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Application of Electric and Acoustic Impedance Measuring Techniques to Problems in Diathermy

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DIATHERMY, or heating of deep tissues, must be accomplished through the absorption of radiant energy in the region to be heated. Conduction methods such as infrared or hot packing fail because of the rapid convection of heat by the flow of blood. Conventionally diathermy has come to be synonymous with high-frequency electromagnetic heating. Recently, however, ultrasonic energy has been introduced to accomplish a somewhat similar clinical purpose.

The effectiveness of these forms of radiation may be evaluated largely in terms of these physical quantities: the depth of penetration, reflection coefficient, and beaming angle, all of which can be computed from the frequency dependent electrical and acoustic impedance of the biological medium.

Rather extensive measurements of the electric impedance of tissues and blood have been carried out in the region up to 100 megacycles by Osswald[1] and by Schaefer[2] and above 1,000 megacycles recently by England[3] and by Herrick and co-workers.[4] Actually, as will be shown, the most promising region for diathermy lies between these two extremes.

For measurements in the frequency range 100–1,000 megacycles a special resonance method[5] has been adopted, which is a modification of a technique first discussed by Chipman.[6] An open-wire transmission line, see Figure 1, is loaded on one side by the sample under investigation and terminated on the other end by a movable short-circuiting plate. The line may be excited either capacitatively or inductively at a point between sample and short-circuiting end. The modulated current is picked up by a small loop protruding from the movable short-circuiting plate. This current is subsequently detected, amplified, and metered. Figure 2 shows the variation of this current as a function of the position of the short circuit for the case where the reflection coefficient of the sample is approximately one half. The points were obtained experimentally. The solid line is theoretical. The slight discrepancy between experiment and theory away from resonance arises from direct pickup

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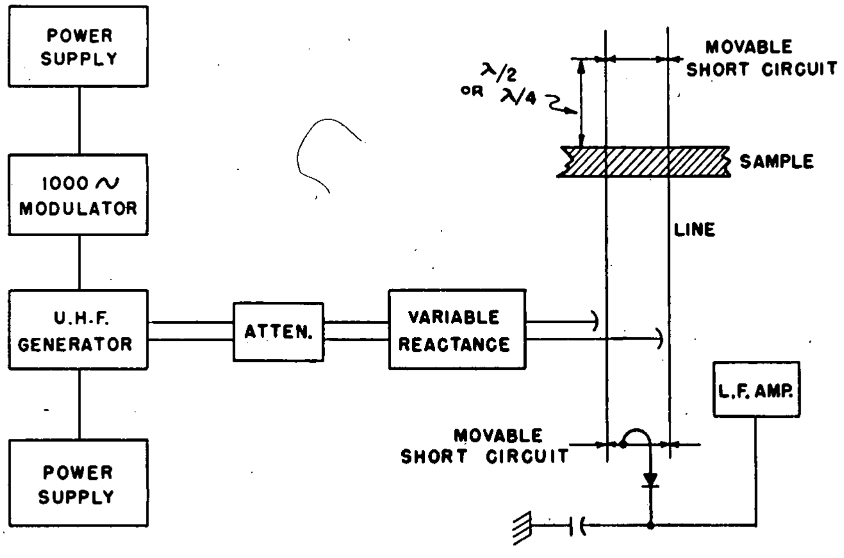

Figure 1. Resonance line for impedance measurements between 100 and 1,000 megacycles

