Short Papers

Development of Double-Electrode Applicator for Localized Thermal Therapy

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***Abstract*—A double-electrode applicator for localized thermal therapy is developed by breaking through the construction principle of the capacitive applicator. To make the beam of the electric field narrow, a ferrodielectric material is introduced as the sub-electrode. The optimum configuration of the double electrode and the material constant in each part of this applicator are investigated theoretically and experimentally. Good localized deep-heating characteristics are obtained at an operating frequency of 13.56 MHz and an output power 450 W by choosing a ferrodielectric material ($BaTiO_3$) with a relative permittivity of 6000 as the sub-electrode.**

***Index Terms*—Applicator, benign prostatic hyperthermia, capacitive heating, ferrodielectric material, hyperthermia, thermal therapy.**

I. Introduction

Thermal therapy using RF/microwaves is expanding to new medical fields including not only hyperthermia, but also cardiology, urology, and otolaryngology [1], [2]. In particular, RF/microwaves has been widely used to treat benign prostatic hyperplasia (BHP), and have gained international approval [2].

A local deep-heating applicator has been demanded for these treatments. Generally, however, it is difficult to realize a local deep-heating applicator system with a heating depth of more than 6 cm using a noninvasive method. This is inherent to the heating principle using electromagnetic waves. In dielectric heating, many kinds of noninvasive applicator have been proposed for microwave frequencies [3]. However, heating depth is restricted by the skin depth's principle. To avoid the skin depth's restriction, when we use the RF, a large applicator is usually needed for deep uniform heating. For instance, as shown in Fig. 1, in the case of a capacitive applicator with a circular conductive electrode, the diameter of the electrode needs more than 1.5 times the space between both electrodes to heat a heating body uniformly [4] as follows:

$$d \geq 1.5h. \tag{1}$$

That is, to heat the heating body without hot spots arising, an electrode with a diameter of 30 cm is needed when the thickness of the heating body is 20 cm. This paper describes a method of localized regional deep heating using a double-electrode capacitive applicator. To concentrate the electric field, ferrodielectric materials were introduced. Theoretical analysis of the electric-field distribution in a human tissue model was conducted to determine the optimum configuration of the double-electrode applicator using the finite-element method (FEM). The heating characteristics were also investigated in detail taking a few material constants as parameters. The heating tests were conducted using an agar phantom subject to the guideline assigned by the Quality Assurance Committee, Japanese Society of Hyperthermia Oncology (QAC, JASHO) at frequency 13.56 MHz. The empirical results show that localized regional heating is possible with 5-cm width at the highest temperature at the depth of 10 cm.

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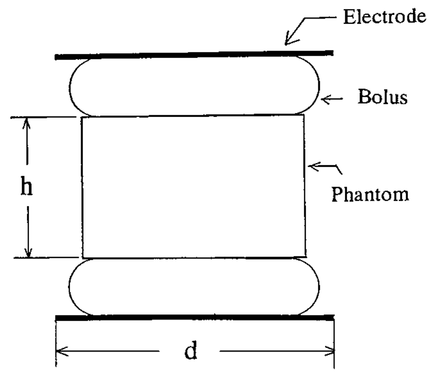

Fig. 1. Conventional applicator in capacitive heating

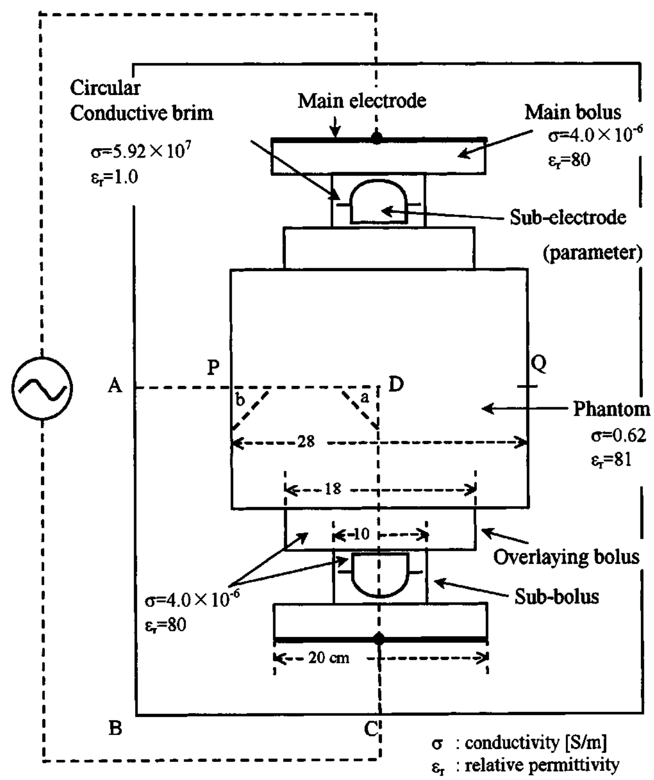

Fig. 2. Model of analysis.

