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Fundamental physical concepts underlying absorption of microwave energy by biological material

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The degree of biological damage sustained when a living organism is exposed to microwave radiation is related to the amount of energy absorbed which, in turn, depends upon the complex permittivity of the constituents. In this paper the variation of permittivity and conductivity with frequency is discussed and some examples are given for pure water. The relevance of the above concepts to microwave radiation absorption is explained.

WHEN A BODY is placed in a beam of electromagnetic radiation varying proportions are reflected, transmitted or absorbed. The principal parameter determining the distribution of energy between these three states are the frequency of the incident radiation and the complex permittivity of the constituents of the medium. The purpose of this paper is to examine the absorption of microwaves by biological material and to interpret this absorption in terms of the above mentioned parameters.

Theory

When a plane wave is incident at 90° on a flat surface of an infinite medium the proportion of energy reflected, r is

$$r = \frac{(n-1)^2 - k_0^2}{(n+1)^2 + k_0^2} \qquad 1$$

This is a classical formula based upon Maxwell's equations for the electromagnetic field and contains n, the refractive index of the medium in question. (It is assumed that the wave is incident in air, whose refractive index may be taken as unity).

The extinction coefficient is denoted by k_0 which determines how far the wave will penetrate into the mdeium; quantitatively the opwer falls off by a factor of $\exp(-4\pi k_0{}^2/\lambda)$ for each distance x traversed. For the case of a finite medium of irregular shape equation 1 must be suitably modified but it is still true that n, k_0 and λ are the dominant parameters in determining the reflection coefficient r, and hence the transmission coefficient $1 - r$.

For microwaves it is more convenient to discard the spectroscopist's terminology and to express n and k_0 in terms of the complex permittivity $\hat{\epsilon} = \epsilon' - j\epsilon''$. These are simply related by the expressions

$$\hat{\epsilon} = \epsilon' - j\epsilon'' = (n - jk_0)^2$$

$$\epsilon' = n^2 - k_0{}^2, \quad \epsilon'' = 2nk_0$$

ϵ' is the real part of the permittivity and is usally simply referred to as the permittivity. Alternatively it may be called the dielectric constant but although this has been fashionable for some years, it is now rightly going out of use because in many cases ϵ' is not contant but is strongly dependent on temperature and frequency. ϵ'' is the dielectric loss, or absorption of energy per cycle and is related to

$\epsilon'' = 60\lambda\sigma$ where λ is in cm and σ in $ohm^{-1}\ cm^{-1}$.

To complete the list of useful parameters the attenuation coefficient α is introduced, defined as one half the inverse of the distance required to reduce the wave intensity by a factor of $1/e$ where $e = 2.718$. These various parameters are further interrelated as follows

$$\alpha = \frac{2\pi k_0}{\lambda} = \frac{\pi\lambda_m \epsilon''}{\lambda^2} = \frac{60\pi\sigma\lambda_m}{\lambda} \qquad 4$$

where λ is the wavelength in the medium.

The general conclusions can be summarized in two statements

(a) If a medium of high permittivity is irradiated in air a high proportion of the incident energy is reflected, and vice versa.

(b) Of the radiation transmitted through the interface the amount absorbed is directly proportional to σ and hence strongly dependent on α and ϵ''.

In concluding this section mention must be made of the fact that the conductivity σ is made up of two components, corresponding to the motion of free ions and to dipolar rotation respectively. In principle other mechanisms can contribute to an observed σ but for investigations made in the microwave region, the above mentioned are the only two that need be considered. The absorption of energy due to ionic conductivity is entirely analogous to the Joule effect observed when a current flows through a metallic conductor but the dipolar energy loss is somewhat different in its origin and will be discussed now.

Dipolar relaxation

Molecules are either polar or non-polar i.e. they may or may not have a permanent dipole moment. Polar molecules are characterised by having a permittivity which is strongly dependent on frequency and temperature whereas non-polar substances have values of ϵ' lying between 2–3 and exhibit practically no dependence on either frequency or temperature. Also, for non-polar materials ϵ'' is virtually zero which means a negligible amount of energy is absorbed from any applied electric field.