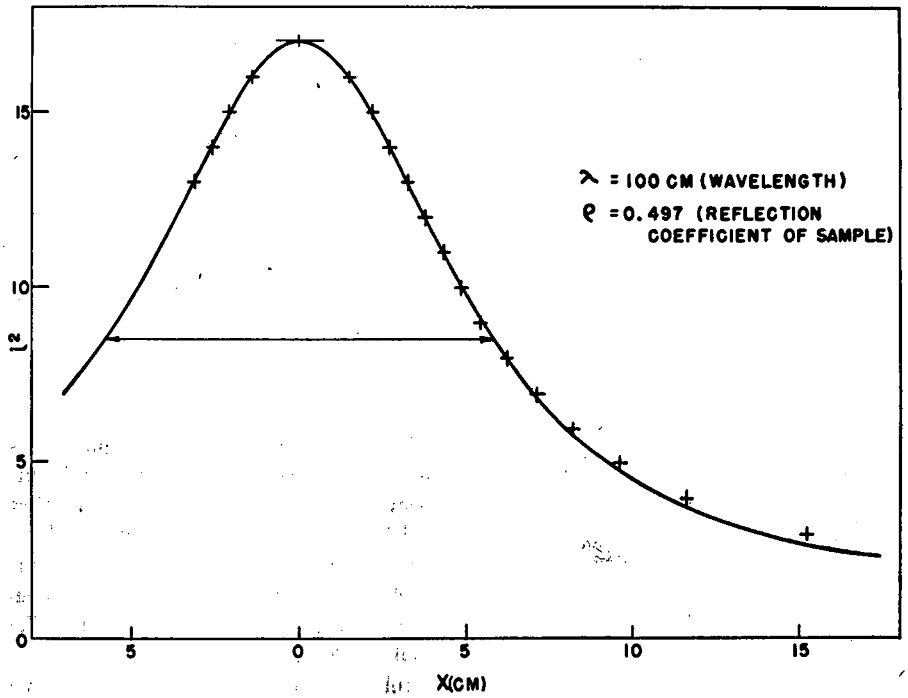

Figure 2. Resonance curve (points are experimental, curve calculated)

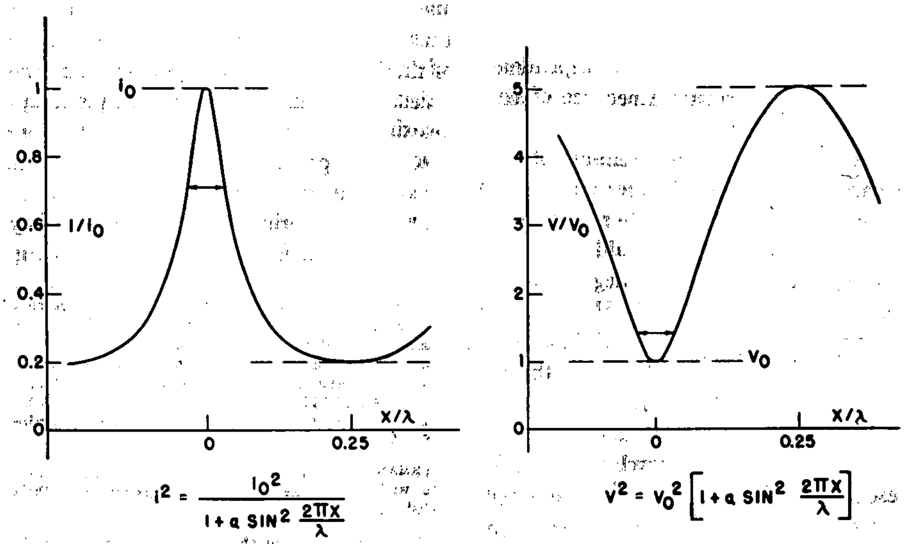

Figure 3. Comparison of resonance curve with standing wave pattern

between generator and pickup loop. In the resonance region the agreement is excellent. Actually the discrepancy serves to illustrate one of the advantages of this resonance method over conventional methods. It can be shown that, as illustrated in Figure 3, the voltage distribution along a transmission line as measured in the conventional standing wave method and the current distribution which is measured in the new resonance method are reciprocals of each other.[5] Thus, the resonance method requires the determination of the bandwidth of a maximum of current, whereas the standing wave method necessitates an investigation of a minimum of voltage.[7] Hence, the resonance method is less sensitive to stray fields and harmonic disturbances than the standing wave method. As a consequence, it is possible to measure with accuracy sample impedances which depart from the characteristic impedance of the line by factors up to 1,000.

By comparison with coaxial lines, open-wire transmission lines are flexible, accessible, and simple to construct. However, because of susceptibility to external disturbances and undesirable modes of excitation (as between system and ground), they are seldom used. The advantage of the resonance method, however, is that it makes it possible to obtain a high degree of accuracy with open systems. Measurements of the impedance of water have been conductance by the authors in the range from 36 to 200 centimeters, using an open-wire resonance system. The results are in good agreement with theoretical expectations.

Figure 4 shows measurements in this range, which have been obtained for blood, along with the results of other workers at higher and lower frequencies. The results are expressed in terms of dielectric constant and specific resistance. It can be seen that the data form a consistent pattern. The variation with frequency shown here is attributed to two different mechanisms. The existence of cell membranes in the blood causes a Maxwell-Wagner dispersion in the neighborhood of 1 megacycle.[8,9] This produces the change in the dielectric constant curve, which begins to appear, above 1 meter. The change below 30 centimeters results from Debye relaxation of the water molecules.[10] The dielectric constant between 30 and 100 centimeters is somewhat lower than that of water—54 as against 80 for water. This is explained by the presence of protein molecules.

