FDTD for Bioelectromagnetics: Modeling MICS Implant in the Human Body

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Medtronic Inc. has developed a communication system for implanted medical devices. For MICS (Medical Implant Communications System) to be successful, it is important to be able to predict the electromagnetic performance of such an implant.

FCC Part 95, section 95.603(g) requires manufacturers of MICS transmitters perform a Finite Difference Time Domain (FDTD) computational modeling report showing compliance with radiofrequency radiation exposure requirements as specified in 1.1307 and 2.1093.

This report is a summary of the FDTD modeling and simulation results for SAR for the Medtronic MICS compatible implant.

FDTD Modeling

The Finite Difference Time Domain, or FDTD, modeling was originally developed by [Yee[1]] and has been described extensively in the literature. The method is a direct solution of the differential form of Faraday's and Ampere's laws. These differential equations are converted into difference equations using the central difference approximations. The field components are interleaved on each unit cell, so that the E and H components are half a cell apart, which is referred to as "leap-frog" scheme. In addition to being leap-frogged in space, they are also leap-frogged in time. The E field is assumed to be at time $n\Delta t$, and the H field is assumed to be at time $(n+1/2)\Delta t$.

The steps in the FDTD solution are:
1) Define model values of ε, ρ, and μ at each location
2) Assume initial conditions (usually that all fields and the sources are zero)
3) For each time step, n
   a) Specify fields at source
   b) Calculate E(n) for all locations
   c) Calculate H(n+1/2) for all locations
4) Stop when the solution has converged. For transient fields, this means all the fields have died away to zero. For sinusoidal fields, this means that all the fields have converged to a steady-state sinusoidal value.

FDTD has become the preferred method for bioelectromagnetic calculations at radio frequencies. It is efficient for modeling large-scale heterogeneous penetrable objects — like the human body. FDTD allows the use of many dielectric constants, allowing definition of different types of tissue and organs within the body.

FDTD has numerous other advantages for more advanced modeling. It is very accurate and fairly easy to use. It operates with a regular, orthogonal grid, with the wave frequencies of the modeling dependent on the dimensions of the grid. In the case of MICS modeling, a 5 mm grid of six million cells allowed creation of a model effective up to 1 gigahertz. Newly available high performance absorbing boundary conditions allow good computations throughout the body without the distortions that occurred in earlier models as a result of reflections from the outer radiation boundaries of the model.

FDTD provides an explicit time advance, with no systems of equations to solve. It can be applied to a wide variety of materials, such as the range of tissues in the human body. It allows for arbitrary incident fields, and is useful for far- and near-field exposure conditions including coupled sources.

The Visible Human Model

[1] **Yee, K.S.**, Numerical solution of initial boundary value problems involving Maxwell's equations in isotropic media, *IEEE Trans. Ant. Prop.*,14(3), 302, 1966

The human body model used for these analyses is the High Fidelity Human Body Model which is provided with the Remcom XFDTD software. MICS modeling started with a human body model obtained from REMCOM, Inc. This model was created from “frozen man” slices from the Visible Human Project, obtained via the Internet and meshed using custom software. The software used for the analyses is Remcom XFDTD version 5.3

The bioelectromagnetic human body model is a digitized version of a real human body. A donated cadaver was frozen and sliced in 5 mm slices. Each slice was identified for parameters such as muscle, fat, and bone. The results were digitized to create a total numerical model, using a 5 mm cell, for a total of about six million cells. Twelve different types of tissue were identified. Constitutive parameters were assigned based on the original data, and checked and corrected using interactive editing.

Figure 1 shows a demonstration cross-section of the high fidelity human body model.

Figure 1. Sample bioelectromagnetic human body cross-section model.

Figure 2 shows an actual section of the human body. Figure 3 shows a corresponding bioelectromagnetic model section. The segmentation of the model and different colors for different types of tissue are clearly visible.

