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MICROWAVE HEATING SYSTEM USING LENS APPLICATOR FOR LOCALIZED HYPERTHERMIA

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SUMMARY

A computer controlled microwave heating system for hyperthermia was developed with direct contact lens applicator to deposit the energy of electromagnetic field deep in human tissues. The results show that with the applicator operate at 2450 MHz, over double of heating depth was realized compared with simple waveguide applicators. And the heating result using the developed system show that the fluctuations of temperature at the heating location in the model of human tissues were maintained within ±0.3 °C of the set temperature. These results are available for the clinical hyperthermia treatment of cancer.

INTRODUCTION

The development of noninvasive localized heating technique for the human body is indispensable for hyperthermia treatment of cancer. To use electromagnetic(EM) energy is one of the best means to achieve this purpose. At high frequencies, applicators of convenient size may be used to focus EM energy on selected areas of the body. However, the depth of penetration is generally shallow[1]-[3].

The authors have been suggested that the penetration depth increased using EM field converging lens applicator at high frequencies [4]-[6]. In this paper, microwave heating system with direct contact lens applicator is presented, and calculations are performed to compare the distributions of the EM field radiated from the aperture of the lens applicator and simple waveguide applicator operate at the same frequency, and experiments are performed to compare the temperature distribution in the model of human muscle heated with the lens applicator operates at 2450 MHz and with waveguide applicators operate at the same frequency and 433 MHz.

DESIGN OF LENS APPLICATOR

Fig. 1 illustrates a practical lens applicator in our heating system. And Fig. 2 (a) and (b) show the end view of the applicator along x-z plane (i.e. magnetic field plane (H-plane)), and y-z plane (i.e. electric field plane (E-plane)) of Fig. 1, respectively. The illustration indicates

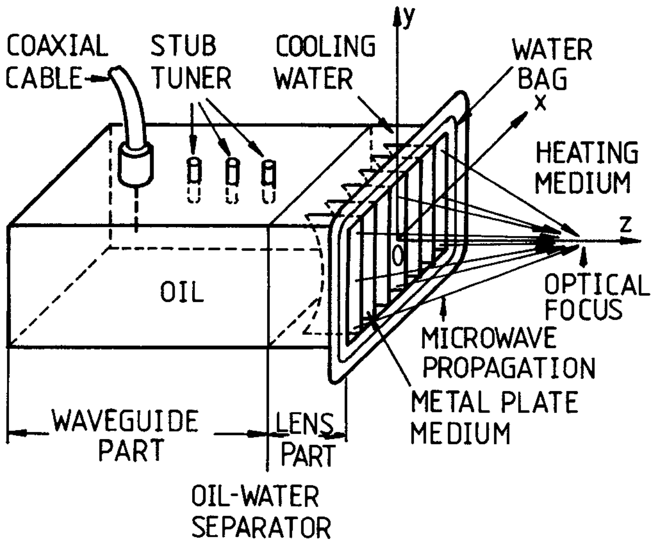

Fig. 1. Schematic of lens applicator.

parallel metal-plate medium with plate distance d_i (i= 1, 2, 3, 4) and filled with water as the dielectric material with dielectric constant $\varepsilon' - j\varepsilon''$ (relative dielectric constant of pure water is 68 - j12 (30 °C) at 2450 MHz [7]) is inserted into waveguide so that the metal-plates are in parallel to the E-plane of the waveguide. Letting λ be the wavelength of the EM wave in the dielectric material, the EM wave in the metal-plate medium has the propagation mode of TE_{10} for the range of separation d_i between each pair of the metal-plate satisfying $\lambda/2 < d_i < \lambda$. The propagation constant k_i^* then is given by

$$k_i^* = \sqrt{\omega^2\mu(\varepsilon' - j\varepsilon'') - (\frac{\pi}{d_i})^2} \qquad (1)$$

where ω is angular frequency of EM wave and μ is permeability of the dielectric material. This applicator is designed to have a optical focus of the radiated microwave EM field from the aperture of the applicator under condition when the medium is loss-free. The shape of each metal plate is designed by the use of geometric optical theory and given by

