2) Series inductance decreases the value of phase shift, whereas shunt capacitance increases this value.

3) Shunt capacitance seems to be the most dominating reactance affecting the phase shift. This suggests that an arrangement which can vary shunt capacitance across the diode may be used for the adjustment of phase shift in the finally fabricated circuits.

4) Effects of the forward-bias and the reverse-bias resistances on phase shift are very small as compared to that of reactances.

References

[1] R. V. Garver, "Broad-band diode phase shifters," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-20, pp. 314–323, May 1972.

Effects of the Surroundings on Electromagnetic-Power Absorption in Layered-Tissue Media

PAOLO BERNARDI, SENIOR MEMBER, IEEE, FRANCO GIANNINI, AND ROBERTO SORRENTINO

Abstract—**The influence of the surroundings on the interaction between electromagnetic (EM) waves and biological tissue is examined by schematizing the environment by a perfectly conducting screen placed beyond the irradiated tissue. The effects of standing waves, which are created in this situation, are determined as a function of the electrical and geometrical parameters of the structure. In particular, the hazard increase due to the presence of the screen combined with a phase disuniformity of the incident field—an elementary schematization of the "near-field"—is pointed out.**

I. Introduction

The use of equipment for industrial heating which uses electromagnetic (EM) energy has become more and more widespread in recent years. This apparatus generally operates at frequencies between 1 and 100 MHz with a power output of several hundreds of kilowatts [1]. Consequently, for the purpose of specifying a standard for protection against EM radiation, the interest in the phenomena of the interaction between EM waves and biological tissue has been extended also to this frequency range. In this approach, it has been necessary to reexamine several of the simplifying hypotheses generally valid at microwaves, but not sufficiently verified at lower frequencies [2]–[4]. In the microwave field, in fact, it is often possible to consider that the tissues are isotropic, that the radiating field can be schematized by a uniform plane wave, that the interaction takes place in free space, and that the tissues can be represented by models infinite in size. On the contrary, in the frequency range where the aforementioned equipment operates, the anisotropy of certain types of tissue should be taken into account; the interaction with man usually takes place in the radiative, or even reactive, "near-field" of the radiating equipment; the EM generator is often installed in an enclosed environment, usually consisting of industrial sheds; finally, the dimensions of the tissues play a part one cannot exclude from consideration. The usual approach to such complex problems consists in changing the aforementioned assumptions one at a time in such a way as to evaluate the influence of a single aspect of the phenomenon. In this way, the dependence of the absorbed power distribution on the curvature of the radiated surface and on the orientation of the body with respect to the incident plane-wave vector has been pointed out by adopting spherical and spheroidal models of the human body [5]–[7]. On the other hand, the influence of the anisotropy of the muscle on the absorbed-power distribution [8] and of the disuniformity of the field radiated by particular types of sources (e.g., the dipole with corner reflector [9] and the rectangular aperture with a given field distribution [10]) has been illustrated through the analysis of a single- or multiple-layered plane model.

The aim of the present work is to bring out, by the adoption of a plane model, the hitherto neglected influence of the surroundings on the interaction phenomena. In fact, the use of industrial heating equipment inside enclosed spaces in the presence of reflecting surfaces makes it impossible to consider the interaction as taking place in free space. The adoption of a plane model, besides making a substantial simplification of the analytical treatment, is justified since the phenomenon which can be thus brought out, can be more or less remarkable but not absent when one adopts a model more closely relevant to man or experimental animals in complex fields.

II. The Multilayered Model

The simplest schematization of the interaction between the EM field and biological tissue, in which account is taken of the environment, is shown in Fig. 1. Beyond a layered model, consisting of N biological tissues, and irradiated by a uniform plane-wave incident at angle θ, a perfectly conducting screen is placed at a distance d. Within each layer the field can be expressed as a superposition of a forward and reflected wave. From homogeneous Maxwell equations one obtains

$$\left.\begin{aligned} E_i^{\pm} &= \frac{H_{zi}^{\pm}}{j\omega\varepsilon_{ci}}\left[-j\beta_{0y}x_0 \pm k_{xi}y_0\right] + z_0E_{zi}^{\pm} \\ H_i^{\pm} &= \frac{E_{zi}^{\pm}}{j\omega\mu_0}\left[j\beta_{0y}x_0 \mp k_{xi}y_0\right] + z_0H_{zi}^{\pm} \end{aligned}\right\} \exp\left(\mp k_{xi}x - j\beta_{0y}y\right) \tag{1}$$