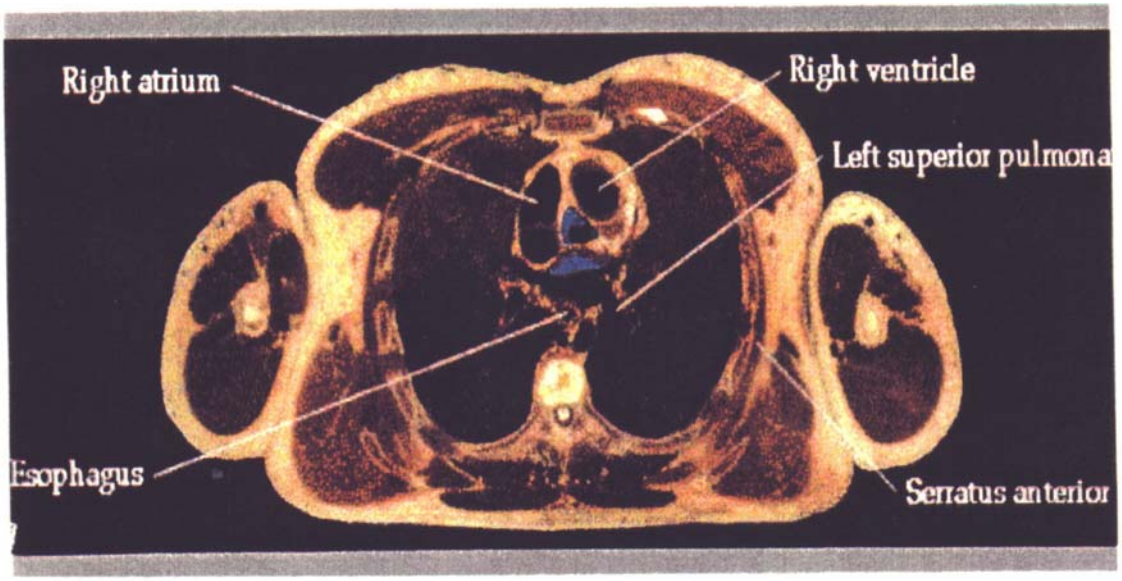

Figure 2. Human body section

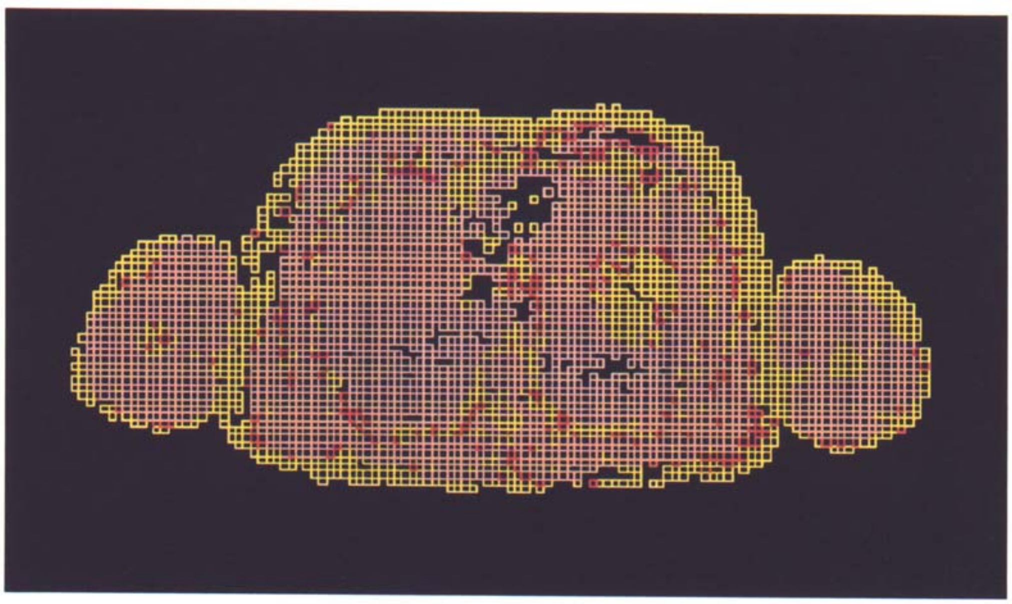

Figure 3. Bioelectromagnetic human body model corresponding to the section shown in Figure 2.

MICS Implant

The MICS implant is shown in Figures 4 and 5.

