Heating Performance of Soft-heating Element with LC-booster for Invasive Hyperthermia Therapy

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The soft-heating method is an implantable hyperthermia method that can control the ultimate temperature of heating elements by using the Curie temperature of the magnetic material used in the element. It is a safe heating method. High heat generation has been achieved for heating elements by forming a metal ring around a core made of a ferrite-based magnetic material having a low Curie temperature. However, to generate a magnetic flux for heating deep inside the body, an exciting coil with a high withstand voltage and large allowable current has been required. In this research, we reduce the load on the exciting system, by developing a novel heating element using the LC-booster method. This wireless power transfer technology is excellent in matching with the load resistance and is proposed as a method for improving the performance of the heating element itself. Our proposed LC-booster method has better heat generation performance than the conventional methods. In addition, we prove that the performance could be improved by increasing the resonant frequency.

Key words: hyperthermia, soft-heating method, Curie temperature, wireless power transfer, LC-booster

1. Introduction

In recent years, many effective treatment methods have been proposed for cancer. However, the early detection of cancer is critical because it dramatically improves the survival rates after treatment. In deep cancer, often an important visceral organ is affected; therefore, extensive excision not only leads to the loss of function but also increases the risk of death. In the case of deep areas, physical access for frequent surgical treatment becomes complicated. To reduce the burden on the patients, we need local treatment that can preserve function.

Implantable hyperthermia is very effective for local treatment. One embedded hyperthermia method is the soft-heating method [1], which uses a heating element that combines a metal ring with a magnetic material of the Low Curie temperature. The soft-heating method uses a functional heating element that can control the short-circuit current flowing in the metal ring in a high-frequency magnetic field by using the Curie temperature of the magnetic material. As a result, the ultimate temperature of the element can be controlled. In other words, there is no need to adjust the output of the power source in the exciting system according to the temperature. Furthermore, by using a magnetic material with a Curie temperature higher than 42.5 °C, which is a typical treatment temperature for hyperthermia, the heating area can be expanded and the tumor tissue completely necrotized. Therefore, the risk of growing again can be reduced. It is similar to radiofrequency ablation (RFA) in that the heater temperature needs to be raised to 42.5 °C or higher. However, unlike RFA, the temperature of the heating element in the soft-heating method can be kept constant as described above; therefore, a cooling system is not necessary to prevent overheating. In [2], we confirmed that by using this method, a high therapeutic effect can be expected from the relationship between the progress of the tumor and the treatment conditions when a heat-generating element was inserted into a mouse’s B16 melanoma [2]. For this, we required an excitation frequency of 200 kHz and a magnetic flux density of 3 mT. It is not easy to realize this condition deep inside the body. However, if we could improve the heat generation capacity of the heat-generating element, it would be possible to alleviate the excitation conditions, and we could facilitate the miniaturization and high functionality of the exciting apparatus. Therefore, in this research, to improve the heating capability of the heating element, we generate sufficient heat from the heating element even in low magnetic flux density by incorporating the LC-booster method [3], which has been established as the wireless power transfer (WPT) technology. The purpose of this study is to fabricate a prototype heating element that incorporates the LC-booster method, which is more efficient than the conventional methods. We did this by measuring the frequency characteristics of the input power and the temperature characteristics in a high-frequency magnetic field.

2. Configuration of Heating Element

2.1 Conventional type

Fig. 1 shows the equivalent circuit of a conventional heating element. \( L_1 \) is the inductance of the exciting coil; \( L_2 \) is the inductance of the metal ring; \( r_1 \) is the equivalent series resistance (ESR) of the exciting coil; \( r_2 \) is ESR of the metal ring; and \( M_2 \) is the mutual inductance between them. The size of our element is largely different from the size of the exciting coil; therefore, \( M_2 \) is very small. Under this low coupling
condition, by keeping the current of the exciting coil constant, the induced voltage of the metal ring of the heating element can be made constant, and the heat output $P$ can be stabilized. We assume that the current of the exciting coil is $I_1$, then $P$ can be written as follows:

$$P = \frac{\omega^2 r_2 M_{12}^2}{r_2^2 + \omega^2 L_2} |I_1|^2$$  \hspace{1cm} (1)