where ε_{ci} is the complex permittivity of the i layer and k_{xi} the complex propagation constant in the x direction; $\beta_{0y} = \omega\sqrt{\mu_0\varepsilon_0}\sin\theta$ is the phase constant in the y direction of the incident wave. The upper signs refer to the forward field and the lower signs to the reflected field, respectively. All the tissues are assumed to have the vacuum permeability μ_0. Given proper boundary conditions, it is possible to express the field in the i layer in terms of that in the $(i+1)$ layer

$$\begin{aligned} E_{zi}^{\pm} = \frac{\pm 1}{2k_{xi}} & \left[E_{z(i+1)}^{+}(\pm k_{xi} + k_{x(i+1)})\right. \\ & \cdot \exp\left(\pm k_{xi} - k_{x(i+1)}\right)d_i + E_{z(i+1)}^{-}(\pm k_{xi} - k_{x(i+1)}) \\ & \left.\cdot \exp\left(\pm k_{xi} + k_{x(i+1)}\right)d_i\right] \end{aligned}$$

$$\begin{aligned} H_{zi}^{\pm} = \frac{\pm\varepsilon_{ci}}{2k_{xi}} & \left[H_{z(i+1)}^{+}\left(\pm\frac{k_{xi}}{\varepsilon_{ci}} - \frac{k_{x(i+1)}}{\varepsilon_{c(i+1)}}\right)\right. \\ & \cdot \exp\left(\pm k_{xi} - k_{x(i+1)}\right)d_i + H_{z(i+1)}^{-}\left(\frac{\pm k_{xi}}{\varepsilon_{ci}} + \frac{k_{x(i+1)}}{\varepsilon_{c(i+1)}}\right) \\ & \left.\cdot \exp\left(\pm k_{xi} + k_{x(i+1)}\right)d_i\right] \end{aligned}$$

Manuscript received November 11, 1975; revised January 27, 1976. This work was partially supported by the Consiglio Nazionale delle Ricerche, Italy.

The authors are with the Institute of Electronics, University of Rome, Rome, Italy.

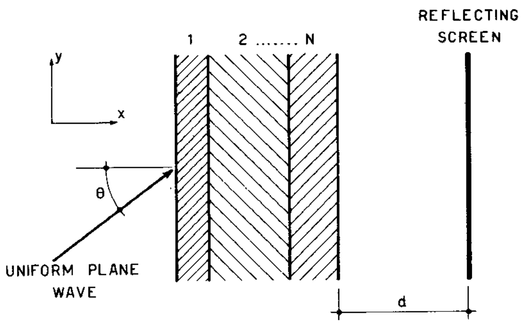

Fig. 1. The layered plane model in the presence of a reflecting screen.

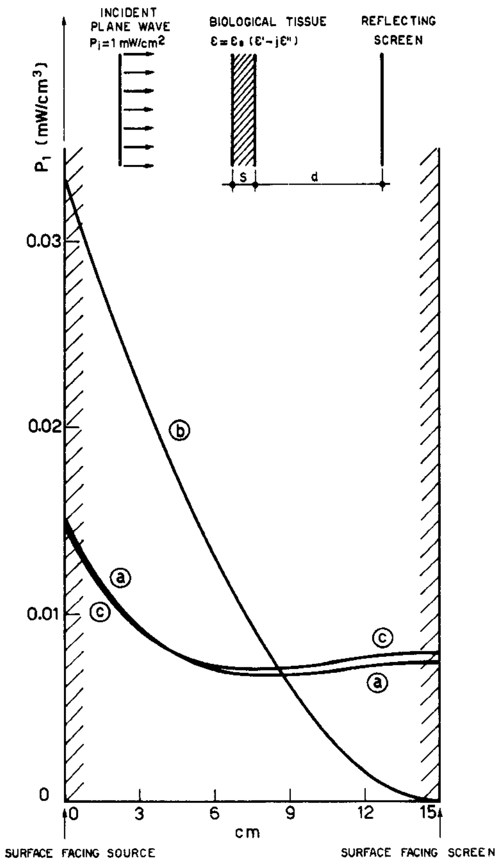

Fig. 2. Absorbed-power distributions within the muscle tissue at $f = 30$ MHz. (a) Without reflecting screen. (b) Reflecting screen placed at $d = m\lambda/2$, where $(m = 0,1,2,\cdots)$. (c) Reflecting screen placed at $d = (2m + 1)\lambda/4$, where $(m = 0,1,2,\cdots)$.

where d_i is the thickness of the i layer. In this way it is fairly easy to program a computer to determine the field inside the tissue layers as well as the absorbed-power distribution and the total absorbed power.

