International Journal of Science and Technology



http://www.ejournalofsciences.org

# An Iterative Method for the Determination of Temperature Distribution in Patients Undergoing Brain Magnetic Resonance Imaging (MRI) Examinations

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## ABSTRACT

To measure directly, the temperature within the human brain is difficult because of the inherent problems associated with recording physiological variables during the operation of an MR scanner. The main aim of this study is to use numerical method to predict the temperature distribution in the brain of MRI patients. One hundred and twenty-six (126) patients were assessed at Diagnostic Imaging Centre and 37 Military Hospital, Ghana. A modified Pennes' bio-heat equation was solved using an iterative method based on the finite difference method (FDM) and MATLAB programming language theoretically and experimental results were used to validate the model. Results from the numerical model showed an average change in temperature of 0.03 °C, 0.04 °C, 0.07 °C and 0.08 °C for SAR values of 0.1 W/kg, 0.4 W/kg, 1.4 W/kg and 1.6 W/kg respectively. The results regarding the steady state temperature distribution, specific absorption rate and temperature rise compared and validated with the experimental data were all within acceptable safe levels.

**Key-words:** *finite difference method (FDM), bio-heat equation, temperature distribution, MATLAB Software*

## 1. INTRODUCTION

Thermal effects in setting standards for limiting human exposure to non-ionizing radiation is playing very important role [1]. The United States Food and Drug Administration (USFDA) guidelines has set a limit for the core temperatures and must not rise by more than 1 $^{o}$C [2,3] and not greater than 38 $^{o}$C in the head for patients undergoing MRI procedures. In this study an iterative method based on finite difference method has been used to determine temperature distribution in brain tissues during MRI examination. The model derived will be used as physical measuring techniques for brain temperature estimation which is difficult to achieve. So far there is no record of any such work done in the country and therefore, will serve as a basis for future research work on MRI temperature distribution. It will provide the needed scientific data on the MRI facilities to ascertain compliance with international standards and to produce a working protocol for routine application. The results would also contribute significantly to the body of knowledge on the subject matter for the international scientific community.

## 2. MATERIALS AND METHOD

The methodology presented in this section forms the theoretical and experimental framework of the study. This study was carried out at the Magnetic Resonance Imaging Unit of the 37 Military Hospital, located on the Liberation road, Accra and the Diagnostic Centre Limited, East Legon, No. 3 Maseru Street, Accra.

### 2.1 Experimental Method

The experimental technique used involves on-site measurement of parameters performed at the 37 Military Hospital and the Diagnostic Centre Limited, Ghana. One hundred and twenty-six (126) patients for MR imaging of the brain were assessed from the MRI units. The pre- and post-tympanic temperatures were read and recorded before and after the MRI scan by inserting a digital clinical thermometer (accuracy 0.1 $^{o}$C) into the right ear of the patient close to the tympanic membrane. The total scan duration results and specific absorption rate (SAR) values for each sequence were recorded.

### 2.2 Theoretical Analysis

To compute the temperature rise in the brain, the numerical model of Pennes' bio-heat [4] which accounted for the heat exchange between the blood capillaries and the tissues and assuming there is complete thermal equilibrium with its environment prior to RF heating [5]. The Penne's equation is modified in equation (1) by adding heat term, ρSAR due to EM radiation exposure as:

$$C\rho \frac{\partial T_N}{\partial t} = K\nabla^2 T_N - V\rho_b C_b (T_N - T_b) + \rho SAR \quad (1)$$

where, C is the specific heat capacity, ρ, tissue density, k, thermal conductivity, $h_m$, the heat generated by metabolism and $h_b$, blood perfusion rate , v is volumetric perfusion rate of blood, $\rho_b$ and $C_b$ are the density and specific heat of the blood respectively where, $T_N$ is the pre-scan tympanic temperature, $T_b$ is the post scan tympanic temperature, t is the time and ρSAR is the rate of electromagnetic power deposition. The thermal properties relating to brain tissues and blood are taken to be constant as shown in Table 1A and table 1B

