Evaluation of RF Heating on Hip Joint Implant in Phantom during MRI Examinations

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Introduction

We should be careful in MRI procedures in patients with a metallic implant because there is a risk of injury. In particular, if the implant is made of a magnetic substance, displacement and rotation of the implant by the static magnetic field and RF heating may take place, leading to serious accidents during the MRI procedure. MRI examination is generally forbidden in such a case. Therefore, detailed medical examination by interview has been crucial before the beginning of MRI procedures in most hospitals. But if the material of the implant is titanium or stainless steel, the MRI examination is often performed, because in this case the risk is relatively low compared with that of magnetic substances. However, the risk of RF heating was pointed out even in cases of a non-magnetizing metallic implant exposed to RF irradiation.

There have been many reports on RF heating during MRI procedure.1-6) Recently, investigations of MRI safety for 3 T MR scanners were reported.7-9) Despite such detailed studies, there is no definite guideline for measures concerning RF heating for implanted patients up to now.

In our previous studies concerning RF heating of a humerus implant embedded in a gel-phantom during MRI procedure, several factors affecting RF heating were investigated, including the depth from the phantom surface, specific absorption rate (SAR), angle between the implant and static magnetic field, and position of the implant in the RF irradiation coil in a 1.5 T MR system.10) Moreover, we performed electromagnetic simulation of RF heating and compared the results with the experimental ones.10) RF heating of the implant was considered to be caused by a complicated interaction between the eddy
current in the implant and that in the phantom. Maximum temperature rises were observed at both ends of implants having large curvatures. The RF heating increased more as the implant was closer to the phantom surface and as SAR was larger. The temperature rise was in proportion to the increase of the SAR. In addition, no RF heating took place outside the RF irradiation coil. The implants used in surgery are composed of various materials and have various sizes and shapes. Temperature rises in a simple bar-shaped implant made of stainless steel were observed at both ends. However, it is not confirmed whether the heating point is the same or not for the implant with a complicated shape. In addition, we have investigated the influence of various kinds of materials on RF heating using simple metal balls. Despite these situations, there has been no report concerning RF heating of the implant made of various materials and having different sizes and shapes. Therefore, in this study, we examine RF heating of two kinds of hip-joint implants that have different sizes and shapes and are used in clinical practice. Furthermore, we perform electromagnetic simulation of RF heating and compare the results with experimental results.

1. Methods

1-1 MRI procedure

All examinations were performed with a 1.5 T MR scanner (MAGNETOM Symphony, SIEMENS). The maximum RF-heating condition could be obtained by setting parameters described as follows: scan plane, coronal; pulse sequence, HASTE (half Fourier acquisition single-shot turbo spin echo); echo time, 248 ms; repetition time, 1030 ms; field of view, 50 cm; slice thickness, 5 mm; matrix, 256×256; number of excitations, 32; number of slices, 25; number of echoes, 256; presaturation pulse, parallel-AP; and scan time, 15 min. The transmit/receive body coil was used. The whole-body averaged SAR predicted on MR console was about 2.5 W/kg for these settings and a body weight of 13 kg, using body coil in the first-level management operation mode. The transmit/receive body coil consists of four irradiation coils (35×70 cm). These constitute two pairs of opposite coils for 90 degrees phase-shifted exposure. In order to operate the first-level management mode, the output gain of RF power was adjusted manually. Moreover, the power supply of the gradient magnetic field was set in off-mode to derive only the effect of RF irradiation.

1-2 Two kinds of hip joint implants and phantom

In this experiment, we used two kinds of implants made of cobalt-chromium alloy and titanium alloy, respectively. Both implants were a nonmagnetizing metallic implant (Zimmer Inc.). The head of these implants made of chromium alloy was common and was shown as a in Fig. 1. This common head had a semi-spherical shape, and measured 28 mm in diameter (a). The two implants had a stem that was 140 mm long in the case of the Co-Cr implant (b), and 160 mm long in the case of the Ti implant (c). The shapes of the neck part of both implants were the same and had an equal bending angle, but as for other details of the two implants, they had different shapes and widths, as shown in the figure.