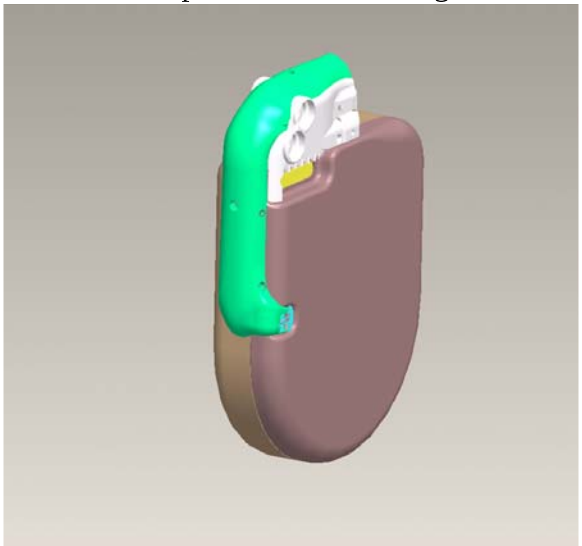

Figure 4: MICS implant with antenna.

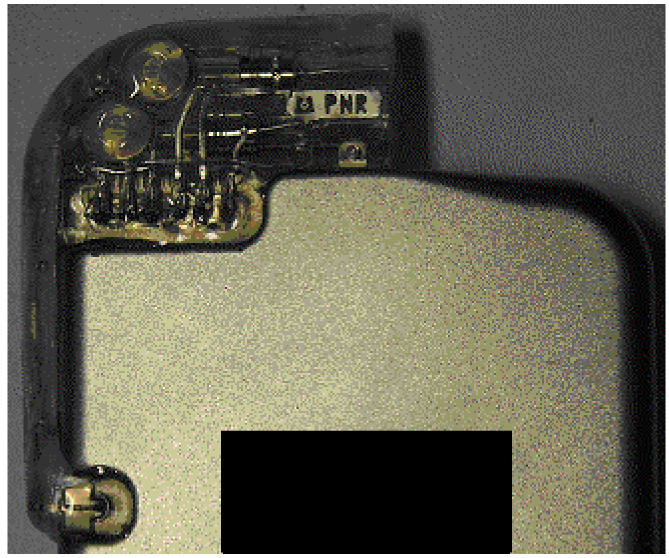

Figure 5: Photo of actual device

Figure 6 shows the High Fidelity Human Body Model in the chest area of the body with the MICS implant in place in the upper left quadrant, modeled at UHF.

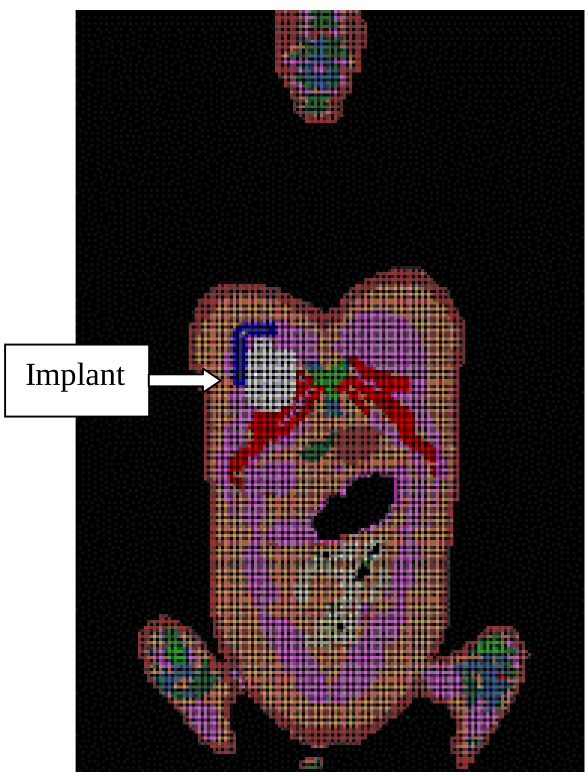

Figure 6. The MICS is visible in the upper right quadrant of the chest in this section.

For the High Fidelity Human Body Model, the depth of implant was 1 cm, typically. Detailed analyses verified 1 cm depth was sufficient to verify SAR limits are being met.

Specific Absorption Rate Modeling

The human body model can be used to evaluate the safety of the MICS implant by examining the Specific Absorption Rate (SAR) in the body. In general, the FDTD method calculates the time-domain vector E and H fields at every location inside and outside of the body. These can be converted to frequency domain fields (magnitude and phase at given frequencies). From them, values commonly of interest in bioelectromagnetic simulations can be calculated, including specific absorption rate, current density, total power absorbed, temperature rise, etc.

