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Interaction of Microwave and Radio Frequency Radiation with Biological Systems

HERMAN P. SCHWAN, FELLOW, IEEE

***Abstract*—A survey of thermal and nonthermal effects is presented with some recommendations for future work. A basis of all biophysical considerations are the electrical properties including dielectric constants and conductivities for nearly all body tissues. Equations are presented which summarize previous experimental work and state dielectric constant and conductivity for tissues of high water content as functions of macromolecular content and frequency. No evidence is available supporting resonance behavior. Previous thermal work includes determination of depth of penetration values and the relative absorption cross section of man and was the basis for present standards.**

Nonthermal principles which explain many previous observations are largely due to field-induced forces. Such effects occur in the human body only at field-strength levels which are thermally dangerous. Several important conclusions are made. 1) Field-force effects cannot be enhanced by use of pulsed fields. 2) It is not possible to directly stimulate nerve membranes by microwave fields. 3) It is unlikely that macromolecular resonances can be excited in body fluids and tissues. Finally, a guideline for future standard work in complex fields is proposed. It is based on the concept of a tolerance current density, which is stated to be near 3 mA/cm² between 1 and 1000 MHz, and which can be larger above 1000 MHz.

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The biophysical principles which pertain to the interaction of nonionizing electromagnetic radiations with biological systems are not discussed. This was done in the past on several occasions. The field will be summarized only briefly and attention will be given to problems not already dealt with satisfactorily. We intend to concentrate on some topics that are presently of particular interest.

Biophysics of Electromagnetic Radiation

A. Dielectric Properties of Tissues Observed at Microwave Frequencies

THIS area has been very well investigated in the past. Today we know the electric properties of practically all tissues, and as a matter of fact, we understand the measured values in terms of structure and function of the tissues. There are only a few things that remain to be done and we shall indicate them after demonstrating some typical results.

The dielectric behavior shown in Fig. 1 is typical for tissues of high water content. A decline in the dielectric constant ϵ with increasing frequency occurs at lower frequencies. Above 100 MHz the curve levels off and then eventually above about 10 000 MHz it drops off again very markedly. The change of ϵ at lower frequencies is well understood. It is due to the fact that cellular membranes with a capacity known to be about 1 $\mu F/cm^2$ membrane surface affect the tissue impedance at lower frequencies. In the plateau region between 100 and 10 000 MHz the membranes are short circuited and, therefore, become electrically invisible at frequencies in excess of some 100 MHz. We shall remind you later of the fact that the curve comes to a plateau as the membranes are short-circuited. The second decline of ϵ at high frequencies reflects the fact that biological systems contain water and that the dielectric properties of water are subject to change with frequency. Fig. 2 shows the specific resistance ρ of blood as a function of frequency. The behavior is again typical of tissues of high water content with a small change of ρ at low frequencies and a very pronounced one at high frequencies in excess of 1000 MHz. The sharp drop at very high frequencies is due to the fact that the conductivity of water changes very strongly at high frequencies.

Fig. 3 relates to fatty tissue. Fatty tissue, of course, has a low water content, and the dielectric behavior of fatty tissues is not quantitatively understood quite as well as that of tissues of high water content since the ratio of free and various types of bound water are not well established. The dielectric constant ϵ data are plotted versus the water content, with each point reflecting an experimental determination. The relationship between water content and the dielectric constant is apparent. Water has a high dielectric constant and fat a low one, and as the water content of subcutaneous fatty tissue varies, a corresponding increase in the dielectric constant should occur. The same arguments apply to the conductivity. In Fig. 4 the conductivity K is plotted against water content with a clear indication of the relationship between water content and microwave conductivity. Results as shown in Figs. 3 and 4 have been obtained at a variety of frequencies and the results are always qualitatively the same with due allowance for the frequency-dependent properties of water.

