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Development and Testing of a 2450-MHz Lens Applicator for Localized Microwave Hyperthermia

YOSHIO NIKAWA, MAKOTO KIKUCHI, AND SHINSAKU MORI

Abstract **—A new type of applicator with a convergent lens for localized microwave hyperthermia is developed. A lens applicator of direct contact type was designed to conduct actual and progressive experiments with phantoms of simulated fat and muscle tissues heated at 2450 MHz. The experimental results showed that the heating power penetration depth increased 40 percent with this applicator as compared to a simple rectangular waveguide applicator with the same size aperture that had generally been used for microwave hyperthermia. Our applicator had a concave-shaped aperture and was designed to contact well with the heating medium whose shape was cylindrical like a human body.**

I. Introduction

The development of noninvasive localized heating techniques for the human body is indispensable for hyperthermia. Dielectric heating by electromagnetic (EM) waves is one of the best means for providing these heating techniques. EM techniques and applicators for medical diagnosis and therapy have recently been observed [1]–[3]. To perform effective hyperthermia, the design of an applicator to transfer EM energy to the treatment area is an important problem. When microwave EM fields are used, the depth of penetration is generally shallow and it is difficult to heat deep-lying tissues and relatively large tissue volumes. To overcome this difficulty, many different applicators have been developed [4]–[7]. The desired characteristics of a direct contact applicator for microwave hyperthermia are to deposit EM energy effectively in the defined tissue volume, to have a good impedance matching, and to be easy to handle. In view of these characteristics, hyperthermia applicators still have much room for improvement [8].

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Y Nikawa and S. Mori are with the Department of Electrical Engineering, Faculty of Science and Technology, Keio University, 3-14-1 Hiyoshi, Kouhoku-ku, Yokohama, 223 Japan.

M. Kikuchi is with the Department of Medical Engineering, National Defense Medical College, 3-2 Namiki, Tokorozawa, Saitama, 359 Japan.

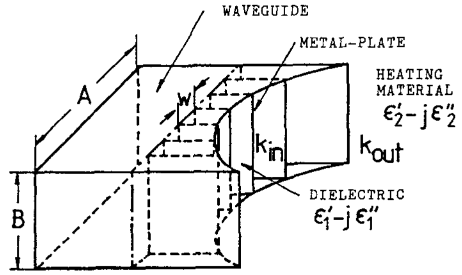


Fig. 1. Schematic of lens applicator of direct contact type.

The excellent features of this new type of applicator with a convergent lens, designed by geometrical optics and a concave-shaped aperture that provides good contact with the cylindrical-shaped human body, have been previously presented [9]–[11].

Our plan of presentation is as follows. In the second section, we propose a new lens applicator for hyperthermia in order to deposit EM field energy inside the deep medium, and carry out heating experiments using phantom modeling material for human tissues. We calculate theoretically the electric field distribution from the applicator. We compare our results with the electric field distribution obtained from traditional waveguide. Finally with our apparatus, we present and discuss the results.

II. Development of Lens Applicator

A. Design Principle of the Lens Applicator of Direct Contact Type

Assume that a parallel metal-plate medium with plate distance w and filled with a dielectric material with complex dielectric constant $\epsilon_1' - j\epsilon_1''$ ($= \epsilon_1^*$) is inserted into a waveguide so that the metal plates are in parallel to the E-plane (see Fig. 1). 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 TE_{10} for the range of a constant separation w between each pair of the metal plate satisfying $\lambda'/2 < w < \lambda'$. The propagation constant k_{in} then is given by

$$k_{in} = \sqrt{\omega^2\mu(\epsilon_1' - j\epsilon_1'') - \left(\frac{\pi}{w}\right)^2}. \quad (1)$$