Fig. 1 Shapes of two kinds of hip joint implants. The head part of two implants was common and semi-spherical, and measured 28 mm in diameter (a). The two implants had a stem that was 140 mm long in the case of the Co-Cr implant (b), and 160 mm long in the case of the Ti implant (c). The shapes of the neck part of both implants were the same and had an equal bending angle, but as for other details of the two implants, they had different shapes and widths, as shown in the figure.
1-3 Temperature measurements

Two fiberoptic thermometers FL-2000 (Anritsu Keiki Inc.) were used for temperature measurements. These thermometers are composed of optical fibers of the length 10 m and are not influenced by the magnetic field and the RF irradiation. The phantom was inserted into the center of a static magnetic field ($B_0$), as shown in Fig. 2b. The RF irradiation coil contained 4 irradiation coils (35×70 cm) constituting 2 pairs of opposite coils which generated circularly polarized RF field. The temperature was measured by forcing the sensors to stick firmly to the implant surface, and the difference between the values before and after 15-min RF irradiation was adopted as an experimental temperature rise.

The temperature of each implant surface was measured at 6 positions, indicated as #1–#6, from the tip to the head, as shown in Fig. 3. The temperature rise at a position on one implant was compared with that at the corresponding position on the other implant. The temperatures were recorded at 1-second intervals from 1 min before 15-min RF irradiation to 10 min after the RF irradiation. The temperature of the MR scan room was maintained in advance at 24 °C, and the phantom was left more than 4 hours to equilibrate it with the room temperature before the experiment. All measurements were performed 3 times and the averaged value was considered to be the experimental temperature.

1-4 Electromagnetic-field analysis

The model design of both the implants and the phantom was performed with pre-post processor Femap (UGS Co., Ltd.), which was based on the finite element method. The RF heating of the implants and the phantom was simulated with the electromagnetic-field analyzing software of PHOTO-EDDYjω and the thermal conduction analyzing software of PHOTO-THERMO (PHOTON Co., Ltd.), which were also based on the finite element method. PHOTO-EDDYjω is a static- and transient-field analysis software that is capable of calculating the eddy current, except the hysteresis loss. The electric current density and the amount of heating due to Joule...
loss can be also calculated with this software. As input parameters, the shape of the object, relative magnetic permeability, electrical conductivity, electric current and frequency of the RF, and the boundary conditions are given.

The electric current $I$ of the RF irradiation coils was estimated from the RF power loaded on a pair of coils which was displayed on the MR console and the impedance $Z$ of each coil. The electric current $I$ can be calculated from the equation $I=(P/Z)^{1/2}$, where $P$ is the RF power loaded on each coil. Since each coil of the pair is connected in parallel, $P$ is half of the displayed RF power. In this experiment, values of $Z$ and $P$ were 100 $\Omega$ and 1445 W, respectively, then we obtained the value of $I$ to be 3.8 A. The resonance frequency of this MR scanner was 63.8 MHz.

PHOTO-THERMO is a thermal conduction analysis software that is capable of calculating temperature distribution. As input parameters, the shape of the object, thermal conductivity, specific heat, mass density and the boundary conditions are required.

### 2. Results

#### 2-1 Temperature rises at various positions

Both of the hip joint implants have a complicated shape, as shown in Fig. 3, where measured positions in this experiment are shown as #1–#6, respectively. Temporal temperature changes of all measured positions are shown in Fig. 4a and 4b for Co-Cr and Ti implants, respectively. As can be seen from the figure, the temperature increased gradually with RF irradiation on and decreased rapidly with RF irradiation off, particularly at the tip positions of #1 on both implants. The maximum temperature rise reached 9.0±0.8°C for the Co-Cr implant and 5.3±0.2°C for the Ti implant at 15 min after RF irradiation was on.

Experimental temperature rises were compared with simulated ones for all measured positions in Table 2. Temperature rises increased at both ends of the implants (#1 and #5), where tendencies were similar to those in a humerus nail implant. However, the position #5 at the head of the implants showed a lower temperature rise in comparison with position #1 at the tip of the implants, because the curvature of position #5 was considerably smaller than the corresponding position of the humerus nail implant in our previous study.10, 11) The temperature rises at position #3, which had the largest curvature, and at position #6, where a hole existed, were found to be relatively low.
2-2 Simulated eddy current and temperature maps

We performed the simulation by electromagnetic-field analysis with PHOTO-EDDYjα and PHOTO-THERMO for the implants embedded in phantom after 15-min RF irradiation, as shown in Fig. 5. In the figure, the eddy current maps for the Co-Cr and Ti implants are shown in Fig. 5a and 5b, respectively, and the temperature maps for the Co-Cr and Ti implants are shown in Fig. 5c and 5d, respectively. It can be seen that the eddy current generated in the phantom flows through the periphery of the phantom, and concentrates on both ends of the implants. As a result, maximum temperature rises can be seen at the tip parts of both implants in three-dimensional temperature maps of Fig. 5c and 5d.

