Optimization of Resonant Circuit and Evaluation of Magnetic Field Uniformity with 50 mm Gap Magnetic Field Generator

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Heating mediators for magnetic hyperthermia treatment (MHT) are dependent on magnetic field strength. Therefore, a hyperthermia applicator that generates a homogeneous magnetic field is required. We fabricated a 50 mm gap magnetic field generator (hereinafter called the 50 mm prototype), and the guideline for optimizing combination of parameters of the resonant circuit was suggested to maximize the estimated heating index (product of frequency and magnetic field strength). We found that a 7×2-turn coil is optimal for the 50 mm prototype. We consider that this optimization method is applicable for designing a full-scale hyperthermia applicator. The uniformity of magnetic field strength distribution in the 50 mm prototype was measured by a pickup coil, and we show experimentally that magnetic circuit type magnetic field generator is appropriate for the MHT applicator. The feasibility of a full-scale MHT applicator was increased by the suggestion of guideline for high-estimated heating index operation and the demonstration of magnetic field homogeneity.

Key words: hyperthermia, magnetic field generator, magnetic circuit, resonant circuit, uniform magnetic field

1. Introduction

Hyperthermia therapy has gained attention in recent years as a new cancer treatment. In current clinical practice, it is performed with induction heating in the radio frequency range (8 MHz or 13.56 MHz) and dielectric heating in the microwave range (430 MHz or 2450 MHz) \(^1\). In this study, we focused on magnetic hyperthermia treatment (MHT), which can heat the cancer tissue locally using relatively low frequencies (100 kHz to 1 MHz). The treatment procedure is as follows. A heating mediator such as an electrical conductor \(^2\), magnetic fluid \(^3\), or bulk magnetic material \(^4\) is inserted around the cancer tissue. An alternating magnetic field is applied to the heating mediator from outside the body and the mediator is heated by eddy-current loss, Neel and Brownian relaxations, or hysteresis loss. The target temperature of the heating mediator is between 42 and 45 °C \(^5\).

The specific absorption rate (SAR) of heating mediators is proportional to the magnetic field strength to a power of between 1.5 and 2.3 \(^6\). As magnetic field strength has a large influence on SAR, a homogeneous magnetic field is required and the heating mediator must be capable of being heated correctly anywhere in the body. Therefore, a hyperthermia applicator is required to generate a homogeneous (±5%) magnetic field over a large area (5–10 L \(^7\)). Additionally, for the widespread adoption of MHT, it is desirable that the hyperthermia applicator should be as simple as possible. However, a full-scale MHT applicator requires a large-capacity power supply. This is why that a MHT applicator that operates on condition of high-estimated heating index is required. Estimated heating index is product of frequency and magnetic field strength and in proportional to SAR of heating mediator.

The guideline for high-estimated heating index operation is required when designing a full-scale MHT applicator. There has been no study that focuses on estimated heating index and no suggestion about the guideline for optimizing resonant circuit of MHT applicator. We consider that optimizing resonant circuit improves estimated heating index of MHT applicator. We evaluated the resonant characteristics with the 50 mm prototype. Assuming that SAR is proportional to the product of frequency and magnetic field strength, the guideline for optimizing circuit parameters that maximize estimated heating index was suggested. Moreover, we applied this guideline to 50 mm prototype and confirmed that the optimal resonant circuit parameter was uniquely determined. This guideline is helpful for designing a full-scale MHT applicator.

In previous research, it has been shown that magnetic field uniformity in the magnetic circuit type magnetic field generator by the electromagnetic field analysis \(^8\). In this paper, we experimentally demonstrated magnetic field uniformity in the 50 mm prototype to consolidate validity of the magnetic circuit type magnetic field generator. By the suggestion of the guideline for high-estimated heating index operation and the experimental demonstration of magnetic field uniformity, the feasibility of a full-scale MHT applicator was improved.