When such a waveguide applicator, with the metal-plate medium filled with dielectric material, is made to contact to another dielectric material at the aperture, the EM wave refracts at the boundary of dielectric materials, as is seen from the theory of geometrical optics. Letting the complex dielectric constant of the dielectric material in contact with the applicator be $\epsilon_2' - j\epsilon_2''$ ($= \epsilon_2^*$) (see Fig. 1), the propagation constant of the medium k_{out} is given as in

$$k_{out} = \beta - j\alpha \quad (2)$$

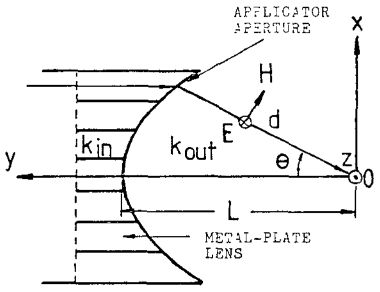


Fig. 2. End view of lens applicator of direct contact type.

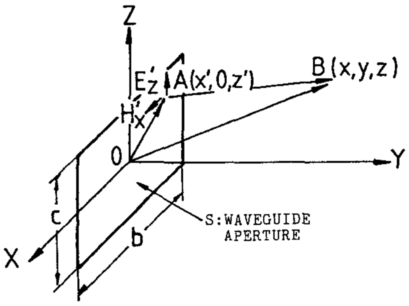


Fig. 3. Rectangular aperture of waveguide applicator with rectangular coordinates.

using the attenuation constant α and phase constant β given by

$$\alpha=\sqrt{\tfrac{1}{2}\omega^2\mu\left(\sqrt{\epsilon_2'^2+\epsilon_2''^2}-\epsilon_2'\right)}$$

$$\beta=\sqrt{\tfrac{1}{2}\omega^2\mu\left(\sqrt{\epsilon_2'^2+\epsilon_2''^2}+\epsilon_2'\right)}. \quad (3)$$

For the EM wave going from the metal-plate medium to the dielectric medium, the index of refraction n is given by

$$n=\frac{k_{\text{in}}}{k_{\text{out}}}. \quad (4)$$

Letting $\epsilon_1'=\epsilon_2'$, $\epsilon_1''=\epsilon_2''$, i.e., assuming that the dielectric material filled in the metal plate has the same dielectric constant as that of the dielectric material in contact with the applicator, it follows that $\text{Re}(n)<1$, making it possible to construct the lens applicator with a concave-shaped aperture [14].

The lens applicator is designed so that the EM wave is focused on a point in the H-plane when the medium is loss-free. The configuration of the aperture of the applicator can be determined by geometrical optics. Namely, let the focal length on the H-plane be L. The distance d from the focus to the aperture in Fig. 2 is expressed in terms of θ as

$$d=\frac{[1-\text{Re}(n)]L}{1-\text{Re}(n)\cos\theta}. \quad (5)$$

B. Theoretical Considerations on EM Field Propagation

The microwave EM field distributed from the lens applicator can be determined by the Kirchhoff–Huygens principle [12]. The time factor $\exp(j\omega t)$ (ω is the angular frequency of the EM wave) has been split off.

According to the Kirchhoff–Huygens principle, the EM field at an observing point **B** is

$$\mathbf{E(B)}=-\frac{1}{4\pi}\int_S[-j\omega\mu(\hat{\mathbf{n}}\times\mathbf{H})G+(\hat{\mathbf{n}}\times\mathbf{E})\times\nabla G+(\hat{\mathbf{n}}\cdot\mathbf{E})\nabla G]\,da. \quad (6)$$

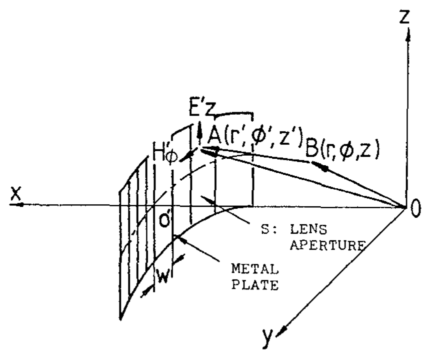


Fig. 4. Aperture of lens applicator with cylindrical coordinates.

