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Heat generation ability in AC magnetic field and their computer simulation for Ti tube filled with ferrite powder

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ABSTRACT

The heat generation ability of needle-type materials was studied for the application of thermal coagulation therapy in an AC magnetic field. Although the Ti tube without the $MgFe_2O_4$ powder or Ti rod showed poor heat generation abilities in an AC magnetic field, the temperature was significantly increased by the presence of ferrite powder in the Ti tube. We confirmed using a computer simulation that the eddy loss of the Ti tube was increased by the enhanced magnetic flux density due to the ferrite powder in the Ti tube. The heat generation of the ferrite filled Ti tube was increased by utilization of the quenched $MgFe_2O_4$ powder from elevated temperature. The relative magnetic permeability of the quenched ferrite was enhanced with the decrease in the inverse ratio of the cubic spinel structure. The heat generation ability was increased with the increase in the relative magnetic permeability of the Ti tube with ferrite powder. The calculated joule loss based on the experimental results showed an agreement with those using the computer simulation.

1. Introduction

Thermal coagulation therapies, such as microwave coagulation therapy and radio frequency therapy, have been used against cancerous tissues. In these therapies, an antenna-like needle must be inserted into the tumors from outside the body, and then microwaves or a radio frequency is radiated for local coagulation. Thermal coagulation can also be realized by application of an AC magnetic field from external coils to the tumors using magnetic materials such as powder-type [1–10] and needle-type materials [11–14].

For the powder-type material, the drug delivery system (DDS) using nano-sized magnetic particles encapsulated in a liposome is applicable for thermal coagulation therapies of hepatoma. Oxide magnetic materials such as magnetite ($FeFe_2O_4$) have been investigated for this therapy, since a nano-sized magnetite powder having a good heat generation property can be easily prepared by a coprecipitation method [1–5]. To develop a new heat generation material, we found that the $MgFe_2O_4$ powder showed a maximum enhancement of temperature in the AC magnetic field [6,7]. The reason for this enhancement of the temperature was attributed to the high hysteresis loss in the B–H magnetic properties [8,9]. Furthermore, we found that Ca^{2+} substitution into the Mg^{2+} site of the $Mg_{1-x}Ca_xFe_2O_4$ system effectively improved the heat generation ability [9,10].

In the case of the needle-type materials, they are directly inserted from the surface into tissues such as cervical cancer and breast cancer. $MgFe_2O_4$ ferrite needle was prepared by sintering and then investigated for this type of therapy [11–13]. Utilization of a metal material seems to be easier for the needle having a high heat generation ability by eddy loss. On the other hand, the complex type materials using a ferrite rod implanted into a metallic ring have been reported for the same application [14]. In this case, the temperature was controlled using the Curie point of the selected ferrite material with a metal ring. The studies of the ferrite materials and metal materials are very important for improving the heat generation ability. In some metals, Ti metal is suitable for application as a medical material, since Ti has already been used as an implantable material in human bones. We have briefly reported that the heat generation ability of the needle-type Ti was significantly improved when the $MgFe_2O_4$ ferrite powder filled the core of the Ti tube [15]. We considered that the heat generation property would depend on the change in the magnetic properties of the ferrite powder.

In this study, we investigated the heat generation ability of the needle-type Ti tube filled with the $MgFe_2O_4$ ferrite powder and

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evaluated it using a computer simulation. Furthermore, we prepared the $MgFe_2O_4$ ferrite powder having a higher relative magnetic permeability by rapid quenching from elevated temperature.

2. Experimental

2.1. Sample preparation and characterizations

Samples of the Ti tube (OD:1.4 mm∅, ID:1.2 mm∅, Length:20 mm) and Ti rod (OD:2.0 mm∅, Length:20 mm) were used as the heat materials (99.5%, Nilaco Co.). For the $MgFe_2O_4$ ferrite powders, a commercial material (Kojundo Chemical Lab. Co., Ltd., 99.9%) was used to fill the inside of the Ti tube. In order to obtain the quenched ferrite powder, the powder sample in crucible was dropped from furnace at an elevated temperature into water at room temperature, and then collected using a paper filter and dried at 100 °C. The X-ray diffraction (XRD) patterns of the dried powders were recorded using a Rigaku Rint 2000 diffractometer with Cu-Kα radiation and a scanning rate of 1.0°/min at 40 kV and 40 mA. The hysteresis loss and the relative magnetic permeability of the ferrite powder were obtained between −500 and +500 A/m using a B–H analyzer (HP E5060A, Hewlett-Packard Co., Ltd.). For this measurement, ring-type samples (outside diameter was about 20 mm, inside diameter about 13 mm, and height about 5 mm) were prepared using a mixture of the ferrite powder and epoxy resin adhesive (4:1 weight ratio).