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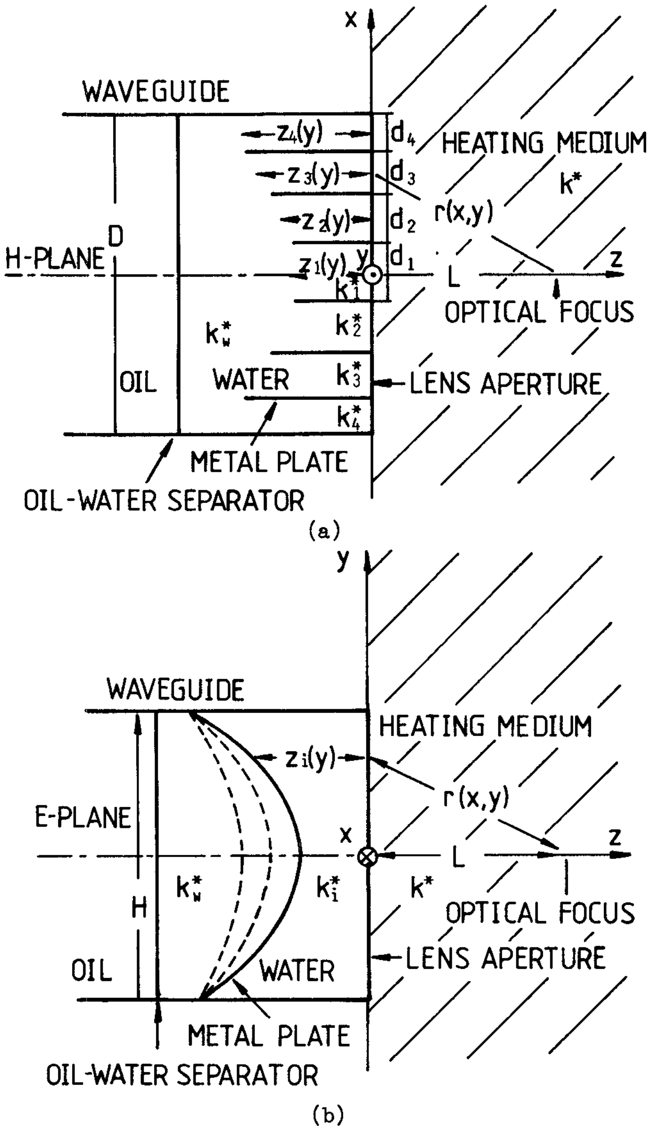

Fig. 2. End view of lens applicator in direct contact with the heating medium, along (a) H-plane, and (b) E-plane, (d_1=10 mm, d_2=9.8 mm, d_3=8.3 mm, d_4=7.5 mm, d=67 mm, H=50 mm, L=40 mm).

$$\mathrm{Re}(k_i^*)z_i(0)+\mathrm{Re}(k^*)r(x,0)$$
$$=\mathrm{Re}(k_1^*)z_1(0)+\mathrm{Re}(k_w^*)(z_i(0)-z_1(0))+\mathrm{Re}(k^*)L \qquad (2)$$

in the H-plane, and

$$\mathrm{Re}(k_w^*)(z_i(y)-z_i(0))+\mathrm{Re}(k^*)L$$
$$=\mathrm{Re}(k_i^*)(z_i(y)-z_i(0))+\mathrm{Re}(k^*)r(x,y) \qquad (3)$$

in the E-plane, where k_w^* is the propagation constant in the waveguide, expressed as

$$k_w^*=\sqrt{\omega^2\mu(\varepsilon'-j\varepsilon'')-(\frac{\pi}{D})^2} \qquad (4)$$
,

k^* is the propagation constant of the heating medium, r(x,y) is the distance from the aperture of the applicator to the focal point, and the other parameters are indicated in Fig. 2.