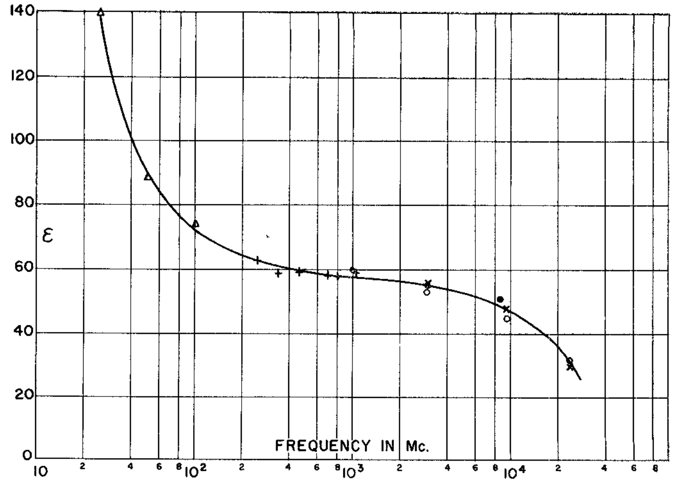


Fig. 1. Dielectric constant ϵ of blood as function of frequency.

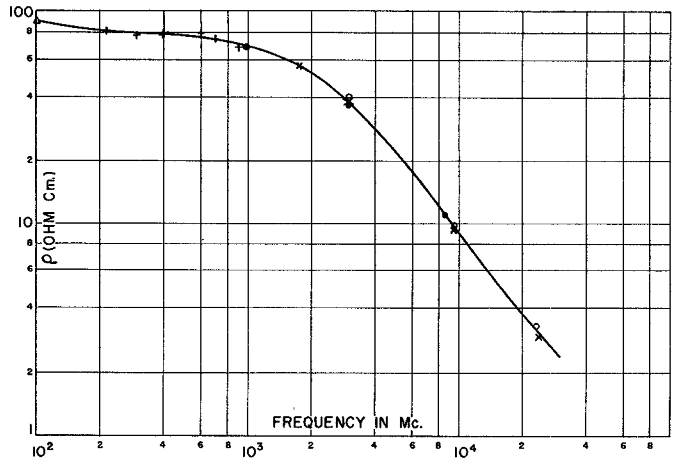


Fig. 2. Specific resistance ρ of blood as function of frequency.

There is no great need for further work on the dielectric properties of tissues at microwave frequencies. The accumulated knowledge about electric properties at microwave frequencies can be cast into the following simple equations:

$$\epsilon = 5 + \frac{70 - P}{1 + (1.5/\lambda)^2} \tag{1}$$

$$K = K_0 + \frac{70 - P}{60\lambda} \frac{(1.5/\lambda)^2}{1 + (1.5/\lambda)^2} \tag{2}$$

if the wavelength λ is given in centimeters and the conductivity K in mhos per centimeter. Dielectric constant ϵ and conductivity K are given here for tissues of high water content as a function of wavelength in air, where P is the volume fraction occupied by macromolecular components. The low-frequency conductivity K_0 is observed between 1 to 10 MHz and depends on the salt content. K_0 typically has about half the value characteristic of physiological saline solution. Thus, from wavelength and weight percentage of macromo-

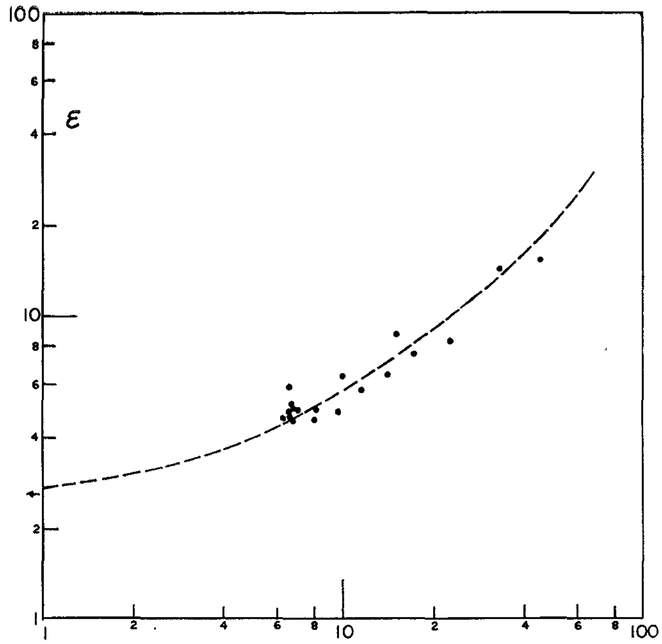


Fig. 3. Dielectric constant of fatty tissue as function of its water content. Frequency, 900 MHz. ϵ of fatty tissue, 900 mHz, 25°C.