Here, $\omega$ is the angular frequency. Therefore, it is possible to improve $P$ by applying the magnetic flux density from the outside without changing the element structure. Also, from (1), when $r_2$ is regarded as a variable, $P$ becomes the maximum when $Q_2$ is 1. As a method for realizing it, [4] proposed a method for adjusting the resistance by changing the thickness of the metal ring. We conducted the above animal experiments under the exciting condition (200 kHz, 3 mT) by using a heating element whose metal ring thickness had been optimally adjusted. We estimated the specifications about the coil for realizing this exciting condition in the deep part of the body (approximately 60 mm). The exciting coil assumes a spiral shape with one end at the center of the circle and the other end at the circumference. We assume that the coil radius is $R$, and the magnetic flux density in the $z$-axis direction is $B_z$. At a position vertically separated from the coil center by $z$, $B_z$ is given as follows [5]:

$$B_z = \frac{\mu_0 N I}{2R} \left( \ln \frac{R + \sqrt{R^2 + z^2}}{z} - \frac{R}{\sqrt{R^2 + z^2}} \right)$$  \hspace{1cm} (2)

Let us assume that $R$ is 150 mm and $z$ is 60 mm, and the magneto motive force $NI$ required for $B_z$ to be 3 mT is approximately 1000 AT. If the number of turns is 10, a current of 100 A is required. It is difficult to develop enough power supply unit for the specification. Therefore, it is essential to improve the performance of the heating element to miniaturize the exciting system.

### 2.2 LC-booster type

To solve the above problems, we propose a method that incorporates the LC-booster (a WPT technology) in a heating element. In WPT, the LC-booster system can change the magnetic field distribution near the load coil by incorporating an LC resonator between the transmitting and receiving coils and improving the efficiency at a specific load. Energy can be efficiently sent to the load; therefore, the heat output of the heating element may be improved. Fig. 2 shows a schematic diagram of the heating element and the equivalent circuit when the LC-booster system is incorporated. The difference from the WPT case is that the load resistance is shorted to form a one-turn metal ring, and the other points are the same. Using similar studies, researchers have proposed a method in which the LC resonant circuit itself is heated by using the RF/micro band electromagnetic field [6] [7]. The temperature needs to be constantly monitored because the temperature reached depends on the thermal equilibrium determined between the electromagnetic wave output and the surrounding environment. However, the structure proposed in this research does not require any temperature measurements because the ultimate temperature is determined in principle by the Curie temperature, and heat generation and temperature control are simultaneously realized by the hybrid heating structure of the LC resonant circuit and the metal ring. In this circuit configuration, the currents of LC-booster part and the metal ring cause a change in the magnetic flux density inside the core. The change can affect the core loss and the loss at the coil and the metal ring. In this study, the loss is equal to the heating performance. Therefore, it is important to evaluate the loss of the heating elements with different configuration (in this study, core only, conventional type, LC-resonator type, and LC-booster type).

![Fig. 1 Schematics of exciting part and heating element (conventional type).](image1)

![Fig. 2 Schematics of heating element (LC-booster type).](image2)
3. Evaluation of Heating Performance

3.1 Heating elements

We actually manufactured the four heating elements in order to confirm the heating performance. Fig. 3 shows the heater elements, and Table 1 shows the specifications of the elements. The magnetic material used was NP22D, a Ni-Zn ferrite manufactured by Hitachi Metals (see Table 2 for specifications). The metal ring was constructed by winding a conductive copper foil adhesive tape (TERAOKA 8315 0.05, copper foil thickness 0.018 mm) around the ferrite material. In addition, the resonator coil was constructed by winding the polyurethane copper wire (diameter 0.08 mm) 100 times on the metal ring. The board was connected at the end of the lead wire 100 mm from the heating element so that the resonator capacitor (film capacitor) could be easily replaced. First, the heating capacity was estimated by measuring the input power characteristics by using the prototype heating element.

