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Thermal Field Analysis for *In Vitro* Exposure Apparatus in Rectangular Waveguide with Transversal Slits

Rui TOKUNAGA, Yukihisa SUZUKI, Toshiyuki TANAKA, and Masao TAKI
Graduate School of Engineering, Tokyo Metropolitan University
E-mail: ruit@com.eei.metro-u.ac.jp

Abstract: Numerical studies are performed on the temperature distribution in a microwave exposure setup for *in vitro* study. The setup is a waveguide with slits, on which a cell culture dish is placed to be exposed to 2.45 GHz microwaves. The maximum SAR is 50 W/kg at the location of cells for the input power of 0.7 W. We analyse the spatial and temporal characteristics of the thermal field in the exposure setup. The maximum temperature is 39.5 ℃ at an environmental temperature of 37 ℃, suggesting that the environmental temperature should be set about 2.5℃ lower than the desirable temperature at the cells. The temporal characteristics suggest that intermittent exposures cause little difference from continuous wave exposure in terms of temperature elevation due to the large time constant ($\geq$900 s) as compared with the period of pulse repetition.

Key words: SAR, *In Vitro*, High Frequency Electromagnetics, Intermittent Exposure, Thermal Field Analysis

1. Introduction

The opportunity for people to be exposed to an electromagnetic waves in daily life has been increasing with rapid spread of cellular phones. Accordingly, the concern about possible health risks from radio communication equipments is growing, so that investigation about safety against exposure to high frequency electromagnetic fields is needed.

In vivo studies, which use laboratory animals, have been thought as important measures in the health risk assessment of the living-body exposed to electromagnetic waves. If electromagnetic fields should cause any effects on laboratory animals, however, there arises a problem that it is difficult to study detailed information on biophysical mechanisms through *in vivo* experiments. Therefore, the experiments in cellular levels, or *in vitro* studies are also necessary.

Thermal effect is one of the influences that electromagnetic waves have on a living body. Present guidelines on limiting exposure to radio frequency (RF) fields imposed limitations on the value of specific absorption rate (SAR [W/kg]) based on the thermal effects. However, it is also necessary to consider possible non-thermal effects. The tissue is exposed to rather strong field in the case of local exposures in a small area in such a case as the exposure by a mobile phone. Temperature of the tissue does not rise significantly because the heat is rapidly removed due to blood circulation. For the purpose of the studies of non-thermal effects, it is necessary to distinguish the outcome due to physical factors, such as heat and temperature slope, from effects of electromagnetic fields.

What has to be noticed is that it becomes the more difficult to distinguish the artifact of heat from real effects, as the exposure is the stronger. So, it is necessary to characterize the temperature change due to the exposure as correctly as possible.

In order to grope for experimental conditions to solve such a problem, we developed a computer program to analyze the thermal field in a container. The program make it possible, by using the result of the electromagnetic analysis by the FDTD method, to analyze the spatial and temporal characteristics of temperature distribution of the object for arbitrary exposure conditions.

In this research, numerical analyses with two exposure conditions are performed. One condition is to expose the object to the continuous electromagnetic field of a fixed strength. Another is to expose the object intermittently or instantaneously. The time course of the temperature change is calculated to examine if the thermal condition is equivalent to that of the continuous exposure with the same average power.

2. Thermal Field Analysis

Thermal fields are analysed using the technique of numerical simulation. Because the thermal field may influence the living body, we should know the spatial and temporal characteristics of thermal field as correctly as possible, when an experiment on non-thermal effects is performed.

2.1 Heat Conduction Equation

The thermal fields surrounded by a boundary can be analyzed by solving a heat conduction equation, an the assumption that the heat is transported only by conduction. It is necessary to set up a suitable initial value and boundary conditions to obtain an appropriate solution. The heat conduction equation is given by

$$\rho c\frac{\partial T}{\partial t} \quad = \quad \nabla \cdot (k\nabla T) + \rho \times SAR \qquad (1)$$

where ρ is the density [kg/m^3], c is the specific heat [J/K·kg], T is the temperature [K], k is the thermal conductivity [W/m·K], SAR is the amount of absorbed energy per unit mass, and is given by

$$SAR = \frac{\sigma E^2}{\rho} \tag{2}$$

where σ and E are the conductivity and the magnitude of internal electric field, respectively. The thermal distribution is calculated by finite difference method based on equation (1).

2.2 Boundary Conditions

The transportation of heat is expressed by heat flux defined by $\vec{q} = -k\nabla T$ [W/m^2]. The heat flux on the boundary is given by the boundary condition as follows;

$$\vec{q} \cdot \vec{n} = h(T_w - T_f) \tag{3}$$

where $\vec{n}$ is the normal vector of the boundary, h [W/m^2] is the heat transfer coefficient. T_w and T_f [℃] are the temperatures of the fluid distant enough from the boundary facet and near the boundary facet, respectively.

Although the heat transfer coefficient depends on very many parameters, we assume for simplify that the heat transfer coefficient is fixed in the calculation model.

