Multi-Directional Excitation System and Clinical Coil Model for Soft-heating Hyperthermia

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Abstract: The soft-heating method induces hyperthermia with elongated heating elements implanted in the body. The element produces heat under high-frequency magnetic field generated by an excitation coil placed outside the body. The element has thermo-sensitive ferrite in a metal loop. Notably, the temperature of the element does not exceed the Curie point, providing an automatic mechanism that limits the heating temperature and enables safe treatment. The heat output of the element depends on magnetic field strength, excitation frequency, and the angle between the element and the incident magnetic field. For example, heating becomes largest when the incident magnetic field is parallel to the long axis of the element. However, the heating area of an element is limited, and multiple elements must be implanted to target a tumor from various angles. Excitation using a solenoid coil or a flat coil is only in one direction, but magnetic field needs to be generated in multiple directions. We use two coils because magnetic field sources in at least two directions allow for a multi-directional magnetic field. It is well known that a current phase difference of 90° between two coils results in a rotating magnetic field. However, induced current might damage the power supply if inductive coupling occurs between the two coils. In addition, a coil without electromagnetic coupling is difficult to apply to the human body. Accordingly, we propose a new method for realizing a multi-directional magnetic field, as well as a clinical coil model. The method uses two excitation frequencies, and a multi-directional magnetic field is obtained at a certain position. Additionally, an important characteristic is that the power supply is safe even if electromagnetic coupling occurs in the coil model. Using this technique, we successfully heated elements placed in various directions.

Key Words: excitation coil, multi-direction, soft-heating, dual frequency

Introduction

Soft-heating is a method of inducing hyperthermia in which a heating element is implanted in the body1-5. We have also reported the success of animal experiments6,7. Implanting a heating element is
a minimally invasive medical procedure. The element, wherever it is implanted, can be heated if magnetic field of medium intensity is incident thereon, and the technique can be applied to various affected parts of the body. This approach is promising for inducing local hyperthermia where only the area around the implant is efficiently heated. When a ferromagnetic material is implanted as the heating element, local hyperthermia is called magnetic hyperthermia, which has been widely studied [1-9,11,12]. The heating element produces heat under high-frequency magnetic field generated by a coil placed outside the body. In using local hyperthermia to treat tumors, it is necessary to minimize the damage to normal tissue; temperature control is therefore a critical technical challenges. Because of automatic temperature control, the heating element that we have developed is useful in this need.

**Principle of heating**

In our needle-shaped heating element, a metal loop is attached to a thermo-sensitive ferrite element. The heating mechanism shall be discussed in detail in the following. The thermo-sensitive ferrite has a predetermined Curie point, and the element temperature does not go over it. Fig. 1 shows the mechanism of the automatic temperature control of the element. \( T \) is the element temperature, and \( T_c \) is the Curie point of thermo-sensitive ferrite. If \( T < T_c \), the magnetic field is concentrated on the ferrite due to its large magnetic permeability. Temperature \( T \) rises as short-circuit electric current flows through the metal loop. At \( T > T_c \), the temperature rise is suppressed due to the abrupt decrease of the magnetic permeability of the thermo-sensitive ferrite. As a result, the temperature of the element does not go over the predetermined Curie point. Thus, the element temperature is controlled automatically. Here, some level of frequency and magnetic field is needed to reach the Curie point. For example, if the length is approximately 10 mm, a sufficient amount of heat is generated at frequency of 200 kHz and magnetic field of 3 mT. This frequency value is relatively low and this magnetic field is relatively weak [1,8]. Thus, the soft-heating method can excellently preserve normal tissue, and is expected to be a promising local hyperthermia treatment.

**Multi-directional excitation system**

However, the soft-heating method has problems stemming from the needle shape of the heating element. Heat generation is strongly dependent on the angle between the long axis of the element and the

![Fig. 1. Principle of the automatic control of the temperature.](image)

\( T \) is the temperature of the heating element, and \( T_c \) is the Curie point of thermo-sensitive ferrite. The magnetic body uses gold plating for the metal loop. The magnetic field is generated by the excitation coil.
incident magnetic field. In magnetic hyperthermia, the device to transmit energy for heating is an excitation coil. Although there are many reports on excitation coils\textsuperscript{8–12}, most of these coils are large and generate a magnetic field in a single direction. When needle-shaped elements are used, medical practitioners implant the elements at various angles in accordance with the size and shape of the tumor. However, it is impossible to realize effective heating using only a single-direction magnetic field. This is one reason why needle-shaped elements are not widely used to induce hyperthermia. Therefore, using a multi-directional magnetic field becomes necessary to excite the elements.

