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SPECIAL ARTICLE

Microwaves in medical and biological research

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Recent work on the absorption of microwave radiation in the frequency range 10^9 c/s to 3×10^{10} c/s is reviewed, with particular reference to materials of biological interest. The relative importance of ionic conduction, dipolar relaxation, particularly of water molecules, and resonance is discussed briefly. Conventional methods for dielectric constant and loss measurements at microwave frequencies can be adapted for use with biological materials and a number of such modifications is described. The results of investigations into the dielectric properties of water, the most abundant biological material, proteins and a variety of body tissues are outlined and discussed in terms of established dielectric theory. High power microwave generators have been used to study tissue heating, the heating pattern comparing favourably with predictions from the radiation propagation constants and the thermal properties of the materials. A few experiments on the effects of microwaves on animal tumours and on viruses are described.

INTRODUCTION

Electromagnetic radiation has been used as a therapeutic agent in medicine for many centuries, and long before their nature was understood heating by infra-red rays and the curious beneficial effects of solar ultra-violet were well appreciated. In more recent times, extensions of the known electromagnetic spectrum seem to have led inevitably to a study of the biological effects of the radiations and the possibilities of their use in medicine. The discovery of X-rays and its immediate consequences produced new tools, not only for the diagnosis and treatment of disease, but for fundamental studies of both animate and inanimate matter. On the other hand, although the results are not so spectacular, the use of high frequency currents in the "radio" range of frequencies, where localized or general body heating is required, is an accepted feature in the practice of physiotherapy.

Developments during the 1939–45 war opened up a largely neglected range of the spectrum when pulsed and continuous wave sources of radiations between 1 and 50 cm wavelength were produced for use in radar. During the war many speculative inquiries came to hospital departments concerning the possible physiological ill effects of these radiations on operators. Observers who investigated this problem, Daily,[1] Hollis,[2] and Lidman and Cohen,[3] found no evidence of a biological effect other than that due to heat production. Hence no serious ill effects of microwave radiation were envisaged. On the contrary, it was considered that microwave radiation might prove a useful thermogenic agent in the practice of physiotherapy if the problems of dosage measurement and method of application to patients could be solved. Physical investigations have been carried out with this object in view. Concurrently, the search for any specific action of intense microwave fields on micro-organisms, virus particles, and other biological molecules has been commenced.

The ready availability of stable low-power sources of microwaves gave impetus to the study of the behaviour of dielectrics at these frequencies and of molecular relaxation processes. Investigations of the dielectric properties at microwave frequencies of biological materials have been included in this field, although, in an embryonic state, useful information regarding relaxation processes and molecular structure in living tissues and protein solutions has already been obtained. The propagation constants of human tissues, as determined from dielectric constant measurements, have been of great value in connexion with studies of microwave propagation in the human body.

ABSORPTION BY BIOLOGICAL MATERIALS IN THE MICROWAVE REGION

In a review such as this it will be of value briefly to outline the relative importance of the different processes which may give rise to the absorption of energy from microwave radiation propagated in biological materials.

From the point of view of microwave propagation, most materials of biological interest can be regarded as "lossy" dielectrics which are frequently macroscopically or microscopically heterogeneous. The processes by which dielectric loss occurs and thereby energy is transferred to the medium depend obviously on the nature of the material and the frequency range of radiations in use. Electronic conduction does not enter into the question, but ionic conductivity, resonance and molecular relaxation are all possibilities.

In general, ionic conductivity is frequency independent up to frequencies higher than those considered here. However, in heterogeneous materials such as animal tissues and cell suspensions, specific ionic conductivity increases with increasing frequency up to the region of 10^8 c/s. This effect is due to intracellular fluids being separated from the extracellular fluid by thin non-conducting membranes. Cell contents are thus shielded from low-frequency fields, but are able to provide increasing contributions to dielectric loss as the frequency rises. At microwave frequencies the effect of the cell membranes becomes negligible and the specific ionic conductivity of a cell suspension can be assumed constant in the microwave region at a value higher than obtains

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at lower frequencies. This is exemplified below in the case of whole blood.

It is interesting to speculate on the possibilities of resonance absorption in the microwave region by molecules which make up living matter and the consequent possibilities of specific biological actions which may be used diagnostically or therapeutically. Although, in the opinion of some authorities, resonance absorption at microwave frequencies is a possible process of absorption by large biological molecules, it is likely that the practical importance of such absorption in therapeutic applications would be very small, though it would be of great interest from the point of view of molecular structure. With one or two possible exceptions, evidence of such absorption at microwave frequencies is as yet lacking.