III. Normal Incidence

Consider the simple case of a linearly polarized plane-wave incident normally on a single layer of muscle tissue. The influence of the reflecting screen is shown in Fig. 2 where the absorbed power distribution inside the muscle is indicated in the cases of interaction in free space (curve *a*) and in the presence of the screen placed at distances $d = m\lambda/2$ (curve *b*) and $d = (2m + 1)\lambda/4$ (curve *c*), where $(m = 0,1,2,\cdots)$ at the frequency of 30 MHz. (At about this frequency the greater part of industrial heating equipment operates.) As can be seen, the presence of the screen at a distance multiple of $\lambda/2$ strongly changes the absorbed-power distribution and produces a notable increase both of the total absorbed power and of the power density on the radiated surface. Such an effect, however, is strictly dependent on the various parameters at stake, i.e., the distance between the screen and the tissue, the frequency of the radiating field, the thickness of the muscle layer, the direction of propagation, and the plane of polarization of the incident wave.

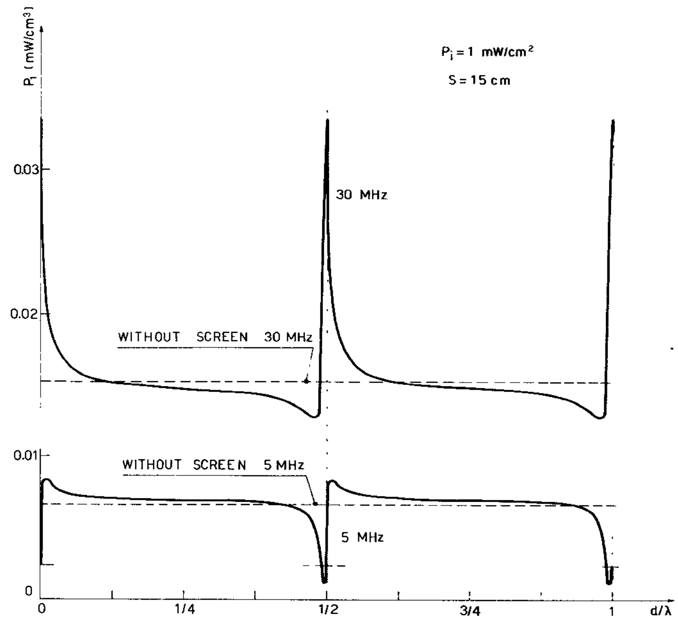

Fig. 3. Absorbed-power density at the irradiated surface as a function of d/λ at $f = 5$ MHz and $f = 30$ MHz.

In Fig. 3 the absorbed-power density on the radiated surface as a function of the distance d of the reflecting screen is shown for two frequency values: 5 and 30 MHz. As can be noted, with respect to the case of free-space interaction, the standing waves created by the screen produce opposite effects at the two frequencies. In particular, for the distances $d = m\lambda/2$, at which the screen produces the most remarkable effect, there is a net diminution at 5 MHz, while at 30 MHz there is a net increase, of the absorbed power. This behavior is easily explained since the tissue is about 0.09λ thick at 5 MHz and 0.24λ at 30 MHz, and therefore the shorting plane at $d = 0, \lambda/2, , \cdots$ produces an approximate null in the electric field at the front surface at 5 MHz and an approximate maximum at 30 MHz.