2.3 Stability Conditions

Cell-size was set 0.5 mm to model the 1 mm-thick wall of a cultivation container. Then, the time-step was set 1 ms, which is the maximum value satisfying the stability condition derived from the cell size.

3. Models and Method

The apparatus to be investigated is a rectangular waveguide with transversal slits, which was developed in our previous study [2]. The frequency used is 2.45 GHz, and the TE_{10} mode (the basic mode of the waveguide) is employed. Figure 1 shows the calculation model. Cells are placed at the bottom of the cultivation container, which is divided into four small compartments. We choose four points(points A, B, C, and D) as reference points in the bottom along the center of the container. We calculate the thermal field in the whole container but we will show the results only at those reference points.

Assuming that cells are cultivated within an incubator prior to the exposure, the initial temperature of the medium, the cultivation container, the metal, and the inner air are set 37 ℃ in our analysis. Since the experiment is performed in another incubator, we can set a different environmental temperature during the exposure.

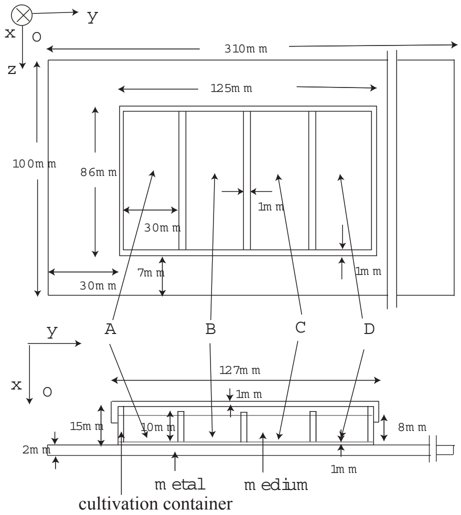

Figure 1: model

Table 1: Constants of Materials Used for the Cultivation

	k[W/m·K]	ρ[kg/m^3]	c[J/K·kg]
medium	6.0×10^{-1}	1.0×10^{3}	4.2×10^{3}
cultivation container	8.0×10^{-2}	1.1×10^{3}	2.0×10^{3}
metal	7.0×10	2.7×10^{3}	9.2×10^{2}
air	2.4×10^{-2}	1.2	1.0×10^{3}

The constants of materials used for the calculations are shown in Table 1. The values for the medium are assumed as those of water.

The SAR distribution is obtained from a result of FDTD analysis of the electromagnetic fields using equation (2). The SAR distribution used in the study is shown in Figs. 2 and 3 for the maximum SAR value of 50W/Kg. The maximum SAR is around the point B.

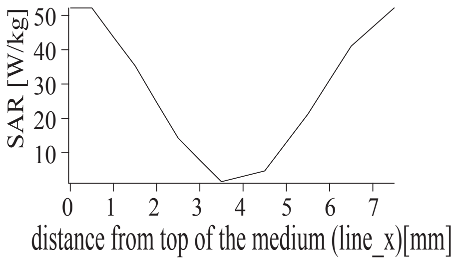

Figure 2: SAR distribution along the line passing the point B in parallel to x-axis.

4. Analysis Conditions

4.1 Continuous Exposure

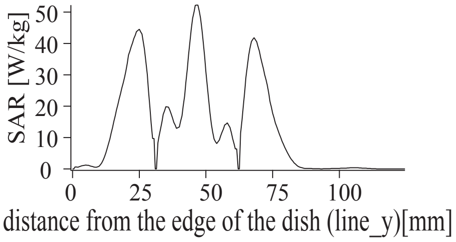

Figure 3: SAR distribution along the line passing the point B in parallel to y-axis.

One exposure condition is continuous exposure. We analyzed the thermal fields for the continuous exposure conditions for two different temperature of the surrounding area, 37℃ and 35℃.

4.2 Intermittent Exposure

Another exposure condition is intermittent exposure. We can expose the cells to more strong electromagnetic fields, keeping the average power the same, by using this method. The influence may differ between being exposed to strong fields only for a short time, and being continuously exposed, even if they have the same average power. On the other hand, the thermal condition is expected to be determined by the average power.

5. Results

5.1 Continuous Exposure

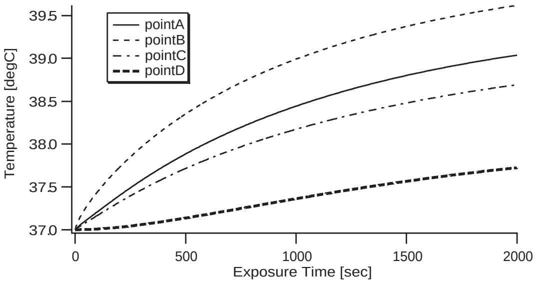

Figure 4: Time response of the temperature at the point B in case of the temperature of the surrounding air set to 37 ℃.

Figure 4 shows a result of the analysis of the time response of the temperature at the position of points A to D when the environmental temperature is set 37 ℃. It shows that although the system does not reach the stationary state in 2,000 seconds, the temperature of the medium of the point B is already higher than 39.5 ℃, indicating that the temperature at the stationary state is too high to investigate non-thermal effects. The time constant in this case is about 9.0×10^2 seconds.