This is exactly the field that would be produced by a distribution of electric current over S (the aperture of the applicator, see Figs. 3 and 4) with surface density **K**, a distribution of magnetic current of density **K***, and a surface electric charge of density ρ, where

$$\mathbf{K}=-\hat{\mathbf{n}}\times\mathbf{H}\quad \mathbf{K}^*=\hat{\mathbf{n}}\times\mathbf{E}\quad \rho=-\epsilon_1^*\hat{\mathbf{n}}\cdot\mathbf{E}. \quad (7)$$

The value of **E** and **H** in (7) are those just inside the surface S, $\hat{\mathbf{n}}$ is the unit vector perpendicular to the surface, and $G=\exp(-jk_{\text{out}}R)/R$, where R is the distance between the observing point **B** and the point of the aperture S.

Thus, for microwave hyperthermia, the rectangular applicator has been used [13]. The applicator produces, on the surface of the aperture, the following electric field distribution (see Fig. 3):

$$E_z'=E_0\cos\left(\frac{\pi x}{b}\right). \quad (8)$$

In our experiment, the temperature elevation is measured at the distance R which is much larger than $|1/k_{\text{out}}|$. The radiating near-field in that region is calculated theoretically. The z-component of the field transmitted from the aperture of the rectangular waveguide applicator $E(x,y,z)$ is

$$E(x,y,z)=j\frac{k_{\text{out}}}{4\pi}\iint_S E_z'G\frac{1}{R}\left[\frac{\eta}{\eta'}\left[(x-x')^2+y^2\right]+y\right]dx'\,dz' \quad (9)$$

where

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

η and η' are the intrinsic impedance of the dielectric material in contact with the applicator, and that in the waveguide, respectively.

In our case, the electric field distribution has the following form (see Fig. 4):

$$E_z''=E_0\cos\left(\frac{\pi r'}{2A}\sin\phi'\right)\left|\sin\left(\frac{\pi r'}{w}\sin\phi'\right)\right| \quad (10)$$

on the aperture of the lens applicator.

In the cylindrical coordinates, the z-component of the field, transmitted from the aperture of the lens applicator $E(r,\phi,z)$, is

$$E(r,\phi,z)=j\frac{k_{\text{out}}}{4\pi}\iint_S E_z''G\frac{1}{R}\left[\frac{\eta P}{\eta''R}+[r'-r\cos(\phi'-\phi)]\right]r'\,d\phi'\,dz' \quad (11)$$

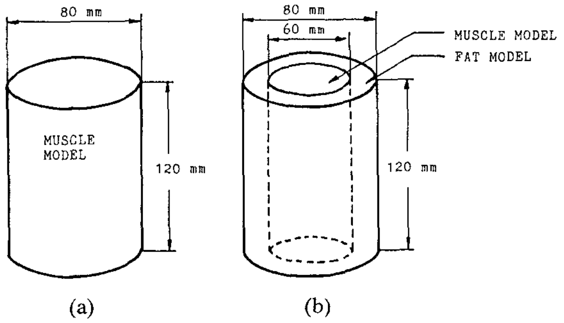


Fig. 5. Phantom modeling materials for human tissues. (a) Single-layer, and (b) double-layer.