This suggested investigation of the behavior of the structure at various frequencies between 5 and 100 MHz. In Fig. 4 the behaviors of the total absorbed power P_{tot}, and of the power density on the radiated surface P_1, are considered with reference to the absence of reflecting surfaces and the presence of a screen at $d = m\lambda/2$. The influence of screen increases the hazard in the frequency range between ~ 15 and ~ 60 MHz; in particular, near 30–35 MHz the presence of the screen doubles the power density P_1 and increases by 50 percent the total absorbed power P_{tot}. Outside this frequency range, however, the screen has the effect of diminishing both P_1 and P_{tot}. Fig. 4 was obtained by using for the electrical parameters of the muscle tissue the data obtained by Schwan and reported in [5], [11]; some of the values estimated by such references are shown in Table I.

Another parameter which notably influences the power absorption is the thickness of the muscle layer. Fig. 5 shows, at the frequency of 30 MHz, P_{tot} and P_1 as functions of the

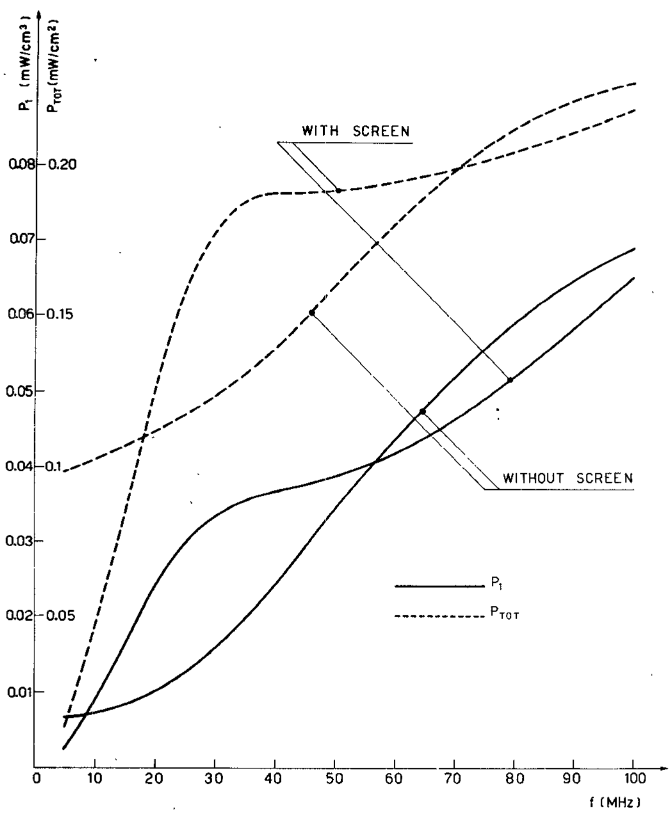

Fig. 4. Total absorbed power P_{tot} and power density at the irradiated surface P_1 versus frequency for a muscle layer of 15 cm.

TABLE I
ESTIMATED COMPLEX RELATIVE DIELECTRIC CONSTANT $\varepsilon' - j\varepsilon''$ FOR THE MUSCLE TISSUE

f (MHz)	ε'	ε''
5	210	2335
10	160	1132
20	129	539
30	110	374
40	98	310
80	74	186
100	71	160

thickness: the two cases of the absence of the screen and of the screen at $d = m\lambda/2$ are considered. As one would logically expect, at sufficiently large thicknesses, in practice larger than 40 cm, the presence of the screen is, in fact, irrelevant. Conversely, for small thicknesses, below 5 cm, the presence of the screen is strongly felt, making the power absorption within the tissue tend toward very small values. In the absence of the screen, however, and with the thickness tending toward zero, the power density P_1 absorbed on the surface facing the source tends to a finite value, depending on the losses of the tissue. The total power P_{tot} absorbed by the tissue per unit area of radiated surface first increases strongly with the diminishing thickness and then rapidly tends to zero. (For reasons of scale this effect is not noticeable from Fig. 5.) So the presence of reflecting surfaces increases the hazard for intermediate values of muscle thickness—particularly around 15 cm. In these cases, the absorbed power is greater than that which can be inferred from a