SAR is an important measure of the amount of power the implant is putting into the human body per kilogram of tissue. For near-field applications, such as a medical implant with telemetry transmitter, it is important to determine if the device complies with the ANSI/IEEE safety guidelines[ANSI] and FCC guidelines. These guidelines state that an exposure can be considered to be acceptable if it can be shown that it produces SAR's "below 0.08W/kg, as average over the whole body, and spatial peak SAR values not exceeding 1.6 W/kg, as averaged over 1 g of tissue (defined as a tissue volume in the shape of a cube)"[ANSI].

SAR for the MICS implant was evaluated for the Medical Implant Communication System operating at 0 dBm, or power input of 1 milliwatt into the body. The SAR at a given location is given by the following formula

$$SAR = \frac{\sigma_x}{\rho_x}|E_x|^2 + \frac{\sigma_y}{\rho_y}|E_y|^2 + \frac{\sigma_z}{\rho_z}|E_z|^2$$

where σ is the electrical conductivity and ρ is the mass density at the location of interest.

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Three different values must be evaluated to ensure that the implant meets safety standards:

- the maximum SAR considering total power applied to total weight
- the maximum SAR considering the same amount of power applied to 1 gram of tissue
- the maximum SAR considering the same amount of power applied to 10 grams of tissue.

To assist in the understanding of simulation results for the 5 milli-meter resolution High Fidelity Human Body Model, an example of a 1 milli-meter resolution implant in muscle tissue only is shown in figure 7. The implant model is on the left and the simulation result in muscle tissue is on the right. Colors in the simulation result on the right denote relative SAR levels.

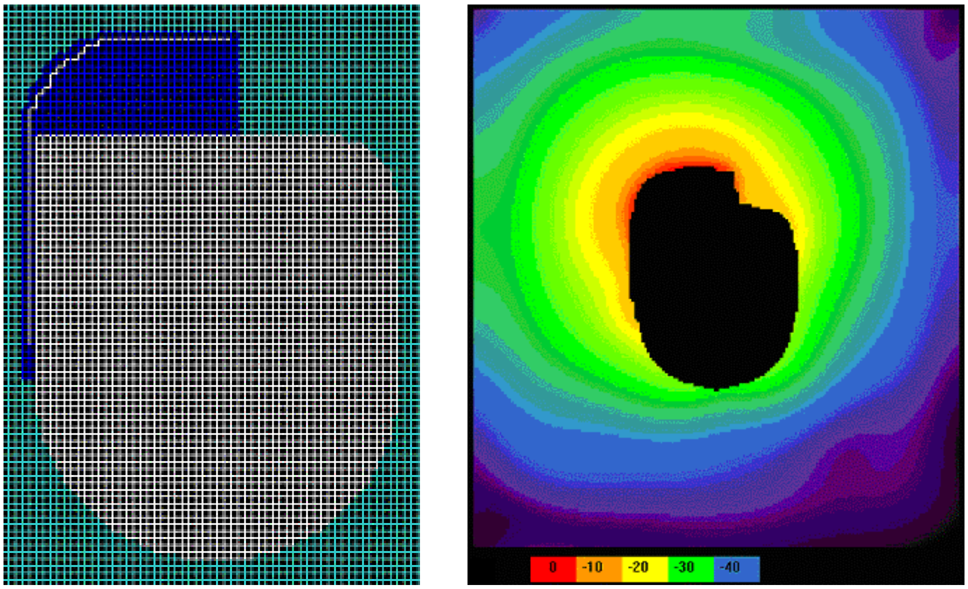

Figure 7. Example of 1 mm model implant in muscle tissue only.

The SAR simulation result plots in Figure 8 show the relative SAR levels for the 5 mm High Fidelity Human Body Model with MICS implant at two slices of the body.