In addition, the results of electromagnetic-field analysis only for implant parts after 15-min RF irradiation are shown in Fig. 6. In the figure, the eddy current maps for the Co-Cr and Ti implants are shown in Fig. 6a and 6b, respectively, and the temperature maps for the Co-Cr and Ti implants are shown in Fig. 6c and 6d, respectively. The eddy current maps in both implants showed similar tendencies, that is, the eddy currents flowed from the tip to the head through the edge of the implant, and reached a maximum at the outer periphery of the central region of the stem. Maximum temperature rises were seen at the tip parts of both implants.

3. Discussion

In this experiment, RF heating was proved to take place at both ends even in the hip joint implants having

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Table 2  Comparison of experimental and simulated values for the temperature rises (°C) at 6 measured positions.

<table>
<thead>
<tr>
<th></th>
<th>Measured position</th>
<th>#1</th>
<th>#2</th>
<th>#3</th>
<th>#4</th>
<th>#5</th>
<th>#6</th>
</tr>
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<tbody>
<tr>
<td>Co-Cr</td>
<td>Experimental value</td>
<td>9.0</td>
<td>0.6</td>
<td>0.5</td>
<td>1.0</td>
<td>1.8</td>
<td>0.5</td>
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<tr>
<td></td>
<td>Simulated value</td>
<td>9.1</td>
<td>2.5</td>
<td>1.6</td>
<td>1.6</td>
<td>2.0</td>
<td>2.0</td>
</tr>
</tbody>
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<table>
<thead>
<tr>
<th></th>
<th>Measured position</th>
<th>#1</th>
<th>#2</th>
<th>#3</th>
<th>#4</th>
<th>#5</th>
<th>#6</th>
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<tbody>
<tr>
<td>Ti</td>
<td>Experimental value</td>
<td>5.3</td>
<td>0.4</td>
<td>0.6</td>
<td>0.8</td>
<td>1.3</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>Simulated value</td>
<td>9.9</td>
<td>1.3</td>
<td>1.3</td>
<td>1.8</td>
<td>3.0</td>
<td>1.8</td>
</tr>
</tbody>
</table>
complicated shapes, as well as in the bar-shaped implant in our previous study.\(^{10,11}\) The positions showing maximum temperature rises were in agreement with each other in the experiment and the electromagnetic simulation for both implants. In the simulation, values of temperature rises were well reproduced for the Co-Cr implant, but were considerably different from experimental values for the Ti implant.

As can be seen from the eddy current maps (Fig. 5a, 5b), the current flowed through the surrounding of the phantom in a loop, and the induced current in both implants flowed from the one end to the other (Fig. 6a, 6b). Thus, the generated induced current concentrated at the tip of the implant. And this current passed through the region of larger electrical resistance of the phantom. Consequently, RF heating was thought to be caused by the Joule loss resulting from the sudden increase of electrical resistance at the border between the tip of the implant and the phantom. Similar phenomena have already been reported.\(^{14-17}\) Based on this finding, it was thought that RF heating was not observed at position #3, which had the largest curvature in this geometry.

In the following, we consider the difference in RF heating in Co-Cr and Ti implants. First, one of the reasons is thought to be the influence derived from the difference in the physical properties of the materials. The cobalt-chromium alloy has a little larger magnetic permeability than the titanium alloy, and consequently is easy to absorb RF power. In addition, the temperature is easy to rise in the cobalt-chromium alloy, because its specific heat is smaller, and its thermal conductivity is larger than that of the titanium alloy (Table 1). This may be the reason why the temperature of the Co-Cr implant rises more rapidly than that of Ti implant. The electrical conductivity of the phantom is very small compared with those of the two implants. However, there is still a definite difference in RF heating, even though the difference of electrical conductivity between these two implants is much smaller than that between the phantom and the implants.