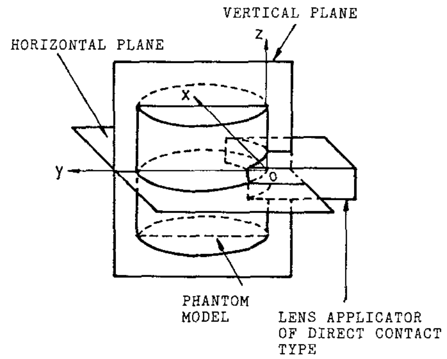


Fig. 6. Schematic of the phantom model directly contacted with the lens applicator

TABLE I
PARAMETERS USED FOR DESIGNING LENS APPLICATOR

Parameters	Real part	Imaginary part
k_{in} (m^{-1})	2.61×10^2	-8.33×10^1
k_{out} (m^{-1})	3.66×10^2	-5.93×10^1
n	7.30×10^{-1}	-1.09×10^{-1}

TABLE II
COMPOSITION AND ELECTRIC PROPERTIES OF MODELS

Modeling material	Dielectric constant		Composition
	Real part	Imaginary part	Percentages by weight
Muscle	49.6	16.5	75.44 H_2O 0.91 Nacl 15.20 Polyethylene powder 8.45 Super stuff
Fat	4.5	0.84	85.20 Laminac 4110(P-1) 14.50 Al powder 0.24 Acetylene black 0.06 MEK peroxide

TABLE III
THERMAL PROPERTIES OF MODELS

Modeling material	Specific heat (cal/gm.°C)	Density (gm/cc)	Thermal conductivity (cal/cm·°C·s)
Muscle	0.86	1.0	1.3×10^{-3}
Fat	0.24	1.3	0.46×10^{-3}

with

$$P = \sqrt{r^2 + r'^2 - 2rr'\cos(\phi - \phi')}$$

$$R = \sqrt{P^2 + (z - z')^2}$$

where ϕ is the azimuth angle (see Fig. 4), and η'' is the intrinsic impedance in the metal-plate medium.

The reason why we have considered the z-component of the electric field only is that the x- and y-components of the electric field turn out to be negligible.

C. *Experimental Setup for Heating the Phantom Modeling Material of Human Tissues*

The lens applicator is designed and constructed by the method described above. The applicator can conveniently be attached to the biological body of cylindrical shape. When the contact cannot be close enough, a soft dielectric material is filled between the aperture of the applicator and the body to improve the matching. This matching scheme is also used in the heating experiment of the model.

The waveguide used in the applicator is WRJ-2.6 ($A = 86.4$ mm, $B = 43.2$ mm in Fig. 1). The frequency used in the heating of the phantom model is 2450 MHz. In the applicator, metal plates of thickness 0.5 mm in parallel to the E-plane divide the inner space of the waveguide into seven equal areas ($w = 11.9$ mm). A dielectric material with the same dielectric constant as the muscle is filled between metal plates. Table I shows k_{in}, k_{out}, and n (focal length of the lens L is 120 mm).

Our heating materials are chosen to be the same as either single-layer or double-layer phantom modeling materials for human tissue [16]–[18] (see Fig. 5). The materials and constituents used by Guy [17], Stuchly [18], and ourselves are shown in Table II. Our muscle model has a cylindrical shape (see Fig. 5(a)), and our fat–muscle model has a cylindrical shape with two layers (see Fig. 5(b)).

These two models are sometimes referred to as phantom models hereafter. The materials can be bisected by a plane through the central axis as well as a plane perpendicular to the axis. After an EM wave is irradiated, the material is bisected and the temperature distribution is observed. A liquid crystal film is placed on the plane of bisection to observe the temperature distribution. A spectrum analysis of the reflection of the white light radiated on the film is made in two dimensions. The liquid-crystal film is composed of a polyethylene film base 100 μm thick, with a cholesteric ester liquid-crystal coating. The temperature response was sufficiently fast.

The spectrum of the light reflected from the liquid crystal changes from the infrared through the visible light to the ultraviolet region for a temperature change of 5 °C. We prepared four types of the liquid-crystal films with the initial temperature being 28, 32, 36, and 40°C. The material has the same thermal property as the biological object [19] (see Table III). Immediately after heating the material, we measured the temperature of the heat generated inside.

The microwave energy is generated by a magnetron (2M156). The generated frequency is 2450 MHz, and the power is transmitted through a WRJ-2.6 waveguide. The power of the microwave at the aperture of the applicator is 5.8 W.