3.2 Experimental method

The input power \( P_0 \) (active power) to the exciting coil consists of the power consumption \( P_1 \) of the exciting coil, the core loss \( P_c \), the power consumption \( P_k \) in the LC-booster part, and the power consumption \( P_2 \) in the metal ring part. If we assume that the current \( I_1 \) of the exciting coil is constant, then the input power when the heating element is disposed in the exciting coil. Therefore, the power consumption \( P \) of the entire heating element can be obtained from the following equation.

\[
P = P_1 + P_k + P_2 = P_{in} - P_1
\]

However, the existing exciting coil is much larger than the heating element; therefore, the coupling is low and it is not easy to measure the changes in the input power. Therefore, by using a small solenoid coil close to the heating element size, it is possible to evaluate the relative performances between the different heating elements by enhancing the coupling to raise the measurement sensitivity. The experimental environment is shown in Fig. 4. The small solenoid coil used in the experiment was 40 mm in length and 32 mm in diameter. There were 17 turns. \( P_{in} \) is obtained from the ESR \( r \) (measured using an LCR meter (Agilent E4980A)) and the current \( I \) (from the LCR meter) as follows:

![Fig. 3 Heating elements for experiment.](image)

![Fig. 4 Experimental circuit (for Type C and LC-booster type, resonance capacitor is outside micro exciting coil).](image)

Table 1 Specifications of heating elements.

| Type   | A     | B     | C     | LC-booster |
|--------|-------|-------|-------|------------|
| Core   | ○     | ○     | ○     | ○          |
| Copper foil | –   | ○     | –     | ○          |
| Coil   | –     | –     | ○     | ○          |

Table 2 Specifications of ferrite core.

| Item               | Value  |
|--------------------|--------|
| Length [mm]        | 10     |
| Width [mm]         | 1.2    |
| Shape              | Octagonal prism |
| Curie temperature [°C] | 90     |
| Initial permeability | 2200  |

Micro exciting coil

30 mm

Heating element

17 turns

LCR meter

Fig. 4 Experimental circuit (for Type C and LC-booster type, resonance capacitor is outside micro exciting coil).
\[ P_{\text{in}} = rI^2 \]  

(4)

The heating elements used in the experiment are the four elements shown in Fig. 3. The capacitance value of the capacitor connected to Type C is 36.8 nF. (Hereinafter, the capacitance value mentioned will be the indicated value, not the measured value.) The capacitance value of the capacitor connected to the LC-booster type was the same as that of the capacitor connected to the Type C element. \( P_{\text{in}} \) was measured by changing the frequency from 20 kHz to 900 kHz. In this study, to clarify the characteristics of the heater with almost the same shape, the types of core material, copper foil and wire material are not changed.

3.3 Comparison of heating performance

Fig. 5 shows the measurement results of the frequency characteristics of the power consumption of the heating element. In Type A, it was confirmed that \( P \) rises in the high-frequency band, but it was a much smaller value than other heating elements. \( P \) is considered to be almost equal to \( P_c \) at this time, the core loss contributed less to the performance of the heating element. In Type B, \( P \) increased with the increase in frequency. However, in the Type C and the LC-booster type elements, \( P \) increased rapidly at a specific frequency. In particular, the highest value was Type C. As compared with the LC-booster type, Type C showed a high Q factor. In other words, the effective frequency band was narrow. Therefore, we assume that Type C is susceptible to capacitance changes in the connected capacitor; these changes include variations in the capacitors, the molds of the heating elements, and the in-vivo permittivity. However, although \( P \) is lower in the LC-booster method than that in Type C, the usable band was wide. Therefore, the LC-booster type was less susceptible to capacitance changes. To confirm the characteristics, we measured \( P \) when the capacitance of the connected capacitor was increased without changing the frequency. The results are shown in Fig. 6. In Type C, an increase in the capacitance by approximately 9% caused \( P \) to decay to 40% of its value before the increase. However, the rate of the LC-booster type was 92%. It is possible for the LC-booster type to maintain the performance if a capacitance change occurs. Therefore, the LC-booster type heating element is suitable for practical purpose.