Figure 5 shows a result of the analysis of the time response of the temperature at points A to D when the environmental temperature is set 35 ℃. The result shows that, after 2,000 seconds, the thermal environment reaches the stationary state, and that the temperature at the point B converges to about 38 ℃.

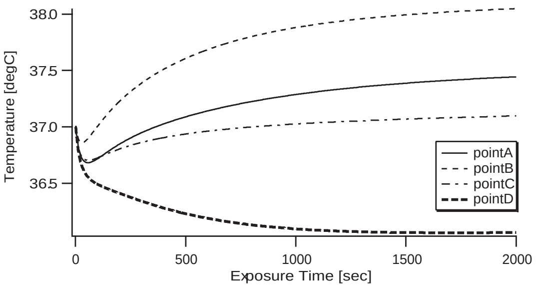

Figure 5: Time response of the temperature at the point B in case of the temperature of the surrounding air set to 35 ℃.

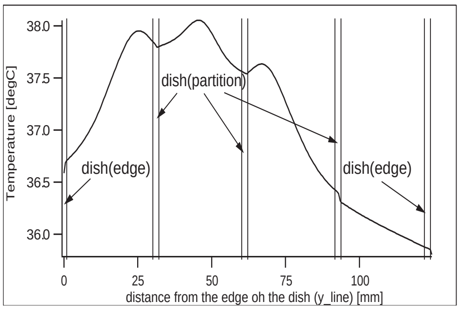

Figure 6: Temperature distribution along the line passing the point B in parallel with y-axis.

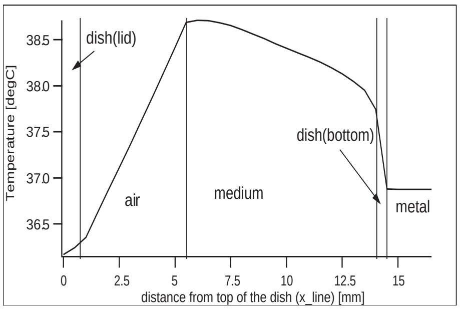

Figure 7: Temperature distribution along the line passing the point B in parallel with x-axis.

Figures 6, 7, and 8 show the temperature distributions along the lines passing the point B and parallel to the y-, x-, and z-axes, respectively, after 2,000-second exposure under the condition that the surrounding air is 37 ℃. The temperature distribution of the culture medium along the x direction (Fig. 7) shows that the temperature becomes higher as approaching the surface of the culture medium. This temperature distribution is not likely to cause convection of the culture

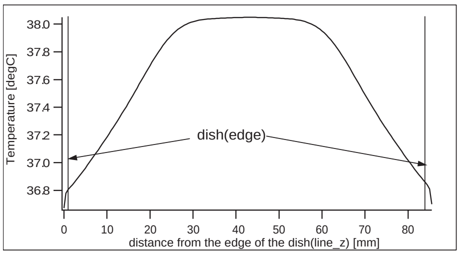

Figure 8: Temperature distribution along the line passing the point B in parallel with z-axis.

medium. This result is preferable for the experiment because the convection would give mechanical stress to cells.

5.2 Intermittent Exposure

The duty ratio of the intermittent exposure is given by the following equation.

$$\text{(duty ratio) } [\%] = \frac{H}{T_u} \times 100, \qquad (4)$$

where H is a cycle, T_u is the exposure time for a cycle.

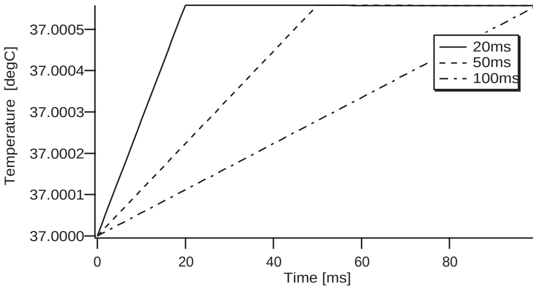

Figure 9: Temperature at the point B. (Duty ratio: 20%, 50%, 100%)

Figure 9 shows the time response of the temperature at the point B caused by the intermittent exposure for a cycle. The result shows the difference in the duty ratios causes little difference in the thermal field. Therefore, we guess that intermittent exposures cause little difference in thermal field from continuous exposures under the condition that a cycle of intermittent exposures is much smaller than the time constant(≥900 s) of temperature elevation.

6. Conclusion

The temporal characteristics of the temperature distribution in the cultivation container is analyzed. The result of continuous exposure shows that the time constant is 9.0×10^2 seconds in case of environmental temperature of 37 ℃. The temperature in the container rises over 39.5℃ in $2,000$ seconds. This condition is inappropriate for the investigation of non-thermal effects, since thermal effect could occur. The numerical analysis is also performed for another case in which environmental temperature is 35 ℃. The result shows that the maximum temperature converges to about 38 ℃

It is suggested from the results that intermittent exposures cause little difference in temperature from continuous wave exposure, because the time constant is large enough (≥900 s). Actually, the temperature does not depend on duty ratio in our results, if the average power is the same.

Acknowledgements

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