Glaser

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DETERMINATION OF THE ABSORPTION OF MICROWAVE RADIATION BY A BIOLOGICAL SPECIMEN IN A 2450 MHz MICROWAVE FIELD

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Abstract—Research into the biological effects of microwave radiation has expanded over the past few years. More detailed and complex experimental work is necessary in order to assist the responsible agencies in setting safe levels of exposure. It is important that the amount of energy absorbed by the biological specimen or the dose to the specimen be accurately determined. Unless this dose parameter is known, the results of the study will be of limited value. This paper provides a technique for determining the energy absorbed by a biological specimen in a laboratory situation. The time–temperature profiles were measured by using a thermistor which was tested for its microwave field insensitivity. A mathematical technique for determining the time–temperature profiles for exposures at any power density is presented.

INTRODUCTION

With the increased use of microwave radiation in domestic and commerical ovens, communications, industrial processing, radar and medical diathermy, and therefore, the increased potential for exposure of larger segments of the population, research into the biological effects or possible health hazards has received renewed emphasis. In order to set safe levels of exposure which will prevent harmful effects to individuals and not unduly restrict the beneficial use of microwave radiation, well designed, quantitative investigations are essential.

A large amount of research into the biological effects of microwave radiation has been done.[1–3] Due to the lack of accurate measurements of the energy density of the microwave fields and the energy absorbed by the biological specimen, much of the information is of limited value for determining safe exposure levels. The failure to adequately quantify the investigations has resulted in a disagreement in the scientific community as to whether there exists harmful nonthermal or specific effects, or if all harmful effects are thermal in nature.[4,5] Since the measurement of the microwave energy absorption is difficult due to the interaction of the microwave field with the measuring device and the possibility that the detector when placed in the specimen causes changes in the absorption patterns; this failure to quantify the results is not surprising. Any future bioeffects research must have accurate measurements of fields and doses to the specimen in order to provide information which can be used to set safe levels of exposure to microwave radiation.

Not any single detector or technique for determining the dose to a biological specimen will apply to all exposure situations. Parameters such as frequency or wavelength of the radiation, whether the field is continuous wave, pulsed, or modulated, and the shape, size, and characteristic of the biological specimen must be considered in the experimental design. This paper presents a technique for evaluating the dose to small biological specimens in the laboratory when exposed to a 2450 MHz CW microwave field. The detector used is a thermistor which has been tested for its insensitivity to this 2450 MHz CW microwave field. A mathematical description of the results is presented which provides the capability of determining the dose at any power density after measuring the time–temperature profile at one power density.

EXPERIMENT AND ANALYSIS

The microwave exposure system used in this study generates a 2450 MHz CW microwave field and is described in Ref. 6. The system is

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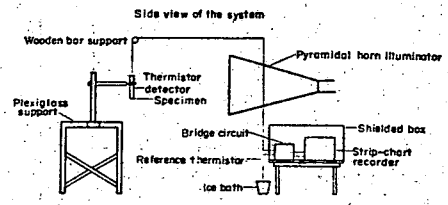

FIG. 1. Experimental exposure system consists of an absorber-lined, pyramidal horn illuminator. The specimen was a 5 ml sample of distilled water in a plastic test tube.

capable of producing a power density range at the specimen of 0–500 mW/cm² over a 6 in. diameter circle. The source of the radiation is a magnetron and the radiator is a pyramidal horn.