2. Experiment equipment

As a preliminary stage for fabrication of a full-scale MHT applicator, we fabricated a prototype that has 50 mm gap and magnetic poles with a cross-sectional area of 90×90 mm\(^2\) (Fig. 1). The purpose of this prototype is the evaluation of the resonant circuit, the verification of the guideline for optimizing the resonant circuit and the demonstration of magnetic field uniformity. Too narrow gap makes it difficult to measure the magnetic field distribution. To evaluate the magnetic field...
distribution by the multi-point with a pickup coil (spatial resolution: x-axis 1.3 mm, y-axis 10 mm, z-axis 10 mm), the gap width was 50 mm. The circuit was composed of a pair of E-type ferrite cores (TDK, PC40), and excitation coils were wound about the magnetic poles. The pair of excitation coils was connected in series. We refer to the number of turns of the coil as (number of turns on one side) × 2. The excitation coil was composed of copper pipe (inner diameter 2 mm and outer diameter 3 mm) to circulate cooling water.  

Fig. 2 shows the simplified equivalent circuit of the resonant circuit. $L_a\ C_a$ is inductance ($L_a=0.9 \ \mu \text{H}$) and capacitance ($C_a=360 \ \text{pF}$) of the 50 Ω coaxial cable. AC resistance of excitation coil $R_e$ was only considered as resistance component because it has the most significant influence on impedance characteristic. The combined impedance between terminals A and B is expressed by Eq. (1). The impedance between terminals A and B was measured using an LCR meter (HIOKI, 3532-50).

$$Z = \text{Re}(Z) + j\text{Im}(Z) = \frac{\alpha \gamma + \beta \delta}{\gamma^2 + \delta^2} + j\frac{\beta \gamma - \alpha \delta}{\gamma^2 + \delta^2}$$

$$\alpha = -\omega^2 L_e R_e (C_c + C_m)$$
$$\beta = -\omega^2 L_e (L_e + L_c) (C_c + C_m) + \omega L_m$$
$$\gamma = \omega^2 L_m (L_e + L_c) C_c C_m$$
$$\delta = -\omega^2 L_m C_c R_e + \omega R_e (C_c + C_m)$$

(1)

The excitation current $I_e$ is expressed Eq. (2).

$$|I_e| = \frac{V C_m}{\sqrt{(R_e (C_c + C_m))^2 + \{\omega (L_e + L_c) (C_c + C_m) - \frac{1}{\omega}\}^2}}$$

(2)

3. Experimental results

3.1 Characteristics of resonant circuit

We evaluated the changes in impedance locus by varying the resonant circuit parameters. Fig. 3 shows the measured impedance locus when the inductance of excitation coil $L_e$ was changed. In the resonance band, the impedance locus starts near the imaginary axis and moves in a clockwise direction with increasing frequency before returning to the imaginary axis. To maximize the power factor and minimize the reflected power, the impedance locus should pass through the matching point (50+j0 Ω) and a matched frequency should be chosen. For example, the impedance locus of a 3×2-turn coil should be reduced and a 10×2-turn coil should be expanded for impedance matching, as shown in Fig. 3.

The size of the impedance locus was evaluated from the maximum value of the real part impedance $\text{Re}(Z)$. Fig. 4(a) shows that the size of impedance locus reduces with increasing inductance. Fig. 4(b) shows the relationship between inductance of the excitation coil and the resonant frequency $f_r$. A diamond indicium was calculated value that was obtained from the impedance locus by Eq. (1). The experimental value of the 50 mm prototype was obtained using a filled circle. We define the resonant frequency $f_r$ as the frequency at which the phase of impedance becomes 0 from a positive value. When the phase did not equal 0, the minimum frequency was adopted and plotted using an unfilled indicium. When calculating the impedance locus by Eq. (1), the measured frequency characteristic of AC resistance of the 50 mm prototype was applied to the resistance $R_e$. As for the calculation value in Fig. 4(a), there is the variation to approximate curve due to the resistance frequency characteristic that has the measurement error. The difference between the calculated value and experimental value, shown in Figs. 4(a), 5(a) and 6(a), was due to the parasitic capacitance between the internal wiring and the metal housing of the matching box.