II. Construction of Applicator

To concentrate the electric field into a narrow beam, a ferrodielectric material as a sub-electrode has been introduced. Fig. 2 shows the present double-electrode applicator. This figure shows the cross section of the double-electrode applicator with a heating material. RF power is applied to a pair of circular main electrodes by an RF oscillator. A

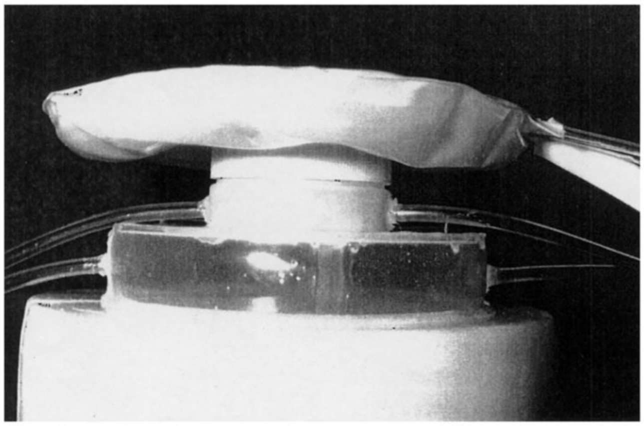

Fig. 3. Configuration of applicator.

circular copper plate with a diameter of 20 cm is used as the main electrode. To cool the electrode and take a matching for a load or a heating material, the main bolus is attached to the circular copper electrode. The main bolus consists of silicone rubber and can circulate cooling water. A pair of sub-boluses consist of a cylindrical container made of plastic and silicone rubber, which can also circulate cooling water. A sub-electrode, i.e., a ferrodielectric material in the shape of a hemisphere, is set up inside the sub-bolus. This ferrodielectric material has a brim, which is a circular copper ring. This brim plays the role of reducing the strong couple of electric field of the ferrodielectric material and making uniform beam-like heating possible. Further, an overlay bolus is placed under the sub-electrode to take matching for an electric field at the boundary between the overlay bolus and the heating material and to cool the surface of the heating material. In the actual construction, the sub-bolus or sub-electrode is integrated with an overlay bolus, which can handle the present applicator easily, as shown in Fig. 3.

This construction is based on the principle that an electrostatic field can be concentrated on the surface of a material with a large value for permittivity. In the present case, the electric field between both electrodes is considered to be approximately the same as the electrostatic field. This is because the space between electrodes is too narrow compared to the wavelength at the operating frequency of 13.56 MHz. Accordingly, it is expected that localized regional heating becomes possible by concentrating the electric field onto a pair of ferrodielectric materials.

III. Theoretical Investigation

A. Optimum Configuration in Double-Electrode Applicator

To determine the optimum configuration of the double-electrode capacitive applicator, the electric field and temperature distribution are analyzed in many configurations using the FEM [5]. The model for analysis is considered to be of a symmetrical shape around the central axis. Therefore, the two-dimensional fundamental equation for the scalar potential or the electrostatic field is analyzed.

As for temperature distribution inside the homogeneous agar phantom, the fundamental heat equation is solved by substituting the electric field obtained by FEM analysis. The size of the model and each part of the material constants are shown in Fig. 2. The value of the ferrodielectlic material is taken as the parameter.

Fig. 4 shows the best example of theoretical and the experimental temperature distributions. This experimental data correspond to the configuration in Fig. 2. From extensive data in many applicator configurations, the case in Fig. 2 was selected particularly from the viewpoint of concentrating the electric field without hot spots arising.

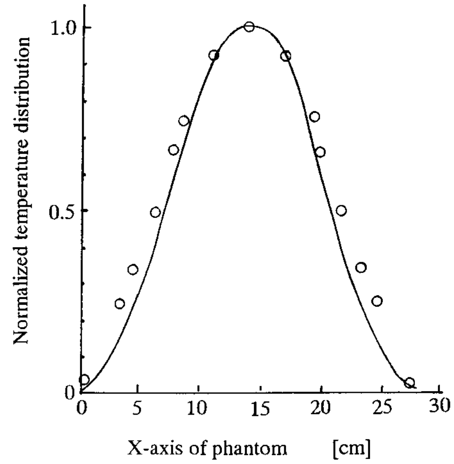

Fig. 4. Temperature distribution along X-axis.