Reflection and absorption coefficient α have been computed from these data and are presented in Table I. The absorp-

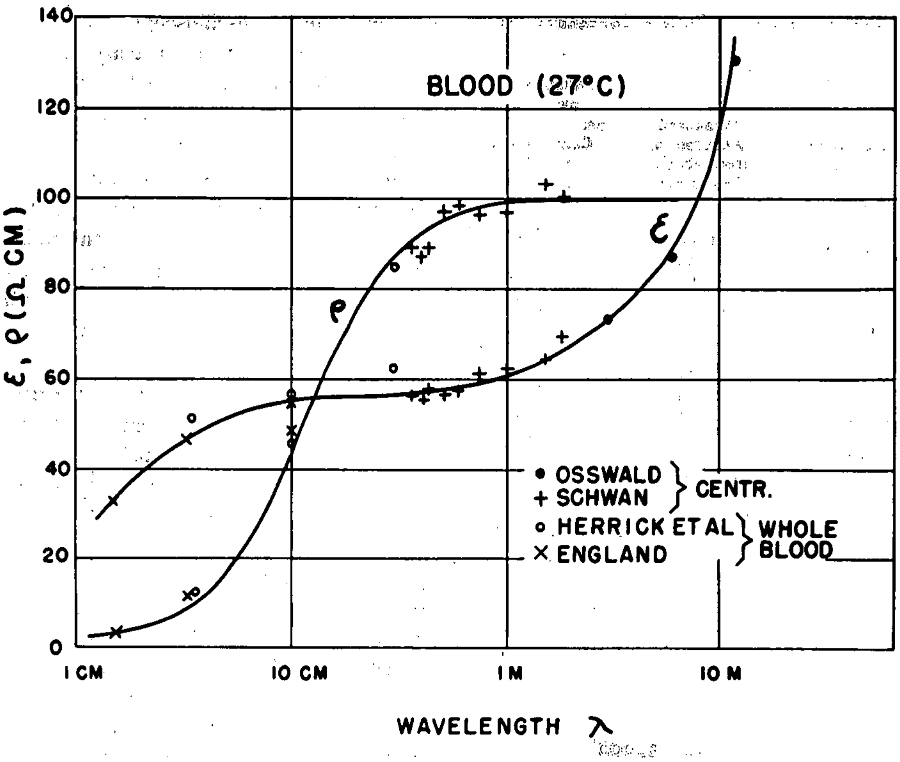

Figure 4. Dielectric constant (ε) and resistivity (ρ) of blood as function of wave length

Table I. Reflection and Absorption of Electromagnetic Radiation

Wave Length	Reflection Coefficient, Per Cent	Depth of Penetration (1/α)
10 meters	92	5 centimeters
1 meter	80	2 centimeters
10 centimeters	75	7 millimeters
1 centimeter	70	0.3 millimeter

tion is expressed in terms of depth of penetration of the intensity, that is, the depth in tissue at which intensity reaches $1/e$ of its surface value. Since cell membranes, proteins, and saline are from the electrical point of view the major constituents of all tissues of high water content, it can be said that the results for blood are characteristic of such tissue in general. The depth of penetration here decreases with decreasing wave length. For wave lengths less than 10 centimeters, the penetration is not significantly higher than could be obtained from surface heating. Use of wave lengths greater than 3 meters, on the other hand, is undesirable. If such relatively low-frequency energy is applied in form of electromagnetic radiation, any beaming is practically impossible. And, if it is supplied by high-frequency current, excessive selective heating of the subcutaneous fat layer results.[11] We therefore conclude that the optimum range for electromagnetic diathermy lies between 30 and 100 centimeters. In this range, the reflection coefficient for an air-tissue interface is rather high. It has been suggested for highest efficiency that the impedance between source and tissue be matched by filling the intervening space with a material of low loss and high dielectric constant.[12–15]

A similar approach has been taken in the investigation of the heating of tissue by high-frequency sound. Relatively little work has been reported on the acoustic impedance of tissue. However, measurements by Hueter[16] and Pohlman[17] have been sufficient to show that frequencies in the order of 1 megacycle are of interest for diathermy.