Fig. 4 shows that the trend of the calculated value agrees with that of experimental value. The resonant frequency $f_r$ is inversely proportional to the inductance of the excitation coil (Fig. 4(b)). Coils with a small inductance (a small number of turns) have higher operating frequencies but weaker magnetic fields. Conversely, a coil with large inductance (a large number
of turns have a stronger magnetic field but a lower operating frequency. There is therefore the trade-off relationship between frequency \( f \) and magnetic field strength \( H \).

Fig. 5(a) shows the relationship between matching capacitance \( C_m \) and the size of the impedance locus. Fig. 5(b) shows the relationship between matching capacitance \( C_m \) and resonant frequency. As shown in Fig. 5, the trend of the calculated value qualitatively agrees with that of the experimental value. Resonant frequency \( f \) increases with decreasing \( C_m \) (Fig. 5(b)). However, an increasing \( f \) brings increasing AC resistance \( R_e \). Eq. (2) shows that excitation current \( I_e \) decrease with increasing \( R_e \); the magnetic field becomes weaker. Therefore, there is also a trade-off between frequency \( f \) and magnetic field strength \( H \).

Fig. 6(a) shows the relationship between matching inductance \( L_m \) and the size of the impedance locus. As shown in Fig. 6, the trend of the calculated value qualitatively agrees with that of the experimental value. The impedance locus expands monotonically with increasing \( L_m \). Fig. 6(b) shows the relationship between matching inductance \( L_m \) and resonant frequency \( f \). In the change from \( L_m = 4.09 \mu H \) to \( 5.24 \mu H \), the change of experimental \( f \) is only -3.8 kHz because the influence of \( L_m \) on \( f \) is small. This is in contrast to the significant changes in impedance locus (Fig. 6(a)). It is found that \( L_m \) is uniquely determined for impedance matching at the
time of choosing \( L_0 \) and \( C_m \). Therefore, we adjust the matching inductance \( L_m \) for impedance matching.

Figs. 4, 5 and 6 show the characteristic of the equivalent circuit qualitatively agrees with that of the experimental resonant circuit with the 50mm prototype. Therefore, we show that the simplified equivalent circuit is appropriate to describe circuit characteristics and the above resonant circuit characteristic is applied to other excitation coils, such as a full-scale applicator.

### 3.2 Guideline for optimizing circuit parameters

According to our investigation of resonant circuit characteristics, we found that there is a trade-off between magnetic field strength, resonant frequency. Therefore, we consider that there is an optimal combination of the resonant circuit parameter. In this section, we show the guideline for examining the optimal combination of circuit parameters that maximizes the estimated heating index while maintaining matching conditions by changing various parameters.

We show the optimization procedure below. Firstly, we set \( L_0 \) and \( C_m \). After that, impedance locus was adjusted to the matching point with \( L_m \). Secondly, a fixed input power was applied in this paper 180 W. Thirdly, the excitation current \( I_e \) and frequency \( f_e \) were measured and magnetic field strength \( H \) was calculated. Fourthly, the estimated heating index was evaluated from the product of frequency \( f \) and magnetic field strength \( H \). This series of flow was executed until the maximum value of estimated heating index was found.

The multiplier of \( f \) and \( H \) differs depending on the type of heating mediator. For instance, the SAR of an electrical conductor is proportional to \( f^2 H^2 \), that of a magnetic fluid is proportional to \( fH^2 \), and that of a bulk magnetic material is proportional to \( f^2 H^2 \). We evaluated \( f^2 H^2 \) for an electrical conductor and \( fH^2 \) for a magnetic fluid or bulk magnetic material.

We applied the above-described procedure to the 50 mm prototype and acquired \( L_0, H \) and \( L_m \) in a plurality of combinations of circuit parameters. Fig. 7(a) shows the relationship between matching capacitance and excitation current when the input power is 180 W. The excitation current having a larger number of turns is smaller when \( C_m \) is greater than 500 pF. Coils having a larger number of turns can generate a strong magnetic field even though the exciting current is small (Fig. 7). However, although increasing the number of turns increases the strength of the magnetic field, the frequency is reduced as a result (Fig. 8). Additionally, although it is better for a stronger magnetic field to increase \( C_m \) (Fig. 7(b)), an increase in \( C_m \) reduces the frequency (Fig. 8).

