SAR Analysis of a Needle Type Applicator Made from a Shape Memory Alloy Using 3-D Anatomical Human Head Model

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Abstract: This paper describes the possibility of a new heating method with a needle applicator made of a shape memory alloy (SMA) to expand the heating area for interstitial brain tumor hyperthermia treatments. The purpose of the study described here is to show the capability of the method to expand a defined heating region with the developed three-dimensional (3-D) anatomical human head model using the finite element method (FEM). One major disadvantage of RF interstitial hyperthermia treatment is that this heating method has a small heating area. To overcome this problem, a new type of needle made of a SMA was developed. The specific absorption rate (SAR) distributions of this proposed method, when applied to the 3-D anatomical human head model reconstructed from two-dimensional (2-D) MRI and X-ray CT images, were calculated with computer simulations. The calculated SAR distributions showed no unexpected hot spots within the model. The heated area was localized around the tumor. These results suggest that the proposed heating method using the SMA needle applicator and the developed method for reconstructing a 3-D anatomical human head model are capable of being used for invasive brain tumor hyperthermia treatments.

Key Words: 3-D anatomical human model, shape memory alloy, needle type applicator, SAR distribution, brain tumor
Introduction

As the human brain is protected by the skull, it is not easy to heat deep brain tumors non-invasively with exterior applicators. Radio frequency (RF) and microwave (MW) interstitial hyperthermia systems with needle type applicators\(^1\)\(^-\)\(^3\) are used in clinical practices to invasively heat malignant brain tumors. In order to expand the heating area of needle type applicators, the authors et al. proposed a new type of needle applicator made of a shape memory alloy (SMA)\(^4\)\(^-\)\(^5\). The developed SMA needle type applicator was also tested with computer simulations and heating experiments using agar phantoms\(^5\).

This paper presents computer simulation results with the three-dimensional (3-D) anatomical human head model using the finite element method (FEM). First, a method of expanding the heating area of the needle applicator with a SMA is presented. Second, the proposed method of reconstructing the 3-D anatomical human head model from two-dimensional (2-D) MRI and X-ray CT images for FEM analysis is described. Finally, results of the estimated current vector and SAR distributions are discussed. From these results, it is clear that the proposed methods for estimating SAR distribution with the 3-D anatomical human head model and for expanding a heating area using a SMA needle applicator are useful for clinical treatments.

Materials and methods

SMA needle type applicator

Fig. 1 shows an illustration of our heating system. In Fig. 1a, a needle applicator is inserted into a brain tumor and it can be heated by a RF current between the needle applicator and a discoid electrode.

![Image](image_url)

Fig. 1. Illustration of the needle applicator.

a. Heating system; b. Changing form of the SMA.
The method for expanding a heating area using a SMA needle type applicator was also proposed\(^{4-7}\). The SAR distribution inside a human body can be calculated by equations (1) - (4):

\[
\nabla \cdot ((\sigma + j\omega \epsilon_r \varepsilon_0) \nabla \phi) = 0 \tag{1}
\]

\[
E = -\nabla \phi \tag{2}
\]

\[
W_h = \frac{1}{2} \sigma |E|^2 \tag{3}
\]

\[
SAR = \frac{1}{\rho} W_h \tag{4}
\]

where \(\rho\) is the volume density of tissue, \(W_h\) the heating power generated by the high-frequency current in a human head, \(\phi\) the electric potential and \(\varepsilon_r\) the relative dielectric constant. Equation (1) can be solved numerically by the finite element method (FEM)\(^{6,7}\). Here, JMAG-studio, a FEM application, was used in the computer simulations.

The SMA continuously changes its own shape, during heating, corresponding to different temperatures. However, it is not easy to calculate the SAR distribution inside the human body for the varying shapes of the SMA. Here, as temperature rises, we assumed that the changes of the SMA needle type applicator occur in three steps. Fig. 1b shows the varying shapes of the SMA, bent to 0, 22.5 and 45 degree angles under 3 minutes of heating respectively\(^6\).