The experimental arrangement is shown in Fig. 1. The simulated specimen was 5 ml of distilled water in a plastic test tube. The test tube was supported at the top by a plexiglas test tube holder supported by a plexiglas frame. The detector used to measure the change in temperature was a thermistor with a 0.15 in. bead. The thermistor was tested to determine if there were interaction effects with the microwave field, or if artifacts were produced by the presence of the thermistor in the simulated biological specimen. The temperature detection system is shown in Fig. 2. The reference thermistor was identical to the test thermistor. The variable resistances in the bridge arrangement

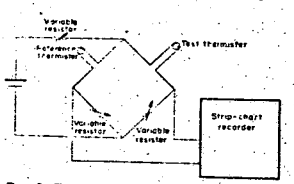

FIG. 2. The thermistor readout circuitry included a bridge arrangement with variable resistors to adjust for maximum sensitivity. The output from the bridge circuit was recorded on a strip-chart recorder.

had an upper limit of 10,000 Ω. These variable resistors in conjunction with the scales on the strip-chart recorder allowed adjustment of the system to any desired sensitivity. The solid state strip-chart recorder and bridge circuit were placed inside a copper screen wire enclosure to shield them from any extraneous fields. The connectors of the test thermistors were not in the microwave field but plugged into the bridge circuit inside the screen wire enclosure. The leads of the test thermistor were inserted into a 0.20 in. diameter braided copper shield which extended to within two inches of the thermistor tip. The braided copper shield and the copper screen wire enclosure were grounded to the recorder ground so that all components had a common ground. The power density at the test thermistor was set at 100 mW/cm² by using the Narda power density meter and probe (model 8100). The time–temperature profile of the thermistor placed in air at the specimen location is shown in Fig. 3. The temperature at the thermistor tip were also measured with a precision mercury thermometer immediately after the microwave field was terminated. These temperatures are shown in Fig. 3 and agree within 0.1°C with the values measured by the thermistor. Therefore, the temperature rise at the thermistor location is a real one and not due to the specific heating of the thermistor bead or an artifact caused by the electromagnetic interaction with the leads. The rise in temperature at the thermistor location was found to be due to the heating of the absorbing material surrounding the specimen location and its irradiating to heat the cavity space.

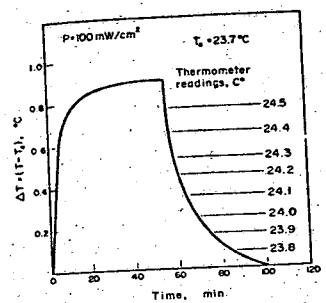

FIG. 3. The time–temperature profile for the thermistor placed in the microwave field with air as the surrounding medium is presented. Immediately after the power was terminated, a thermometer was placed at the thermistor location to check the thermistor temperature measurements.

Guy[7] has shown that metal electrodes increase the local absorption of microwave energy by two orders of magnitude. Tests were performed to determine if the presence of the thermistor in the 5 ml of distilled water caused any change in absorption. The 5 ml specimen was exposed to a 100 mW/cm² power density level with the thermistor in the solution while the microwave source was operating. The time–temperature profile was measured. The solution was then exposed to 100 mW/cm² without the thermistor in the solution while the field was on, but immediately after the field was terminated the thermistor was placed in the solution and the cooling curve was recorded. This second test was also performed by placing a thermometer and a copper-constantant thermocouple with a 0.05 in. bead into the solution after the field was cut off. The thermocouple was used due to its fast response time. The results of these tests are shown in Fig. 4. The cooling curves for all the tests are in agreement within the experimental accuracy of our investigation. These results indicate that the presence of the thermistor in the 5 ml specimen during irradiation does not produce a change in absorption.

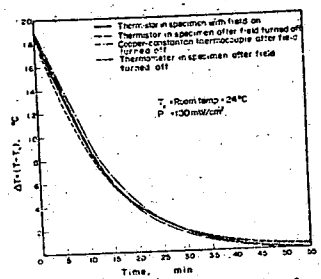

FIG. 4. The cooling curves of the specimen after the microwaves were cut off were measured by various techniques in order to determine if the presence of the thermistor in the specimen caused artifactual effects.

Time–temperature profiles for exposure to different incident power densities were recorded after the evaluation of the validity of our detector system. The exposures were always at 2450 MHz frequency, and the specimen was always 5 ml of distilled water in a plastic test tube. A rubber stopper with a hole for the thermistor was placed in the top of the test tube to prevent evaporation. These time–temperature profiles are shown in Fig. 5. The data presented for each power density is the average of four tests. The repeatability of the results is within 1°C. Some of this variation is due to the change in room temperature which can be maintained within $\pm\frac{1}{2}$°C of a predetermined level.

