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DIRECT CONTACT APPLICATOR WITH CONVERGENT EFFECT OF EM FIELD FOR MICROWAVE HYPERTHERMIA

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SUMMARY

A new type applicator for microwave hyperthermia operated at 433 MHz is proposed. This applicator, which is a waveguide array type, has a convergent effect of the electromagnetic field radiated from the applicator, and focal length of it can be changeable. The electric field distributions in the model of human tissues from the aperture of the applicator were measured, and the simulation of temperature distributions was performed in the model heated with the applicator.

INTRODUCTION

For microwave hyperthermia, it is difficult to deposit electromagnetic (EM) energy deep in human tissues[1][2]. The applicators which can deposit EM energy in the lossy medium with the convergent effect of radiated EM field in the magnetic field plane, and can stare the heating pattern in the medium have been proposed[3][4]. In this paper, a new type applicator for microwave hyperthermia at 433 MHz is presented. This applicator has the convergent effect of the EM field both in the magnetic field plane (H-plane) and in the electric field plane (E-plane). Therefore, the peak of the electric field (E-field) intensity is produced in the dissipative medium. The location of the focus can be changed easily by shifting the metal plates parallel to the E-plane in the applicator. The distributions of the E-field radiated from this focal location controllable applicator (FLC applicator) were measured in the salt solution for the model of human tissues. Furthermore, with use of the results of the E-field measurement and the heat transport equation, the theoretical temperature distributions in the model of human tissues with blood flow were simulated.

DESIGN OF THE FLC APPLICATOR

The geometry of the FLC applicator is shown in Fig. 1. This applicator is a waveguide array type, and the metal plates have been set inside the applicator to divide the aperture of the applicator into several zones. When the propagation mode of EM wave is TE_{10}, the propagation constants in the medium between the metal plates in the applicator are expressed as

$$k^*_i = \sqrt{\omega^2\mu\cdot(\varepsilon'-j\varepsilon'') - (\pi/d_i)^2} \quad (i = 1, 2) \qquad (1\text{-a})$$

$$k^*_{wj} = \sqrt{\omega^2\mu\cdot(\varepsilon'-j\varepsilon'') - (\pi/d_{wj})^2} \quad (j = 1, 2, 3) \qquad (1\text{-b})$$

where ω is the angular frequency of the operating EM wave, μ is the permeability of the medium in the applicator, $\varepsilon' - j\varepsilon''$ is the complex permittivity of the medium in the applicator, and d_i, d_{wj} is the width between the metal plates. The lengths and the widths of the zones divided by the metal plates are calculated with following equation to have a optical focus both in the H-plane and in the E-plane when the heating medium is loss free.

$$[\mathrm{Re}(k^*_{w1})-\mathrm{Re}(k^*_{w2})]\cdot l_0(y) + [\mathrm{Re}(k^*_i)-\mathrm{Re}(k^*_{w3})]\cdot l_i(y) + \mathrm{Re}(k^*_i)\cdot z_i + \mathrm{Re}(k^*)\cdot r_i(y) = \mathrm{Const.} \qquad (2)$$

$$(i = 1, 2;\ -h/2 < y < h/2)$$

where k^* is the propagation constant of the heating medium, $r_i(y)$ is the length between the optical focus and the aperture of the applicator, and z_i, $l_0(y)$, $l_i(y)$ are the lengths of the zones divided by the metal plates as indicated in Fig. 1. Therefore, this applicator can converge radiated EM field in the H-plane and the E-plane. By moving metal plates parallel to the E-plane to vary the width between the metal plates d_i, d_{wj}, the focal length r_0 can be changed.

Furthermore, the FLC applicator is filled with water to attain compact size and good impedance matching to the direct contacted heating medium such as human tissues. On the aperture, the water bag is attached to perform surface cooling of the heating medium and to keep the concave shaped aperture in good contact with the medium whose shape can be approximated by a cylinder.