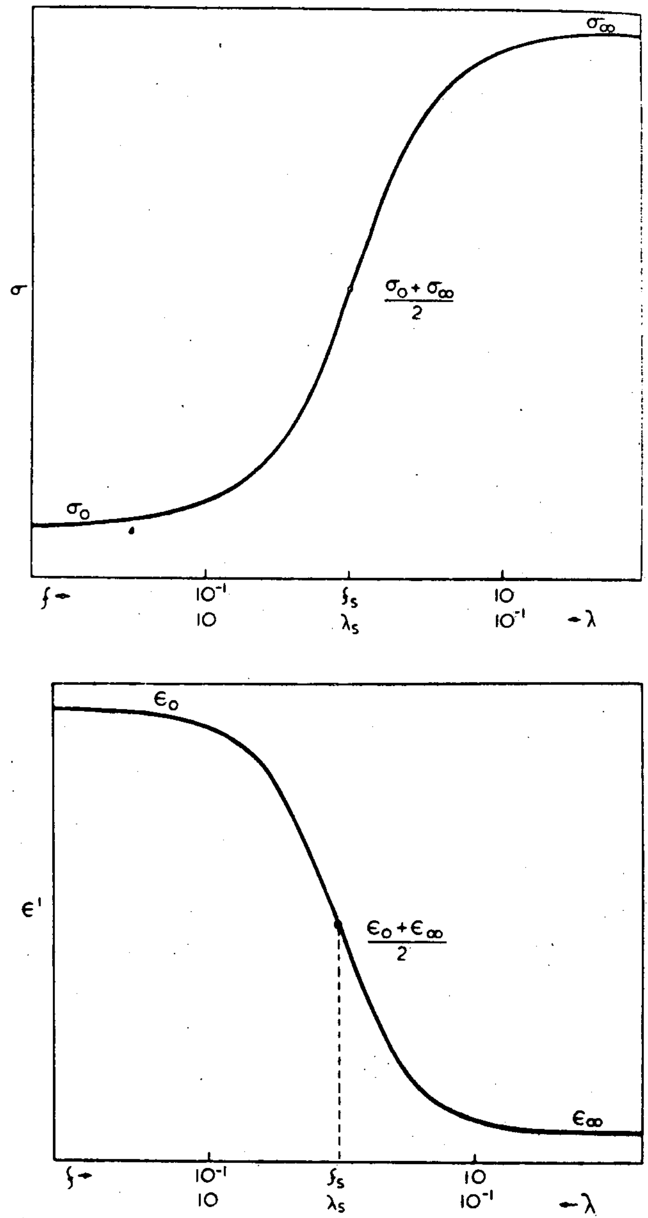

Fig. 2 Variation of permittivity and conductivity through a dispersion region

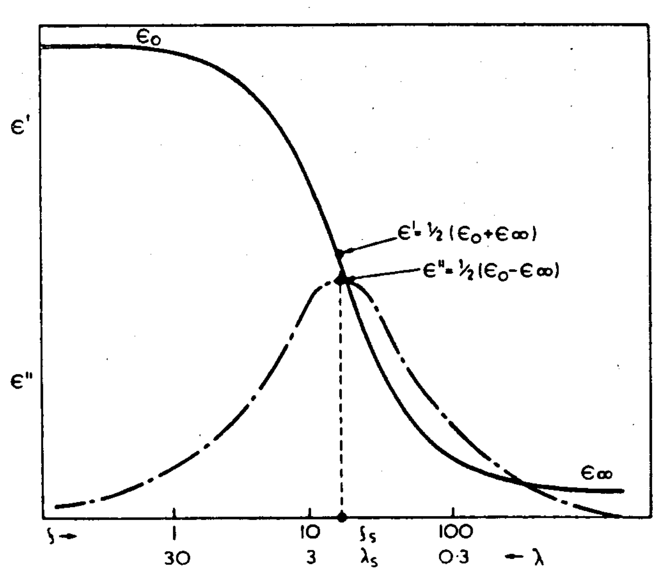

Fig. 1 Dielectric dispersion in water at 20°C

The dielectric behaviour of a typical polar substance, and one very relevant in the study of microwave hazards, is shown in **Fig.1** where the curves for water at 20°C are exhibited. The permittivity ϵ' falls from 80 (ϵ_0) to about 4.5(ϵ_∞) as the frequency increases from 100MHz–100GHz, while ϵ'' reaches a peak value at the frequency when $\epsilon' = \frac{1}{2}(\epsilon_0 + \epsilon_\infty)$. This frequency is called the relaxation frequency (f_s) and has a corresponding relaxation wavelength $\lambda = c/f_s$ and relaxation time $\tau = 1/2\pi f_s$ where c is the velocity of light. In **Fig.2** the curve is shown (general case) for conductivity, with the curve for ϵ' alongside for comparison. The conductivity increases through the relaxation region, reaching a maximum value when $f \gg f_s$. The variation of α with frequency is of a similar form and, for example, the value for water at 20°C is about $0.02 cm^{-1}$ at 600MHz rising to $20 cm^{-1}$ at 35GHz and finally levelling out near $50 cm^{-1}$ at around 300GHz.

Discussion

Because the aqueous content of the human body is 70% it is clear that a study of the microwave absorption in water gives a reliable guide as to what will happen in the body. In fact the dielectric properties of any given tissue are almost entirely decided by its water content. However, it would be a mistake to conclude that organs of the body with a high water content are necessarily the most vulnerable to microwaves; biological damage depends upon the temperature rise produced, which in turn depends both on the thermal capacity and the ability for heat to be conducted away. These factors may outweigh the fact that the medium in question has a high attenuation coefficient for microwaves and is the explanation why the eye and testis, both of which have poor paths for heat conduction, are so sensitive to microwaves.

On the other hand in microwave diathermy care is necessary in testing any areas with an appreciable amount of synovial fluid due to the selective absorption of radiation by this substance. These and associated questions have been dealt with at length by Cook (1952) and by Schwan and Peirsol (1954a, 1954b).