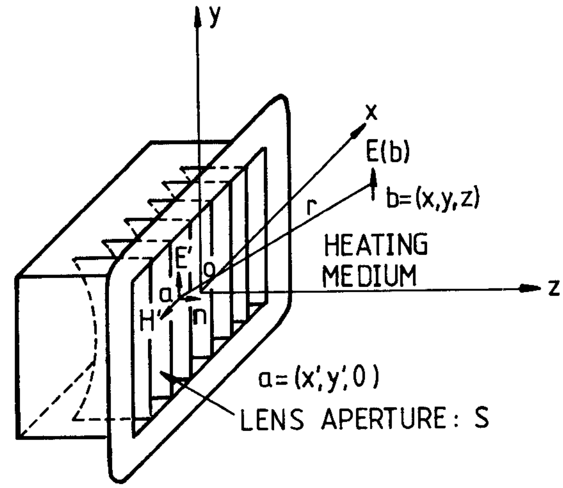

Fig. 3. Aperture of lens applicator with rectangular coordinates.

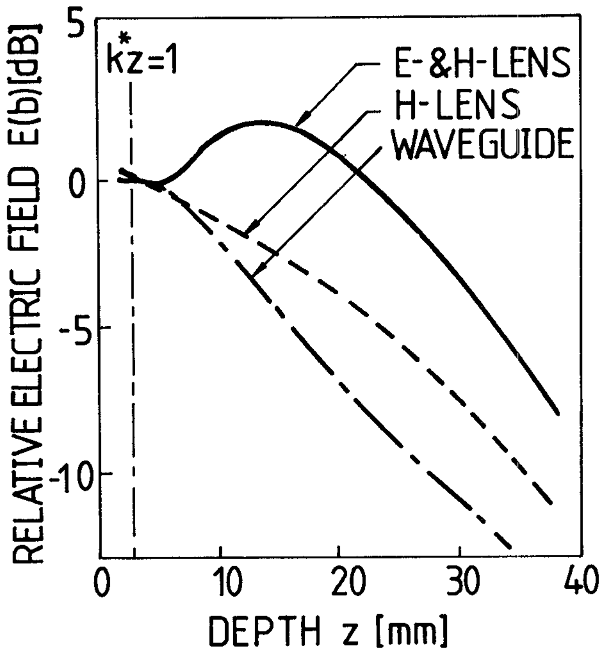

Fig. 4. Calculated relative electric field in the phantom modeling material of muscle radiated 2450 MHz microwave by several types of the applicator.

THEORETICAL CALCULATION

The actual heating medium has a large loss and the wavelength cannot be neglected, then the diffraction theory is used to estimate the intensity of the electric field inside the heating medium. The z-component of the electric field in the radiating near-field region transmitted from the aperture of the lens applicator is calculated by adding radiated EM field from each zone of the aperture of the lens applicator. According to the Kirchhoff-Hygens principle, the EM field E(b) at an observing point b=(x,y,z)(see Fig. 3) is

$$E(x,y,z) = j\frac{k^*}{4\pi}\iint_S E'G\frac{1}{r}\left[\frac{\eta}{\eta'}[(x-x')^2+z^2]+z\right]ds \qquad (5)$$

where

$$r = \sqrt{(x-x')^2+(y-y')^2+z^2} \qquad (6)$$

$$G = \exp(-jk^*r)/r \qquad (7)$$

η is the intrinsic impedance of the heating medium, and η' is the one in the waveguide enclosed by the metal plates. The reason why we have considered z-component of the electric field only, is that the x- and y-component of the electric field turn out to be negligible.

Using equation (5), calculation of the EM field distribution inside the model of human muscle (whose relative dielectric constant is 49.6-j16.5 at 2450 MHz) were made radiated EM wave by three types of the applicator operate at 2450 MHz, for simple waveguide, two dimensional (H-plane) convergent lens applicator (H-lens) and three dimensional convergent one (E- & H-Lens). The aperture size of each applicator D x H in Fig. 2 is 67.2 x 50.0 mm. The result shown in Fig. 4 is normalized at the the position of $k^*z=1$. The deeper area than this position ($z> |1/k^*|$), the radiation field comes to be dominant, the error of the calculation is small in this area. From the result shown in Fig. 4, by using our lens applicator of the three dimensional convergent type (E- & H-lens), high intensity of the electric field could be produced in the deep area of the lossy heating medium, and attenuation of the EM field vs. depth was decreased with using the lens applicator compared with the waveguide applicator of the same aperture size. These results predict the possibility of effective deep and localized heating in the dissipative medium.