The third process to be considered is the relaxation of dipolar molecules or groups. The relaxation times of proteins in aqueous solution are in the region of 10^{-7} sec, giving maximum energy absorption per cycle in the ordinary radio-frequency range (10^6 c/s). Water, on the other hand, shows anomalous dispersion in the range 10^9 to 10^{11} c/s so that it is strongly absorbent in the microwave region. Since water is a major constituent of all living biological material, its relaxation plays a prominent part in absorption processes. Up to the present, significant absorption by dipole orientation of other constituent molecules or groups in such materials has not been demonstrated.

Summarizing, it can be said that: (*a*) ionic conductivity in biological materials is frequency independent in the microwave region, and provides an energy loss per cycle inversely proportional to frequency; (*b*) energy loss per cycle due to water relaxation increases with frequency through the microwave region and becomes maximal at frequencies (depending on temperature) in the region of 2×10^{10} c/s; and (*c*) significant microwave absorption by resonance processes or by dipole orientation in molecules other than water has not yet been found.

An example of the relative importance of ionic conductivity and water relaxation can be given in the case of human muscular tissue. The ratio of the contributions to dielectric loss by ionic conductivity and water relaxation decreases from 14 at 10^9 c/s (free-space wavelength = 30 cm) to 0·05 at 3×10^{10} c/s (free-space wavelength = 1 cm), with equal contributions at approximately 4×10^9 c/s. The combined effect on the linear energy absorption coefficient for plane waves propagated in human muscle is to cause this coefficient to increase slowly with frequency from 10^9 c/s to 3×10^9 c/s, and then much more rapidly as the frequency increases above 3×10^9 c/s.

TECHNIQUES FOR DIELECTRIC CONSTANT MEASUREMENTS

In the study of absorption processes the fundamental problem reduces to the measurement over a wide frequency range of a complex dielectric constant, $\epsilon' - j\epsilon''$, where the loss tangent, ϵ''/ϵ', may be comparatively large. The experimental problem involves the adaptation of existing methods to the peculiarities of the media under consideration.

Methods of measurement of the dielectric constant of conventional dielectrics at microwave frequencies are based on well-known relationships (see, for example, von Hippel and Breckenridge,[4] or Jackson[5]) between the dielectric constant and other parameters. Redheffer[6] has provided a valuable survey and summary of thirty existing methods. In principle, any of these methods could be used to determine the dielectric constant and loss of materials of biological interest. However, the high dielectric constant and loss of most biological substances, together with their other peculiar properties, limit the choice of method.

Experience has shown that, to achieve the highest accuracy, methods of choice are those in which measurements are made in the material itself. Thus direct measurements of α (the attenuation coefficient) and β (the phase constant) for progressive or stationary waves in the material (contained in coaxial line or wave-guide) lead to the calculation of the complex dielectric constant from its relationship with the propagation constant, $\alpha + j\beta$.

Buchanan[7] has recently devised null methods used successfully for accurate measurements of both α and β in liquid or solid materials of biological interest at frequencies near 10^{10} and $2{\cdot}4 \times 10^{10}$ c/s. In one method, one output from an oscillator feeds via wave-guide to a liquid cell and another to a cut-off attenuator. The outputs of both feed the arms of a hybrid tee from which the combined signal goes to a wave-guide mixer. Using a receiver as detector, phase and magnitude balance of the two signals is obtained at as many consecutive wavelengths in the cell as possible. Accurate measurements of α and β are thus obtained. A modification of this method using a probe at two fixed points in a sample of material in a short-circuited wave-guide section can be used for both liquid and solid specimens with a wide range of loss characteristics. A method described by Collie and others[8] has provided accurate results for the dielectric constant of water and ionic solutions. This method involves direct measurement of α in two specimen-filled wave-guides, the dimensions of which are chosen to be just above, and just below, cut-off. The method has also been used recently for measurements on protein solutions.[9]

For measurements on liquid biological materials[10] at frequencies in the range $1{\cdot}5 \times 10^9$ to 5×10^9 c/s it has been found convenient to use a method which is the coaxial version of a twin-line method employed for investigations on water and ionic solutions by Knerr[11] and Cooper.[12] In this method, the signal strength in an air-filled section of line is dependent on the position of a movable short-circuiting plunger in an adjacent specimen-filled section. Observations of plunger position and the corresponding signal strength when the latter passes through minimum and maximum values provide directly the propagation constant of the wave in the specimen.