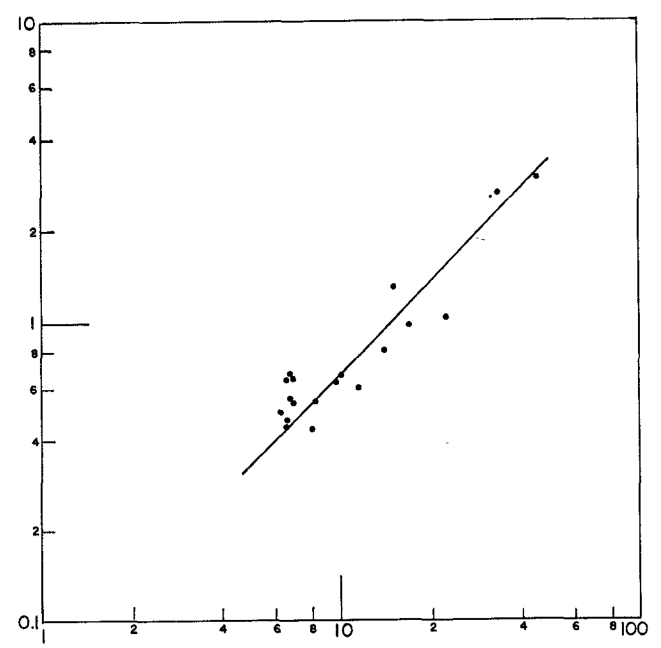


Fig. 4. Conductivity of fatty tissue as function of its water content. Frequency, 900 MHz. K in mmho/cm. K of fatty tissue, 900 mHz, 25°C.

lecular components in the tissue, dielectric constant and conductivity can be predicted at any frequency. The accuracy of the equations is better than ten percent for tissues of high water content.

It ought to be stated that the preceding reported behavior excludes any sort of resonance behavior.

In the case of tissues of low water content such as subcutaneous fat, bone, and both yellow and red bone marrow, we are not able, at present, to cast our knowledge in such simple equations since we are not quite sure what appropriate mixture formulas apply and about the state of water. Various forms of water are known to be in existence in tissues, normal water as we know it and "bound" water which is attached to the surface of macromolecular components. Knowledge of the physical properties of bound water as found for instance in fatty tissue is at the present time virtually absent.

B. Depth of Penetration

Absorption coefficients and various related quantities such as depth of penetration can be readily calculated from electrical properties as a function of frequency. We have provided these data in the past. Absorption coefficients change with frequency and all of the results which are available for tissues of high water content can be expressed analytically in terms of ϵ and ρ by formulating the two approximate expressions which are given in (3) and (4)[1]

$$D = \frac{\sqrt{\lambda\rho}}{17} \sim f^{-1/2}, \quad \text{for} \quad 60\lambda > \epsilon\rho \tag{3}$$

$$D = \frac{\sqrt{\epsilon\rho}}{377} \sim f^{-2}, \quad \text{for} \quad 60\lambda < \epsilon\rho. \tag{4}$$

