Development of Ferrite Core Applicator System for Deep-Induction Hyperthermia

Youji Kotsuka, Eiji Hankui, *Member, IEEE,* and Yasushi Shigematsu

Abstract— **To achieve deep-induction hyperthermia, a ferrite core applicator system has been developed. The clinical goal is to produce a temperature rise of 7.5°C at 10 cm tissue depth. Deep heating becomes possible by introducing an auxiliary electrode to control an eddy current. The auxiliary electrode has been designed to optimize the eddy current with respect to the magnetic flux density. The optimization was performed by solving the fundamental equation using the finite element method (FEM). A flexible auxiliary electrode, which can be used for clinical treatments, has been manufactured. Heating tests have been conducted with the new applicator system, which operates at 4.0 MHz. The experimental results demonstrate that the system is capable of producing a temperature rise of 7.5°C at 10 cm depth, without heating an overlaying fat layer.**

I. Introduction

THERE ARE TWO methods of induction heating. One method uses implants which produce local heating. The other is a noninvasive method using external applicators for regional heating. The method of arranging external applicator by solenoids for magnetic induction heating has been reviewed by Oleson [1]. Applicators using helical coils have been proposed by Ruggera *et al.* [2], Hagman [3] *et al.*, and Kern *et al.* [4]. A magnetrode applicator and its magnetic field has been analyzed by Elliot *et al.* and Storm *et al.* [5], [6]. A spiral coil induction applicator has also been proposed by Antich *et al.* [7]. A deformed type of spiral coil has been proposed and its magnetic field distribution has been analyzed by Kimura *et al.* [8]. These applicators have been studied for implant heating or whole body heating.

One type of applicator for noninvasive heating of tissue consists of one-turn coil made of conductive plate [9]. This applicator is capable of synthesizing the eddy current in the center of human body. It has been shown that by changing the geometric arrangement of the coil or its shape, one can control the location of the heating region within the tissue volume [10]. An applicator using a toroidal transformer [11] and one system where the current flow is parallel to the body surface [12] have been proposed for tissue heating. However, these induction heating systems have not fully utilized the method of controlling the eddy current distribution for control of the energy absorption distribution.

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This paper describes a noninvasive deep hyperthermia system based on a ferrite core applicator using auxiliary electrode to control heat generation. The ferrite core applicator system makes it possible to heat deep tissues using relatively low output power as compared to conventional induction applicators.

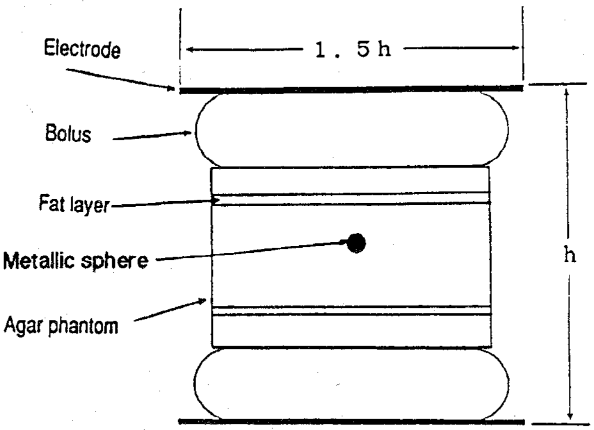
As first step in this development, the magnetic field distribution and the resultant eddy current distribution was theoretically analyzed using the finite element method (FEM) to solve the fundamental equation. The ability to control the eddy current distribution by using an auxiliary electrode was simulated. The effect of a conductive plate and flexible conductive rubber as electrode material was also studied theoretically. The ferrite core is cooled by circulation of low viscosity silicon oil. The cooling system has been optimized to keep the fluctuation of temperature in the tissue model to within ±0.3°C. The simulations have been confirmed experimentally using a human tissue model. These experiments confirmed the result of the theoretical simulation that this non-invasive 4 MHz hyperthermia system can raise the temperature by 7.5°C after 15 min heating at a depth of 10 cm.

II. Methods of Deep Heating Using Electromagnetic Radiation

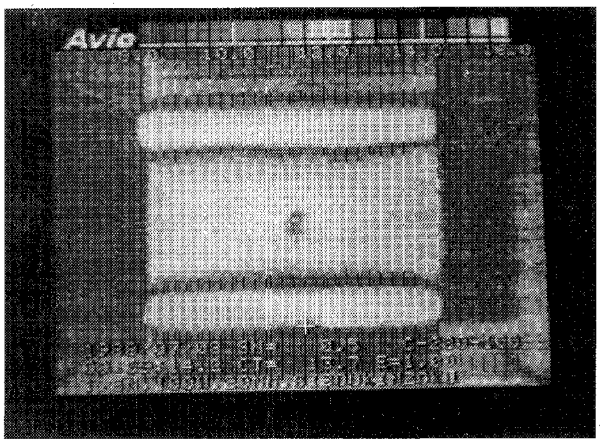
To achieve hyperthermia at depth of more than 6 cm, many kinds of applicator systems have been proposed.