2.2. Measurement of heat generation ability in AC magnetic field

Fig. 1 shows the apparatus for the measurement of the temperature in the AC magnetic field. The sample tube was placed in a glass case (Pyrex: 20 mm∅, 45 mm) with 10 ml of water. The tube was placed in a vertical direction using a hole in the center of the plastic base. The temperature of the water was measured in order to estimate the heat generation ability of the sample tube in the AC magnetic field. The temperature measurement was started after keeping the room temperature at 25 °C in ambient air for several hours. Air was bubbled into the glass case for stirring of the water. The AC magnetic field was applied to the sample using an external coil. The coil consisted of eight loops of copper pipe (6∅) wound around a polypropylene (PP) bobbin (48 mm∅ × 40 mm). The copper pipe was cooled by flowing water to maintain its temperature and impedance. The coil was connected to a power supply (T162-5712B, Thamway Co., Ltd.) through an impedance tuner. The applied AC magnetic field was 1.77 kA/m at the center of the coil and fixed at 370 kHz. An infrared thermometer (505 s, Minolta Co., Ltd.) was used for the sample temperature measurements.

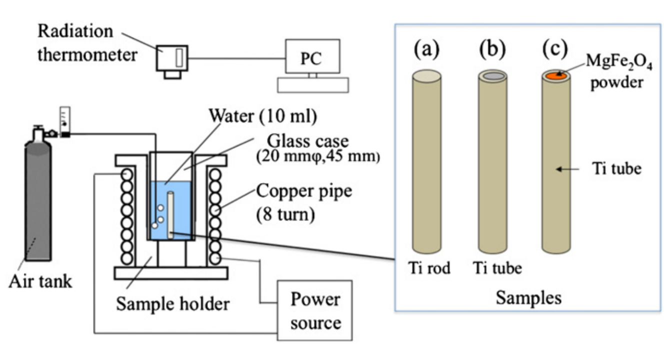

Fig. 1. Apparatus for temperature measurement of samples in AC magnetic field.

2.3. Computer simulation

A comparison of the heat generation by a computer simulation was carried out using the electromagnetic field analysis software, JMAG Studio, ver.9.1 (JRI Solutions, Ltd.). The conditions for the simulation were the same as those for the experiment. In this case, we simulated only the needle materials without the heat transfer to surrounding water. The magnetic permeability of the ferrite powder for the simulation utilized the results of the B–H analyzer. The electrical conductivity of the $MgFe_2O_4$ for the simulation was measured using a complex impedance method. The physical data of the Ti metal and $MgFe_2O_4$ for the simulation was mainly obtained from Ref. [16]. The number of meshes for the simulation was 200 (W) and 50 (H) for all the materials, such as the Ti rod, the Ti tube, and filled ferrite.

3. Results and discussion

3.1. High heat generation ability of the Ti tube filled with $MgFe_2O_4$ powder

Fig. 2 shows the temperature enhancement (ΔT) of the 10 ml of water for one needle-type sample versus time in the AC magnetic field (370 kHz, 1.77 kA/m). The temperature increased with time and became saturated after 50 min for all the filled samples. Table 1 lists the weight and heat generation ability of the test samples. The heat generation ability ($J\,s^{-1}\,g^{-1}$) was calculated using a temperature enhance ratio ($dT/dt = K\,s^{-1}$) for the initial 2 min of the ΔT measurement using this equation

$$\text{Heat generation ability} = C(dT/dt)/M \quad (1)$$

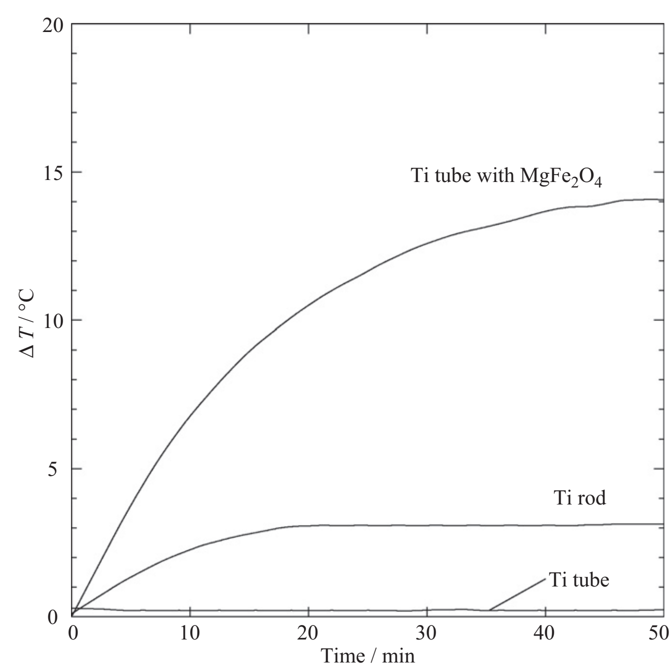

Fig. 2. Temperature enhancement (ΔT) of 10 ml of water using the heated needle-type sample versus time in an AC magnetic field (370 kHz, 1.77 kA/m). The size of samples is OD: 1.4 mm∅, ID:1.2 mm∅, length: 20 mm for tube OD:2.0 mm∅, length: 20 mm for rod.