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Comparative Evaluation of Electromagnetic and Ultrasonic Diathermy

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Both ultrasonic and ultra high frequency electromagnetic diathermy have become available to the medical profession in the period following World War II. Both are forms of radiation diathermy, in which energy is radiated from generator into patient; in this sense they differ from short wave diathermy, in which the patient is a part of the electrical circuit of the generator. Although one is a purely mechanical phenomenon and the other electromagnetic, both ultrasonic and electromagnetic diathermy, as forms of radiant energy, may be studied by completely analogous methods. Thus, it is possible to make close quantitative comparisons of the heating effectiveness of the two forms of radiation diathermy.

Hot packs, infrared and other methods of surface application of heat fail to produce significant temperature rises at depths greater than one or two centimeters below the skin, because the heat so applied is carried away by blood flow before it can be conducted to the deep tissues. The various forms of diathermy, on the other hand, are able to produce desirable deep heating because the primary energy first penetrates into the tissue and then is converted into heat. Thus, the heat generation is determined largely by the depth to which the primary energy penetrates into the tissue. This *primary depth of penetration** is related to the physical properties of the tissue itself. Heat flow by conduction and convection will tend to smooth out temperature differences so that the final distribution of temperature as a function of depth of tissue will be somewhat different from the curve of heat production. From the actual temperature distribution, is determined what may be called an *effective depth of penetration.* The effective depth of penetration must be determined by direct temperature measurement. The primary depth of penetration of the radiation may be computed from the electrical and acoustical properties of the various tissues. The effective depth of penetration provides information of immediate concern to the physician. The primary depth of penetration is of more fundamental interest for it is this quantity which is directly controlled through design and application of diathermy equipment. It may be anticipated that a study of this fundamental quantity will point the way to basic improvements in radiation diathermy techniques.

Radiation techniques are suitable for purposes of deep heating only if they provide a noticeable increase in the effective depth of penetration, as compared to methods of surface heating. The effective depth of penetration is in general

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*The **primary depth of penetration** has a specific quantitative meaning when defined for a given homogeneous medium. In such a medium the intensity (primary energy flow per sq. cm.) decreases according to the exponential relation $I = I_o e^{2\lambda x}$ where ^{x} is the **absorption coefficient** of the medium. The primary depth of penetration is arbitrarily defined as the depth at which the intensity is reduced by absorption to $^{3.7}/_{10}$ of its surface value, i.e., $^{1}/e$. This applies to both forms of radiant energy but has no meaning in the case of short wave diathermy.

greater than the primary depth of penetration. Thus, to be useful, the primary depth of penetration of the radiation must be about as great as or preferably greater than the effective depth of penetration which can be obtained by surface application of heat.

Following are discussions of the data which lead to depth of penetration values for electromagnetic and ultrasonic radiation. Subsequently a comparison is made of various aspects of the heating effectiveness of the two forms of diathermy.

Electromagnetic Radiation

Once the dielectric constant and resistivity for a given medium is known, these data may be used to compute the absorption or depth of penetration of electromagnetic radiation in that medium. Measurements of these quantities for certain tissues and blood have been made, using bridge and transmission line techniques with excised samples. The picture for blood in the range of frequencies of interest to diathermy is essentially complete, with measurements by Osswald[2] and Schaefer[3] in the range below 100 mc. by Schwan[4] between 100 and 1000 mc., and Herrick[5] and England[6] from 1000 to 10,000 mc. These data are shown in figure 1*. Enough is known concerning the physical relationship between the constituents of tissue and their dielectric properties to say that this picture as it has been obtained for blood will apply very closely to all tissues with high water content. The corresponding depth of penetration values are given by the lower curve of figure 3. These then may be considered to apply for muscle tissue as well as blood. It can be seen from this figure that muscle frequencies greater than 1500 mc. have little to offer in depth of penetration that could not be obtained as well by surface heating.