We proposed a multi-coil system to generate magnetic field in two directions. In this study, two coils are the magnetic field sources and generate the synthetic magnetic field. If we have a two-directional magnetic field, it becomes possible to change the direction of magnetic field with time by using different frequencies or electric current phases in the two magnetic fields. The current phase difference of 90° with the same frequency between two excitation coils is well known as a condition of a rotating magnetic field. However, the coil models with electromagnetic coupling are needed in clinical practice. When there is electromagnetic coupling between two coils connected to series resonance circuits and driven same frequency, a large induced current is created and may damage to each power source of the coil. Therefore we chose the dual frequency excitation method.

In this study, we investigate the amount of heat generated depending on the angle of element placement, and as well as a system that generates a multi-directional magnetic field in order to address the above-mentioned problems.

Materials and methods

\textit{Angle dependence and heating area of heating element}

The temperature dependence was measured by changing the angle of magnetic field incident on the heating element. In all measurements, the temperature sensor, ANRITSU FL-2000, was used. This sensor is non-contact and unaffected by high-frequency magnetic field. The Curie point of the element was 70°C. The element was placed in an insulation material, and under the excitation conditions, the frequency was 200 kHz and the magnetic field strength was 0.5 mT. A solenoid coil was used as the excitation device. The solenoid coil generated a uniform magnetic field in the axis direction of the coil in the vicinity of the coil center. The heating element was placed at the center of the solenoid coil. As shown in Fig. 2, the angle of 0° was defined as when the long axis of the element and the coil axis of the

![Figure 2: Examples of setting angles between a solenoid coil and an element.](image-url)
solenoid coil were in parallel. The setting angles were 0°, 30°, 45°, 60°, and 90° in this measurement.

In addition, in relation to the above experiments, a simulation was performed of the heating area of
the heating element. We used the Finite-Difference Time-Domain method (FDTD method). The Curie
point of the element was 70°C. The length of the element was 10 mm. Both of the incident magnetic
fields are parallel to the long axis of the heating element. First, simulations were performed for the cases
with and without blood flow at the setting angle of 0°. Then, simulations were performed where the
setting angle was changed successively. When the setting angle was used as a parameter, the magnetic
field strength incident on the long axis of the element decreased with the cosine function of the setting
angle, as it was changed from 0° to 90°.

Clinical coil model

The basic clinical coil model is two coils placed to face each other. Fig. 3 shows the two coils and
cross section slice of the XZ plane. In this model, magnetic field is obtained in two directions between
and inside the coils except near the two coil axes. Therefore, we can generate a two-dimensional
multi-directional magnetic field by using dual frequencies. In addition, in the case of the model of Fig.
3, the usefulness is high because a similar multi-directional magnetic field is obtained on a plane
including the Z-axis due to the symmetrical nature of the configuration. Fig. 4 shows an example of
using the face-to-face clinical model. It is here assumed that the coil is used to surround the targeted part.

![Fig. 3. Cross-sectional view of the clinical coil model.](image)

Two-directional magnetic field is generated between and inside the two coils. The multi-directional magnetic field is obtained on the XZ plane by using dual frequencies.

![Fig. 4. Examples of using a clinical coil model.](image)

The clinical model, compared with the basic model, can be more easily placed on the human body.
Heating experiments using clinical coil model with multi-directional excitation

Using the face-to-face clinical coil model shown in Fig. 3, the temperature characteristics of the element were measured to determine whether the element placed at various angles shows a heating effect. The temperature of the element surface was measured for 600 s. Fig. 5 shows the outline of the experiment. As shown in Fig. 5, the setting angle of 0° was when the element was placed perpendicularly to the coil axis. The coils used were solenoid coils, of the same shape and number of turns, placed to face each other. The diameter of each solenoid coil was 90 mm. The distance between the two coils was 30 mm, and the coils were arranged so that the center of the heating element was always 15 mm from them. Here, the coupling factor of the excitation coils was 0.13. Further, the element was placed inside an insulation material and in a constant-temperature bath, which was set to 37°C. The Curie point of the element was 70°C, and the electric current was 3 A in the two coils. The frequencies of 104 kHz and 171 kHz were used.