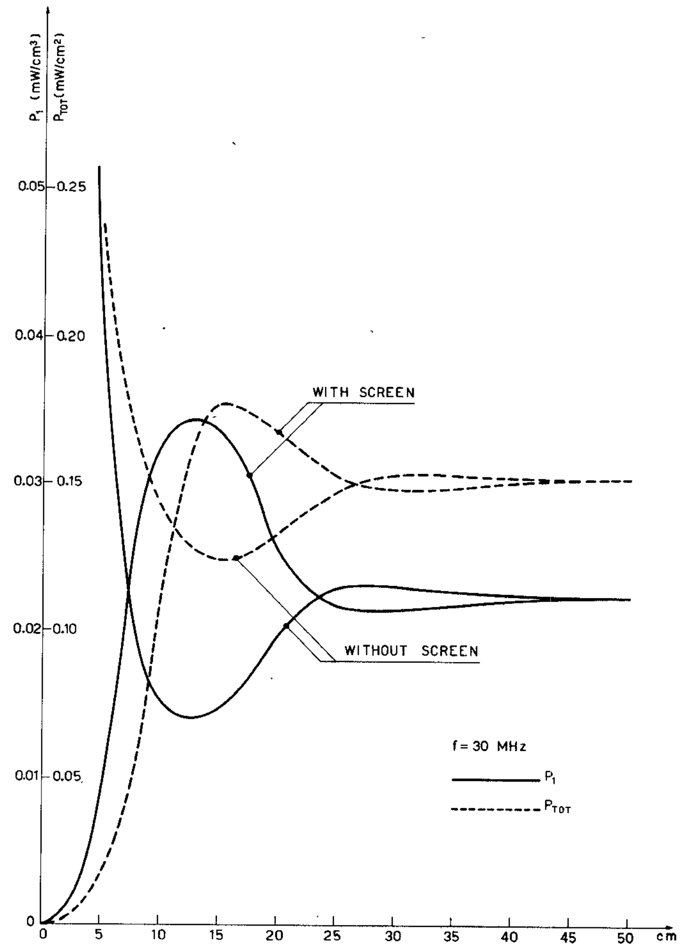

Fig. 5. Total absorbed power P_{tot} and power density at the irradiated surface P_1 versus layer thickness at $f = 30$ MHz.

model of muscle infinitely thick. Such a model, frequently used at microwaves [9]–[12] for determining the characteristics of interaction between the EM field and the biological tissue, is therefore not justified at lower frequencies in the presence of reflecting surfaces. Since the studies of interaction are essentially concerned with the individuation of the most dangerous situations, a human-body model consisting of a layer of tissue of 15 cm turns out to be particularly suitable for frequencies around 30 MHz. It is, moreover, evident that with varying frequencies other values of muscle thickness give place to situations of greater power absorption.

The effect of the screen was also examined, taking account of muscle anisotropy [13]. The investigation was conducted on the basis of the model proposed by Johnson *et al.* [8], which assumes as muscle permittivity a diagonal complex tensor. It was found, however, that the presence of reflecting surfaces produces less-notable effects than in the isotropic case; this remains the case in which situations of greater hazard take place.

A model of human tissues closer to reality would be that constituted by a layer of fat beside one of muscle, or even by a series of three layers, fat–muscle–fat. The calculations done on such models, with a fat layer 1–3 cm thick, in the case of normal incidence, have not led to results substantially different from those already shown. This confirms that at such frequencies, even in the presence of a screen, the power absorption within the