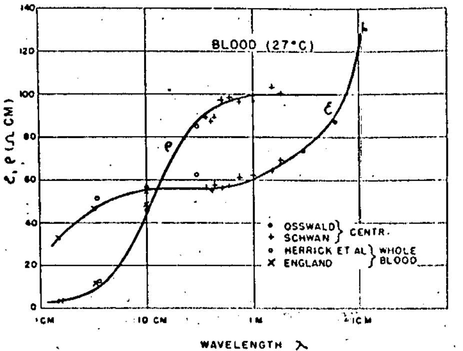

Fig. 1 — Dielectric constant and specific resistivity of blood as function of wavelength. The data of the various authors have all been referred to 27 C.; Herrick's and England's values, originally determined at 38 C., are corrected for 27 C., using temperature coefficients as given by Osswald[2], Corner and Smyth[13], and Schwan[14].

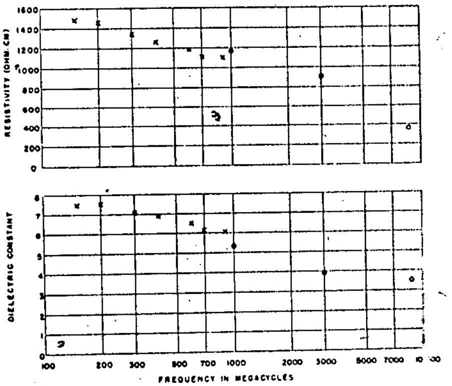

Fig. 2 — Dielectric constant and resistivity of fatty tissue as function of frequency. (The o's indicate Herrick's measurements and the x's indicate measurements used by the authors). Temperature 35 C.

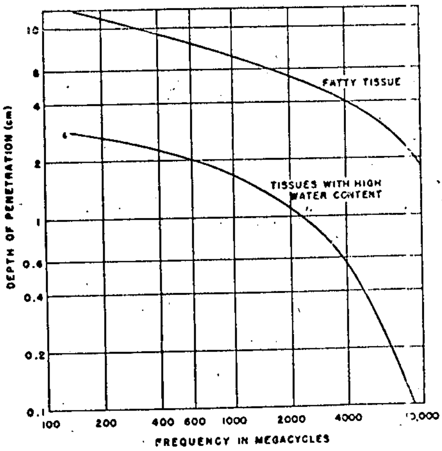

Fig. 3 — Depth of penetration of electromagnetic radiation as function of frequency in fatty tissue and tissues with high water content. Temperature about 35 C.

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*As the data are presented in figure 1, the abscissa is the equivalent wavelength of the radiation in air. This is related to frequency by $\lambda\nu = C$ where λ is wavelength in air (cm.), ν is the frequency in cycles/sec. and $C = 3.10^{10}$ cm/sec. is the velocity of electromagnetic waves in air. Thus, $\lambda = 10$ cm. corresponds to 3000 megacycles, $\lambda = 100$ cm. to 300 mc., etc.

The electrical properties of fat differ considerably from those of muscle. Data for fatty tissue have been reported by Osswald for the range below 100 mc., and Herrick for the range above 1000 mc. However, for the range 100-1000 mc., which is indicated for deep heating of muscle, no measurements of fatty tissue had been made. To complete the picture for fatty tissue, the authors measured horse and pork fat by transmission line techniques. Dielectric constant and resistivity of horse fat along with values of Herrick for dog fat are shown in figure 2. Dryer pork fat has a somewhat higher resistivity and lower dielectric constant than horse fat. Depth of penetration values calculated from the data of figure 2 are given by the upper curve of figure 3.

Ultrasonic Radiation

In the acoustic case, free field methods have been used which directly provide experimental values of the depth of penetration. Pohlman[7] reported measurements of the absorption in fat and muscle at 800 kc.

Ludwig[8] investigated the velocity of sound and density of muscle. Hueter[9] and Esche[10] have indicated that for tissues such as tongue, muscle, brain and glandular tissue, the absorption is a linear function of frequency. To help complete this picture, the authors have recently undertaken measurements of the absorption and velocity of sound in fatty tissue over an extended frequency range. Figure 4 is a summary of the absorption for fat and muscle as it appears in the light of present information. The data are presented in terms of depth of penetration of intensity for frequencies of interest for diathermy. The curve for fatty tissue represents the authors' measurements on pork fat as obtained at 30 C. for 37 C. depth of penetration values are obtained which are about 30% higher. Pohlman's measurement for muscle is also shown. The muscle curve (dashed) is drawn, using Pohlman's value for absorption in muscle and Hueter's observations of the linear dependence of absorption of this kind of tissue on frequency. The interesting observation here is that as in the electromagnetic case, the depth of penetration is greater for fat than for muscle.