Results

Setting angle dependence and heating area of heating elements

Fig. 6 shows the temperature characteristics. The maximum temperature is obtained when the setting angle is 0° or when the incident magnetic field is in parallel with the long axis of the element. On the other hand, it is confirmed that the maximum temperature decreases slowly as the setting angle increases. It is clear that we do not have a temperature rise at the final setting angle of 90°, where the magnetic field and the element are perpendicular to each other.
Fig. 7. Heating area of a heating element in the FDTD method. The area surrounded by a dashed line shows the area greater than 42.5°C. Upper figures show the result without blood flow, and lower figures show the result with blood flow. Left figures show the data in the direction of the long axis of the element, and right figures show the data in the direction of the short axis.

Fig. 7 and Fig. 8 are the simulation results of heating area by FDTD method. In Fig. 7, the upper part shows the result without blood flow, and the lower part shows the result with blood flow of 60 mL/ (100g·min). The left figures show the heated region as viewed from the long axis of the element, and the right figures show the heated region as viewed from the short axis of the element. The part surrounded by a dashed line shows the area greater than 42.5°C, which is the temperature considered effective for killing cancer cells. The upper figures, where the influence of blood flow is not considered, show the theoretically greatest heating area. Here, in both figures, the volume of the area surrounded by the dashed line is about 1,000 cm³. In the lower figures, although the heating area is narrower because of the influence of the blood flow, as compared with the upper figures, it is confirmed that the surrounding area of the element is heated to over 42.5°C. In addition, Fig. 8 shows the results of simulations for the setting angles of 0°, 30°, 45°, and 60°. The figure shows that the area surrounded by the 42.5°C line decreases as the angle of the incident magnetic field increases.
Fig. 8. Heating area of a heating element by the FDTD method. Here, $\theta$ is the setting angle of the heating element, similarly to the setting angle as shown in Fig. 6. $\theta$ is varied in the measurement as a parameter.

Fig. 9. Surface temperature characteristics of a heating element excited by a clinical coil model. The setting angle of $\theta$ is when the long axis of the element is in parallel with the X-axis. The temperature characteristics were measured at the setting angles of $0^\circ$, $30^\circ$, $60^\circ$, $90^\circ$, $120^\circ$, and $150^\circ$. 
Heating experiment using the clinical coil model with multi-directional excitation

Fig. 9 shows the temperature characteristics. By testing the setting angle of 0°, 30°, 60°, 90°, 120°, and 150° in the measurement, it was confirmed that the temperature approximately reached the Curie point at any angle.

Discussion

From Figs. 7 and 8, the importance of multi-directional magnetic field is confirmed in applying a soft-heating method with needle shaped elements. From the heating experiment, it is clear that we have improved characteristics in Fig. 9 as compared with those in Fig. 6.

In this study, we succeeded in realizing a multi-directional magnetic field by using two coils facing each other and driven at two different frequencies. In other words, we solved the issue of heat control in relation to the incident magnetic field and the incident angle. It will be necessary to further consider the cooling effect of the blood flow, but the excitation system can always realize the largest heating range shown in Fig. 7. With this system, a tumor of arbitrary shape can effectively be heated by using a minimal number of elements placed at the most suitable positions. In addition, using this system, we succeeded in realizing actuation under strong electromagnetic coupling, and greatly improving the freedom of coil design compared with the conventional excitation coil.[9–12]. Naturally, in addition to the soft-heating method, the technology can be also applied to any magnetic hyperthermia technique using needle-shaped heating elements, which is also expected to be helpful.

In this study, although multi-directional magnetic field was realized in a two-dimensional plane, it remains necessary to consider generation of a three-dimensional multi-directional magnetic field. It is also necessary to design a coil model that can heat many different parts of the human body efficiently. By solving these issues, we will become able to produce a practical excitation device, which medical practitioners can handle easily without troublesome positioning procedure.

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References