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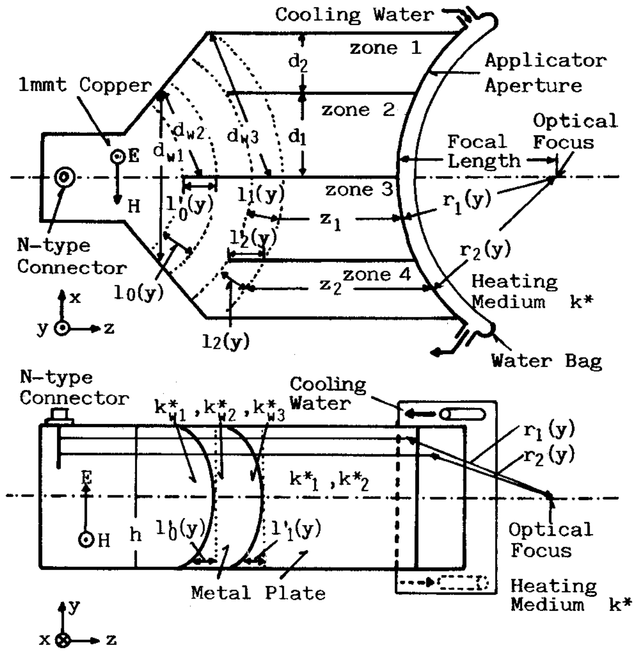

Fig. 1. Geometry of focal location controllable applicator (FLC applicator); d_1 = 60 mm, d_2 = 45 mm and h = 80 mm (operating frequency = 433 MHz, permittivity of water = 78.0 - j5.0).

THE MEASUREMENT OF THE ELECTRIC FIELD DISTRIBUTION

The measurement of the E-field distribution radiated from the applicators was performed in 0.2 % salt solution. The complex permittivity of the 0.2 % salt solution for the model of human tissues is measured as 79 - j35 (at 400 MHz, 29.5 C). The reason why we select 0.2 % salt solution is that the dielectric loss of it is the mean value of that of muscle and fat. The E-field distribution was measured in z-x plane shown in Fig. 2. The results measured along the center axis of the applicator (z-axis) are shown in Fig. 3 and Fig. 4.

Fig. 3 shows the E-field intensity distributions compared the FLC applicator (focal length r_0 = 126 mm) with the normal waveguide and the H-lens applicator (focal length r_0 = 128 mm)[4]. The aperture size of the waveguide applicator is 50 by 50 mm. The H-lens applicator could converge EM field only in the H-plane. As shown in Fig. 3, the attenuation constants of propagating E-field radiated from the waveguide and H-lens applicator were 0.18 dB/mm and 0.10 dB/mm (50 mm $< z <$ 100 mm) respectively, then it was found that by using the H-lens applicator, the attenuation of propagating E-field was decreased by 45 % as compared with the waveguide. Further, by using the FLC applicator, the peak of the E-field intensity was produced at 100 mm in depth, then the FLC applicator could deposit EM energy in a deeper area than the H-lens applicator.

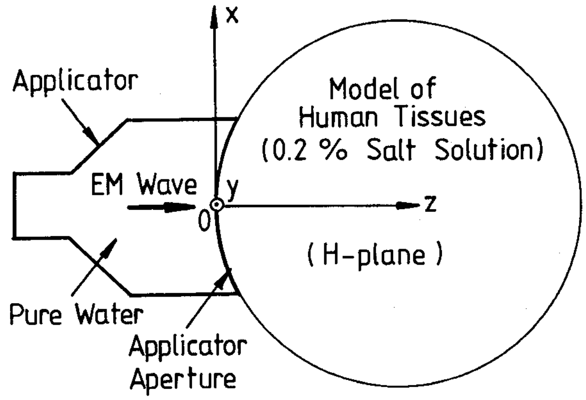

Fig. 2. System of coordinates used to express results of E-field measurement and temperature simulation.

Fig. 4 shows the E-field intensity distributions radiated from the FLC applicator when focal length r_0 was sifted by changing the widths between the metal plates in the applicator d_1, d_2. From this figure, it was found that the location and the intensity of the peak of the E-field could be varied by sifting the focal length r_0.

THE SIMULATION OF THE TEMPERATURE DISTRIBUTION IN THE MODEL OF HUMAN TISSUES

The effect of blood flow cannot be disregarded in actual heating medium such as a human body, so it is necessary to calculate the theoretical temperature distribution in the model of human tissues taking account of blood flow when the model is heated by EM wave radiated from the applicator. For such a purpose, the simulation of the temperature distribution was performed using the results of the measurement of the electric field distribution and the heat transport equation[5]. The initial temperature T_0 and the temperature of blood T_b were 36.5 ℃, The temperature of the surface cooling of the model of human tissues T_w was 15.0 ℃.