For wavelength λ such that 60 λ is greater than the product of dielectric constant ϵ and resistivity ρ of tissue, the depth of penetration D varies with the square root of $\lambda\rho$. That means, in view of the observed fairly frequency-independent nature of ρ, that the depth of penetration changes at low frequencies f with $f^{-1/2}$, i.e., slowly. On the other hand of 60 λ is smaller than $\epsilon\rho$, the depth of penetration is proportional to $\sqrt{\epsilon\rho}$, and with due consideration of the frequency dependence of the resistivity ρ, at high frequencies, it is proportional to f^{-2}. At first the depth of penetration begins to change rather rapidly with frequency above approximately 300 MHz. It eventually declines to a value in the millimeter range at frequencies above 3000 MHz. Equations (3) and (4) are not experimental. They are mathematically derived with due consideration of actual values of conductivities and dielectric constants and at the same time in excellent agreement with known data. The conclusions that we need to draw from the absorption coefficient work are the following: at low frequencies electromagnetic radiation is fairly penetrating and changes only slowly with frequency, while at high frequencies much in excess of 3000 MHz, the total energy which is absorbed by the body is converted into heat in the skin. As a matter of fact, at about 10 000 MHz absorption coefficients apply which are similar to those for infrared.

[1] D is in centimeters, ρ is in ohms per centimeter, λ is in centimeters, and ϵ dielectric constant relative to air.

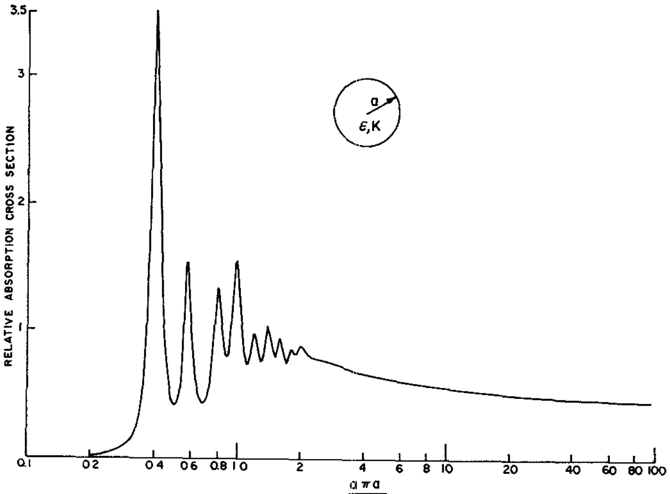


Fig. 5. Relative absorption cross section of a sphere. Relative cross section is the ratio of absorbed to incident energy. $\epsilon=60$. $f=2880$ MHz. $K=10$ mmho/cm.

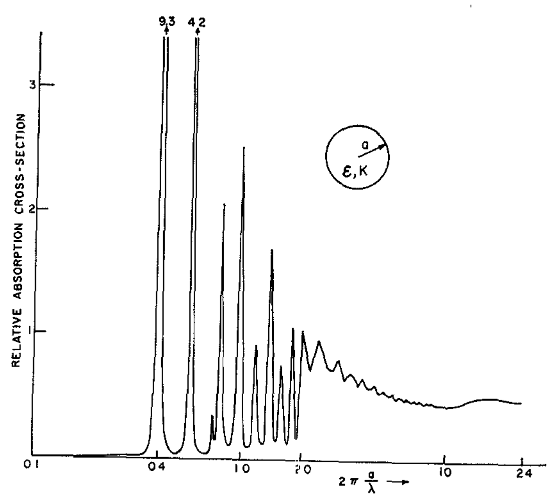


Fig. 6. Relative absorption cross section of a sphere. Conductivity of sphere is 1 mmho/cm while that of the sphere referred to in Fig. 5 was 10 mmho/cm. Note the stronger resonances in the case of the lower losses. $\epsilon=60$. $K=1$ mmho/cm. $f=2880$ MHz. a = radius of the sphere. λ = wavelength (air).

Indeed, data which have been obtained in the infrared region agree well with the extrapolated absorption coefficients above 10 000 MHz.

In our opinion, no further work appears needed with regard to absorption coefficients.

