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A STUDY OF THE HEATING PATTERN OF A BIOLOGICAL BODY INSIDE A RECTANGULAR WAVEGUIDE

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ABSTRACT - Research has been conducted to compute and measure the heating patterns inside a three-dimensional arbitrarily-shaped heterogeneous biological body inside a rectangular waveguide. The profile of dissipated power intensity and temperature was determined with satisfactory accuracy. Immediate application of this technique is to provide guidance for the design of microwave applicators for rapid inactivation of enzymes, for which uniform heating is an important consideration. Numerical computation and thermographic measurements were conducted for the case of rectangular-sided blocks. However, the computer program is capable of solving for arbitrary shapes.

The salient features of electromagnetic modeling of this problem has been previously reported (J.J.H. Wang, IEEE MTT Trans. 26, 457-462, 1978). Recently, the calculation and measurement of temperature distribution, which is directly related to the thermal inactivation of enzymes, were successfully conducted. The equivalent heat source due to the dissipation of electromagnetic wave is first determined by the dissipated electromagnetic power density which is then related to the temperature distribution by the heat equation. The experimental results were recorded with thermographic paper and a heat-sensitive camera. Satisfactory agreements were observed between calculation and measurement. A difficulty in the calculation of temperature distribution was experienced near the edge of the test block. This difficulty was overcome by using the heat equation instead of the usual method in which the temperature distribution was related to the dissipated power density with a proportionality constant.

SUMMARY

Introduction - The distribution of cyclic AMP in the brain can be used as an important tool in neurochemical research such as in the evaluation of the effects of hormones or drugs in the central nervous system. In order to determine the distribution of cyclic AMP, however, it is necessary to inactivate rapidly two enzymes, adenylate cyclase (AC) and phosphodiesterase (PDE), which produce and degrade cyclic AMP, if left inactive. Otherwise, the level of cyclic AMP concentration to be studied may be distorted in a few seconds after the animal is sacrificed. There are two types of widely-used inactivation techniques--liquid nitrogen freezing and microwave heating. The disadvantages of liquid nitrogen freezing include the slowness of the process, the nonuniformity of the freezing pattern throughout the brain, and the inconvenience in post-mortem dissection at freezing temperatures. With microwave heating, the inactivation of enzymes can often be achieved with exposure times on the order of 1-2 seconds of less, permitting subsequent required dissection of the brain at room temperature.

Microwave inactiviation can be carried out by an open or closed system. In the open system, a plane wave is employed to illuminate the animal without the direct interference of enclosing conducting boundaries. The disadvantages of the open system include a large power source required and the necessity of containment of radiated power with a conducting screen room or an anechoic chamber. The closed system, such as a rectangular waveguide, is highly efficient in power usage and has negligible leakage power which is desirable as far as radiation hazard and man-made noise are concerned. As a result, recent research in microwave inactivation techniques has been concentrated in the closed system type, such as the rectangular waveguide applicator (1).

Electromagnetic and Thermal Modeling - The analysis involves two steps, namely, the computation of the distribution of power dissipation and the calculation of the resulting temperature distribution. The first step involves the solution of an electromagnetic boundary-value problem which has been previously reported (2). The second step involves the solution of the heat conduction problem with the heat source represented by an equivalent distributed source of dissipated power density. The measurements were made by recording the temperature profiles with thermographic paper and a heat-sensitive camera.

Previous discussion of the electromagnetic modeling technique (2) did not provide sufficient details about the handling of the singularity of the Green's functions in the source region, which has recently become a subject of considerable controversy. In the present approach, the principal volume is chosen to be a rectangular-sided cell whose dimensions along the longitudinal axis approaches zero while dimensions in the other two coordinates remain constant. The selection of principal volume is

therefore in agreement with all the known views in the literature.

The thermal problem can be handled with the heat equation with appropriate initial and boundary conditions. The distributed heat source is the density of power dissipation of the electromagnetic wave. The heat equation being used is as follows:

$$\frac{\partial T}{\partial t} = a^2 \nabla^2 T + 4\pi a^2 s \quad , \tag{1}$$

where T = temperature distribution function,
t = time,
∇^2 = Laplacian operation,
a = $K/\rho c$, K being the heat conductivity, the density, and c the specific heat of the medium,
S = $P_d/4\pi K$, and
P_d = heat source distribution.

Both T and P_d in Equation (1) are functions of time t and the spatial coordinates. P_d represents the distributed source which is a known quantity computed from the electromagnetic model. The solution of Equation (1) together with all the initial and boundary conditions has been obtained for several elementary geometries. For complex geometries, numerical matrix methods such as the finite-difference method can be used. For simple cases, an approximate formula used by Guy (3) is very convenient. The short-term temperature rise T is approximately proportional to the power dissipation at the point of interest, namely,

$$P_d \cong \alpha \rho c \Delta T, \tag{2}$$

where ρ and c are defined in Eq. (1), and α is a coefficient related to the exposure time. Based on Eq. (2), the relative short-time temperature distribution is approximately the same as that of the power dissipation. Guy did not indicate the origin nor the rationale for Eq. (2). However, Eq. (2) can be considered to be a special case of Eq. (1) during a short period after t = 0. Since $\nabla^2 T = 0$ at t = 0−, as was the usual case, we have $\nabla^2 T \cong 0$ at T = 0+, and Eq. (1) can be approximated by Eq. (2).

Eq. (2) is often satisfactory when applied to the interior region of a homogeneous portion of a dielectric body of low thermal conductivity. It fails to provide useful results near the edge of the dielectric body or at the interface of two different types of dielectrics, as was noted by Guy (3). For example, Guy's measurement of temperature profile of a block, formed with muscle in Region 1 and fat in Region 2, exhibited gross deviation at the interface from his calculated power dissipation curve. Thus, Eq. (2) appeared to fail in the neighborhood of the interface between the fat and the muscle tissues. Guy then proceeded to correct this discrepancy by enforcing the continuity of temperature at the interface. Although his approach appears reasonable on a qualitative basis, many questions remain to be answered.

A more rigorous approach was taken in the present study by using the diffusion equation of (1). We first investigated the fat-muscle block of Guy and were able to obtain good numerical results. However, we have found that the temperature distribution is quite time dependent, being fastly varying in the first five seconds. Thus, the temperature profile cannot be simply established by recording within, say, five seconds after the heating.

Computations and Measurements - Two types of thermographic measurements were made: one using thermographic paper and the other using a thermographic camera. The thermographic paper measures the peak temperature during and after the exposure time but does not record accurate data. Furthermore, it is always difficult to place a thermographic paper at the proper location without affecting the experiment. The thermographic camera is more accurate but is also difficult to look at the interior of a tissue. Comparisons between the calculated and measured relative temperature profiles were made for rectangular sided blocks of muscle and Stycast Hi-K16, respectively; both were place inside a WR284 Waveguide operating at about 2450 MHz. While satisfactory agreements were observed, it was observed that Eq. (1) failed near the edge of the block. In one case, the measured temperature pattern dropped toward the distal (load) end of the block, while Eq. (2) predicted a rise of temperature toward the edge. However, when Eq. (1), the heat equation, was employed, a drop-off of temperature was also noted in the computed results to agree with the measurements. A complete description of the model and the experimental results will be given in presentation.

REFERENCES

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