It is impossible to achieve the deep hyperthermia (i.e. > 4 cm) for the reason of the skin depth's principle (SKP) when using normal microwave antennas. However, by using resonant phenomena, deep penetration of microwave power (i.e., 6 cm) can be achieved. An earlier publication [13] investigates the use of resonant microwaves for deep hyperthermia. A spherical phantom model was used in this work, and the calculations affect the depth of heating. In fact, the dependence of heating depth with sphere size and material constants is very strong and conclusion is that a heating method based on the resonant phenomena of microwaves cannot be used for deep hyperthermia in humans. Accordingly, to attain the deep hyperthermia, the invasive method using a thin coaxial waveguide has been investigated in the microwave frequency [14]. For noninvasive method microwave lens type applicator has been developed [15].

Radio frequency has been successfully used to achieve deep hyperthermia. RF heating method can be applied using two methods. One is a dielectric heating method producing RF capacitive heating and the other is an induction heating method.

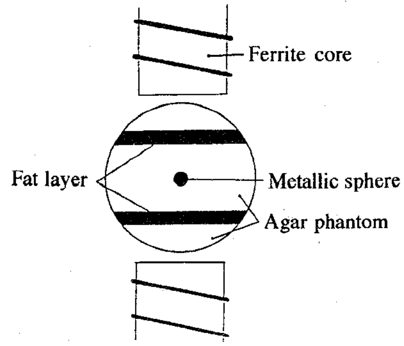


(a)

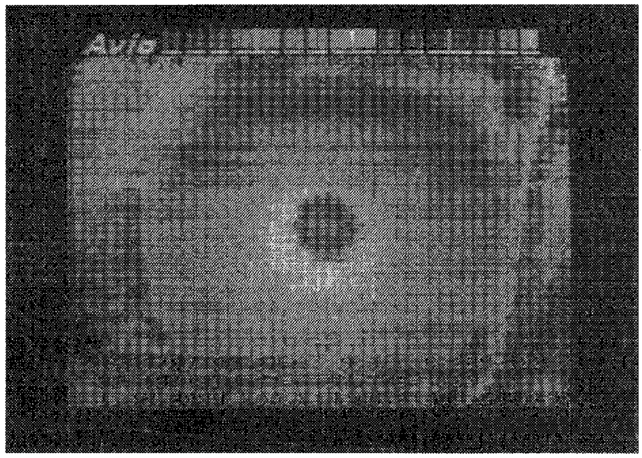


(b)

Fig. 1. Thermographic view of agar phantom with fat after capacitive heating. (a) Capacitive applicator. (b) Thermographic view.



(a)



(b)

Fig. 2. Thermographic view of agar phantom with fat after induction heating. (a) Ferrite core applicator. (b) Thermographic view.

However, as is evident from theoretical boundary value problem, the former method tends to create hot spot in the fat layer of a human body. Fig. 1 shows a thermographic view of empirical result obtained by capacitive RF heating (3 MHz) of a rectangular agar phantom, which is sandwiched between two layers of pig fat perpendicularly to the electric field. A conductive sphere is buried between fat layers. The figure shows that the fat layers are well heated compared to the conductive sphere. Therefore, it may be necessary to cool the human body from the outside to reduce the risk of overheating the fat tissue.

In difference to the capacitive systems, the induction heating has an advantage that it can heat a human body without generating a hot spot in the fat layers. Fig. 2 shows the results from an experiment using inductive heating at 1.5 MHz. A cylindrical agar phantom with two fat layers and a metallic sphere [Fig. 2(a)] is used in the experiment. A conductive sphere is placed in the center between two layers of pig fat. This heating test has been conducted using a toroidal ferrite core with two poles at the center of the core [16]. It is clear that a conductive sphere is well heated without heating fat layers. Microwave heating generates energy by mechanical oscillations of molecular dipoles. Unlike microwave heating, the RF methods generate heat from electric currents, and the heat generation can be calculated using Joule's law. Although well known, these facts are important when we consider the RF heating applicator system. The human body is made up many essential and specific tissues often surrounded by supportive structures and membranes. Within much tissues the individual cells are also surrounded by membranes. These membranes consist mainly of lipid and protein, which are considered to be insulation. It has been pointed out [17] that the presence of membranes and the electrical material constants of the tissue determine the energy deposition and thus the ability to heat when using RF hyperthermia. To verify these facts, the following experiment has been conducted. Fig. 3 shows a capacitive heating case when two conductive spheres are placed in inside of an agar phantom. A sphere on the left-hand-side is thinly coated with a lipid (phosphatidylcoline) but a sphere to the right-hand-side is not coated. The current avoids the sphere coated by lipid and concentrates on the pure conductive sphere on the right-hand-side. In the case of Fig. 2, the same lipid is also applied. Consequently as shown in Fig. 2, the magnetic field can penetrate the insulating material like a fat layer or a membrane and the induced eddy current can cause heat from the inside of insulating material. Accordingly, the induction heating in RF frequency seems to be superior to capacitive heating to attain deep hyperthermia in tissues where many membranes are present.