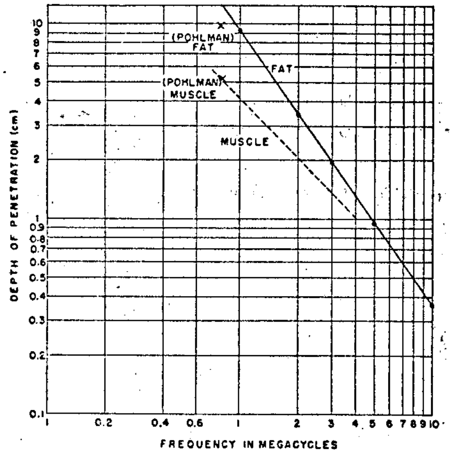

Fig. 4 — Depth of penetration of ultrasound in fat and muscle as function of frequency.

Comparison

Two aspects of the heating effectiveness of electromagnetic and ultrasonic diathermy may be compared quantitatively on the basis of the data already given.

1) *Heating of homogeneous tissues* — The depth of penetration values given in the preceding sections directly characterize the effectiveness of these forms of radiant energy for deep heating of homogeneous tissues. Since effective depths of penetration of from 1 to 2 cm. may be achieved by surface heating methods, the more elaborate diathermy procedures must provide somewhat greater penetration to be warranted. A depth of penetration in muscle of 2.5 cm. with electromagnetic radiation requires a frequency of the order of 200 mc., which is just about the lower limit for practical application of the ultra high frequency radiation technique in diathermy. On the other hand, by the data of figure 4, ultrasonic energy at frequencies of the order of 1 mc. provides depths of penetration of 4 or 5 cm. in muscle. This is the frequency commonly available in clinical ultrasonic genera-

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*Variation from sample to sample was found to be as great as 40%.

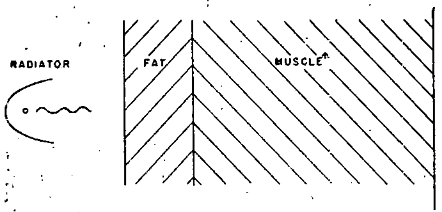

Fig. 5 — Production of heat in muscular tissue which is covered by a layer of subcutaneous fat.

tors. A large increase in the frequency over these values leads to heating which is little better than surface application of heat.

It may be concluded, therefore, that for deep heating of homogeneous tissues with high water content, ultrasound is superior to electromagnetic radiation. This becomes especially true if localized deep heating is desired, for ultrasound can be more sharply beamed than electromagnetic radiation in its useful frequency range[11].

2) *Heating of Fat-Muscle Layers.* — The production of heat in muscular tissue which is covered by a layer of subcutaneous fat (fig. 5) presents a somewhat different problem from that of homogeneous tissues[12]. Both forms of radiant energy have significantly higher depths of penetration in fatty than in muscular tissue. This suggests that the muscle can be selectively heated, and that the radiant energy may penetrate the fat to the muscle with relatively little loss in energy. However, the radiation problem is complicated by the fact that a fraction of the radiant energy is reflected* at the fat-muscle interface and may either add to or subtract from the incident wave to produce alternate maxima and minima of intensity within the fatty layer.

The magnitude and phase of the reflected wave can be calculated from the physical properties of the two media. Knowing this, it is then possible to compute the rate of production of heat per unit volume at each point in the fat-muscle configuration*. For the electromagnetic case, the relative heat production per unit volume is illustrated by the curves of figure 6. The reference level is taken as that in muscle at the fat-muscle boundary. The periodic variations in level in the fatty layer at higher frequencies represent the effect of standing waves on heat development. In the electromagnetic case, approximately 25 per cent of the energy incident at the fat-muscle boundary is reflected. This reflected wave has a phase such that it tends to reduce the field in fat near the interface. This is a fortuitous condition which at lower frequencies helps to reduce the heating of the fatty layer.