C. Relative Absorption Cross Section of Man

What is the effective cross section of the human body to microwaves? Some typical results of Anne's work in our laboratory are presented in Figs. 5 and 6. Here the relative absorption cross section of a lossy sphere is plotted against its radius a. The dielectric constant of the sphere is assumed to be similar to that constant for tissue, about 60, and the conductivity $K=1/\rho$ equal to 10 and 1 mmho/cm, respectively. The relative absorption cross section has a very low value for small sizes, and it goes through resonances for medium values of $2\pi a/\lambda$. These resonances are much more pronounced in the case $K=1$ mmho/cm than for 10 mmho/cm. At higher values of $2\pi a/\lambda$ the absorption cross section levels out to values close to 0.5.

The strongest resonance has a value of nearly 10 in the case of $K=1$ mmho/cm. This value is reduced to 3.5 for $K=10$ mmho/cm. Tissue conductivity values at 3000 MHz and conductivity of biological fluids are even higher, typically near 25 mmho/cm, and resonance behavior is further dampened. The two graphs are illustrations of more extended studies. They indicate well that the sort of macroscopic resonance possible for lower K values is fairly well damped out by biological fluids and therefore not of any great concern. If biological fluids would be only threefold less conductive, resonances might be significant.

All work done so far pertains to the overall relative cross section of man. This cross section is defined as the ratio of the total energy that has been absorbed by man divided by the incident energy. It is not necessarily indicative of the energy distribution inside man or inside the phantoms which have been used by us to simulate man. There is still a remote possibility that there may exist, given proper excitation frequencies, selective hot spots inside the body even though the relative absorption cross section of the body does not indicate a sharp resonance behavior. The reported cross-section data imply that we need not worry too much about such resonances. But the possibility should be checked, particularly at lower frequencies where depth of penetration values are larger, enhancing the possibility of states of resonance.

Work on possible resonance heating is an interesting task and should be undertaken to see if there can be sorts of spatial resonances which lead to hot spots of energy at particular frequencies in particular parts of the body.

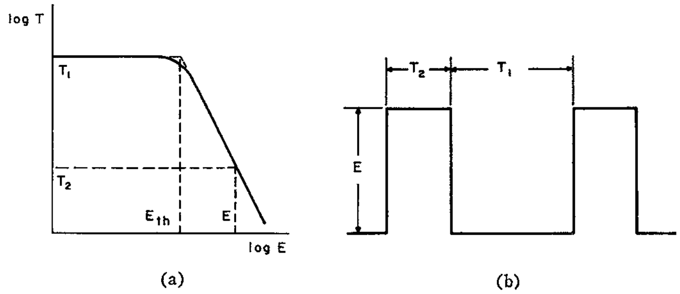
Nonthermal Effects

It has been stated that a definition is lacking regarding thermal and nonthermal effects. We believe that the difference between thermal and nonthermal effects can be very simply formulated. Thermal effects of microwaves exist if the microwave field does not directly cause the effect in question but interacts with the biological media indirectly by virtue of the heat generated; or, thermal effects are present if the heat, irrespective of its genesis, creates the biological effect and not the electrical field itself. Nonthermal effects occur when the electric field or the accompanying magnetic field interact either on a molecular or a macroscopic level. The existence of nonthermal effects has been controversial. Many dubious results have been reported in the field. About 40 years ago European investigators were interested in homeopathic treatment with diathermy, and hundreds of papers have appeared since that purport to report the existence of nonthermal effects. However, much of this work does not instill confidence. Exposing a test animal or an enzyme at a particular frequency or set of frequencies without scientific rationale is unlikely to yield significant results. The past has clearly indicated that the likelihood of hitting in the dark is extremely remote. What is needed is research probing into basic mechanisms which might affect biological systems on a nonthermal basis, either on the microscopic or macroscopic level. We shall now report about some pertinent attempts in our laboratory.