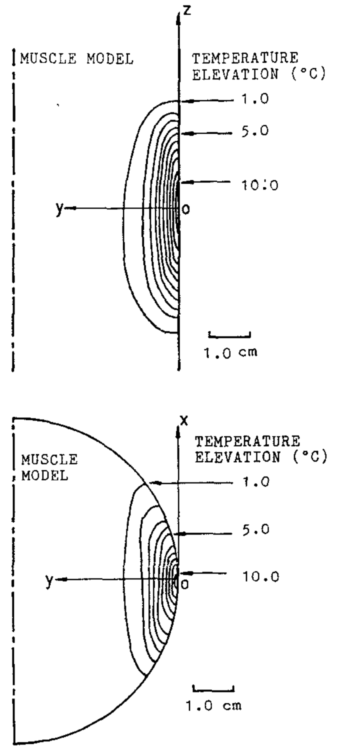


Fig. 7. Distribution of temperature elevation in the muscle model heated with waveguide applicator.

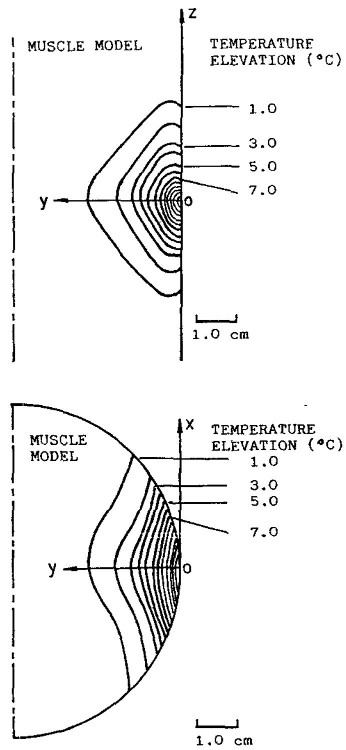


Fig. 8. Distribution of temperature elevation in the muscle model heated with lens applicator.

D. Experimental Results of Heating Phantoms

Using the experimental device described above, the phantom model heating experiment was performed at 2450 MHz. The temperature distribution in the model was examined in the plane through the axis (called vertical) and the plane perpendicular to the axis (called horizontal), as are shown in Fig. 6 with the coordinates. The initial temperature of the model is 28 °C, and the result is shown by equi-temperature lines for the temperature rise with the step of 1°C.

Fig. 7 shows the result for the case where the waveguide WRJ-2.6 is directly contacted (i.e., without lens) with the muscle model to perform heating. This corresponds to the traditional model heating by a waveguide applicator. Fig. 8, in contrast, shows the temperature dependence of the model where the lens applicator is used for heating. Experimental and theoretical distributions of the temperature elevation ΔT in the model heated with the lens applicator are compared in Fig. 9(a) and (b). Also, experimental and theoretical distributions of the temperature elevation ΔT in the model heated with the waveguide are compared in Fig. 9(a) and (b).

Fig. 10 shows the result where the double-layer fat–muscle phantom is heated by the lens applicator. In the above two cases, the heating time is 40 s. The matching dielectric material between the applicator and the phantom model is the same as the muscle model, with the thickness of 6 mm.

III. Discussions and Conclusions

The temperature distribution of our muscle model experiment is evaluated as follows. Since the heat conductivity of the material is low and the heating time is rather short, the temperature rise ΔT in the material can be considered as being proportional to the electromagnetic power P consumed per unit volume, which is given by $\sigma|E|^2/2$, where E is the field intensity in the material and σ is the conductivity of the material.