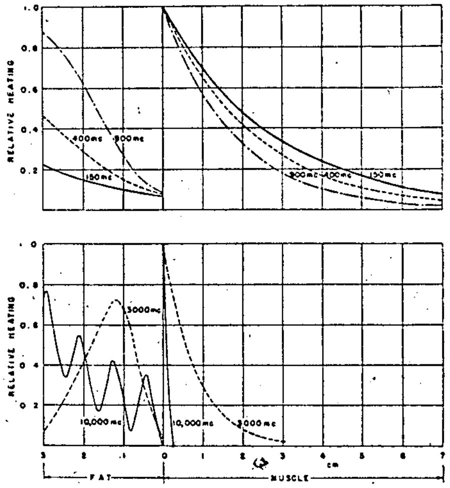

Fig. 6 — Relative heating of the fat-muscle configuration at various frequencies.

In the ultrasonic case only about 2 per cent of incident energy is reflected at a fat-muscle interface. This is sufficient to produce a standing wave pattern in the fat. However, since the wavelength of sound is small the maxima and minima of intensity are so close (roughly 1 mm. apart) that thermal conduction would easily smooth out irregularities in

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*Such a reflection of radiant energy occurs at the interface between any two different media, e.g., there is also a sizeable reflection at an air-tissue interface. It is possible in principle, however, to provide a coupling medium between source and tissue which will minimize this reflection. In the ultrasonic case, such a coupling medium, usually water, is essential to deliver any energy to the tissue. In the electromagnetic case, approximately 70 per cent of incident energy is reflected at air-muscle interface. Hence, even with electromagnetic diathermy, it appears highly desirable to use a suitable coupling medium.

*These calculations are described in detail in reference 12. For simplicity, it has been assumed that the waves are plane and arrive with normal incidence at the plane interface separating the fatty layer from a semi-infinite region of muscle tissue.

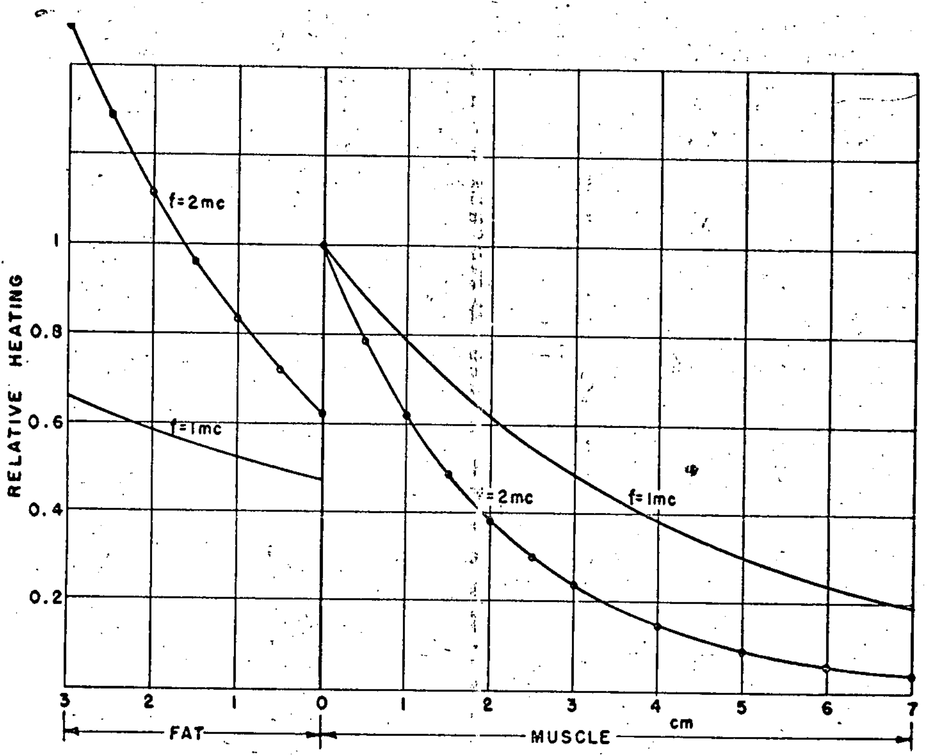

Fig. 7 — Relative heating of the fat-muscle configuration by ultrasonics. Temperature about 30 C. in fat and 37 C. in muscle. For 37 C. about 40% lower values are obtained in fat.

temperature. Relative rate of heat production per unit volume for the ultrasonic case is given in figure 7. Figures 6 and 7 illustrate in detail that for the lower frequencies, both electromagnetic and ultrasonic radiation tend to minimize heat development in the subcutaneous fat layer.