A. Field-Force Effects

We have been interested particularly in one class of effects which we term field-evoked-force effects. These effects relate to forces which are evoked by alternating electrical fields, acting on blood corpuscles, protein molecules, or whatever other biological particles are concerned. It is well established that dc electrical fields can evoke forces acting on particles. We have extended this work to the ac case and discussed various manifestations of field-evoked forces. One outcome of this work was that we understand a variety of observations that have been made by various groups of investigators, as for example, the phenomena of pearl-chain formation as observed for the first time in the 1920's and, more recently, Heller's observation of the orientation of unicellular organisms in electric fields. On the basis of simple physical principles one can calculate the electrical potential energy that the particles are subject to. Evoking the well-known principle that any system will tend to minimize its potential energy, one is then able to predict precisely the sort of phenomena that have been observed, such as pearl-chain formation and orientation of particles. The outcome of this work is that for biological cellular particles, one needs fairly high field-strength values to obtain a force effect, i.e., of the order of 100 V/cm. For macromolecules even higher field-strength values are required. This has to be compared to the tolerance standard of 10 mW/cm^2 which corresponds to 2 V/cm in free space or 0.2 V/cm in tissue. Clearly, at 100 V/cm, associated heating becomes excessive. Thus, in the presence of a continuous alternating field one cannot obtain nonthermal field-force effects at field-strength values which are thermally insignificant.

There is one more problem, however, which has not been entirely dealt with in our presentations of the past. It is the question of whether there is a difference between pulsed fields and CW fields. Very recently we have been interested in relevant experimental research. Saito and Schwan had already estimated the speed with which systems respond to field-force effects. They found that the time constant associated with field-force effects varies inversely with the square of the applied field strength as indicated in Fig. 7, provided that the field strength is larger than the threshold field strength E_{th} which is needed to overcome Brownian disturbance. At lower field strength, the time constant characterizes the speed with which pearl chains break up. In this case for $E < E_{th}$, T varies but little with E. Our recent work with



$$E^2T_1 = \text{constant} \rightarrow \frac{T^2}{T_1} = \left(\frac{E_{th}}{E}\right)^2$$

$$\text{average energy} \sim \frac{T_2E^2}{T_1 + T_2} = \frac{1}{\frac{1}{E^2} + \frac{1}{E_{th}^2}}$$

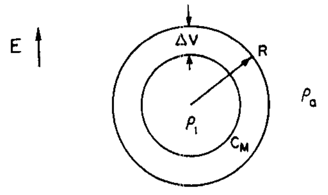
$$E > E_{th} \rightarrow \text{average energy} \sim E_{th}^2$$

Fig. 7. (a) Field strength dependence of the time constant T which states how rapid a field-force effect occurs. E_{th} is the threshold field strength needed to evoke a field-force effect. (b) A particular pulsing manner, where T_2 and T_1 are chosen equal to the time constants with and without field, will optimize the likelihood of a force effect without undue concomitant heating (see text). Equations indicate how in this case only the average energy determines the force effect.

Sher and Kresch was experimental, checking whether the time constant which characterizes the speed of pearl-chain formation indeed changes inversely with E^2. The results are in excellent agreement with the theoretical prediction; the time constant indeed varies inversely with the square of the field strength.

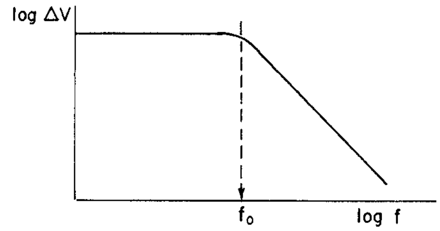
We suspect that what we have observed in the case of pearl-chain formation is of rather general validity for all field-induced-force effects. After all, the product of E^2T is a measure of the total work which has been applied in the presence of a field E to induce the force effect of interest. It is proportional to the energy expended on the particles of interest, where the proportionality factor is only a function of particle geometry and electrical properties but not of E and T. The energy expended on the particles must be independent of T and, hence, E^2T is constant and T is inverse to E^2. The consequences of this argument are far reaching, as will be shown next.