In an attempt to determine the cause of the relatively high absorption of sound observed for tissue, as compared with that for water, which is a major component of many of the tissues, the authors initiated a series of investigations on blood. Figure 5 is a diagram of the mechanical arrangement used in the measurements. The test vessel is divided into two compartments by a rubber diaphragm. One half is filled with degassed water, the other with the liquid under investigation. The transducers are mounted on a sliding assembly with the source in the water chamber and the receiver in the test liquid. The separation between the transducers is held constant and the transducer assembly moved along the axis of the test tank. Variation of receiving intensity with assembly position is used to obtain the absorption coefficient of the sample liquid. Barium titanate plates were used for transducers to cover the range 300–2,400 kilocycles. The magnitudes of the acoustic impedance for water and blood are approximately equal. Hence, there are only small reflections from the liquid interface, and refraction effects at this boundary are negligible. One of the greatest difficulties associated with conventional techniques for measuring absorption in liquids is that the output of the receiving transducer not only depends on the absorption of the liquid but is also a complicated function of transducer separation. This method avoids these difficulties simply by maintaining a constant transducer separation.

Effectively free field conditions are obtained through the use of pulsing techniques, see Figure 6. A pulse of radio frequency is applied to the source. The output of the receiver is amplified and

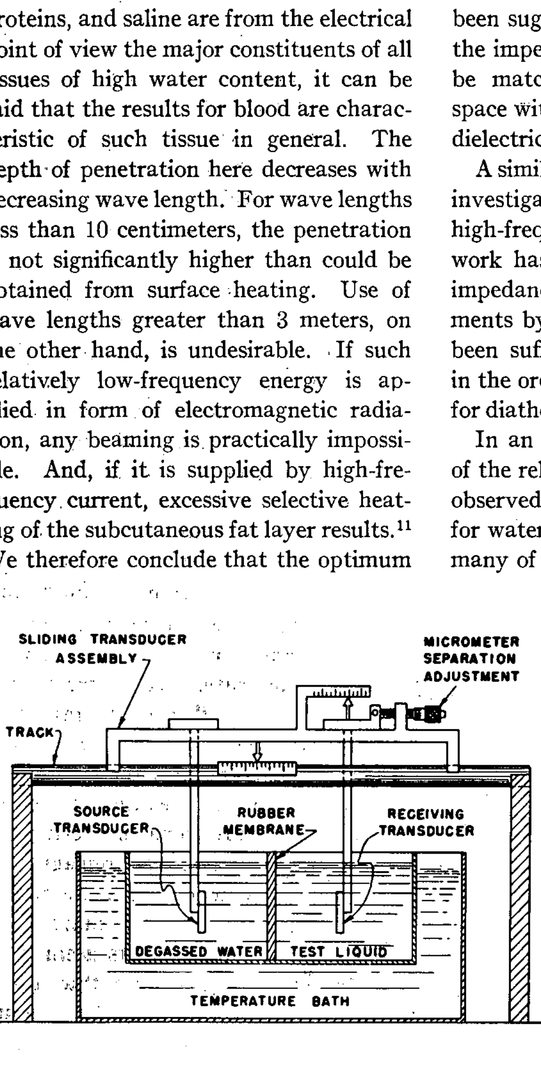

Figure 5 (left). Test cell for absorption measurements of ultrasound in blood

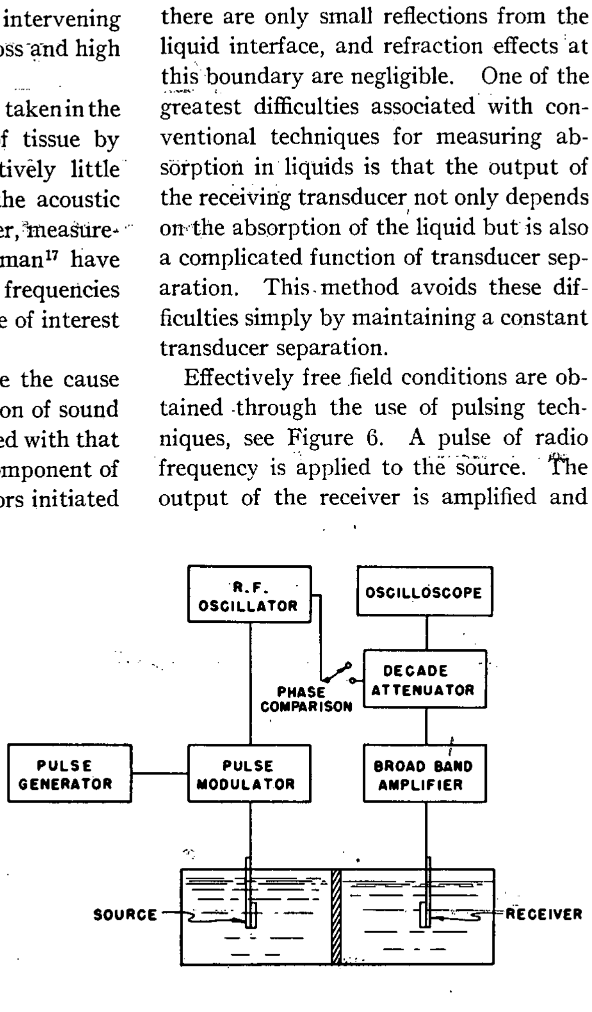

Figure 6 (right). Circuit of sound measuring equipment

Table II. Absorption of Various Biological Solutions as Related to Protein Concentrations

Frequency, Megacycles per Second	Temperature, Degrees Centigrade	Substance	Protein Grams, per 100 Cubic Centimeters	Measured Absorption, Decibels per Centimeter	Absorption per Gram per 100 Cubic Centimeters, Decibels per Centimeter
1.2	20	plasma	5.5	0.08	0.014
		red cells	32.0	0.40	0.013
		hemoglobin	7.0	0.09	0.013
		albumin	12.5	0.16	0.013
1.2	40	plasma	5.5	0.07	0.012
		red cells	32.0	0.34	0.011
		hemoglobin	7.0	0.08	0.011
		albumin	12.5	0.14	0.011
2.4	20	plasma	5.5	0.16	0.030
		red cells	32.0	0.94	0.029
		hemoglobin	7.0	0.17	0.024
		albumin	12.5	0.34	0.027
2.4	40	plasma	5.5	0.13	0.023
		red cells	32.0	0.77	0.024
		hemoglobin	7.0	0.15	0.021
		albumin	12.5	0.29	0.023

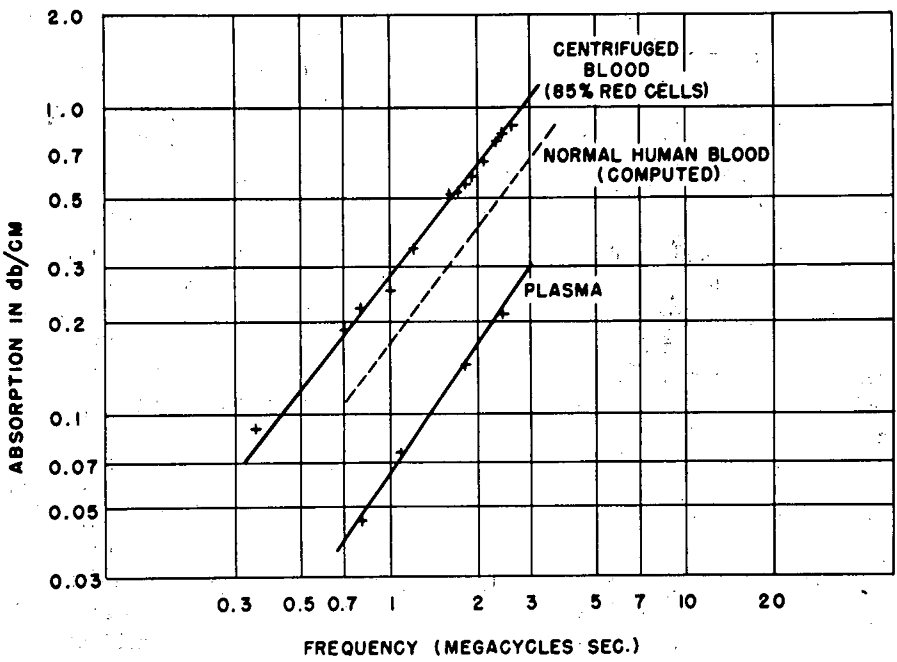

Figure 7 (above). Ultrasonic absorption of blood and plasma as function of frequency