The induction heating method, however, has a problem in that the eddy current has the property of being distributed

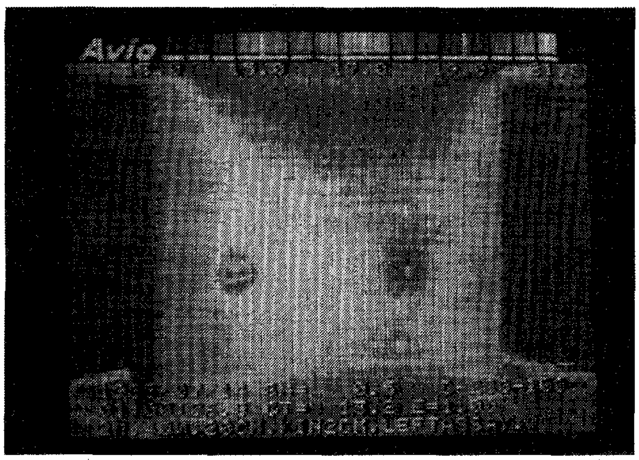


Fig. 3. Experiment for current flow in the phantom with a pure conductive sphere and a conductive sphere coated by lipid. (Right: Pure conductive sphere. Left: Conductive sphere coated with Phosphatdylcoline.)

inherently over the surface of human body. Therefore, the eddy current should be controlled to establish the deep-induction hyperthermia.

The present paper describes to control eddy current using auxiliary electrodes. A deep noninvasive applicator system using a ferrite core has been developed.

III. Construction of Applicator System

To improve the method of irradiation in induction hyperthermia, a ferrite core applicator has first been introduced by one of the authors [18]. Several kinds of ferrite cores have been designed for the induction hyperthermia [16], [19]. By introducing the ferrite core as a part of the inductive heating method, the magnetic field is concentrated between two poles. Consequently, it is possible to achieve local or regional heating using relatively low power, which is also advantageous from the viewpoint of electromagnetic compatibility (EMC).

In the present applicator system, the magnetic field radiation angle and position are easily changed by adopting the structure that each pole is separated. The applicator proposed here consists of two pairs of deformed ferrite cores as shown in Fig. 4(a). The diameter and the length of the ferrite core in the cylindrical portion are 6–8 and 30 cm, respectively. A pair of two ferrite cores, which surrounds five-turn solenoids in each core, are arranged over the surface of the body so that magnetic coupling is achieved between each pair of magnetic poles as shown in Fig. 4(b). This construction is based on the idea that a magnetic field between a pair of ferrite cores, A, B, C, and D is strongly coupled as shown in Fig. 4(b). But, the coupling of magnetic fields between A, C, B, and D have to be designed as weak as possible. In designing the ferrite core applicator, it is necessary to solve the problem of heating caused by loss in the ferrite core. To avoid a temperature rise in the ferrite cores, cooling is provided through a duct in the core and a pipe of conducting watered in which cooling water is circulated is also used as a coil.

To control eddy current, two auxiliary electrodes, made of a conductive material having a cooling effect, are arranged to make contact with the surface of the body to be heated. These