We shall prove that as far as any field-induced-force effect is concerned, a pulsed field can be no more effective than a CW-field of equal average power. We apply a pulsed field as indicated in Fig. 7, i.e., the ratio of "on" and "off" times t_2 and t_1, is given by $(E_{th}/E)^2$. We do this since we choose t_2 and t_1 to optimize our chances to get a nonthermal-field-force effect, and to minimize the likelihood of heating, as will be shown next. The pulse is applied over a period t_2 where t_2 is chosen to be equal to the time constant T_2 that is needed to obtain the effect. If the time t_2 were smaller than T_2 we could not obtain a force effect, since the time required for an effect would be longer than the time of applying the field. And if t_2 were greater than T_2, energy would be wasted to heat without aiding force effects. As the field-induced-force effect takes place, the field is switched off for a period of time t_1. t_1 is chosen equal to the time constant



$$\Delta V = \frac{2RE}{\sqrt{1+[\omega C_M R(-\rho_i + -\rho_a)]^2}}$$

Fig. 8. Alternating potential ΔV evoked across a membrane by a field E_0 directed perpendicular to the axis of the membrane surrounded nerve cell. ρ_1 and ρ_a specific resistances inside and outside the membrane, C_M membrane capacitance per cm² surface area, ω angular frequency, and R cell radius.



$$f > f_0: \quad V = 2RE$$

$$j > f_0: \quad V = \frac{2E}{\omega RC_M(-\rho_i + -\rho_a)}$$

$$= f_0 \rightarrow \omega RC_M(\rho_i + \rho_a) = 1 \rightarrow f_0 R \sim 500$$

Fig. 9. Frequency dependence of ΔV. At low frequencies $f < f_0$ ΔV can be some mV for a field $E_0 = 1$ V/cm and, hence, may excite upon appropriate rectification. However, at frequencies $f > f_0$, ΔV is very much smaller and excitation appears impossible. The equation for f_0 indicates a value below 1 MHz. For further details, see text.

T_1 that corresponds to threshold field strengths; in other words, the time when the force effect just begins to disappear. Before it does, we give the system another burst of energy. Clearly, under such circumstances, we cause minimal heating and optimal likelihood for a sustained force effect. Under such conditions it is easy to calculate the average energy as indicated in Fig. 7. This average energy is, of course, given by E^2T_2 divided by the total time T_1+T_2. Since E is greater than the threshold field strength, the average energy is simply proportional to the square of the threshold field strengths no matter how E and T_1 are chosen. Thus we have demonstrated that the field-force effect is simply given by the rms value of the applied field. Since the times t_1 and t_2 were chosen to enhance the possibility of a field-force effect without unnecessary heating, we conclude that one cannot increase the likelihood of the occurrence of field-force effects by pulsing.

Not much remains to be done in the area of field-force effects. Perhaps the conclusion that pulsing does not enhance such effects needs to be checked experimentally. We also believe that the phenomenon of RF hearing experienced by man exposed to radar is possibly a field-induced-force effect, acting either on the total head or on the macroscopic-sized middle-ear structure, depending on frequency.[2] It would be of interest to have this further investigated.

B. Excitation of Biological Membrane

We alluded before to the fact that membranes are short-circuited by currents of frequency above 100 MHz. Straightforward application of Laplace's equation permits the calculation of the potential ΔV evoked across the membrane of a nerve fiber in the presence of the field perpendicular to the direction of its axis.[3] The result is given in Fig. 8. C_M, the capacity of the membrane, has the usual value of about 1 μF/cm² as well established in neurophysiological work. Fig. 9 shows the frequency dependence of the potential ΔV evoked across the nerve membrane. ΔV is frequency independent at low frequencies and decreases above a certain cutoff frequency. The cutoff frequency f_0 is given in Fig. 9. f_0 is usually smaller than 1 MHz. Introducing typical values of ρ_i, ρ_a, and C_M, and field-strength values which are not thermally significant, one obtains potentials ΔV which are about 10^5 or 10^6 times smaller than the resting potential. According to all modern concepts of neurophysiology about excitation this just cannot stimulate nerves.[4] The result can be stated in another manner. The electrical field strength which exists in a nerve membrane is something like 500 kV/cm. The field strengths applied by a microwave field to the human body are infinitely smaller and, hence, cannot evoke stimulation.