England[13,14] has reported the use of the Roberts and von Hippel method for measurement of the microwave dielectric constant of human tissue specimens. In this method the standing wave set up in an air-filled section of wave-guide or coaxial line terminated by a specimen-filled short-circuited section is measured. England employed different sets of wave-guide apparatus for each frequency used and found it convenient to use half-wavelength distrene transformers between the specimen and air-filled sections. Cook[15] has also investigated the dielectric behaviour of human tissues at microwave frequencies by means of the Roberts and von Hippel method. In these studies one coaxial line apparatus served for measurements on a single specimen over a range of frequency from $1 \cdot 5 \times 10^9$ to 5×10^9 c/s. A feature of this adaptation was the use of a slotted Distrene-filled line in place of the usual air-filled slotted section. This overcame difficulties regarding the formation of a plane dielectric interface (involving some compression when soft tissues are concerned) without introducing complications arising from the need to cover in a single apparatus a wide frequency range.

For low loss materials, such as fatty acid esters and glycerides, much work has been done by the Roberts and von Hippel method using conventional air-filled slotted sections of wave-guide and coaxial line in which to make standing wave measurements. Resonant cavity methods are not suitable for dielectric measurements on high loss biological materials. However, Bayley[16] has employed a coaxial line resonator method for investigations of the dielectric properties of solid crystalline proteins over a frequency range centred near 3×10^9 c/s (7·3 cm to 15·3 cm wavelength). This method was chosen by Bayley because solid proteins have low dielectric loss and are only available in small quantities.

DIELECTRIC PROPERTIES OF WATER AT MICROWAVE FREQUENCIES

By far the most abundant and probably the most important biological material is water. Any biophysical study, therefore, in the microwave region should be preceded by an investigation of the dielectric properties of water at these frequencies. A considerable amount of work on these lines has been carried out but, unfortunately, many early investigators used damped waves, and techniques used more recently have not always been conducive to accuracy. Collie, Hasted and Ritson,[8] however, have published a comprehensive series of experimental results of considerable accuracy on water between wavelengths 1 cm and 10 cm (3×10^{10} and 3×10^9 c/s) and at various temperatures. More recently Cook,[10] using quite different techniques, has confirmed the results. Some examples of the values of the complex dielectric constant are shown in Tables 1 and 2.

In analysing these results, it can be assumed that the only effect contributing to the loss is orientation polarization, ionic conductivity and resonance being effectively absent. On this assumption, the results can be studied in terms of Debye's[17] theory of dispersion in polar liquids, from which the relaxation time of the process concerned can be derived. Some values of the relaxation time so derived are shown in Table 3.

Table 1. *Dielectric constants for water at different wavelengths at 20° C*

Wavelength (cm)	ϵ'	ϵ''
10·00	77·7	13·0
6·48	74·0	18·8
3·195	61·5	31·6
1·262	31·0	35·7

Table 2. *Dielectric constants for water at 3·195 cm*

Temperature (° C)	ϵ'	ϵ''
0	(43·4)	(41·1)
5	49·6	39·2
10	54·4	37·1
20	61·5	31·6
30	64·8	25·6
40	65·5	20·9
50	64·6	17·0

Table 3. *Relaxation time for dipolar orientation in water*

Temperature (° C)	*Cook*[10]	*Collie and others*[8]
0	$1 \cdot 78 \times 10^{-11}$ sec	$1 \cdot 77 \times 10^{-11}$ sec
10	1·28	1·27
20	0·93	0·96
30	0·72	0·74
40	0·60	0·59
50	0·50	0·48

Single values are given in Table 3 but, as pointed out by Cook, the experimental results are equally consistent with the existence of a small spread of relaxation times in water. Such a small distribution of relaxation times can be invoked to link the experimental microwave and long infra-red dielectric constants without introducing any additional dispersion process between the two parts of the spectrum.

Further analysis indicates that the relaxation process in water is closely linked with the rupture and formation of hydrogen bonds. Large increases in the relaxation time of water have been shown[18,19] to take place in mixtures of water with dioxan, a substance with which water forms hydrogen bonds. The influence on the water relaxation time of hydrogen and other types of intermolecular bonding between the water and other molecules and groups (particularly those of biological interest) is being investigated further by Hasted, Haggis and Buchanan.

DIELECTRIC PROPERTIES OF BODY TISSUES AT MICROWAVE FREQUENCIES

The use in medicine for therapeutic tissue heating of condenser field methods has led to a number of studies of the dielectric properties of animal tissues in the "radio" range of wavelengths from 3 to 20 m and beyond (see, for example, Rajewsky[20] and Iwase[21]). In the microwave region, much less information is available (England and Sharples,[13] England,[14] Cook[15,22]). Dielectric measurements in this range on blood, the tissue with the best known structure, are of particular interest. Typical results[10] for whole human blood are shown in Fig. 1 together with comparable results for pure water at the same temperature.