DESIGN OF HEATING SYSTEM

Block diagram of the heating system using our lens applicator is shown in Fig. 5. The system is controlled by the computer. Temperature of the surface of the heating medium is controlled by the flow rate and the temperature of the water in the water bag attached to the surface of the applicator, and that of the deep target is controlled by the transmitted microwave power to the heating medium. Forward and reflect power of the microwave, temperature of the heating medium (3 channels) and that of the cooling water and flow rate of the cooling water are continuously monitored.

RESULTS

Fig.6 shows the result of the temperature elevation vs. depth in the phantom modeling material of muscle heated by the use of the three dimensional converging lens applicator (E- & H-plane converging lens, aperture size D x H in Fig. 2 is 67.2 x 50.0 mm) and the simple waveguide applicator of the same aperture size utilizing our heating system. Using our lens applicator,

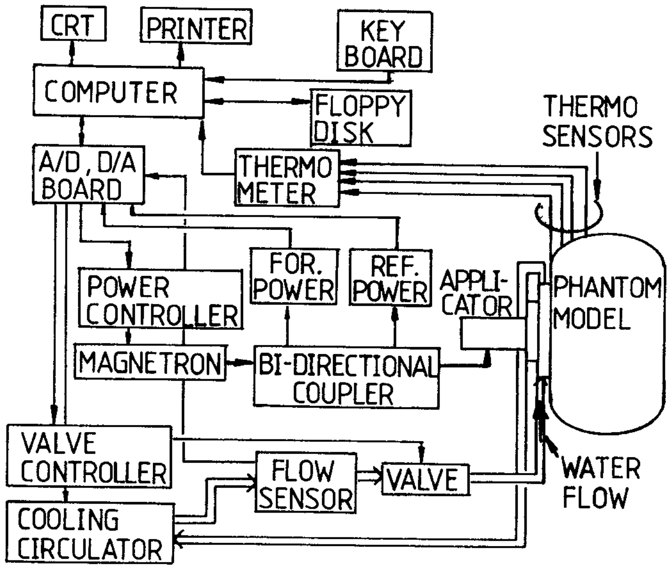

Fig. 5. Block diagram of computer controlled heating system.

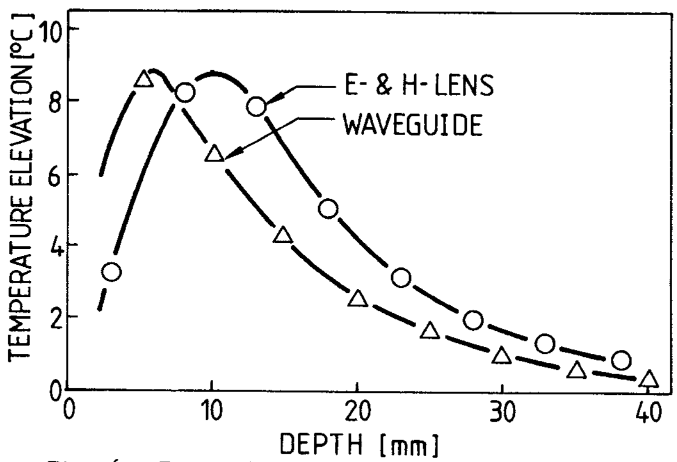

Fig. 6. Temperature elevation vs. depth in the phantom modeling material of muscle heated at 2450 MHz microwave by the lens applicator, and waveguide applicator using computer controlled system (aperture size is 67.2 x 50.0 mm, surface temperature is kept at 20 °C, heating duration is 2 minutes).

maximum temperature area could be produced twice as deep as that of waveguide applicator. Fig. 7 shows the depth of maximum temperature in the model of muscle heated with the lens applicator operate at 2450 MHz with variable temperature of the surface cooling, and with the simple waveguide applicator operate at 433 MHz. Skin depth of the heating medium is 8.4 mm at 2450 MHz and 19 mm at 433 MHz, respectively. From these results, though the skin depth at 2450 MHz is more shallower than that at 433 MHz, the depth of maximum temperature reached twice as deep when heated by lens applicator operates at 2450 MHz than that by waveguide applicator operates at 433 MHz.