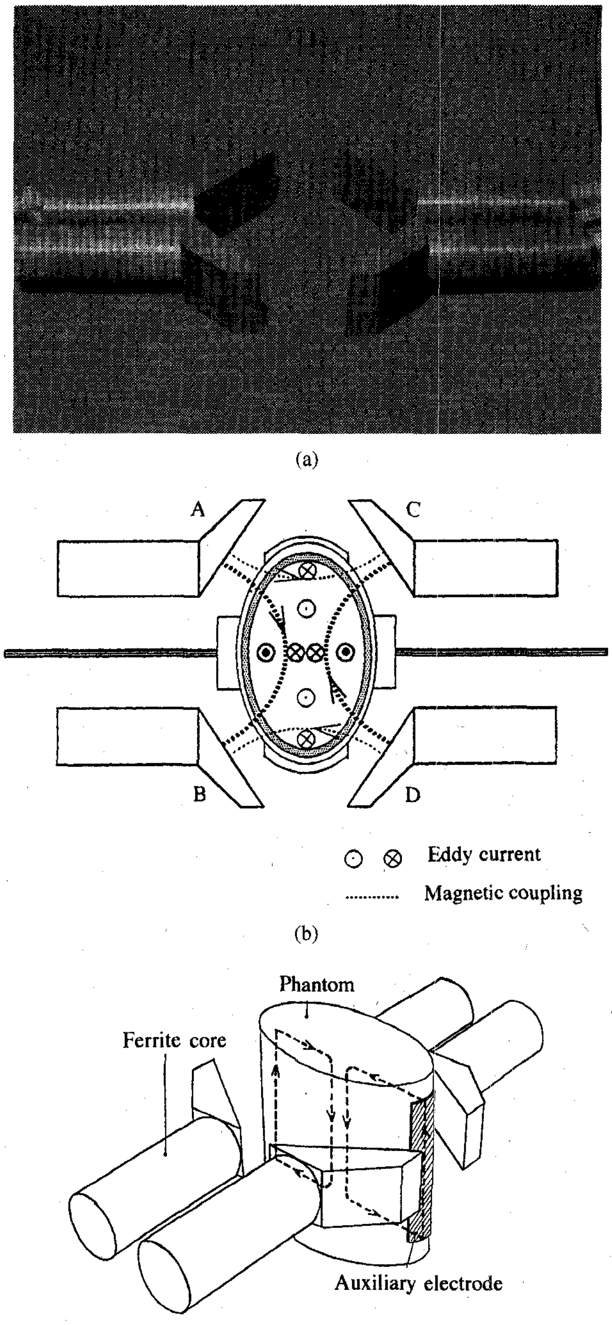


Fig. 4. Deformed ferrite core applicator and its principle. (a) Deformed ferrite core applicator. (b) Arrangement of ferrite core and coupling of magnetic field. (c) Eddy–current flows in a phantom.

electrodes make a current flow in closed loops as shown in Fig. 4(c).

The operating frequency is 4 MHz and the input power is adjustable from 600 to 1000 W.

IV. Analysis

To find a clue to designing the present applicator system, the eddy current distribution and the magnetic field distribution have been analyzed by the FEM. In the present analysis, the following three-dimensional (3-D) fundamental equation for vector potential **A** which takes eddy current into consideration

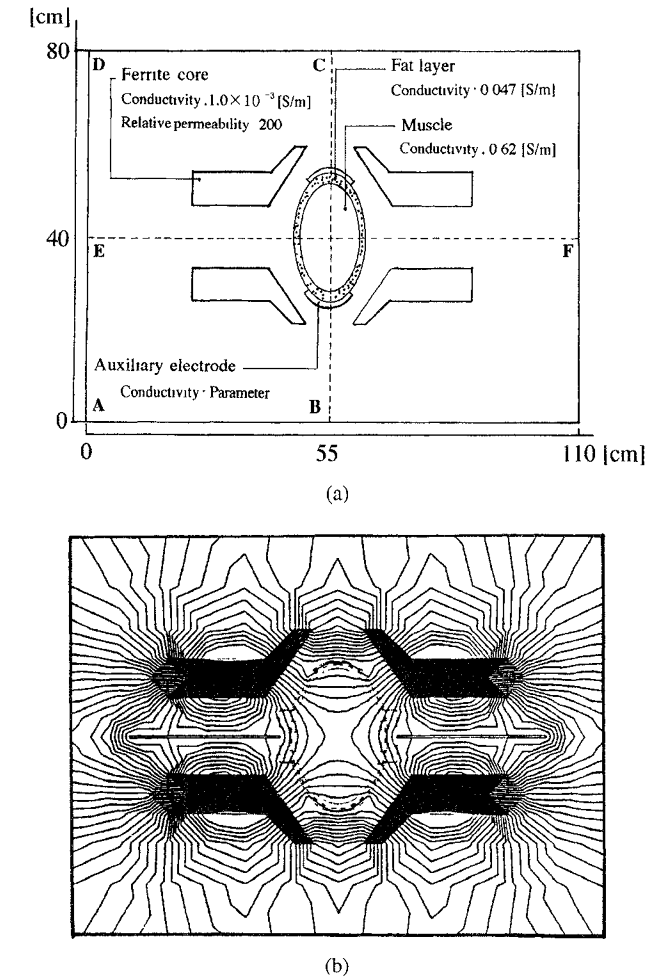


Fig. 5. Model for analysis and magnetic field distribution. (a) Model for analysis. (b) Magnetic field distribution.

is used

$$\nabla \times (\nu \nabla \times \mathbf{A}) = \mathbf{J}_0 - \sigma \frac{\partial \mathbf{A}}{\partial t} - \sigma \nabla \phi \qquad (1)$$

where ν: magnetic reluctance, $\mathbf{J}_0$: forced current density, σ: conductivity, ϕ: electric potential.

By solving the above equations for $\mathbf{A}$ by means of the variational method, the eddy current distribution and the magnetic flux density are obtained. As the magnitude of $\mathbf{J}_0$, 1 A/m^2 is assumed. The number of elements and nodes for the FEM's analysis are about 30 000 and 6000, respectively.