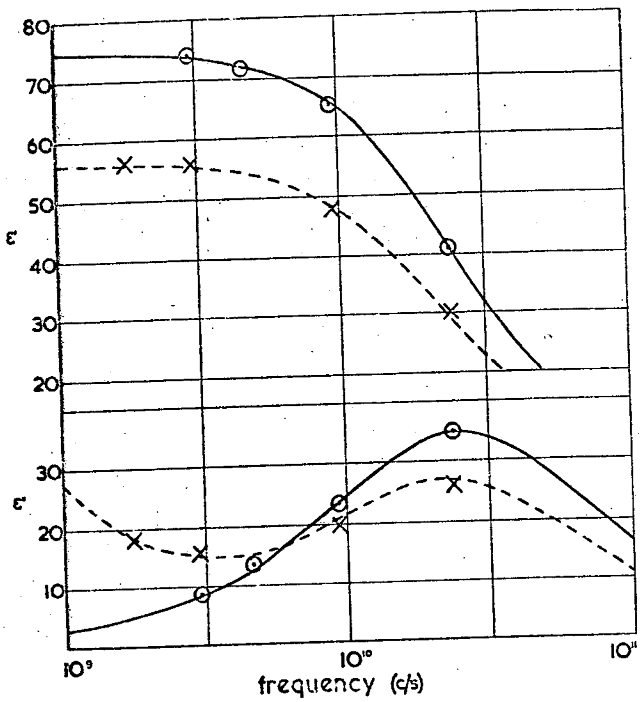

Fig. 1. Variation with frequency of ϵ' and ϵ'' for pure water and whole human blood at 35° C

Experimental points: ○ = water; × = blood.
Theoretical: Full curves—water;
broken curves—blood.
(From reference 10.)

Comparison indicates that the dispersion region of ϵ' for blood is the same as that for water and is due to the orientation polarization of the water molecules present in the blood. Variations in ϵ'', however, suggest that there is another contribution to the dielectric loss in addition to the water molecule relaxation. As the relaxation time of protein molecules is in the region of 10^{-7} sec, it is safe to assume that this relaxation makes a negligible contribution in the microwave region. The additional loss is, therefore, that due to ionic conduction. It has been reported[22] that the blood results satisfy the Debye dispersion equations if an additional term allowing for ionic conductivity is included. It has also been shown[10] that the microwave ionic conductivity and dielectric constant, ϵ', of whole blood are consistent with Danzer's[23] extension of Wagner's[24] dispersion theory for inhomogeneous dielectrics. This theory explains approximately the large drop in ϵ' (from about 5 000 at low frequencies to about 56 at microwave frequencies), and the attendent increase in specific conductivity as the frequency increases. Wagner's theory leads to dispersion equations of the same form as the Debye equations, with a time constant (relaxation time) related to cell membrane and intra-cellular fluid constants.

Further analysis of the results has also yielded estimates for human erythrocytes of intracellular haemoglobin hydration and the ionic conductivity of the intracellular fluid. This is probably the first experimental determination of haemoglobin hydration in human erythrocyte contents without destruction of the cells. The estimates of hydration and ionic conductivity depend very much on the validity of theories for inhomogeneous media. That of Fricke[25] has been used in this case and has given results in accord with expectations.

Turning now to solid human tissues, England[13, 14] has made dielectric measurements on specimens of skin, fat, bone, and some tumour tissues at 10·0, 3·2 and 1·27 cm free-space wavelengths. Cook[15] has also investigated various types of normal and pathological human tissues at wavelengths between 6 and 17 cm. Results obtained at 10·07 cm wavelength are shown in Table 4.

Table 4. *Dielectric constants of human tissues*

Wavelength, 10·07 cm; temperature, 37° C

	ϵ'	ϵ''
Skin		
(*a*) Breast	40·0	12·3
(*b*) Sole of foot	42·4	13·1
(*c*) Near faecal fistula	51·1	15·2
Muscle		
(*a*) Pectoralis major	50·0	17·1
(*b*) Soleus	51·0	18·0
Fatty tissues		
(*a*) Breast (normal)	3·94	0·87
(*b*) Breast (fibrosed by X-rays)	14·7	3·95
(*c*) Abdominal wall	4·92	1·46
(*d*) Near faecal fistula	7·0	1·75
Bone		
Mid-tibia	8·35	1·32

The properties of skin and muscle may be interpreted in very much the same way as those of blood, namely in terms of water molecule relaxation and of ionic conductivity. As before, the dispersion effects of inhomogeneity appear to be negligible at microwave frequencies. The microwave results have been shown to be in accord with estimates of dielectric constant and loss calculated from the known chemical composition of these tissues, approximate protein hydration and extra-cellular fluid volume.