The time–temperature profiles in Fig. 5 can be mathematically described by the use of basic thermodynamic concepts. The change in temperature of the specimen with change in time can be expressed by the equation

$$\frac{dT}{dt} = \frac{P'}{cm} - k(T - T_0), \qquad (1)$$

where P' is the energy absorbed by the specimen per unit time, c is the specific heat of the specimen material, m is the mass of the specimen, k is a heat loss coefficient, T is the temperature of

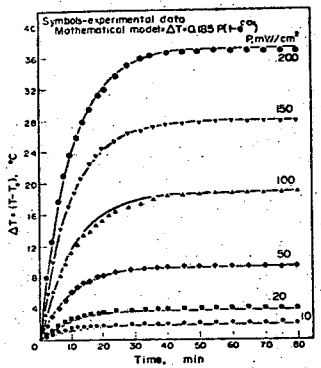

FIG. 5. Comparison of experimental and mathematical time–temperature profiles are presented. The experimental profiles are the average of four tests made on each of the exposure levels.

the specimen at time t, and T_a is the temperature of the specimen at $t = o$.

In the case of microwaves impinging on the 5 ml specimen in the test tube, the energy absorbed is not equal to the energy incident. Therefore, equation (1) can be written as a function of the incident intensity, P,

$$\frac{dT}{dt} = KP - k(T - T_a), \qquad (2)$$

where T is in °C, t is in minutes, P is in mW/cm², and K is a measure of the absorbing characteristics of the specimen in units of (°C/min/mW/cm²). The temperature rise at any time t, ΔT, can be expressed by

$$\Delta T(t) = T(t) - T_a. \qquad (3)$$

Equation (1) then becomes

$$\frac{d\Delta T}{dt} = KP - k\Delta T. \qquad (4)$$

Equation (4) can be integrated and the solution is

$$\Delta T(t) = \frac{KP}{k}(1 - e^{-kt}). \qquad (5)$$

The absorption coefficient, K, can be found from the initial slopes of the time–temperature profiles,

$$\left[\frac{d\Delta T}{dt}\right]_{t=o} = KP \quad \text{or} \quad K = \frac{[d\Delta T/dt]_{t=o}}{P}.$$

Using the average initial slope of all the curves in Fig. 5, the value of K was determined to be 0.0185 (°C/min)/(mW/cm²).

It is now necessary to determine the heat loss coefficient, k. From the time–temperature profiles in Fig. 5, it can be seen that at large values of t, the temperature remains constant with increasing time of exposure. At large values of t, equation (5) becomes

$$\Delta T(t) = \frac{KP}{k}. \qquad (6)$$

Using the value for K of 0.0185 in equation (6) the value of k is found to be equal to 0.10 min⁻¹. Inserting the values of K and k into equation (5), the final equation describing the time–temperature profiles is

$$\Delta T(t) = 0.185\,P\,(1 - e^{-0.10t}). \qquad (7)$$

The calculated time–temperature profiles are also plotted in Fig. 5. The calculated and measured profiles agree within one degree centigrade of each other throughout the time period and the power density range.

DISCUSSION OF RESULTS

The measurement or mathematical calculation of the time–temperature profiles are important techniques for determining the dose to or energy absorption by a biological specimen. Another technique for measuring the energy density at a given location would be the measurement of the electric and magnetic fields. Inside biological material these measurements are very difficult to perform due to the size of the detectors, the complex fields inside biological material, and the lack of information concerning the electric properties of the material. Therefore, at present the determination of the temperature rise in the biological specimen is the most commonly used technique for evaluating the amount of microwave energy being absorbed by the specimen.