**Table 1A: Thermal Properties of the Bloofdand the Brain**

| Tissue | Mass Density ρ kg m$^{-3}$ | Thermal Conductivity K W m$^{-1}$ K$^{-1}$ |
|---|---|---|
| Brain | 1040[a] | 0.54[a] |
| Blood | 1060[a] | 0.51[a] |

**Table 1B: Thermal Properties of the Blood and the Brain**

| Tissue | | Specific heat Capacity C W s kg$^{-1}$ K$^{-1}$ | Volumetric Perfusion V $10^{-3}$kg m$^3$ s$^{-1}$ |
|---|---|---|---|
| Brain | | 3640[a] | 7.3[b] |
| Blood | | 3720[a] | - |

[a]Based on [6], [b]Calculated from the mean values presented in [7] for gray and white brain matter (55 and 22 ml/100 g/min, respectively) assuming a volume ratio between gray and white matter of 6:4.

To achieve the objective of this study, the discrete ordinate finite difference technique was used to solve the bio-heat equation using explicit upwind method with vacuum condition which assumes that the incoming flux at the boundary is zero, i.e. $\Phi$ ($r_b$, w.n<0) = 0, where $r_b$ is a position on the boundary, n is the outward normal on the boundary and w is a unit vector in the direction of the EM flux propagation. The head (brain) was modelled by dividing the brain tissue into four quadrants as shown in Figure 1.

Dividing the set of angular directions into four quadrants as shown in Fig. 1 and applying the finite difference method in 2D and assuming a constant RF exposure over a period of time under steady state conditions, the temperature rise for quadrant (1) is given as

**For Quadrant 1**

$$T_{i,j}^{n+1} = T_{i,j}^{n} + \frac{\Delta t}{\rho_{ij} C_{ij}} . q_{i,j}^{n} - \frac{\Delta t V \rho_b C_b}{\rho_{ij} C_{ij}} T_{i,j}^{n} + \frac{\Delta \, t\alpha\kappa}{\rho_{ij} C_{ij}} \frac{\left(T_{i+1,j}^{n} + 2T_{i,j}^{n} + T_{i-1,j}^{n}\right)}{\Delta x^2} + \frac{\Delta t \beta\kappa}{\rho_{ij} C_{ij}} \frac{\left(T_{i,j+1}^{n} + 2T_{i,j}^{n} + T_{i,j-1}^{n}\right)}{\Delta y^2} \quad (2)$$

where, $q_{i,j} = V\rho_b T_b + \rho SAR$ , represent the source term.

Similar expressions can be obtained for the other three quadrants. A computer software programme was written in MATLAB to implement the equations for four quadrants.

## 3. RESULTS AND DISCUSSIONS

In this section the results from the experimental data and theoretical model of the study are presented and discussed.

### 3.1 Steady State Temperature Distribution

The human brain temperature was set at an average value of 36.19 ºC because majority of the patients (about 57.76%) were within a temperature range of 36.0 ºC to 36.4 ºC from both MRI Units. Figure 2 shows the simulated temperature distribution of patients as a function of time**.** Similar graphs can be obtained for the other three quadrants.