B. Effects of Ferrodielectric Material

A key technology is the ferrodielectric material introduced to concentrate the electric field inside a heating body. Therefore, to obtain design data for the present applicator, the effects of the material constant are investigated theoretically. From this analysis, it is concluded that localized regional heating can be achieved by the ferrodielectric material with a permittivity over 1000.

C. Investigation of Other Parameters

It is important to investigate the nature of the bolus next to evaluation of the ferrodielectric material constant, particularly in the nature of the liquid medium inside the overlay bolus that contacts to the heating material. The effect of changing conductivity inside the overlaying bolus is investigated, while keeping the material constant in the main bolus constant.

These theoretical results suggest that the localized heating characteristic is not obtained if the conductivity takes a large value. It is preferable to use a value of conductivity of less than 1.0 to achieve localized regional heating. In this study, water is effective as the liquid medium inside the overlay bolus, and it is circulated to cool the sub-electrode.

Next, concerning the position of the brim, which is set up on a ferrodielectric material inside the sub-bolus, it became clear that the theoretical heating characteristics exhibited almost the same tendency even if its position is somewhat changed. Accordingly, the middle position on a hemisphere of the ferrodielectric material is adopted to mount the brim.

IV. Development of Applicator

On the basis of theoretical investigation described herein, a new double-electrode applicator has been developed. The operating frequency of 13.56 MHz in the industrial, scientific, and medical band (ISM) band is used and the output power is 450 W. A barium titanate ($BaTiO_3$) with a large permittivity of 6000 is selected as the ferrodielectric material. The main electrode made of a circular copper disk is covered with silicon rubber and cooled by water. As shown in Fig. 3, a sub-bolus containing a ferrodielectric electrode is integrated with the overlay bolus for ease of handling during the actual treatment. Accordingly, the main electrode is only put on the sub-bolus for heating, as shown in Fig. 3. Heating tests were conducted using an agar phantom. Fig. 5 shows the heating pattern of the present double electrode with ferrodielectric materials. From these experiments, it becomes clear that the heating region is well localized in the newly developed applicator. It is also clarified that the localized

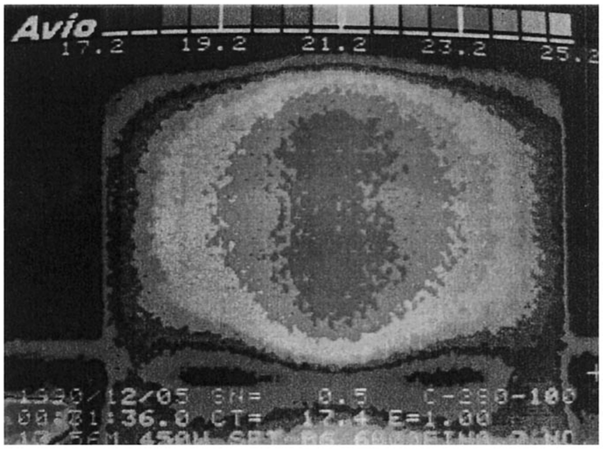

Fig. 5. Thermographic view of the phantom.

width of heating region is almost proportional to the diameter of the ferrodielectric electrode.

V. Conclusion

Theoretical and experimental investigations were conducted in response to the demand for a localized regional heating applicator to treat BHP or other thermal therapies. A double-electrode applicator has been newly developed. To break through the construction principle of the capacitive applicator, the ferrodielectric material has been introduced as sub-electrode. The design criteria for the present applicator were obtained from a detailed analysis of the electric field and temperature using the FEM. Heating tests were conducted at an operating frequency and output power of 13.56 MHz and 450 W, respectively. $BaTiO_3$ with the relative permittivity of 6000 was selected as the ferrodielectric material. It was found that good localized regional heating characteristics were obtained at the depth of 10 cm and the width of the highest temperature are proportional to the diameter of 5 cm in the hemisphere-like ferrodielectric material.

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References

[1] A. Rosen and H. D. Rosen, *New Frontiers in Medical Device Technology*. New York: Wiley, 1995, pp. 312–337.
[2] ——, "RF/microwaves in thermal therapies," IEICE, Tokyo, Japan, Tech Rep. MW98-21, May 1998.
[3] P. F. Turner, "Regional hyperthermia with an annular phased array," *IEEE Trans. Biomed. Eng.*, vol. BME-31, pp. 106–114, Jan. 1984.
[4] "Report of quality assurance committee in Japanese Society of Hyperthermia Oncology," Jpn. Soc. Hypertherm. Oncol., Tokyo, Japan, Tech. Rep., 1986.
[5] Y. Kotsuka, *Electromagnetic Wave Theory*. Bunkyo-ku, Tokyo, Japan: Corona, 1995, pp. 398–452.