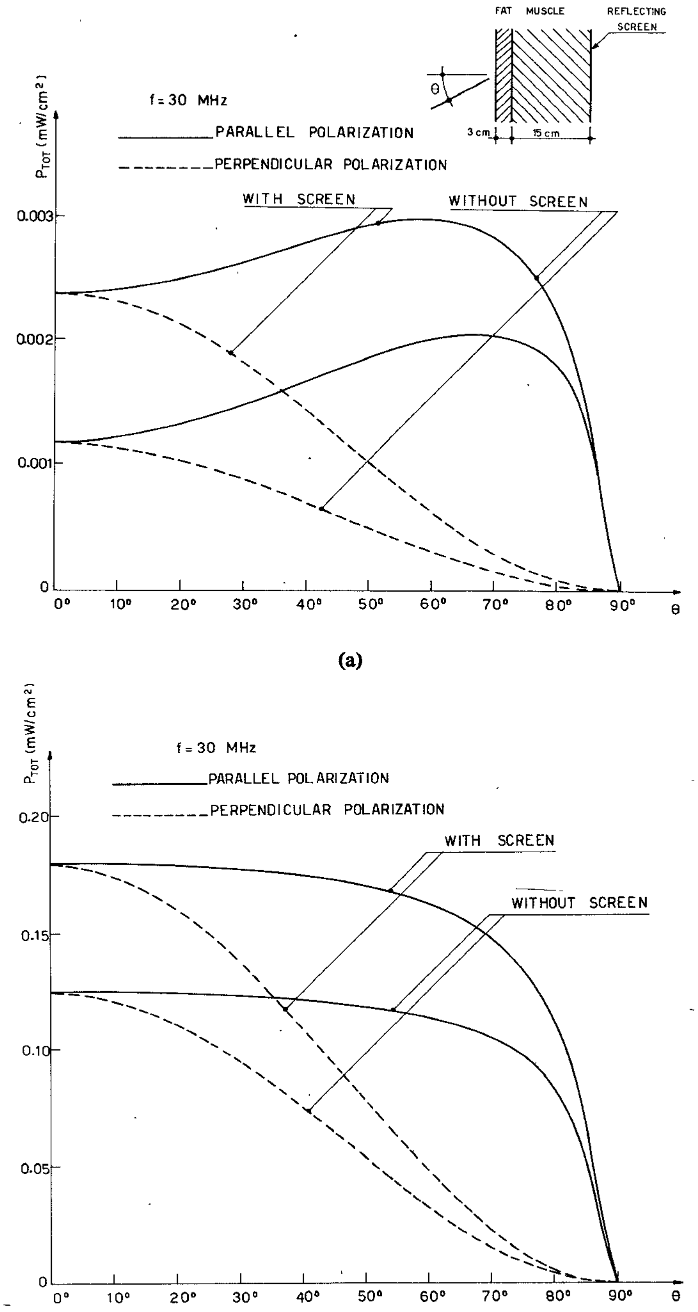

Fig. 6. Total absorbed power P_{tot} (a) in the fat layer ($\varepsilon' = 18.8$; $\varepsilon'' = 7.2$) and (b) in the muscle layer versus angle of incidence θ at $f = 30$ MHz for both and parallel polarization. Incident power: 1 mW/cm² in the θ direction.

muscle tissue is practically unaffected by the presence of a fat layer [11].

IV. Oblique Incidence

It is worth emphasizing the role of the plane of polarization for a wave incident at angles different from 0°. A two-layer model, fat 3 cm and muscle 15 cm, at the frequency of 30 MHz was adopted. In Fig. 6(a) and (b) the values of the total powers absorbed by the fat and by the muscle in the presence ($d = m\lambda/2$) and in the absence of a screen are shown as a function of the angle of incidence. The two cases of polarization, perpendicular polarization [electric-field vector parallel to layers of tissue: $H_{zi} = 0$ in (1)] and parallel polarization (magnetic-field vector parallel to layers of tissue: $E_{zi} = 0$), are considered. In both of these cases it is supposed that the incident wave conveys 1 mW/cm² in the direction of propagation. While in the case of parallel polarization, with the increase of the angle of incidence, the absorbed power undergoes a rapid diminution, in the case of normal polarization this does not happen, except for angles of incidence very close to 90°; and, in fact, the fat layer presents a maximum absorption around 70°. In any case, the presence of a screen produces a notable increase of the absorbed power.

The diminution of the power absorption with the increase of the angle of incidence is, in part, due to the fact that the power conveyed by the wave in the θ direction is distributed over a greater area of the tissue. In real cases of interaction, however, the tissues are immersed in the "near-field" of the radiators in such a way that the direction of propagation of the wave cannot be defined. It appears, therefore, necessary in such cases to refer to power which strikes the tissue per unit of surface. With this view of the phenomenon, a uniform plane wave, independently of the direction of propagation, may be regarded as an EM field which conveys a certain power density in the direction perpendicular to the tissue and has a variable phase on the surface of the model. In this way the wave may be characterized, instead of by the angle of incidence, by its normalized wave impedance, $E_t/\eta_0 H_t$, η_0 being the wave impedance of a uniform plane wave in the vacuum. As a function of this parameter there are thus shown in Fig. 7(a) and (b) the power densities, both total and peak, absorbed by the muscle tissue, for a constant incident power (1 mW) per square centimeter of tissue. It is to be noted that the range $0 < E_t/\eta_0 H_t < 1$ corresponds to the oblique incidence of a parallel-polarized plane wave, while the range $1 < E_t/\eta_0 H_t < \infty$ corresponds to a perpendicular-polarized plane wave. The effects due to the screen and to the disuniformity of the phase of the incident field produce, as one can see, a peak power density absorbed by the muscle as much as 10 times greater than that obtained in the absence of the screen and with the normal incidence of a uniform plane wave ($E_t/\eta_0 H_t = 1$). It is interesting to note that these power values are of the same order of magnitude as those obtained with a spherical model of the human body irradiated in free space [5].