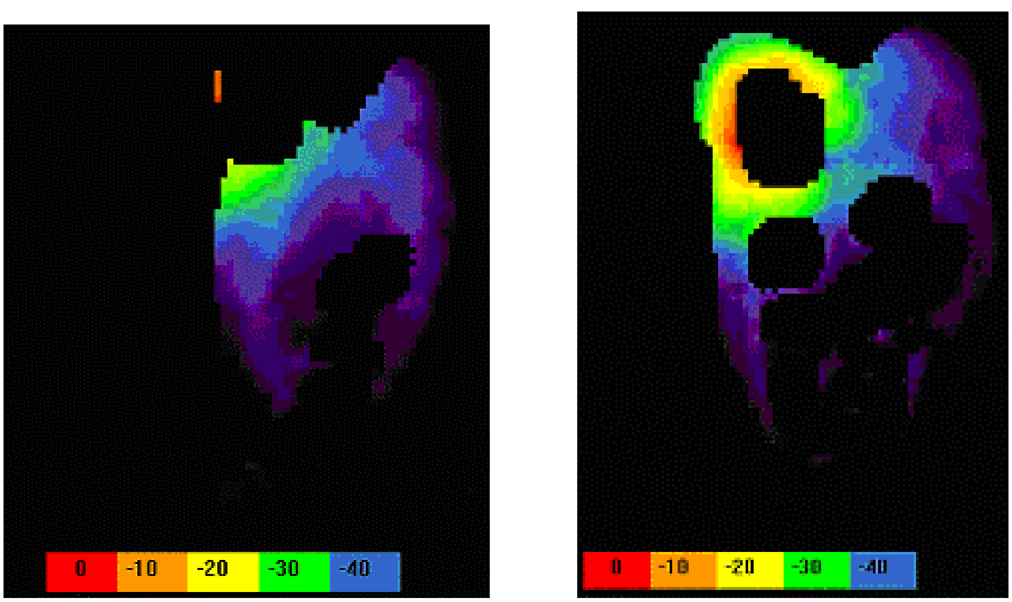

Figure 8. Worst case slice and typical slice for the 5 mm model, respectively

Figure 9 summarizes the SAR statistics required for verifying the safety standards:

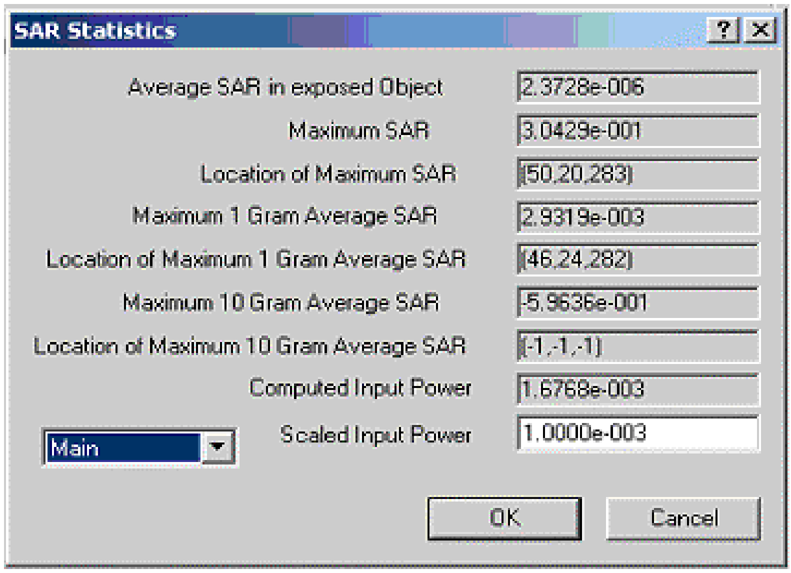

Figure 9. Simulation summary of SAR results

Implant Safety Conclusions

Figures 9 illustrates the important SAR conclusions:

- The SAR average over the whole body is 5.3e-06 W/kg. This is 41 dB below the ANSI safety standard of 0.08 W/kg.
- The maximum 10 g average SAR is 0.59W/kg. This is 8 dB below the ANSI safety standard of 4 W/kg.
- The maximum 1 g average SAR is 2.9e-03 W/kg. This is 27 dB below the ANSI safety standard of 1.6 W/kg.

Summary of FDTD Modeling Conclusions

FDTD modeling has been used with the bioelectromagnetic human body model to obtain implant performance.

Analysis of SAR over the total body, over 1 g of tissue, and over 10 g of tissue reveal an absorption rate of power into the body well within the standard guidelines for safety, demonstrating the ability of MICS to operate safely within the human body.