Fig. 5(a) shows the present analytical model. An elliptic tissue model surrounded by a fat layer is placed in the central portion of the four ferrite cores. The size of elliptic cylinder of the tissue model is 30 cm and 20 cm in its major and minor axes. In the present analysis, due to the symmetry of potential, the computer analysis in the half plane of ABCD in Fig. 5(a) has been carried out. Relative permeability and conductivity of the ferrite core is 200, 1.0×10^{-3} S/m, respectively. The conductivity of fat layer surrounding a tissue model is 0.047 S/m. In the present case, the model equivalent to the muscle of human body is considered as a tissue. It has a conductivity of 0.62 S/m. In all these cases, the relative permeability should be 1.0. Fig. 5(b) shows an example of magnetic field distribution for the two-dimensional (2-D) case in (1) for simplicity. This figure shows an example in the case when two conductive plates of copper are placed along EF axis to attain deep hyperthermia.

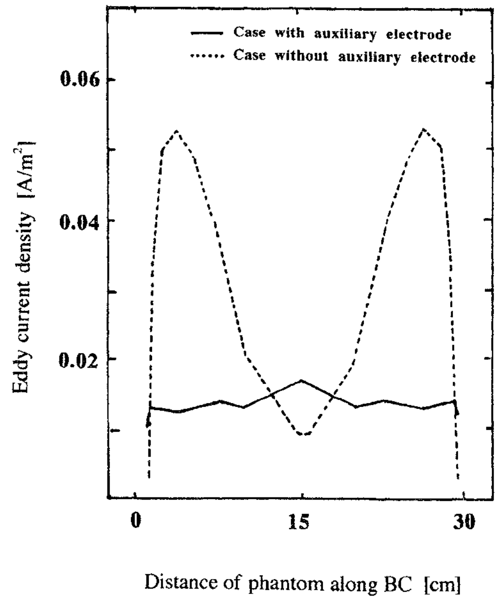


Fig. 6. Eddy–current distribution inside phantom.

V. Numerical Result and Heating Experiment

A. *Effect of Auxiliary Electrode*

Fig. 6 shows the eddy current distribution to investigate the effect of the auxiliary electrode. This figure shows the cross section along the line CB in the model in Fig. 5(a). This numerical calculation has been carried out by (1) in three-dimensional (3-D) case.

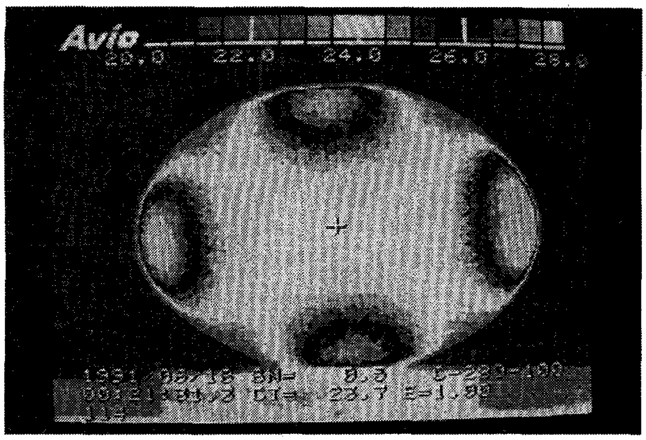
The dotted line shows the case when the auxiliary electrode is not attached. It is found that the value of eddy current takes a maximum value at the both side of phantom. A solid line in Fig. 6 shows the case when the auxiliary electrodes is attached to the surface of tissue model. It is clear that the solid line exhibits relatively flat characteristic with a peak value in the central portion of tissue phantom.

From these figures, it is clear that the heating region is able to be controlled by introducing the auxiliary electrodes.

On the basis of these theoretical suggestions, heating tests have been conducted. Fig. 7(a) shows a thermographic view after heating, using an agar phantom as the elliptic tissue model surrounded by the fat layer at 4 MHz and the input power of 600 W.

As shown in Fig. 7(a), the hot spots occur in the periphery portion of the phantom in the case when the electrodes are not attached to the phantom.

However, when the electrodes are attached to the phantom, the eddy current concentrates on the central portion of the phantom, as shown in Fig. 7(b). Then the central portion of the phantom is regionally heated. Fig. 8 shows the temperature distribution in Fig. 7(a) and (b) along the line of CB in Fig. 5.



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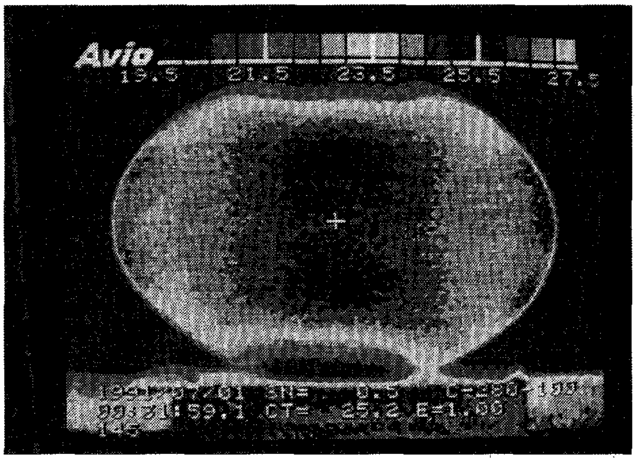


(b)

Fig. 7. (a) Themographic view of phantom after heating without auxiliary electrode by conductive plate. (b) Themographic view of phantom after heating with auxiliary electrodes by conductive plate.