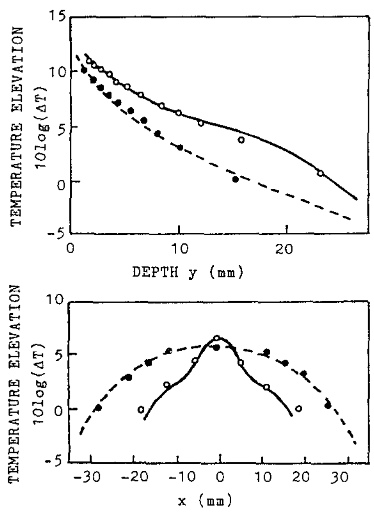
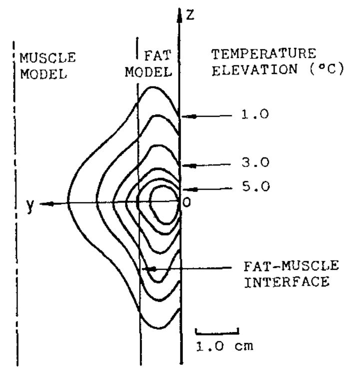


Fig. 9. Calculated and measured temperature elevation in the muscle model. ----- theoretical; ●●●● experimental (with waveguide applicator). ——— theoretical; ○○○○ experimental (with lens applicator).

Based on the results of Figs. 7 and 8, the natural logarithm of the temperature rise ΔT is expressed in terms of the depth y from the surface of the heated material as in Fig. 11.

As is shown in Fig. 11, since the logarithm of the temperature has linear dependence with respect to the depth, the attenuation constant α' in the muscle model can be introduced as a slope

$$\alpha' = -\frac{\Delta \ln(\Delta T)}{2\,\Delta y}. \tag{12}$$



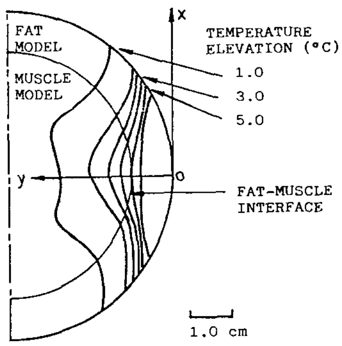


Fig. 10. Distribution of temperature elevation in the fat–muscle model heated with lens applicator.

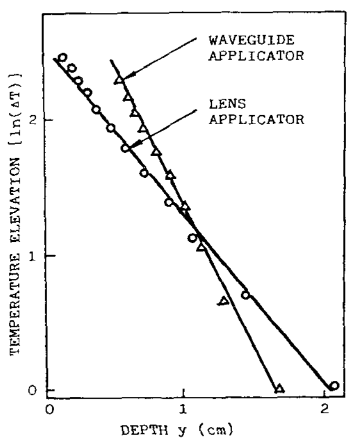


Fig. 11. Temperature elevation versus depth in the muscle model.

Numerically, from Fig. 11 and (12), the attenuation constant for the waveguide applicator is $1.06\times10^{2}\ \text{m}^{-1}$, while that for the lens applicator is $6.25\times10^{1}\ \text{m}^{-1}$.

The lens applicator is geometrically designed so that the EM field should focus on the magnetic field plane (H-plane) in the loss-free medium. In actual fact, since the medium has a large heating loss, no focus is produced in the medium. The attenuation constant obtained by our applicator is smaller by more than 40 percent than the one obtained by the traditional waveguide applicator.

The attenuation constant for the ideal plane wave should be $5.93\times10^{1}\ \text{m}^{-1}$ (i.e., penetration depth 1.7 cm, see Table I). The heating by our proposed applicator can reach as deep as the above theoretical limit. The problem on the convergence on E-plane will be discussed later in a separate paper.

In summary, experimental results agree well with the theoretical ones. In the heating experiment of the phantom model by the lens applicator, the medium has a large loss preventing the EM wave from focusing. In spite of this fact, the EM wave in our case can penetrate into the body by 40 percent deeper than the one obtained from the traditional waveguide applicator used for biological heating by microwaves. The proposed applicator thus paves a way to a more localized deep hyperthermia for biological objects.

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