C. Macromolecular Resonances

There are strong indications that macromolecular resonances cannot be excited in tissue fluids. On the other hand their degraded state, resulting from the viscous damping and the electrical losses of tissue electrolytes, has been observed and discussed in great detail. Much is known about the relaxational behavior of cells, tissues, and macromolecules, and its manifestations; frequency-dependent dielectric constant and conductivity are well investigated. It does not yet provide a base for the postulate of destructive resonant effects caused by thermally insignificant fields.

We have indicated previously that mechanisms which come to mind are not likely to cause nonthermal effects on membranes, cells, and biological macromolecules. This statement is applicable for conditions of practical interest, i.e., it pertains to biological structures in the human body, surrounded by biological fluids and elec-

[2] This does not contradict our previous conclusion that only the average power applied by the field determines if a field-force effect occurs. The average power dictates if the force effects which are the basis of RF hearing take place. The appropriate pulsing is needed to provide a frequency spectrum of the rhythmically occurring force effect which is audible.

[3] A field which is not perpendicular to the nerve axis will evoke a smaller potential across the membrane.

[4] Excitation requires a potential between the inside and outside of a nerve which is a noticeable fraction of the resting potential of about 70 mV.

TABLE I

TOLERANCE CURRENT DENSITY CALCULATION[a]

Total body tolerance
$10\ mW/cm^2 \times 10^4\ cm^2 \equiv 100\ W$
$= \sim 1\ mW/cm^3$
Heat generated by current equal if
$j^2\rho = 10^{-3} \rightarrow j^2 = 10^{-5} \rightarrow j = 3 mA/cm^2$
for $f < 100$ kHz: 1 mA/cm^2
for $f > 1$ GHz: $> 3 mA/cm^2$
Tolerance current density
3 mA/cm^2

[a] The calculation is based on a tissue resistivity of 100 ohm/cm, typical for the frequency range between 100 and 1000 MHz. Different values apply outside this frequency range and necessitate different tolerance current levels below 100 kHz and above 1 GHz. For RF and VHF range, a tolerance current density of 3 mA/cm^2 is suggested.

trolytes and to field-strength levels which are not thermally dangerous and very approximately below 1 V/cm. However, convincing as these arguments may be, they cannot rule out the possibility of nonthermal actions based on principles not yet considered. Much work has been published in support of this contention, even though its quality leaves much to be desired and it has been the subject of criticism. Some of this abundant work was conducted almost 40 years ago, others rather recently. We do not propose that additional poorly conducted work be added to this body of literature of doubtful value. But we do propose that an effort be made to duplicate some of this work under conditions which inspire confidence. We specifically recommend that some of the Russian work be repeated in order to check the validity of the basis of the Russian low standards of exposure.

STANDARDS OF SAFE EXPOSURE

Present Western standards are all in terms of flux levels. We personally believe strongly in the validity of the 10 mW/cm^2 figure in far-field configurations and we have not seen anything to make us think it was a poor suggestion. In the presence of more complicated field geometries, however, the concept of a flux breaks down. What is the hazard to a person near the foot of a perpendicular antenna where only a magnetic field but no E-field exists? And how do we deal with near-field configurations or the hazard in fields resultant from several sources? We shall present what appears to be a new approach to such problems. Whatever biological damage results on a thermal basis is, of course, caused by the currents which are induced in the biological system of consideration. Let us briefly consider what current densities might be significant. A total body tolerance is implied by the 10 mW/cm^2 figure. We assume one side of the human body completely illuminated, i.e., an exposed area of about 1 m^2. Thus the total thermal load is about 100 W or $j^2\rho = 1\ mW/cm^3$ body tissue, where j is current density in tissue and ρ is tissue resistivity. Introducing typical ρ values, the current density derived is near 3 mA/cm^2. The total argument is summarized in Table I. At frequencies below 100 kHz the figure should be somewhat lower and for frequencies above 1 GHz it can be greater than that value. We propose, for complex fields and with regard to related standard work, to set as a guideline the concept of a minimal permissible current density induced in tissue. We can then discuss for each field configuration of interest what this guide implies with regard to external fields.

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