Fatty tissues and bone present a much more difficult problem. In general the fluid contents are lower than for skin and muscle and vary quite considerably from one specimen to another. Furthermore, it seems possible that dispersion in the microwave region due to inhomogeneity is superimposed on that caused by water relaxation in the case of these tissues.

It is interesting to note that in this series of observations the two specimens of pathological tissues, taken from near a fistula and from a fibrosed breast, show different dielectric properties from the corresponding normal. This is almost certainly due to a difference in water content.

DIELECTRIC PROPERTIES OF PROTEIN SOLUTIONS AND SOLID PROTEINS

Measurements made in the conventional radio-frequency range show that relaxation of protein molecules in aqueous solution occurs in the region of 10^6 to 10^7 c/s and that the dielectric constant, ϵ', falls to a steady value, ϵ^*, at frequencies lower than those of microwaves. The contributions to the dielectric constant and loss of such solutions from protein orientation polarization are, therefore, negligible at microwave frequencies. In physiological processes, however, the hydration of protein molecules in aqueous solution is of considerable importance. Hasted, Ritson and Collie[26] have shown that microwave measurements on ionic solutions can give estimates of the hydration of ions and recently Haggis, Hasted and Buchanan[9] have extended this idea to protein solutions. Measured dielectric constants of bovine serum albumin solutions satisfy the Debye equations with relaxation times as for water and with values of ϵ^* decreasing with increasing concentration. This decrement is interpreted as being due to the binding of a proportion of the water molecules to the protein in such a way as to prevent them contributing to ϵ^*. The experimental results of Haggis and others lead to a hydration of $0{\cdot}15 \pm 0{\cdot}1$ gram water/gram protein and suggest an elongated form of molecule. This figure is lower than that generally accepted, but it takes account only of non-relaxing water molecules and some of the molecules bound to the protein surface may be able to make a contribution to ϵ^*. Similar investigations have been carried out with methaemoglobin. Further work on other proteins and particularly on smaller molecules such as amino acids is now being carried out with a view to more detailed interpretation of protein structure and hydration.

Investigations of the dielectric properties of some solid crystalline proteins, amino acids and peptides have recently been reported by Bayley.[16] All the materials studied showed dispersion in the microwave region, possibly due to relaxation of polar groups or a resonance. However, Bayley remarks that it is not certain to what extent the dispersion is due to sorbed water.

TISSUE HEATING BY MICROWAVES

As long ago as 1890, d'Arsonval demonstrated that when currents of frequencies greater than 10 000 c/s were passed through the human body, there was no muscular contraction, but heating of the tissues resulted. Since that time, tissue heating by high-frequency currents has been a routine procedure in physiotherapy. In the early 1930's the development of valves capable of oscillating at high powers in the 30 Mc/s range led to the use of induction and condenser field heating at these frequencies.

With the introduction of the cavity magnetron, extending the frequency range to 3 000 Mc/s and over, the investigation of the clinical possibilities of these radiations followed naturally. The early development of these investigations was largely due to Krusen and his collaborators.[27, 28] In this work the generator consisted of an air-cooled continuous wave magnetron from which the energy (free-space wavelength 12 cm) was fed by a coaxial cable to a director system. The latter, in most cases, consisted of a dipole with a reflector in the form of a hemisphere from 4 to 6 inches in diameter. During irradiation the director is placed a few centimetres away from the skin surface, and skin and subcutaneous temperatures are measured by means of thermocouples immediately after switching off. With this arrangement, as with earlier forms of high-frequency heating, dosage measurement, in the accepted sense of the estimation of absorbed energy at points in the tissues, is almost impossible. This is largely due to the difficulties in predicting the propagation pattern of the radiation and the effects of surface reflection. Control is exercised in terms of the power output of the generator, the director-skin distance and the time of exposure, with the patient's sensation acting as a limiting factor. Using generator powers of the order of 50 to 100 W the American workers carried out extensive investigations on the temperature rises produced in animals and humans and on the effects of the irradiation on blood circulation.

A considerable advance towards the solution of the physical problems of microwave therapy is reported by Boyle and others,[29] and Cook.[30] In their original arrangement, pulsed radiation from a radar set is transmitted directly by way of rectangular wave-guide to applicators (wave-guide flare, etc.) in contact with the tissues. The introduction of a mismatch unit ensures that all energy passing through the guide enters the tissues. This energy can be measured by means of a calibrated wattmeter, thus providing a physically sound dosage system. Owing to the utilization of all the transmitted energy in this method, powers required for therapeutic heating are much lower than when the applicator or director is used at a distance from the skin. A further advantage of the contact applicator method is that, by placing a fine wire thermojunction across the aperture, at right angles to the electric field vector, there is no direct heating of the couple due to field pick-up and so skin temperatures can be measured during exposures.