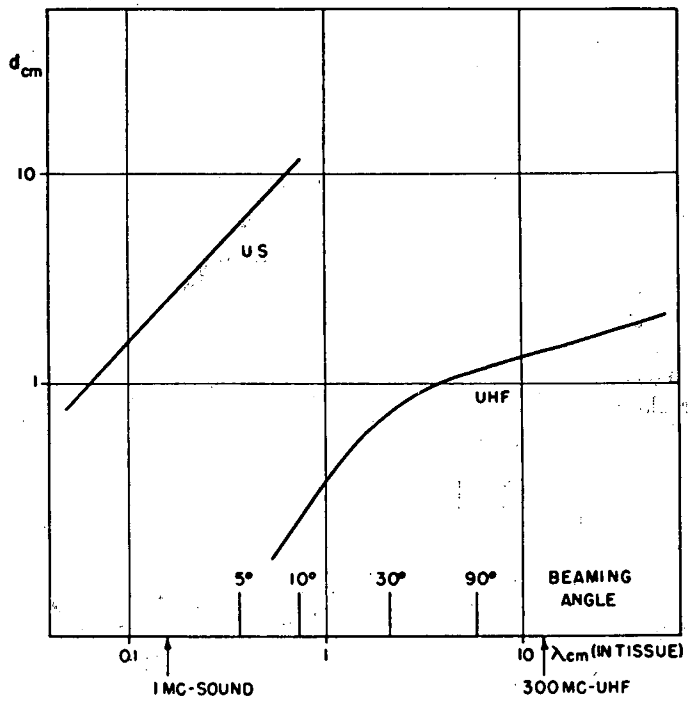

Figure 8 (left). Depth of penetration as function of beaming angle for various types of radiant energy

presented on an oscilloscope. The relative output intensity is measured by use of a decade attenuator which can be adjusted for constant signal at the oscilloscope.

For velocity of sound determinations, the wave length in the test liquid is measured by comparison of phase of the radiofrequency output of the receiver with a direct signal from the generator while the transducer separation is varied by micrometer control.

Figure 7 shows absorption as measured for the red cell residues of centrifuged human blood and for plasma.[18] The absorption is very nearly a linear function of frequency. The velocity of sound in blood is independent of frequency and approximately equal to that of water. In seeking the source of the absorption of ultrasonic energy by blood, it should be noted that the absorption in plasma which contains no cells is of the order of 25 times that for water. Further investigation as summarized in Table II[19] shows that the absorption goes in direct proportion to the protein content for blood and its components. Here the absorption, as measured at various frequencies and temperatures for concentrated red cells, plasma, and solutions of hemoglobin and albumin, is expressed in terms of absorption per unit quantity of protein present in the solution. The agreement in the results for various solutions shows that the proteins, whether in cells or in solution, are responsible for the absorption. Further, the protein content of many of the solid tissues is high enough to account for a large part of the observed absorption on this simple basis.

The actual situation in the solid tissues is somewhat more complicated. There also, however, the absorption appears to be a linear function of frequency and runs only one order of magnitude higher than that of centrifuged blood. Depths of penetration for solid tissues are of the order of 4–8 centimeters at 1 megacycle. Hence, frequencies up to approximately 2 megacycles can be useful for diathermy.

According to clinical reports, high-frequency sound can be used for many of the same applications as electromagnetic diathermy. It will be interesting to compare the two forms of radiation quantitatively on a specific problem, namely, that of the localized heating of the deep tissues. The directional properties of a piston source of either electromagnetic or acoustic energy depend upon the ratio of wave length to piston radius. The wave length of sound in its useful range is considerably smaller than that of electromagnetic radiation and thus sound may be more sharply beamed. This is shown graphically in Figure 8.[20] Here depths of penetration are plotted against wave length both for acoustic and electromagnetic radiation. The corresponding beam angle for a 5-centimeter radiator is also indicated along the abscissa. Over almost all of the useful range of sound the beam suffers practically no divergence. With even the shortest permissable wave lengths of electromagnetic radiation, however, the beaming is poor. From this analysis, it may be concluded that ultrasound is superior to electromagnetic radiation for the purposes of localized deep heating.

Summary

Measuring techniques are described for the dielectric constant and resistivity of biological material at ultrahigh frequencies and for the absorption of ultrasound. Electrical and acoustical data are presented for blood. The significance of these data with respect to the mechanism of absorption of the radiant energy is discussed. From a comparison using the electrical and acoustical impedance of tissue, it is possible to predict advantages of ultrasound over electromagnetic diathermy for the purpose of localized deep heating.

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