The results of the calculation of temperature distributions in the model which has uniform blood flow rate F_0 are presented in Fig. 5 and Fig. 6. Fig. 5 shows the temperature distributions in the model when three types of applicator was used, Fig. 6 shows ones in condition of several focal lengths with use of the FLC applicator. From these results, it was found that the FLC applicator could heat the deeper area, and could control the depth of heating area.

The simulation was performed in the model which has uniform blood flow rate F_0 without in tumor area where the blood flow rate is 1/4 F_0. Fig. 7 shows the temperature distributions in the model when the location of tumor area was varied. As this figure, by use of the FLC applicator, hyperthermic temperature range (42°C - 45°C) was obtained to 65 mm in depth.

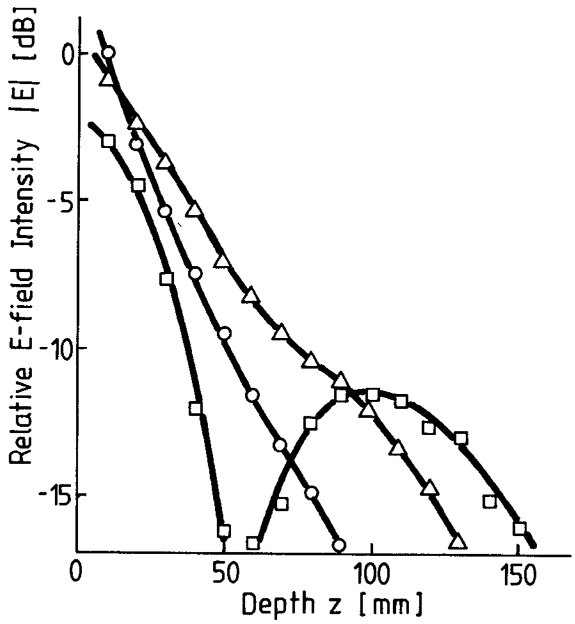

Fig. 3. E-field intensity distributions measured in 0.2 % salt solution when three types of applicator are used.

—○—○— Waveguide Applicator
—△—△— H-lens Applicator
—□—□— FLC Applicator

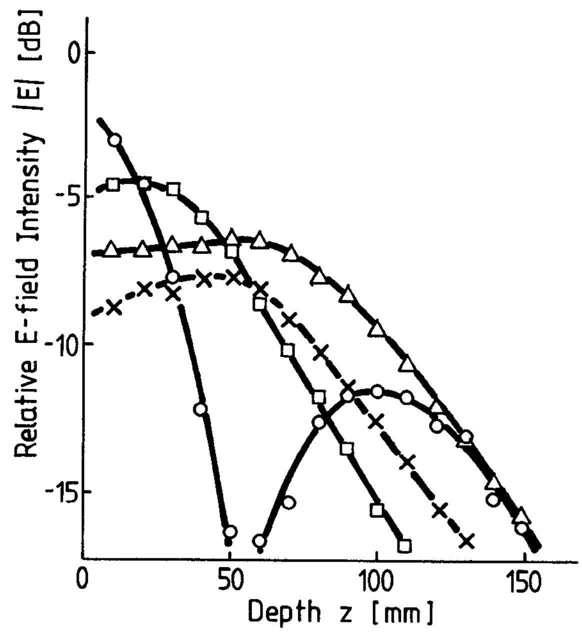

Fig. 4. E-field intensity distributions measured in 0.2 % salt solution when focal length is shifted by using of FLC applicator.

Focal length of FLC applicator:

—○—○— no focus
—△—△— 69 mm
—□—□— 100 mm
—×—×— 126 mm

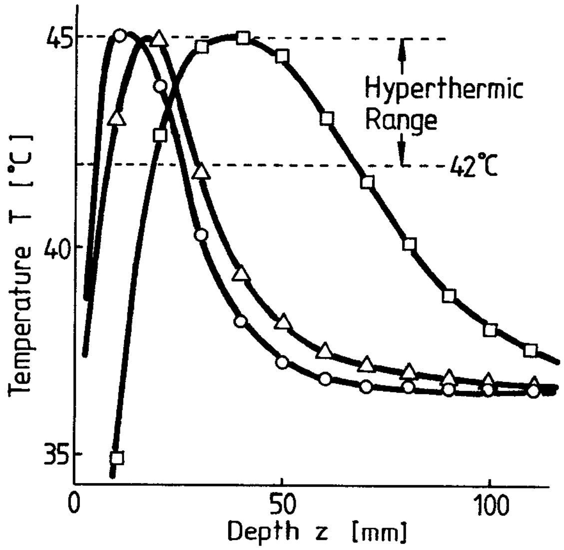

Fig. 5. Theoretical temperature distributions in the model of human tissues with blood flow when three types of applicator are used.