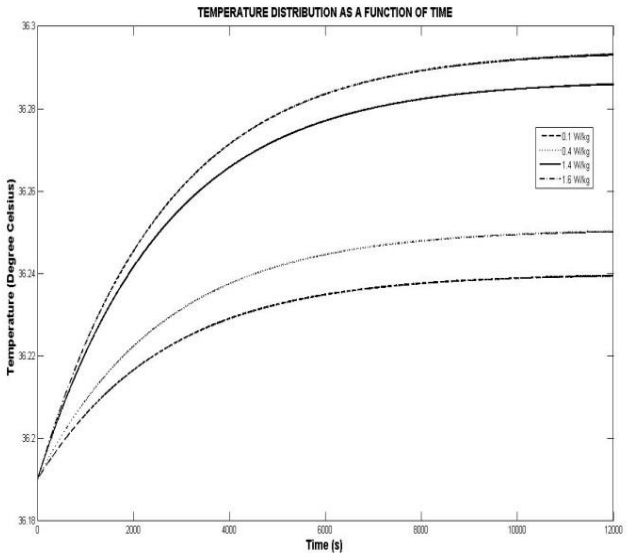


**Fig. 2: The simulated temperature distribution of MRI brain scan for Quadrant I**

### 3.2 Specific Absorption Rate

The Specific Absorption rate (SAR) describes the potential for heating of the patient tissue due to the application of RF energy necessary to produce the MR signal [8]. Figure 3 shows the relationship between change in temperature and SAR values. The SAR values obtained agrees with recommended values of the United States Food and Drug Administration [9].

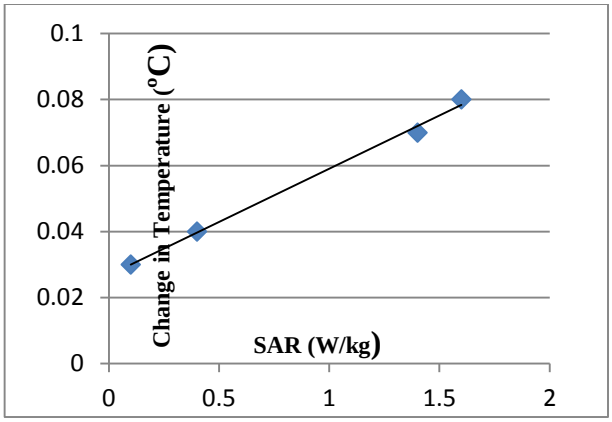


**Fig. 3: Relationship between change in temperature and SAR**

Results obtained from experiment as shown in Table 2 indicate that, the post-scan tympanic temperature increased irrespective of the magnitude of the magnetic field.

**Table 2: Comparison of measured with calculated temperatures**

| Tempera-ture ranges (°C) | No. of patient | Age (years) | TB (°C) | TA Measur-ed (°C) | TA Calculat-ed (°C) |
|---|---|---|---|---|---|
| 36.0-36.4 | 69 | 51.57 | 36.19 | 36.62 | 36.30 |
| 36.5– 36.8 | 42 | 46.10 | 36.65 | 37.11 | 36.76 |
| 36.9– 37.2 | 13 | 42.62 | 36.97 | 37.31 | 37.08 |
| 37.3 - 37.6 | 2 | 47.00 | 37.30 | 37.45 | 37.41 |

Legend: TB and TA are the pre- and post- tympanic temperatures. Ages, pre- and post-scan tympanic temperatures represent average values.

The highest and lowest post-tympanic temperatures predicted were approximately 36.29 °C and 36.19 °C for SAR values of 1.6 W/kg and 0.1 W/kg respectively when the maximum scan duration was 12000 seconds as shown in Figure 2. The lowest SAR value of 0.1 W/kg increased slightly approximately from 36.19 to 36.23 °C which is insignificant compared to the highest SAR value of 1.6 W/kg where there was a sharp increase from 36.19 °C to 36.28 °C in 5000 seconds. Subsequently, the temperature increased gradually with all the SAR values until attaining maximum temperature of approximately 36.29 °C with scan duration of 8000 seconds followed by a gentle increase approaching a plateau after 12000 seconds. It was observed that, the higher the SAR value used the higher the post-tympanic temperature. The SAR values which were less than 1 W/kg had insignificant increase in temperature compared to SAR greater than 1 W/kg.