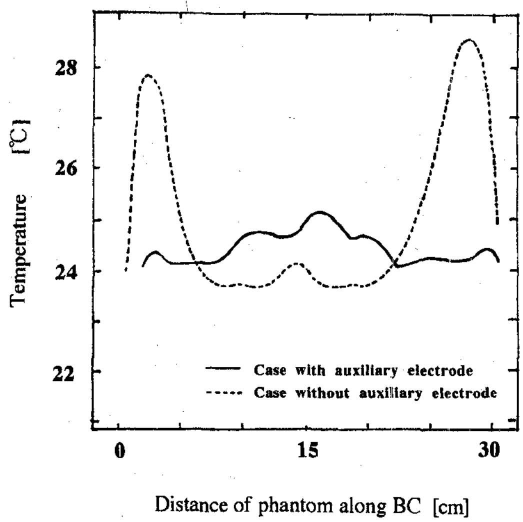


Fig. 8. Temperature distribution inside phantom in Fig. 7.

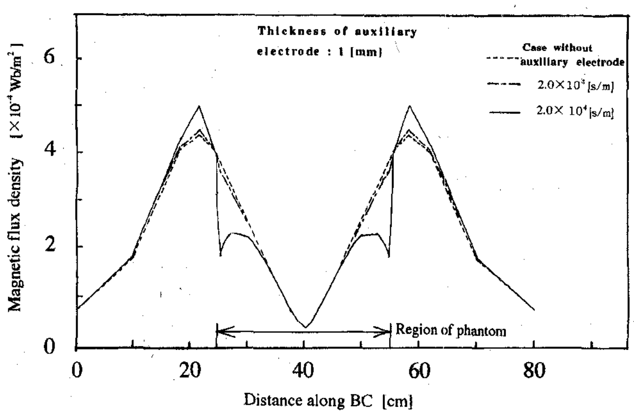


Fig. 9. Magnetic flux density distribution in taking conductivity of auxiliary electrodes as parameters.

In the experiment, two conductive plates, used as the auxiliary electrode, are placed on each side of the phantom with conductivity of 5.82×10^7 S/m, thickness of 0.3 mm, width of 5.0 cm, and the length of 15 cm. Through theoretical and experimental investigations, it is found that it is impossible to heat the deep portion of phantom without using auxiliary electrodes.

B. Investigation on Auxiliary Electrode

In the phantom experiment, conductive plates are used experimentally as auxiliary electrodes. For clinical utilization, it is important to require mechanical flexibility so that the auxiliary electrode can fit the body surface and to have a function of cooling the auxiliary electrode. When rubber is used for this purpose, its conductivity decreases. To investigate this problem, magnetic flux distributions in the inside and outside of the phantom along a line BC have been analyzed in terms of fundamental equation (1) in 2-D case. The dependence of the magnetic flux distribution on the conductivity and thickness of the auxiliary electrode was calculated and Fig. 9 shows the numerical results when the conductivity of the auxiliary electrode is a variable and when the thickness is equal to 1 mm.

In this figure, the values of the magnetic flux density at the both ends of phantom have a tendency of decreasing as the conductivity increases.

Fig. 10 shows the magnetic distributions when the thickness of auxiliary electrode is a variable. And the value of the conductivity is constant (2.0×10^3 S/m). As is evident from this Fig. 10, the magnetic flux densities at the both ends of phantom along the line BC exhibit the same tendency as shown in Fig. 9. Paying attention to these facts, it is determined that a thick, low conductive material like rubber can be applied to the auxiliary electrode in place of a thin high conductivity metal plate. And, the heating effect is the same for both.

C. Heating Experiment by Auxiliary Electrode for Clinical Use

On the basis of the investigation mentioned here, an auxiliary rubber electrode has been manufactured. To give conductivity for the rubber electrode, the electrode is made of silicon rubber containing silver powder. This rubber electrode has the flexibility to fit on the surface of human body and the cooling duct to cool the heat of the electrode, which is caused by the electric current in the electrode. The conductivity of the present rubber electrode is 2.0×10^4 S/m and the thickness is 2 cm.