**Analytical model**

Fig. 2 shows a method of reconstructing the 3-D human head model. The proposed reconstruction method consists of five steps.

![Fig. 2. Method of reconstructing 3-D head model.](image)
In Fig. 2, the first step is to collect MRI images taken at intervals of several millimeters. An exact model can be made so that the visualized intervals are small, but a large computer memory is needed. In the personal computer that was used in this study, the 2-D images of 105 sheets from Virtual Anatomia7 which is the commercial software of a human body were prepared.

The second step is to trace the outlines of human tissues, for example, the skull, white matter, gray matter, ventricles, etc. as shown in Fig. 3. Since it is not easy to trace the outline of each tissue using

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**Fig. 3.** Outlines traced along the boundary of human brain tissues.

**Fig. 4.** Traced outlines and solid model of a skull.
- **a.** Outlines of horizontal section; **b.** Outlines of horizontal and vertical sections;  
- **c.** Reconstructed solid model.
Table I. Electromagnetic properties of tissues at 13.56 MHz.

<table>
<thead>
<tr>
<th>Tissue</th>
<th>σ [S/m]</th>
<th>ε</th>
<th>ρ [kg/m³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skull</td>
<td>0.012905</td>
<td>16.058</td>
<td>1.810</td>
</tr>
<tr>
<td>Tumor (muscle)</td>
<td>0.62818</td>
<td>138.44</td>
<td>1.040</td>
</tr>
<tr>
<td>Ventricle (CSF)</td>
<td>2.0041</td>
<td>108.26</td>
<td>1.010</td>
</tr>
<tr>
<td>Brain White Matter</td>
<td>0.17563</td>
<td>153.12</td>
<td>1.030 (Brain ave)</td>
</tr>
<tr>
<td>Brain Grey Matter</td>
<td>0.32737</td>
<td>263.38</td>
<td>1.030 (Brain ave)</td>
</tr>
<tr>
<td>Cerebro Spinal Fluid (CSF)</td>
<td>2.0041</td>
<td>108.26</td>
<td>1.010</td>
</tr>
<tr>
<td>Bone Marrow</td>
<td>0.012905</td>
<td>16.058</td>
<td>1.810</td>
</tr>
<tr>
<td>Eye ball</td>
<td>0.63</td>
<td>138</td>
<td>1.040</td>
</tr>
<tr>
<td>Fat</td>
<td>0.030354</td>
<td>11.827</td>
<td>920</td>
</tr>
<tr>
<td>Muscle</td>
<td>0.62818</td>
<td>138.44</td>
<td>1.040</td>
</tr>
<tr>
<td>Heart</td>
<td>0.52617</td>
<td>239.13</td>
<td>1.040 (Muscle)</td>
</tr>
<tr>
<td>Needle electrode</td>
<td>$13 \times 10^3$</td>
<td>–</td>
<td>6.942</td>
</tr>
</tbody>
</table>

only an image processing technique, further modification through manual operation was also required to trace the outlines. Therefore more accurate outlines of the tissues could be obtained. Fig. 4 shows the process of extracting the skull.

The third step is to collect and combine the outlines of the tissues shown in Figs. 4a and b.

The fourth step is to create a solid model, as shown in Fig. 4c, from the data in the third step. From the second step to the fourth step, the commercial 3D-CAD software, Rhinoceros\(^7\), was used.

The last step is to create the FEM model shown in Fig. 5. This is the FEM mesh model of a skull created by the commercial pre-processor, Hyper Mesh\(^7\). Furthermore to extract other tissues, the above procedures mentioned were again performed. The physical parameters used in the calculations are listed in Table I\(^8\).

Results

The tissue outlines were combined after carrying out the finite element division of each tissue. The complete model for the FEM calculations was built from these.

