is formed that circuit shown in Fig. 4.

IV. HARDWARE SYSTEM

Fig. 5 shows the proposed system which is composed two generators providing the current to the coils. The commercial induction cookers are used as the generator. An equivalent resistance $\approx 1.4\,\Omega$ is in series between the generator and the Helmholtz coil to limit the supplied current for being avoided from over-load to the generator. The current with frequency 20kHz is monitored by a AC current probe as shown in Fig. 6. The original coil of the induction cooker is replaced by our Helmholtz coil with a series resistance $\mathbf{0.9\,\Omega}$ and an inductance $\mathbf{56\,\mu H}$ (both measured @ 22kHz) considering the complex conjugated matching with the generator. The two sets of Helmholtz coil are orthogonal to each other spatially to form a multi-coils array as shown in Fig. 7 displaying the set-up for heating experiment.

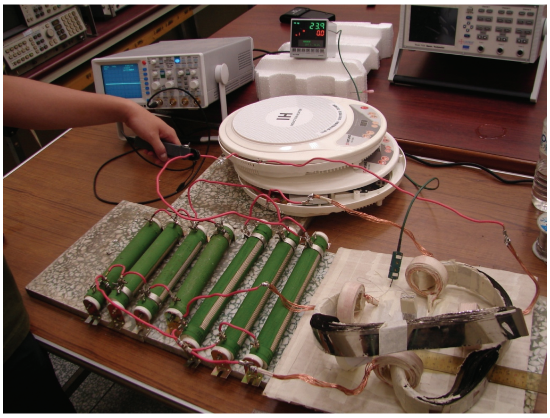

Fig. 5 System with two pairs of Helmholtz coil

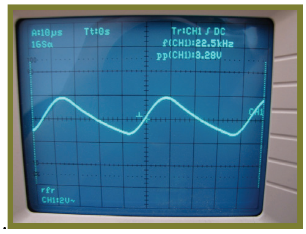

Fig. 6 Current supplied to the coil

Fig. 7 Set-up of heating experiment

V. MEASURED RESULTS

For the purpose of demonstrating the present proposed system for localized hyperthermia, a small sample of pig liver on which 10×10 acupuncture needles ($30G \times 1.5''$ of "An Chi" company, Taiwan) are placed. Usually, the temperature above $42\,^{o}C$ is supposed to be proper to kill the cancer. Based on the criterion, Fig. 8 shows the comparison of how fast the coils can heat the liver sample by using one and two sets of Helmholtz coil. The result shows that a magnetic induction system by using a proper magnetic circuit and using a multi-coil array can be more effective for localized hyperthermia.

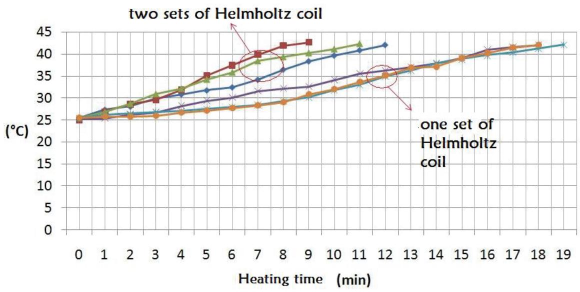

Fig. 8 Temperature increment of one and two sets of Helmholtz coil

VI. Conclusion

In this paper, a magnetic induction system is proposed to be applied in the localized hyperthermia, in which the magnetic circuit composed of amorphous metal is used, and the multi-coil array is suggested. Detail design parameters of hardware and experiment results are well described. The final experiment results of this system confirm the application potential for the target purpose.

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