Temperatures inside a biological specimen have been measured by several techniques. Guy[7] has used the thermograph camera for recording temperature distributions inside biological specimens. This technique has the advantage of eliminating the need for inserting a detector inside the specimen which might change the absorption characteristics. However, this thermographic technique has the disadvantage of requiring sophisticated sample preparation in some cases and cannot be used at all for some biological specimens in liquid media or interior regions where the integrity of the specimen must be maintained. Temperature sensors such as thermocouples and thermistors have also been used. Guy[7] has shown using the thermographic technique that metallic electrodes or probes, such as thermocouples, cause hot spots in the specimen. Thermistors are semiconductors whose resistance changes with change in temperature. The thermistor used in this study was evaluated for interaction problems, and for the conditions used in this study, no extraneous results could be measured.

The time–temperature profiles were measured four times at each power density setting. The data was repeatable to within 1°C from one test to another. The incident power density was measured without the 5 ml specimen by the Model 8100 Narda power density meter. The 5 ml specimen was then located at the same location the Narda probe had been when used to set the power density.

The experimental data has been accurately described by a mathematical equation. This mathematical solution can be very helpful in determining or specifying experimental conditions. Suppose an investigator is exposing bacteria or mammalian cells to a microwave field to evaluate if there are biological effects. It is important that he know the amount of energy absorbed by the specimen. In order to avoid the introduction of foreign biological matter into his specimen by the insertion of the thermistor, he can run the initial test for dosimetry purposes and obtain the time–temperature profile. From this time–temperature profile at a single known power density, he can determine his absorption coefficient, K, and loss coefficient, k, for his particular geometrical arrangement and use them in equation 5, to obtain a mathematical solution. Then the investigator can expose the specimen to any other known power density without the presence of the thermistor and calculate his time–temperature profiles from this mathematical solution.

The mathematical model can also be useful in performing experiments for the detection of nonthermal biological effects. Different techniques exist for studying nonthermal or specific effects. One technique is to measure the time–temperature profile of the exposed specimen and subject the control specimen to the same time–temperature profile. Any difference in effects between the exposed and the control specimens would then be specific effects. The mathematical description or model would assist in obtaining similar time–temperature profiles at various power density levels for both specimens. A second technique for determining nonthermal or specific effects is to subject the specimen to a power density level which maintains the specimen at a given temperature at which the specimen is viable—for example, bacteria at 37°C. The specimen can be exposed at any convenient power density level, the mathematical description can be formulated from the absorption and loss coefficients obtained form the time–temperature profile, and the power density level for maintaining the constant temperature can then be calculated from the mathematical description. Another technique for evaluating nonthermal or specific effects is to expose the specimen at a low level so that the small temperature rise does not have a thermal effect on the specimen—for example, suppose a 2°C rise in temperature causes no measurable thermal effects. Again time–temperature profiles can be measured at some convenient power density level, and the mathematical description can be obtained from the experimentally determined absorption and loss coefficients. The power density level can then be calculated from the mathematical formulation which does not produce a ΔT, temperature rise, greater than 2°C.

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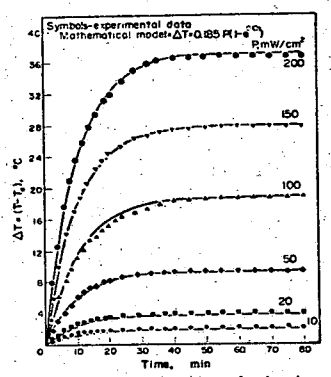

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The discussion above has presented examples where the technique would be useful in either

the determination of energy absorption or the level of exposure to obtain or maintain a given temperature in the specimen. These examples apply primarily to *in vitro* studies where the biological specimen is small and relatively homogeneous. As in the case of most existing techniques, the application to more complex systems such as animal studies is much more difficult. However, with some ingenuity the technique could be applied to specific tissues in animal systems where small probes can be implanted.