—○—○— Waveguide Applicator
—△—△— H-lens Applicator
—□—□— FLC Applicator

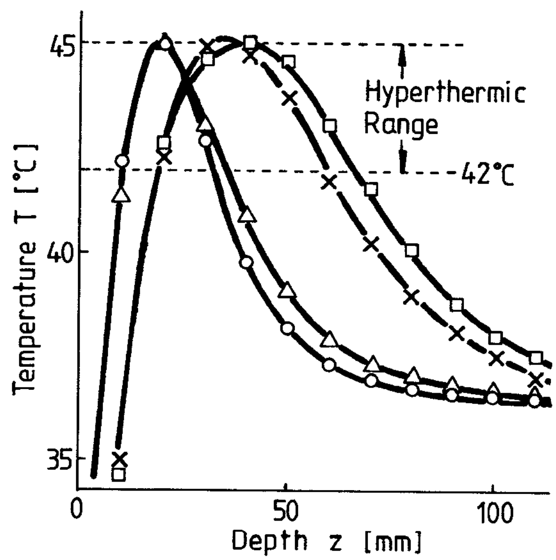

Fig. 6. Theoretical temperature distributions in the model of human tissues with blood flow when focal length is shifted by using FLC applicator.

Focal length of FLC applicator:

—○—○— no focus
—△—△— 69 mm
—□—□— 100 mm
—×—×— 126 mm

CONCLUSION

The focal location controllable applicator (FLC applicator) has been proposed, and the experimental and the theoretical results have been shown to evaluate the applicator.

The results of the E-field measurement in the salt solution for the model of human tissues were shown that the FLC applicator could change the location of the peak of the E-field intensity in the heating medium by moving the metal plates in the applicator to vary the optical focal length of it. From this result, it was found that the FLC applicator had the ability to change the heating location in the lossy medium by moving the metal plates in the applicator. This property was also confirmed with the simulation of the temperature distribution. The results show that, by this ability of the FLC applicator, it is possible to heat tumor area separately.

As shown in the results of E-field measurement, by the convergent effect of EM field of the FLC applicator, the peak of E-field intensity was produced in a deep area of the model of human tissues, and the attenuation of propagating E-field was decreased as compared with previous applicators. Furthermore, on the simulation of the temperature distribution in the model of human tissues with tumor, the depth of the hyperthermic temperature range was obtained to 65 mm, it was increased by nearly 50 % as compared with the previous applicators at 433 MHz[4].

As described above, the FLC applicator could change heating location in the lossy medium, and could heat deep area in depth of 65 mm. Therefore, it is concluded that the selective heating of the tumor in a deep area of human body could be realized with use of the FLC applicator.

ACKNOWLEDGMENTS

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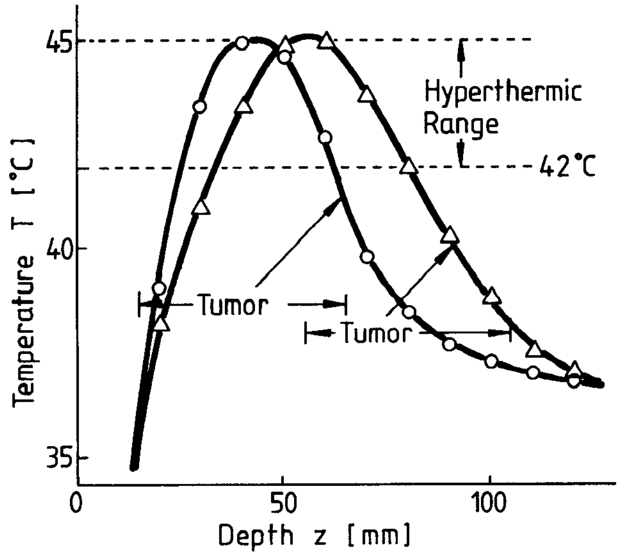

Fig. 7. Theoretical temperature distributions in model of human tissues with spherical tumor tissue when location of tumor area is varied (with use of FLC applicator, focal length = 100 mm).

Tumor area:

—o—o— 15 mm < z < 65 mm

—△—△— 55 mm < z < 105 mm