V. Conclusions

In the present work, a model for studying the interaction between EM waves and biological tissue has been introduced. Although highly idealized, this model allows a quantitative evaluation of the combined effects of the thickness of the radiated tissue, of the surroundings, and of the disuniformity of the incident field.

It has been underlined that these effects can consist in a notable increase both of the peak and the total power absorbed by the tissue. In particular, it has been shown that the polarization and the wave impedance of the field are essential in determining, for a given incident power, the energy dissipated in the tissue samples.

From the observations made, one should conclude that the safety criteria based only on the electric-field intensity or on the power incident on the tissue surface do not have an actual significance. A better characterization of the radiating field appears therefore to be necessary in the light of the results obtained. Such a characterization could be obtained, for instance, by taking into account both the wave impedance and the power conveyed by the incident field.

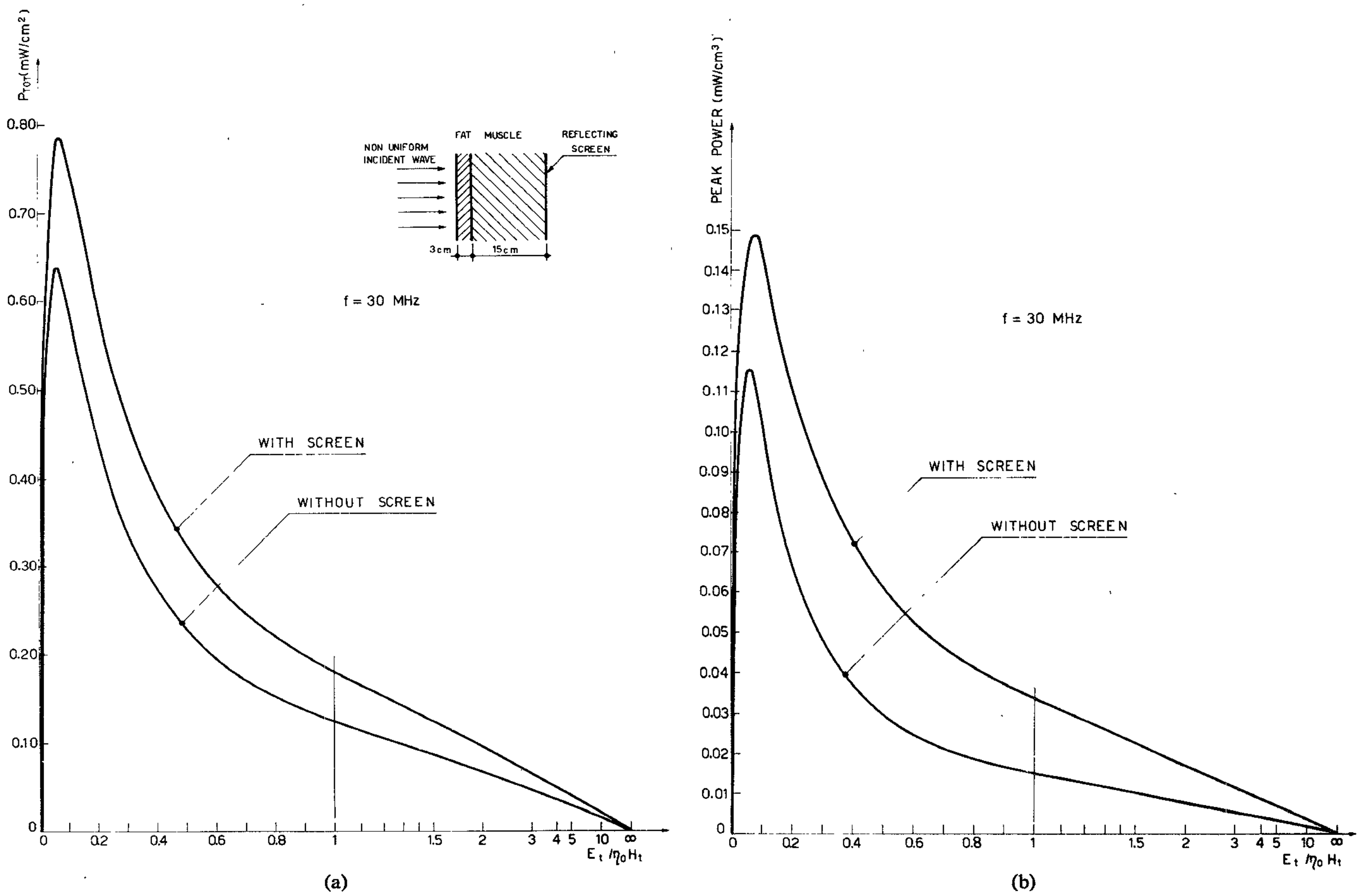

Fig. 7. Total absorbed power (a) and peak absorbed power (b) in the muscle layer versus normalized wave impedance $E_t/\eta_0 H_t$ at the frequency of 30 MHz.

References

[1] T. L. Wilson, "Dielectric heating—A useful industrial tool," *Proc. of 1st Symp. on Electromagnetic Compatibility*, Montreux, pp. 333–336, May 20–22, 1975.

[2] P. F. Wacker and R. R. Bowman, "Quantifying hazardous electromagnetic fields: Scientific basis and practical considerations," *IEEE Trans. Microwave Theory and Techniques*, vol. MTT-19, pp. 178–186, Feb. 1971.

[3] P. Bernardi and F. Giannini, "Inquinamento elettromagnetico da macchine per riscaldamento industriale: Metodi di studio, problemi di misura, valutazione della pericolosità," *Alta Frequenza*, vol. 44, pp. 120–127, March 1975.