Figs. 9 and 10 show the estimated heating index for each type of heating mediator. The optimal combination of parameters in terms of maximizing the estimated heating index varies depending on the heating mediator. This is because the influence of frequency and magnetic field strength on SAR differs depending on the mediator.

The \( SAR \) of electrical conductors is proportional to \( f^2 H^2 \) and is significantly affected by frequency. Hence, the combination using \( C_m = 500 \) pF is optimal because of the higher frequency. The \( SAR \) of a magnetic fluid or bulk magnetic material is proportional to \( fH^2 \) because magnetic field strength has a significant impact on their \( SAR \). Hence, the combination using \( C_m = 1000 \) pF is optimal because of the stronger magnetic field. It was found that the optimal combination of the resonant circuit was uniquely determined for each of the heating mediators. We consider that this guideline is helpful for designing a full-scale and high-estimated heating index operation MHT applicator.
3.3 Experimental demonstration of magnetic field distribution

To demonstrate the validity of the magnetic circuit type magnetic field generator, we measured the magnetic field distribution with a pickup coil. The pickup coil was manufactured with 11 turns of a polyurethane copper wire (ϕ = 0.12 mm). The cross-sectional area of the coil was 1 cm². The magnetic field strength was obtained by measuring the effective value of the induced electromotive force of the pickup coil. Furthermore, electromagnetic field analysis was performed using the finite element method (ANSYS, Maxwell ver.12). The number of turns of the exciting coil was 7×2, the exciting current was 8.3 A RMS, and the operating frequency was 450 kHz. The experimental magnetic field strength was 2.5 kA/m RMS at the center point of the 50 mm prototype (x=0, y=0, z=0) and the analytical value was 2.3 kA/m RMS, thereby demonstrating good agreement with the experimental value. The magnetic field strength was normalized by the center point to investigate distribution.

Fig. 11 shows the surface distribution of the magnetic field strength in the zx-plane, which was obtained by analysis, and the experimental line distribution of the magnetic field. The magnetic field has uniformity to within ±5% between magnetic poles. Figs. 12 and 13 show the surface distribution in the xy-plane and yz-plane and the experimental results. As shown in Figs. 11 to 13, the experimental results agree with the analysis results for any axis. A homogeneous magnetic field is distributed in a cylindrical shape. The diameter of the cylindrical area is 59 mm, and the volume is 0.14 L. Assuming that measurements of the 50 mm prototype are scaled up 6 fold to human body size, the volume of uniform magnetic field becomes 30 L (≈ 0.14 L × 6³). This meets the 10 L requirement. Thus, this design of magnetic circuit type magnetic field generator is appropriate for MHT applications.
4. Conclusion

We fabricated a 50 mm prototype with a magnetic circuit and evaluated the characteristics of the resonant circuit. By measurement of resonant circuit characteristic and equivalent circuit analysis, we show the generality of the resonant circuit of the 50 mm prototype. Therefore, the resonant circuit characteristic that was shown in this paper can be applied to other excitation coils, such as a full-scale MHT applicator. It was found that there is the trade-off relationship between frequency $f$ and magnetic field strength $H$. The guideline for optimizing resonant circuit parameters was suggested by assuming that the product of frequency and magnetic field strength equates to the estimated heating index.

We applied this guideline to the 50 mm prototype. The $7 \times 2$-turn coil (84 µH), $C_m = 500$ pF (for electrical conductor) and $C_m = 1000$ pF (for magnetic fluid or bulk magnetic material) is optimal for the 50 mm prototype. We found that the optimal combination is uniquely determined. We consider that this guideline can be applied to a full-scale MHT applicator, because this guideline has generality.

Furthermore, we evaluated the distribution of magnetic field strength using the 50 mm prototype. It was demonstrated that a 50 mm prototype can generate a 0.14-L volume uniform magnetic field that has uniformity to within ±5%. The validity of the magnetic circuit type magnetic field generator was experimentally confirmed.

The feasibility of the full-scale MHT applicator was increased by the guideline for high-estimated heating index operation and the experimental demonstration of magnetic field homogeneity in the magnetic circuit type magnetic field generator.

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