Recently in the writers' laboratory, a mobile continuous wave apparatus has been constructed, in which the microwave power at $9{\cdot}4$ cm wavelength is fed by way of a flexible coaxial cable to interchangeable rectangular and circular wave-guide applicators. This makes a very suitable arrangement for clinical trials of microwave heating (Fig. 2).

The results published by Cook[30] show that with an input power of the order of $0{\cdot}5$ W per cm^2 the skin temperature rises by about 10° C and then remains constant. At higher powers, pain and burning intervene before the constant level is reached. Cooling is mainly due to blood circulation. This is demonstrated by occluding the circulation during exposure when the skin temperature rises almost linearly to the maximum tolerable level.

The variation of temperature with tissue depth is complicated by the differences in the dielectric properties of

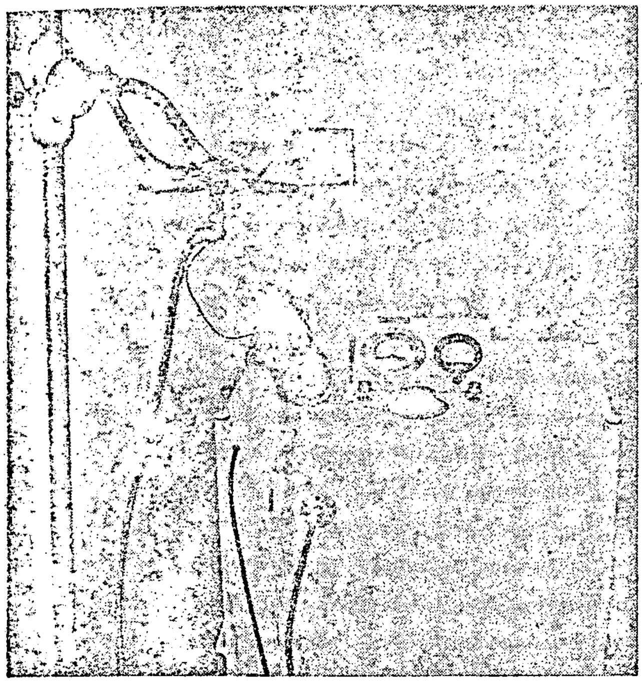

Fig. 2. Continuous wave set ($\lambda = 9{\cdot}4$ cm) for therapeutic applications, with power output up to 50 W

the tissue layers. This is illustrated in Fig. 3 by one curve taken from Cook's results. The curve refers to the application of 3 watts for 2 minutes over an area of 10 cm^2 on a human thigh. The effect of the presence of a 6 mm layer of fat of lower dielectric loss than skin and muscle is clearly shown in the trough of the curve.

For the purpose of microwave propagation, the tissues may be regarded as a series of layers of homogeneous material with different dielectric constants and reflection coefficients. Using the dielectric measurements described earlier it is then possible to calculate the electric field distribution in the tissues along the radiation beam axis. The energy absorption at any point is then proportional to $(\text{field})^2 \times \epsilon''$ and so relative temperature rises can be estimated. The result of such a calculation for the particular example of the human thigh mentioned above is shown in Fig. 3. Heat flow is ignored in the calculation, but its effect would be expected to smooth the theoretical curve to the shape of that observed experimentally. Recently,[30] a more detailed analysis has been made of the experimental results of tissue heating by microwaves in terms of absorbed energy distribution and of linear heat flow in the irradiated region. For short exposures the skin temperature rises observed lead to a thermal conductivity of tissues of $0{\cdot}005$ cal cm^{-1} sec^{-1} $°C^{-1}$, a figure in fair agreement with normally accepted values. If the exposure is prolonged the effective tissue conductivity increases rapidly, indicating the induction by the heating of increased blood flow and hence the removal of heat by the blood to neighbouring tissues.

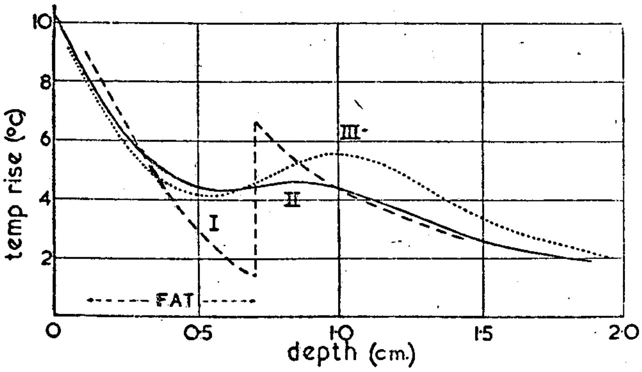

Fig. 3. Variation of tissue temperature with depth in human thigh after 10 cm microwave exposure

Curve I—calculated (neglecting heat flow).
II—experimental, after 2 min exposure.
III—experimental, after 4 min exposure.