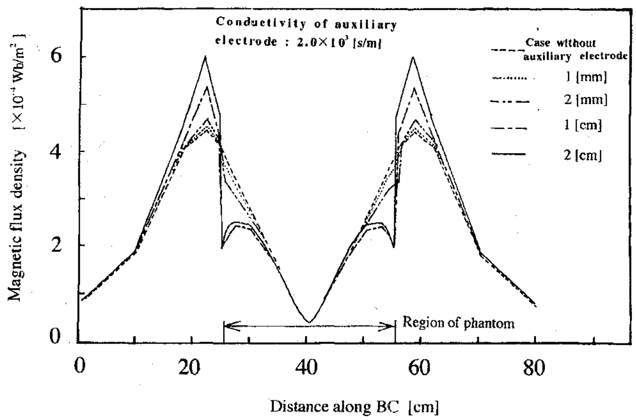


Fig. 10. Magnetic flux density distribution in taking thickness of auxiliary electrodes as parameters.

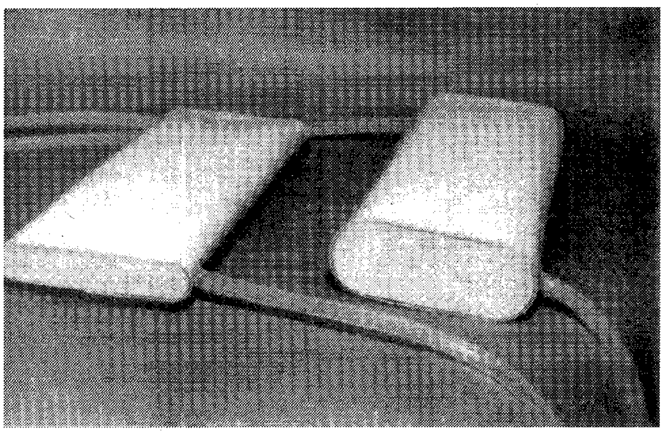


Fig. 11. Appearance of auxiliary electrodes made by conductive rubber.

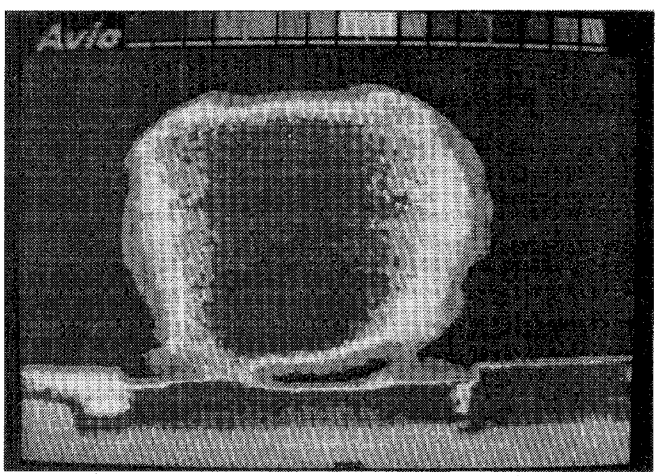
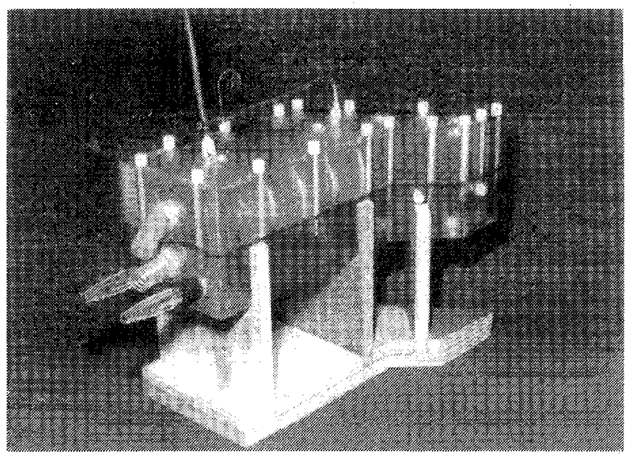


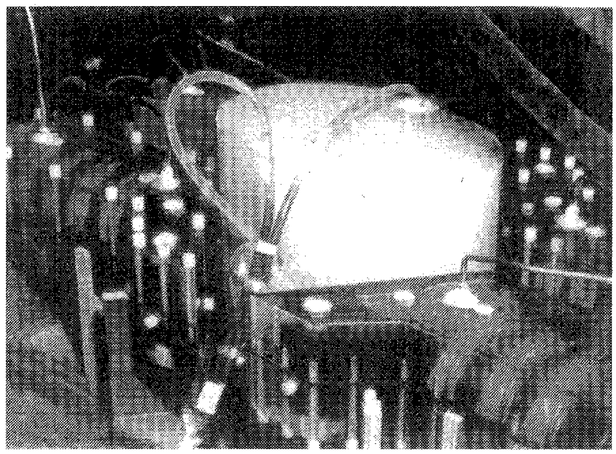
Fig. 12. Themographic view after heating with auxiliary electrodes of conductive rubber.

From the experimental investigations, it is concluded that the length of auxiliary electrode in the present case is greater than 13 cm and a good heating characteristic is normally obtained at 15 cm. The appearance of the auxiliary electrode is shown in Fig. 11.