Next, to clarify the influence of increasing the resonant frequency on the heat generation performance, we considered the relationship between the maximum power consumption and the frequency by changing the capacitance of the connected capacitor. The results are shown in Fig. 7. At this time, the capacitance values of the capacitors used were 6.8, 10, 16.8, and 36.8 nF. Within the measured range, the maximum power consumption increased almost in proportion to the frequency. In other words, increasing the resonance frequency leads to better performance.

4. Heating Experiment

4.1 Experimental implementation

The power that could be supplied from the LCR meter (used in the previous section) was very small; therefore, it was not possible to heat the LC-booster type heating element to observe the temperature rise. Therefore, in this section, by using the exciting coil and the high-frequency power source (which can realize large exciting conditions), we clarify the performance of the LC-booster type element from the temperature characteristic by changing the applied magnetic flux density and the resonance condition. A schematic diagram of the experiment is shown in Fig. 8. In the experiment, we used Helmholtz-type coils for the exciting coil, and the heating element was placed at the
center between the coils. A heat insulating material was used to eliminate the influence of the heat generation of the exciting coil. A fiber optical thermometer (Anritsu Meter FL-2000) was used to measure the temperature, and the measurement time was 300 s. Note that this experiment was conducted at room temperature.

4.2 Temperature profiles for changing magnetic flux densities

Fig. 9 shows the temperature profile when the magnetic flux density was changed to 0.5, 1, 2, and 3 mT. At this time, the exciting frequency was 102 kHz, and the heating elements used were the conventional Type B and the LC-booster type (36.8 nF). We selected an exciting frequency slightly different from the frequency shown in Fig. 7 to consider the allowable current of the capacitor. As a result, the ultimate temperature reached its maximum at an applied magnetic flux density of 3 mT in both cases: 84.9 °C for Type B and 86.2 °C for the LC-booster type. There was no significant difference in the ultimate temperature, and the temperature could be controlled near the Curie temperature. In other words, the LC resonator does not continue to generate heat beyond the Curie temperature. Moreover, when the condition of the magnetic flux density was lowered, the temperature difference after 300 s of the two began to increase, and the temperature difference became approximately 30 °C at 1 mT. This result is similar to the results given in Section 3.3 and shows that the LC-booster type element has better performance than the conventional elements. Therefore, by adopting the LC-booster method, it is possible to control the temperature near the Curie temperature without heat generation beyond it.

**Fig. 7** Transition of maximum power consumption in LC-booster type element.

**Fig. 8** Experimental schematic diagram for measuring temperature profile.

**Fig. 9** Temperature profiles of conventional and LC-booster type elements in high frequency magnetic field.
improve the heat output of the conventional heating element without losing the temperature controllability.

4.3 Effect of high resonance frequency

In Section 3.3, we suggested that performance can be improved by setting the LC-booster type element to a high resonance frequency. Therefore, in this section, we confirm the temperature characteristics by changing the resonance frequency setting for a constant applied magnetic flux density. In the experiment, the capacitance value of the capacitor connected to the LC-booster type was the same as that in Fig. 7, and the capacitor connected to the exciting coil was adjusted so that the exciting frequency approached the frequencies shown in Fig. 7. The measured results are shown in Fig. 10. At this time, the applied magnetic flux density was fixed at 0.5 mT. As a result, by increasing the frequency, the slope of the initial temperature rise became large, and the temperature characteristics under the low magnetic flux density condition of 0.5 mT were improved. The capacitance value of the connected capacitor could be reduced as the resonant frequency was increased. In other words, the volume of the entire heating element can be reduced, which leads to high heat generation.

5. Conclusion

In this paper, we fabricated an LC-booster type heating element, and we evaluated its performance from the frequency characteristics of the input power and the temperature characteristics in a high-frequency magnetic field. As a result, the LC-booster method achieved higher heat generation than the conventional method, and the LC-booster method could maintain temperature controllability. In addition, the LC-booster method has a wider band than the method that uses only the LC resonator. The LC-booster method is not susceptible to capacitance changes and generates stable heat. Furthermore, heat generation can be improved and the volume can be reduced by increasing the resonance frequency.

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