RESONANT ABSORPTION IN THE MICROWAVE REGION

In common with other parts of the electromagnetic spectrum, the idea of specific biological action in the radio wave range has long seemed attractive. Many claims to such specific action and therapeutic usefulness of high frequency currents corresponding to wavelengths in the 5–100 m range have been made. Although few workers interpreted the term "specific action" precisely, the phenomenon sought was essentially that of resonance absorption by vital biological molecules. Thus, if sufficiently strong, it was hoped that such absorption could lead to the inactivation of disease-producing organisms or molecules in vivo at a particular frequency, without causing a large general rise in temperature of the treated tissues.

Claims made by other workers for specific action at different frequencies were investigated by Curtis, Dickens and Evans,[31] who showed that all the observed effects could be attributed to general tissue heating by ionic conduction currents.

The fundamental approach in the search for resonant absorptions is by dielectric constant measurements using low radiation power levels. A report by Dryden and Jackson,[32] suggesting a possible resonant absorption in the microwave region by methyl palmitate, led to dielectric studies of this fatty acid ester with a view to extension to the more biologically-important glycerides. An investigation on methyl palmitate in the microwave region, using a number of frequencies greater than was used by Dryden and Jackson and covering a wide temperature range, was reported by Cook and Buchanan.[33] Their results are summarized in Fig. 4. The plateau in the ϵ' curve round about 4×10^9 c/s, where ϵ'' is a maximum, suggests a resonance absorption mechanism. This suggestion is supported by the fact that the frequency of the absorption peak is independent of temperature and that the plateau in the ϵ' curve persists at low temperatures. On the other hand, the variation of the peak loss with temperature is the opposite to that which would be expected from resonance alone. It has been suggested that the results might be due to both a relaxation and a resonant absorption process occurring together in the microwave region. Further work on other fatty acid esters and related compounds is being carried on by Buchanan and will be reported in due course.

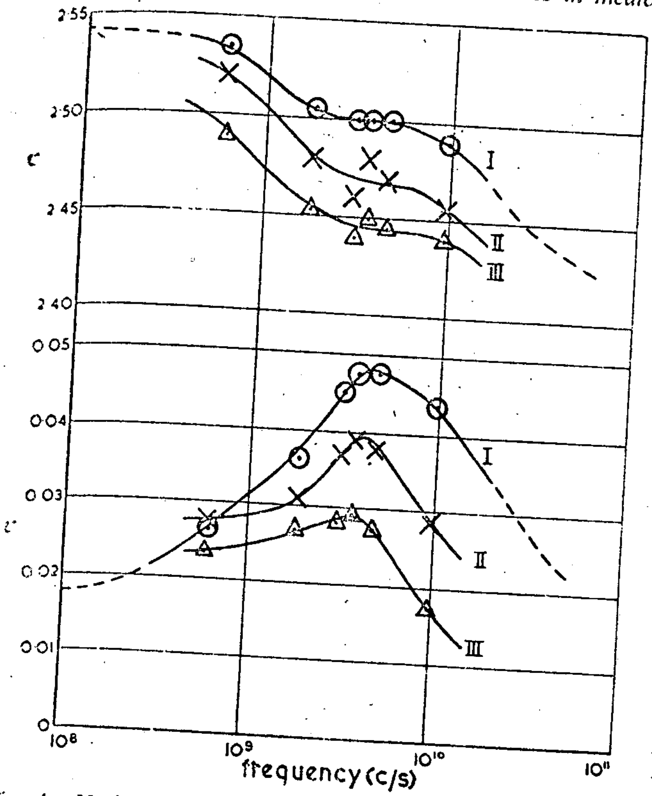

Fig. 4. Variation of the dielectric constant, $\epsilon' - j\epsilon''$, of methyl palmitate with frequency and temperature
Curve I: 22° C; Curve II: 0° C; Curve III: −20° C.

BIOLOGICAL EFFECTS OF MICROWAVES

All work on the biological effects of microwaves so far reported can be explained on the basis of general heat production in the extra- and intra-cellular fluids of tissues, or in the suspension medium of biologically-active agents when these have been irradiated in vitro.

For example, the irreversible biological changes produced in animals by various American workers occurred only when the tissue temperatures exceeded a critical level. The same changes could presumably be produced by other thermogenic agents, and point to no specific action of microwaves.