A second reason is thought to be the difference in the shape of the two implants. The simulated temperature values could not precisely reproduce the experimental
values for the Ti implant, because the model design of the Ti implant was imperfect. That is, titanium mesh is embedded in a cavity in the triangle part of the actual Ti implant, as shown in Fig. 7, but this fact is not reproduced in the present simulation model. The mesh region enclosed with a dotted line in Fig. 7 has a definite boundary and has relatively large effective electrical resistance, and consequently the electric current flowing into the whole Ti implant is suppressed. This is thought to be the reason that the eddy current distribution in the Ti implant changes and the RF heating decreases.

On the other hand, it is thought that the simulated values reproduce well the experimental values in the Co-Cr implant because such a mesh region does not exist in the Co-Cr implant. In this study, we used the tissue-equivalent phantom, which simulated the worst condition for an actual human body. Inside the actual human body, there are various internal organs, bones and tissues, and these have different electrical properties. In addition, there are also blood vessels in the inside of internal organs and surrounding them, and blood flow has a cooling effect on local heating generated inside the human body. Therefore, the application of electromagnetic-field analysis for the actual human body is considerably difficult in the present stage.

4. Conclusion

First, we investigated the dependence of RF heating on the difference in the electrical properties of metallic
implants. As in our previous experiment that used metallic balls of several materials, the temperature rise was larger for the metallic implant having greater permeability and electrical conductivity. Therefore, it was confirmed that RF heating depended on the electrical characteristics of metallic implants.

Second, the part where the temperature readily increased was identified for metallic implants having complicated shapes. As a result, it was found that the temperature rise reached its maximum at tip parts having a large curvature.

Third, the computer simulation with electromagnetic-field analysis proved to be considerably useful for the implants having a simple shape, such as a humerus implant, and a complicated shape, such as the Co-Cr hip joint implant. However, the Ti hip joint implant had a particular composition such as a mesh region, which was not taken into consideration in the model design of the simulation. This is the reason why the precise evaluation of temperature rise with the simulation was rather difficult for the Ti implant.

The fundamental experiment using tissue-equivalent phantom and its electromagnetic computer simulation are thought to be very useful in analyzing the mechanism of RF heating in the MRI procedure.

References

図表の説明

Fig. 1 2 種類の股関節インプラントの形状
インプラント頭部の形状は同じ角度であるが、図のように形状や幅に違いがある。
(a) 2 つのインプラントの骨頭部分は直径 28 mm の半球形
(b) Co-Cr インプラントの幹部の長さ 140 mm
(c) Ti インプラントの幹部の長さ 160 mm

Fig. 2 人体等価ファントムと温度計
(a) 人体等価ファントムの重量は約 13 kg でインプラントは静磁場と平行に埋め込まれた。
(b) ファントムを静磁場の中心に入れた。2 台の温度計は RF 照射や磁場の影響を受けないので、蛍光ファイバー式温度計を使用した。使用した 2 本の光ファイバーの長さは 10 m である。

Fig. 3 Co-Cr および Ti インプラントの測定点
測定は図のように #1 から #6 の先端部から頭部までインプラント表面の 6 点とした。

Fig. 4 すべての測定点の経時的変化
どちらのインプラントも先端部の温度上昇が最大となった。
(a) Co-Cr インプラントの温度上昇
(b) Ti インプラントの温度上昇

Fig. 5 PHOTO-EDDYjo と PHOTO-THERMO を用いたファントムの電磁場解析シミュレーション
図は真上から見たインプラントを埋め込んだファントムの 2 次元の誘電流マップと 3 次元の温度マップ
(a) ファントムに埋め込まれた Co-Cr インプラントの誘電流マップ
(b) ファントムに埋め込まれた Ti インプラントの誘電流マップ
(c) ファントムに埋め込まれた Co-Cr インプラントの温度マップ
(d) ファントムに埋め込まれた Ti インプラントの温度マップ

Fig. 6 PHOTO-EDDYjo と PHOTO-THERMO を用いたインプラントの電磁場解析シミュレーション
図はインプラントを抽出して真上から見た 2 次元誘電流マップと 3 次元温度マップ
(a) Co-Cr インプラントの誘電流マップ
(b) Ti インプラントの誘電流マップ
(c) Co-Cr インプラントの温度マップ
(d) Ti インプラントの温度マップ

Fig. 7 Ti インプラントのメッシュ部分の拡大図
点雑で囲まれた三角状のメッシュ領域は境界が複雑でシミュレーションモデルでは再現できなかった。

Table 1 電磁場解析に用いた材料の物理特性
Table 2 測定した 6 点の温度上昇の実験値とシミュレーション値の比較

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