Perhaps as important as heat development per unit volume is the total heat production in fatty layer as compared to that in muscle. This is obtained by integrating the curves of figures 6 and 7. The results depend upon the thickness of the fatty layer. The case for 1 cm., 2 cm., and 3 cm. fatty layers is illustrated diagrammatically in figures 8a and 8b. In all cases, heat developed in muscle is used as the reference. It can be seen, that for the purpose of penetrating a 1 to 3 cm. layer of subcutaneous fat to produce heat in the underlying muscle, 500 mc. to 1000 mc. electromagnetic radiation has approximately the same effectiveness as 1 mc. ultrasound.

For the radiant heating of fat-muscle configurations as frequently found in the

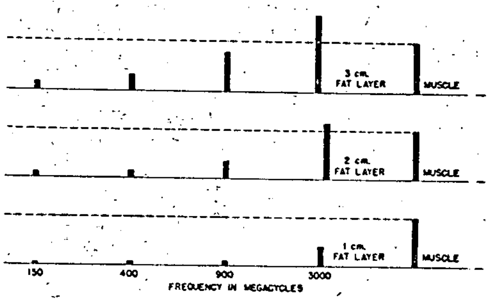

Fig. 8a — Total heat development in fat as compared to muscle by electromagnetic radiation at various frequencies and for various thicknesses of fat layer.

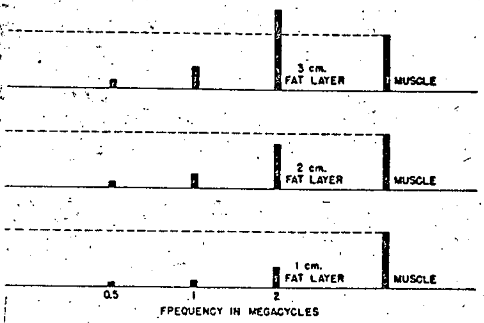

Fig. 8b — Total heat development in fat as compared to muscle by ultrasonic radiation at various frequencies and for various thicknesses of fat layer.

TABLE I

	U. H. F.				U. S.	
	500 Mc.		2500 Mc.		1 Mc.	
	Fat	Muscle	Fat	Muscle	Fat	Muscle
Depth of penetration	High	Medium	Medium	Low	High	Medium
Energy reflected at fat-muscle interface	Medium		High		Low	
Heat development	Low	High	Medium	Medium	Low	High
Beaming	Poor		Medium		Good	
Recommended application	Non-localized deep heating		Surface heating		Localized deep heating	

human body, the following important rule holds. The ratio of heat developed in the subcutaneous fatty layer to that in the underlying muscle becomes greater with increasing frequency. This is true for both types of radiation diathermy, electromagnetic and ultrasonic. Reverse of this rule holds true for short wave diathermy where undesirable heat development in subcutaneous fat is reduced by increasing the frequency.

Summary

On the basis of the electrical and acoustical properties of fatty and muscular tissues, depths of penetration of electromagnetic and ultrasonic radiation have been computed and an analysis of the field pattern due to reflection of radiant energy from fat-muscle boundaries has been carried out from which it is concluded: 1) that to obtain depths of penetration in homogeneous muscle which are superior to that obtainable by surface heating methods, 200 mc. electromagnetic radiation or 1 mc. ultrasonic radiation are suitable; 2) that to obtain desirable heating of muscle which is covered by a layer of subcutaneous fat, electromagnetic radiation at frequencies from 500 to 1000 mc. and 1 mc. ultrasound are recommended, and 3) that the ratio of heat developed in subcutaneous fat to that in muscle and other tissues of high water content increases as the frequency increases.