By using a agar phantom which is surrounded by a fat layer near the surface of it, a heating test has been conducted at 4 MHz with the input power of 600 W.



(a)



(b)

Fig. 13. Appearance of applicator placed in container. (a) Appearance of applicator placed in container. (b) Appearance of heating experiment.

Fig. 12 shows the thermographic view of the phantom after heating. Fig. 12 is an example of the cross-sectional view cutting perpendicularly to the center line of ecliptic cylinder. As seen from this figure, it has become possible to heat the central portion of the phantom without heating the fat layer by introducing the auxiliary conductive rubber electrode.

VI. Development of Applicator System

By controlling of eddy current using the auxiliary electrode, it is possible to reach excellent regional heating pattern in the central portion of phantom. However, the problem of the temperature rise which is necessary for hyperthermia still remains. The applicator presented here has a special feature: it is constructed of ferrite. It concentrates magnetic field distribution and operates with relatively low power. However, if there is a temperature rise in the ferrite core, the efficiency of heating tends to decrease. To improve this problem and keep the fluctuation of temperature constant during heating, a ferrite core is placed in the container which is made of acrylic resin. This container has a structure which can circulate cooling silicon oil. Fig. 13(a) and (b) shows the appearance of the applicator. A heating test has been conducted using this applicator. The heating result obtained is shown in Fig. 14.

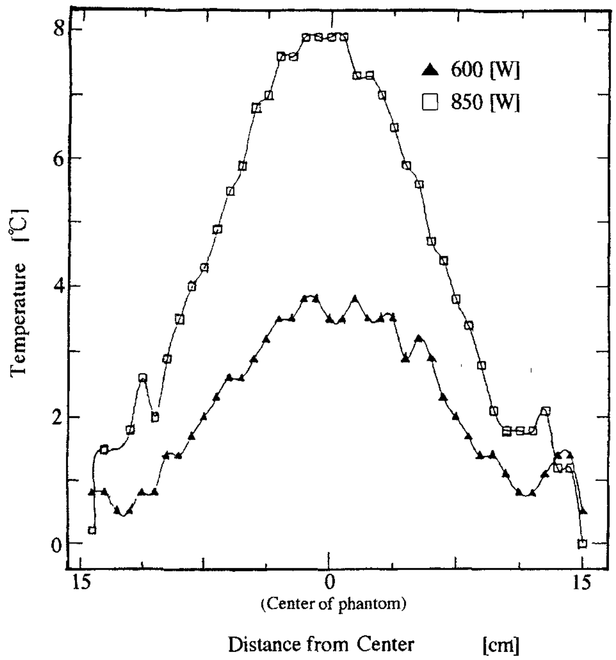


Fig. 14. Heating characteristic by applicator newly developed.

With the maximum output power of 850W at 4 MHz, the temperature rise of 7.5°C is obtained in the depth of 10 cm and the fluctuation of temperature was within ±0.3°C.

As mentioned here, to control the eddy current with the auxiliary electrode, a deep-induction heating system for the noninvasive hyperthermia has been developed.

VII. Conclusion

To achieve deep-induction hyperthermia, theoretical, and experimental investigations have been conducted and a new ferrite core applicator system has been developed. The basic background of adopting the induction heating method has been discussed. One problem which must be resolved in order to achieve noninvasive deep-induction heating is to control of the magnitude and location of the eddy currents.

The main points are summarized as follows:

1) A ferrite core was adopted as an applicator which could concentrate the magnetic field and heat the human body efficiently with low output power. The deformed shape of the magnetic pole with cooling ducts has been proposed. To improve the heating efficiency and keep the temperature fluctuation constant within ±0.3°C, the ferrite core was placed in a container made of acrylic resin. With this construction, it became possible to cool the ferrite core completely and a stable operation also became possible.

2) Based on the concept of controlling the eddy current, a new applicator system with auxiliary electrodes has been proposed. From the theoretical analysis of the fundamental equation using the FEM, the eddy current distribution and magnetic flux distribution were examined to investigate the characteristics of the auxiliary electrodes. It was found that the heating region can be improved by attaching the conductive plates as an electrode.

3) Based upon the FEM analysis, it was found that the characteristic of conductive plate electrode is equivalent to that of the conductive rubber one by adjusting its thickness. Accordingly, from the practical viewpoint, a flexible type of electrode for clinical use was manufactured. The conclusion of these results is that the same heating effects are achieved when using a thick, low conductivity material like rubber as will be achieved when using a thin, high conductivity metal plate.

4) Heating test was carried out using the applicator system newly developed. It was clarified that the temperature rise of 7.5°C in the depth of 10 cm could be obtained without heating a fat layer.

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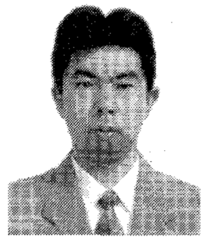

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