[4] J. Bigu Del Blanco, C. Romero-Sierra, and J. A. Tanner, "Microwave power and energy density measurements in the presence of biological specimens of size comparable to the free space wavelength of the imposed radiation," *Proc. of 1st Symp. on Electromagnetic Compatibility*, Montreux, pp. 7–13, May 20–22, 1975.

[5] J. C. Lin, A. W. Guy, and C. C. Johnson, "Power deposition in a spherical model of man exposed to 1–20 MHz electromagnetic fields," *IEEE Trans. Microwave Theory and Tech.*, vol. MTT-21, pp. 791–797, Dec. 1973.

[6] C. H. Durney, C. C. Johnson, and H. Massoudi, "Long-wavelength analysis of plane wave irradiation of a prolate spheroid model of man," *IEEE Trans. Microwave Theory and Tech.*, vol. MTT-23, pp. 246–253, Feb. 1975.

[7] C. C. Johnson, C. H. Durney, and H. Massoudi, "Long-wavelength electromagnetic power absorption in prolate spheroidal models of man and animals," *IEEE Trans. Microwave Theory and Tech.*, vol. MTT-23, pp. 739–747, Sept. 1975.

[8] ——, "Electromagnetic power absorption in anisotropic tissue media," *IEEE Trans. Microwave Theory and Tech.*, vol. MTT-23, pp. 529–532, June 1975.

[9] A. W. Guy and J. F. Lehmann, "On the determination of an optimum microwave diathermy frequency for a direct contact applicator," *IEEE Trans. Biomedical Engineering*, vol. BME-13, pp. 76–87, Apr. 1966.

[10] A. W. Guy, "Electromagnetic fields and relative heating patterns due to a rectangular aperture source in direct contact with bilayered biological tissue," *IEEE Trans. Microwave Theory and Tech.*, vol. MTT-19, pp. 214–223, Feb. 1971.

[11] C. C. Johnson and A. W. Guy, "Nonionizing electromagnetic wave effects in biological materials and systems," *Proc. IEEE*, vol. 60, pp. 692–718, June 1972.

[12] H. P. Schwan, "Biophysics of diathermy," in *Therapeutic Heat and Cold*, S. Licht, Ed. New Haven, Conn., 1965, Sec. 12, pp. 63–125.

[13] S. Rush, J. A. Abildskov, and R. McFee, "Resistivity of body tissues at low frequencies," *Circ. Res.*, vol. 12, pp. 40–50, Jan. 1963.