Examining equation 1 in terms of **Figs 1 & 2** it is clear that a substantial amount of energy is reflected by the human body below 3GHz.

For the proportion not reflected the penetration into the body is good, due to the low value of α. Above this frequency the value of ϵ' diminishes rapidly while α and σ increase equally rapidly. Hence the amount of microwave radiation reflected will decrease but the penetrating power of the transmitted radiation also decreases, thus making it very difficult to generalise about how the hazards to various tissues will depend on frequency.

To predict how a particular organ will behave under given exposure conditions it may be necessary to construct a phantom filled with a liquid having the same permittivity and conductivity as the organ in question. Because all body tissues hav ϵ' lying in the range 4–80 and σ between 10^{-5} and $10^{-1} ohm^{-1} cm^{-1}$ it follows that any liquid chosen as a tissue substitute must be continuously adjustable in these ranges. A common choice is a mixture of water-dioxan-potassium chloride, since permittivity can be varied nearly independently of conductivity by adjusting the dioxan content while σ can be altered with little change in ϵ' by changing the concentration of the KCl. This procedure has been described by Schwan (1959) using results on water-diosian mixtures obtained by Cook (1951). The dielectric parameters of the various tissues of the body have been reported by Schwan (1957), who also summarises the experimental techniques. Recent developments in experimental methods are described by Young & Grant (1968) and Grant & Keefe (1968).

Conclusions

Many of the practical uses of microwaves, whether medical, military, domestic or industrial involve the use of frequencies lying in the dispersion region of water, with the consequent rapid variation in permittivity and conductivity. Hence the evaluation of any possible biological effect arising out of using, say, a radar set at 35GHz poses quite different problems from those encountered when investigating the effects of waves originating from a microwave cooker (2.45GHz). Good predictions of the energy absorbed in all cases can be made from a knowledge of the dielectric parameters of the medium and this can then be followed up by investigating the behaviour of the appropriate tissue substitute.

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