The calculated temperature distribution predicted a maximum scan duration of 200 minutes which is about three times higher than the experimental range from 23-51 minutes. It has been shown that the post-tympanic temperature does not depend on the scan duration. This means that the longer a patient stays in the MRI machine, the brain temperature would not be affected if the temperature is still being regulated between 36 °C and 38 °C by the hypothalamus and continuously fluctuates due to diurnal as indicated by DIEurope [8]. According to International Commission on Non-Ionizing Radiation Protection [2, 3], no limit exists on the maximum duration of an RF power deposition if the temperature guideline is not exceeded by 1 °C. The results obtained from theoretical calculation suggest that the quantity of energy deposited within the brain may not adverse effect on the patient. Therefore, according to IOP [11] and this study, MRI could be said to be a relatively safe imaging technique.

According to the data summarized in Figure 6, Quadrant (II) and (IV) recorded the same values for the temperature change with their corresponding SAR values. Quadrant (I) recorded the highest change in temperature of 0.10 °C of SAR value of 1.6 W/kg while Quadrant (III) recorded the lowest change in temperature of 0.01 °C of SAR value of 0.4 W/kg. It was observed that the post-scan tympanic temperature increased with each SAR value used. There were no statistically significant differences in each quadrant of the brain implying that the amount of energy deposited by the MRI scanner was evenly distributed. Linear regression showed a significant relationship between SAR values and change in temperature as shown in Figure 7. Also by comparing the values of change in temperature of the calculated to the measured values, it was realized that, the simulated values were ten (10) times lower than the experimental values. The data indicated that there were no excessive temperature elevations or other deleterious physiological consequences related to the exposure to RF radiation. It should be noted, however, that the maximum temperature rise computed on the basis of the equations for brain tissues is a steady-state estimate which is derived under the assumption of a constant RF exposure over a period of time much longer than the thermal equilibration time.

The experimental values for the change in temperatures were higher than the calculated values this may be attributed to the fact that the model was not able to account for the numerous critical variables such as the patient's age, the amount of subcutaneous fat and the physical condition of the individual, which might affect the thermoregulatory responses of a human subject. Most patients that are exposed to RF radiation during MR procedures have underlying health conditions such as hypertension, diabetes, cardiovascular diseases or are taking medication that can seriously impair their ability to dissipate heat and this confirms a review article by Shellock [12].

## 4. CONCLUSIONS

The values of the pre-scan tympanic and post-scan tympanic were all within guidance levels which did rise by more than 1.0 $^{o}$C rise and not greater than 38 $^{o}$C in the head (brain) for patients undergoing MRI procedure, according to the guidance limit set by ICNIRP for core temperatures. This research work addressed the temperature distribution of patients undergoing MRI brain examinations in terms of the steady state temperature, specific absorption rate and temperature rise using theoretical analysis and experimental methods, and compared with the USFDA standards.

From the study, a mathematical formalism has been proposed to estimate the temperature rise induced by the RF coil in the human brain by modifying the Pennes bio-heat equation. This method provides a simple approach to predict the potential temperature change in patients undergoing MRI brain scan with known SAR values. For SAR values of 0.1 W/kg, 0.4 W/kg, 1.4 W/kg and 1.6 W/kg a corresponding average change in temperature of 0.03 $^{o}$C, 0.04 $^{o}$C, 0.07 $^{o}$C and 0.08 $^{o}$C were recorded in this study. The agreement between the calculated and measured change in temperature values indicate that such consideration and measurement could be valuable in validating numerical methods and implementing safety limits. The results regarding the steady state temperature distribution, specific absorption rate and temperature rise compared and validated with the experimental data were all within acceptable safe levels.

## ACKNOWLEDGEMENT

My special thanks goes to the staff of the MRI Unit at 37 Military Hospital especially, Dr. (Lt Col) Andrew Kaminta, Head of Radiology Department as well as the staff of the Diagnostic Centre Limited especially, Atta Osei and Mr. Ernest Eduful and Mr Peter Davor of Ghana Atomic Energy Commission.

This work was financed with support from the Ghana Atomic Energy Commission, the University of Ghana and Ghana Standards Authority.

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