Fig. 8 shows the heating result of the phantom modeling material of muscle using our heating system. Initial temperature of the model

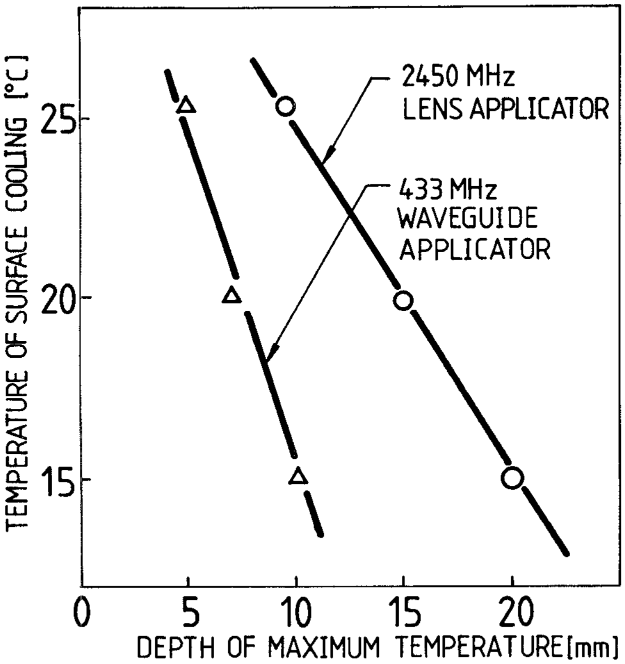

Fig. 7. Experimental result of temperature of surface cooling vs. depth of maximum temperature of phantom modeling material of muscle heated with the lens applicator operates at 2450 MHz and with direct contact waveguide applicator operates at 433 MHz of thesame aperture size with the lens applicator (aperture size is 60.0 x 52.0 mm).

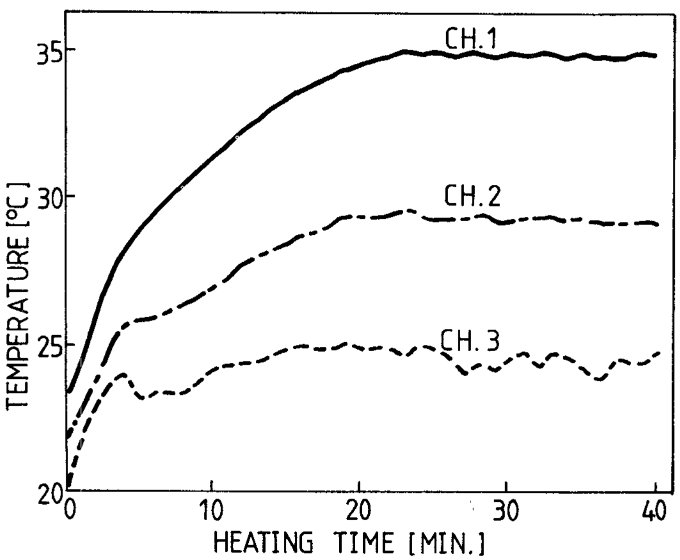

Fig. 8. Temperature vs. time in the phantom modeling material of muscle heated with the lens applicator using computer controlled system (temperature is measured by the thermo-couplesensor located 10 mm in depth (CH. 1), 5 mm in depth (CH. 2), and surface (CH. 3)).

was 20 °C and the set temperature elevation in 10 mm depth was 15 °C. The temperature is maintained at 35 °C (10 mm in depth) within plus or minus 0.3 °C. Furthermore, the depth of heating could be controlled by the temperature and flow rate of the surface cooling water.

CONCLUSIONS

The result show that with the lens applicator of three dimensional convergent type (E- & H-plane lens) , the intensity of electric field could be localized deep area in the heating medium. With surface cooling device, the position of maximum temperature heated with lens applicator was obtained twice as deep as that with simple waveguide applicator. And the depth of maximum heating was also twice as deep as that with using simple waveguide applicator operate at 433 MHz. Furthermore, the depth of maximum temperature could be controlled by the temperature and flow rate of the surface cooling water in addition to control the radiation power of microwave to the heating medium. These results thus paves a way to realize more effective microwave hyperthermia treatment of cancer.

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