In some preliminary experiments Boyle and others[29] irradiated about 9 cm² of an animal's leg at 8 W for 5 min. No general effects on the animal were observed, but the limb became rigid, swollen and discoloured at the site of application. Post-mortem coagulation necrosis was observed in the subcutaneous tissues, an effect which would be expected from any heating process. Clark[34] has summarized and analysed a number of other observations on intense microwave heating of living tissues. He demonstrates the serious tissue damage which can be caused, particularly in organs such as the eye lens and the testes, which have small blood and nerve supplies. One of the dangers suggested by Clark is that with radiations of the order of 10 cm wavelength, a positive temperature gradient may be set up in the tissues, the deeper structures being at a higher temperature than the skin with its warning mechanism of pain. It has, however, been pointed out[30] that this should only occur under very exceptional conditions in which the skin is vigorously cooled by external means. Under all normal conditions of irradiation no tissue is subject to a greater temperature rise than the skin and this in general will not tolerate a temperature of more than 45° C.

A few attempts have been made to destroy malignant tumours in animals by means of microwave heating. Superficial tumours in mice have been irradiated (10 cm microwaves) using a modification of the wave-guide contact applicator described previously. Regression of tumours has been observed, presumbly due to coagulation following the heating. England[37] has obtained similar results when irradiating small rat tumours with 3 cm microwaves. Insufficient evidence has been obtained to estimate the future possibilities of this process.

De Seguin and others[35] have reported the biological effects of microwaves of 21 cm wavelength. The effects on microbes in vitro, tissue cultures and laboratory animals were all found to be due to general heating.

An attempt to destroy a virus by specific microwave absorption is reported by Epstein and Cook.[36] In one series of experiments small quantities of material containing the virus of the Rous fowl sarcoma were placed between mica sheets, mounted in a wave-guide and irradiated with 10 cm microwaves. During irradiation the temperature was allowed to rise freely. Under these conditions absorption of energy by dipolar orientation and ionic conduction in the medium surrounding the virus particles will be very high and will result in considerable temperature rises. After irradiation the virus material was found to be incapable of producing tumours, its activity having been destroyed by the heating. In a second series the specimens were maintained at −70° C by means of solid carbon dioxide. At this temperature absorption by ionic conduction and dipolar orientation in the medium or in the virus itself is negligible. Epstein and Cook found no evidence of inactivation of the virus under these conditions, indicating that in the frequency range used there is no specific resonant absorption.

The results up to the present of irradiations of biological materials by microwaves at relatively high power may be summarized thus: (*a*) no evidence has yet been produced of any specific biological effects other than heating due to ionic conductivity and dipole orientation; (*b*) heating of tissues takes place to an extent depending on the nature and depth of the tissues, but under all normal conditions the greatest temperature rise is in the skin which serves as a warning mechanism of possible ill effects.

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ORIGINAL CONTRIBUTIONS

Characteristics of the hot cathode electron microscope gun

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Experiments have been carried out on hot cathode, high-voltage three-electrode electron guns. The brightness has been measured and found under optimum operating conditions to approach closely the value expected from the theoretical considerations developed by Langmuir. The effect of varying geometry over a fairly wide range is shown to be of secondary importance, except in as far as it influences the bias conditions and current efficiency. The mechanism of electron beam formation is discussed briefly.

The type of electron gun used on the electron microscope and, in some cases, other instruments such as the electron diffraction camera and high-speed cathode-ray oscillograph, consists (Fig. 1) of a tungsten hairpin filament as cathode, a modulator electrode or cathode shield, and an anode with a central hole to allow the beam to leave the gun. The electrodes are mounted coaxially and the shield is usually biased negatively with respect to the cathode, the anode/cathode voltage ranging from 20 kV to 100 kV or more.

The performance of this type of gun has been discussed by several authors. Hillier and Baker[1] described some peculiarities of the focused spot which occur under certain operating conditions. Ellis[2] analysed the gun performance by an approximate trajectory tracing method and showed that an image of the cathode would be formed between cathode and anode. Von Borries[3] described the measured properties of the electron micr... scope gun, giving curves of the performance in terms of various geometrical parameters. Modifications of the electron gun geometry to give a real instead of virtual focus were described by Bricka and Bruck,[4] Steigerwald,[5] Renaud,[6] and Ehrenberg and Spear.[7, 8] Only Bricka and Bruck have attempted to relate the brightness given by the virtual and real focus types of gun to Langmuir's[9]* theoretical limiting value; unfortunately their experimental results are somewhat restricted and appear to be in error owing to the aperture used in th...

* *Note added in proof:*

A paper by J. Dosse† has recently come to our attention which the author attempts to correlate measured brightness w... the theoretical value. Conclusions similar to ours in ... respects are reached but for a different type of electron gun.

† *Z. Phys.*, **115**, pp. 530–56 (1940).