SUMMARY OF RESULTS

A mathematical description of the time–temperature profiles for exposure of a biological specimen to a microwave field has been determined. The equation

$$\Delta T = \frac{KP}{k}(1 - e^{-kt}),$$

describes the time–temperature profile. The absorption coefficient, K, and loss coefficient, k, can be obtained from one experimental time–temperature profile. These coefficients will depend upon the container holding the specimen, geometry of the specimen, electric properties of the specimen, whether the field is continuous, pulsed, or modulated, and the frequency of the radiation. After obtaining the mathematical model for the particular experimental situation, the model can be used to determine the time–temperature profile for any power density level. The mathematical model will be particularly helpful in determining the power density level which will hold the specimen at a desired constant level or will not increase the temperature above a given level. The validity of the model is dependent upon the capability of measuring the time–temperature profiles at one power density level so that the absorption and loss coefficients can be accurately determined. Extreme care must be taken to assure that the measured profiles are correct and not distorted by the interaction of the microwave field and the detector used to make the measurements.

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BIOLOGICAL EFFECTS IN RODENTS EXPOSED TO 10^8 PULSES OF ELECTROMAGNETIC RADIATION

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Abstract—Rodents were exposed to electromagnetic pulse (EMP) radiation to test the hypothesis that rapid changes in electric and magnetic fields would induce injuries in biological systems with high cell turnover rates. The AFRRI EMP generator provided five pulses per second with a peak electric field intensity of 447 kV/m with a 5 nsec rise time and 550 nsec 1/e fall time. Exposures, totalling 10^8 pulses, were continuous except for approximately 2 hr, 5 days per week for biological sampling and animal care during 38 weeks. Biological assays were periodically conducted in exposed and nonexposed animals at appropriate intervals.

It was observed that the reticulocyte count in exposed rats was nearly always greater than in nonexposed rats. However, there were no concomitant differences in peripheral erythrocyte counts between the two groups, nor did radioactive iron incorporation indicate increased cellular production in the irradiated group. Platelet counts in exposed rats were decreased about 10% below those in the nonexposed group most of the time. Levels or relative counts of circulating leukocytes did not differ between the two groups. Bone marrow cellularity was not different between the two groups. Analysis of chromosomes from bone marrow cells showed nodetectable increases of aberrations in EMP exposed rats. Routine chemical analysis of blood demonstrated similar values in the two groups. Histological studies indicated no effect of EMP. Observations of fetuses from pregnant rats showed no abnormalities. No incidence of mammary tumors was observed in the female Sprague–Dawley rats. In leukemia prone AKR/J male mice, leukemia did not occur earlier in EMP exposed animals, nor was the fraction of leukemic mice greater in this group when compared with the nonirradiated control mice.

The present experiment utilizing the above-described physical parameters represented a condition exceeding by several orders of magnitude that normally encountered by humans who operate EMP facilities. Exposures of rodents under these conditions indicated no apparent acute injuries.

INTRODUCTION

The utilization of electromagnetic pulse (EMP) generators by industry and military establishments and the exposure of personnel during routine operation have occurred in recent years (Bowers and Frey, 1972; Hirsch and Bruner, 1970). This potential hazard to man has been a matter of concern, and safety standards have been proposed (DeMoss, 1971). However, there are not enough biological data to establish firm standards.

Basically, EMP consists of a pulse of radio-frequency waves with a nearly instantaneous rise in the electric and magnetic fields and a subsequent decline in the fields. EMP radiation may be represented as a traveling wave consisting of transverse electric and magnetic oscillating fields; the amplitude of the oscillations is directly related to the power density of the field. There could be an effective energy exchange from the electromagnetic field to the medium whenever these forces are sufficient to alter the kinetic or potential energy of the molecules in the medium. A contributing effect of heat is not predicted because of the low average power of the EMP. It may therefore be questioned whether exposure to EMP could present a thermal hazard to man.

However, at the molecular level in biological systems there are vital ionic and electrochemical processes which could be altered by rapid pulses of electric and magnetic fields. These altered processes could acutely affect biological systems with high cellular turnover, such as the hematopoietic and the reproductive