Fig. 6 shows the FEM model divided into tetrahedron elements which are necessary for calculating electric fields and SAR distributions. In Fig. 6, the details of the eye ball, skin and the respiratory tract could not be expressed due to the restrictions of our computer real memory and the FEM software. The total number of elements in the FEM model is 957,930.
Fig. 7 shows the results of the normalized magnitude of the electric field distributions inside the human tissue calculated by the FEM. Fig. 7a shows the entire electric field distribution around the non-SMA needle applicator used in clinical treatments. In Fig. 7a, the electric field distribution is concentrated on the narrow area only around the needle. Fig. 7b shows the electric field distribution around the SMA needle applicator bent to 0, 22.5 and 45 degree angles. From Figs. 7a and b, it is found that the electric field of the SMA applicator is broadly distributed in accordance with the shape of the SMA electrode.

Fig. 8 shows the results of the calculated electric fields for the SMA applicator in the horizontal cross sections. In Fig. 8, it is also clear that

**Fig. 6.** 3-D FEM mesh model of the whole head.

**Fig. 7.** Calculated electric fields of needle applicators.  
(a) Non-SMA applicator; (b) SMA applicator.
the electric field of the SMA applicator is broadly distributed inside the tumor in these cross sections.

Fig. 9 shows the normalized SAR distributions calculated by the FEM for the proposed SMA needle applicator. Fig. 9a represents the SAR distribution in the case of a needle applicator without a shape memory function. On the other hand, Fig. 9b shows the SAR distribution with a shape memory function when the SMA applicator bends from 0 to 45 degree angles. Fig. 9b shows that the SAR distribution has increased over a larger area in a tumor compared with the distribution in Fig. 9a.

Discussion

We developed the SMA needle type applicator to expand the heating area of interstitial hyperthermia and also tested this with computer simulations and heating experiments using agar phantoms9). The 3-D voxel model of the human body for FDTD calculations, which is divided into cubic cells, was developed by the NICT group10,11). This 3-D voxel model has advantages and disadvantages. The advantages are
high flexibility and usability. On the other hand, this model lacks of the ability to conform to an
individuals specific conditions and it requires a large computer memory. In other examples, the FEM
models of the human head were built to study injury mechanisms due to impacts\(^{12-14}\) and to study some
fields\(^{(15)}\). These FEM and FDTD models represent typical human models with no deformities, and are
used for each purpose.

In the present study, in order to check the validity of the FEM calculations for hyperthermia
treatments, a method for reconstructing a 3-D human head model with a brain tumor and applicators was
proposed and also checked with FEM calculations. The 3-D FEM model, created by the proposed
method, consists of nonlinear elements. Therefore, an area of interest can be divided into more detailed
elements, as shown in Fig. 6. We carried out SAR analysis with this 3-D model using a personal
computer which had 12 GB real memory and a Core i7 processor. The calculation time is about 1 min,
and we could also consider the possible methods for practical use. On the other hand, in order to create
the 3-D FEM model with high precision as shown in Fig. 6, it is necessary to correct the outlines of the
tissues with manual operation. Therefore, the work of about two hours is required.

As shown in Fig. 9, the calculated SAR distributions for the proposed SMA needle applicator with
the 3-D anatomical human head model showed no unexpected hot spots within the model. It also
expanded the heating area which can also be seen in Fig. 8. The heated area was localized around the
tumor. These results suggest that the proposed heating method using the SMA needle applicator is
capable of being used for invasive brain tumor hyperthermia treatments.

Conclusion

This paper described the method for reconstructing the 3-D anatomical human head model from
two-dimensional (2-D) MRI and X-ray CT images for FEM analysis. This paper also described the
heating method using the SMA needle applicators for brain tumor hyperthermia treatments. In order to
show the validity of the proposed method, SAR distributions were estimated using a computer simulation with FEM and were discussed. From these results, it is confirmed that the proposed methods for estimating SAR distributions with the 3-D anatomical human head model and for expanding the heating area using a SMA needle applicator are useful in clinical treatments.

We are now trying to estimate temperature distributions during hyperthermia treatments with the proposed methods.

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References