The conclusions of the above comparison are summarized in table 1. The cases illustrated are for 2450 mc. microwave radiation, which is the frequency commonly used in clinical practice today, as well as 500 mc. ultra high frequency electromagnetic radiation, which is recommended on the basis of the foregoing findings, and 1 mc. ultrasound. Ultrasound is especially suited for localized deep heating, while ultra high frequency electromagnetic radiation at roughly 500 mc. shows promise for purposes of more generalized deep heating.[11,12]

References

1. Schwan, H. P.; Carstensen, E. L., and Li, K.: Application of Electric and Acoustic Impedance Measuring Techniques to Problems in Diathermy. Transactions and Bimonthly Publications, American Institute of Electrical Engineers 6:106, 1953.
2. Osswald, K.: High Frequency Conductivity and Dielectric Constant of Biological Tissues and Fluids. Hochfrequenztechnik und Elektroakustik 49:40, 1937.
3. Schaefer, H.: Measurement of High Frequency Absorption in Blood and Its Components in the Range of Short Electrical Wavelengths 3 to 6 Meters. Ztschr. f. d. ges. exper. Med. 92:341, 1933.
4. Rajewsky, B., and Schwan, H.: The Dielectric Constant and Conductivity of Blood at Ultrahigh Frequencies. Die Naturwissenschaften 35:315, 1948.
5. Herrick, J. F.; Jelatis, D. G., and Lee, G. M.: Dielectric Properties of Tissues Important in Microwave Diathermy. Federation Proc. 9:60, 1950, and personal communication.
6. England, T. S.: Dielectric Properties of Human Body for Wavelengths in the 1-10 cm. Range. Nature 166:480, 1950.
7. Pohlman, R.: The Absorption of Ultrasound in Human Tissue and Its Dependence on Frequency. Physikalische Ztschr. 40:159, 1939.
8. Ludwig, G. D.: The Velocity of Sound Through Tissues and the Acoustic Impedance of Tissues. J. Acoustical Soc. America 22:862, 1950.
9. Hueter, T.: Measurement of Ultrasonic Absorption in Animal Tissue and Its Dependence on Frequency. Die Naturwissenschaften 35:285, 1948.
10. Esche, R.: Investigation of the Absorption of Ultrasound in Animal Tissue

and Plastics. Akustische Beihefte 1:71, 1952.

11. Schwan, H. P., and Carstensen, E. L.: Advantages and Limitations of Ultrasonics in Medicine. J.A.M.A. 149:121, 1952.
12. Schwan, H. P.; Carstensen, E. L., and Li, K.: Heating of fat and muscle layers by electromagnetic and ultrasonic diathermy. Transactions & Bimonthly Publications AIEE 6:483 (Sept.) 1953.
13. Corner, W. P., and Smyth, C.: The Dielectric Dispersion and Absorption of Water and Some Organic Liquids. J. Am. Chem. Soc. 65:382, 1943.
14. Schwan, H.: The Conductivity of Blood and Blood Serum at Different Temperatures. Ztschr. f. d. ges. exper. Med. 109:531, 1941.

Discussion

Dr. Thomas P. Anderson (Hanover, N. H.): The comparison of action in tissues of electromagnetic energy and sound vibrations is difficult because of the difference in the nature of their wave propagation and therefore, their difference in physical behavior in tissue. However, it has been helpful to have pointed out in this paper the selection of proper frequencies for both these forms of energy and also the importance of the thickness of the subcutaneous fatty layer. By using the frequencies recommended here one can minimize the heat developed in the subcutaneous fat layer.

In considering the use of these new forms of energy in medicine, the question arises: "Why is deep heating desirable?" It is generally thought that heat is applied to relieve pain, the mechanism of action being the increase of circulation. Is the increase in circulation greater with the deeper heating of these two forms of energy than the increase of circulation that comes about with superficial heating by other more common forms of energy? From a clinical evaluation, there appeared to be no particular advantage in relieving pain with the deeper heating as reported in Friedland's clinical studies with ultrasonic energy which were made last year.

There should be some qualifications on the author's generalization that the effective depths of penetration of heat is the same for tissues of the same water content and, therefore, the same for blood and muscle. In using ultrasonic energy, one has to consider that muscle is not a homogeneous tissue but has many tissue interfaces which greatly alter the transmission of the ultrasonic energy through the muscle tissue.

It is a pleasure to hear a paper with a scientific approach to the problems involved in using ultrasonic energy and ultra high frequency electromagnetic radiations in medicine instead of the usual clinical impressions which are more often recorded in the literature.