Resonant circuit as magnetic device for cancer therapy

Yasushi Takemura
Department of Electrical and Computer Engineering, Yokohama National University
79-5 Tokiwadai, Hodogaya, Yokohama, 240-8501, Japan
E-mail: takemura@ynu.ac.jp

Abstract. Fabrication and characterization of a resonant circuit as magnetic device for hyperthermia treatment are discussed. The resonant circuit consisting of a closed connection of an inductor and a capacitor raised its temperature by an externally applied magnetic field. As the resonant circuit was heated efficiently, it could be excited by a weak RF magnetic field of magnetic resonance imaging (MRI). By using a ferrite core for the inductor, the efficiency of temperature rise of the circuit was improved, which attributed to the miniaturization of the implant size.

1. Introduction
Hyperthermia is a therapeutic procedure of raising the body temperature for cancer treatment. Various established treatments of surgical operation, radiotherapy and chemotherapy suffer from risks of scar and negative side effects. The hyperthermia is expected for reducing those risks. The hyperthermia elevates the local temperature above 42.5 deg C. to kill cancer cells, while most normal tissues are not damaged at the temperature below 44-45 deg. C [1]. When the body temperature rises, the heat is dissipated by cooling through blood circulation. A sluggish blood flow in the cancerous tissues leaves them vulnerable at the elevated temperature. This process of killing the cancer is safe for surrounding healthy tissues.

A technique for local heating is essential in terms of capability of warming the cancerous tissue locally as compared with whole body heating. Among various warming methods proposed for the local heating, e.g. magnetic nanoparticles [2], the hyperthermia using implants is expected to warm cancerous tissue in deeply located. The implants of tiny elements inside of the body are heated up by an external energy source. A combination of magnetic materials as the implants and a magnetic field applied from outside of the body has attracted much attention [3, 4]. In order to minimize harmful effects associated with high frequency magnetic field to the body, the external magnetic field should be less intense with a lower frequency as possible. It is expectable to use a resonance circuit for the implant, which generates heat efficiently by the applied external magnetic field [5]. It was found that the resonant circuit was heated up to 40 deg. C by the weak applied magnetic field of 3.4 μT at 63.9 MHz [6]. It has been also proposed to use a RF pulse (high frequency magnetic field) from a magnetic resonance imaging (MRI). As a preliminary result, RF magnetic field of the MRI with a low duty factor could raise the circuit temperature up to 13 deg. C [7].

In this paper, the resonant circuit as magnetic device for cancer therapy is discussed in detail, including excitation by RF field from the MRI, higher efficiency of heating using magnetic core in inductors, and miniaturization for delivering through catheter or injector as lower invasive process.
2. Resonant circuit as hyperthermia implant

The resonant circuit used in this study was consisted of a closed connection of an inductor and a capacitor. When an ac magnetic field is applied to the inductor coil, a current flows by an electromotive force induced in the coil, \( v \), as shown in Fig. 1. An electric power consumed in the circuit, \( P \) in active power, is described as

\[
P = \frac{r_s}{Z^2} v^2
\]

(1)

where \( Z \) and \( r_s \) are impedance and residual resistance of the circuit, respectively. In case that the frequency of the applied ac field equals to the resonant frequency of the circuit, the power \( P \) is described as

\[
P_{\text{resonance}} = \frac{1}{r_s} v^2
\]

(2)

because the reactance in \( Z = j\omega L + \frac{1}{j\omega C} + r_s \) is zero.

As the electromotive force induced in the coil, \( v \) is proportional to the frequency of the applied magnetic field, higher frequency is preferable for a higher temperature rise.

The circuit was consisted of an inductor (3.4 \( \mu \)H) and a capacitor (18 pF). Its resonant frequency was 63.9 MHz. The diameter and number of turn of the coil were 6 mm and 9, respectively. The temperature rise of the circuit was measured by an optical thermometer, whose result was not affected by a magnetic field with high frequency. Its sensor tip was attached to the coil. Preliminary results of the temperature rise of the circuit excited by an ac magnetic field with continuous waveform have been reported [6]. It was found that the highest temperature rise was obtained when the frequency of the applied field matched to the resonant frequency of the circuit.

3. Temperature rise of resonant circuit

3.1. Excitation by MRI

A temperature rise of a resonant circuit excited by a RF pulse of MRI was measured. The 1.5-T type commercial MRI system was used. The center frequency of the modulated RF magnetic field was 63.9 MHz. The magnetic field of the modulated RF pulse was applied to the circuit under a normal procedure for the MRI diagnostics. The direction of the inductor coil was adjusted to the \( x \)-, \( y \)- or \( z \)-axis, where the \( z \)-axis was parallel to the direction of the dc magnetic field in the configuration of the MRI system. The RF pulse was applied in the directions of the \( x \)- and \( y \)-axes which were perpendicular to the \( z \)-axis. Figure 2 shows the temperature rise of the circuit as a function of the duration of the MRI operation. The circuit raised its temperature up to 20-30 deg C. after 5 min when the coil was aligned to \( x \)- or \( y \)-axis which was parallel to the direction of the RF pulse. Field strength of RF pulse of MRI for clinical use in hospitals is normally a few \( \mu \)T and its duty ratio is quite low comparing with a continuous wave. It should be noted that the resonant circuit is heated by this weak RF magnetic field. The temperature did not rise in case that the RF magnetic field did not penetrate the coil aligned to \( z \)-axis. The slight difference of temperature rise between \( x \)- and \( y \)-axes were due to different power cycle
Because the inductor acts as a magnet, the resonant circuit implant might degrade the MRI images as artifacts. Figure 3 shows the T1-weighted MRI image of an agar phantom with an inserted resonant circuit. The agar was semi-hard, but the position of the circuit was not shifted in the MRI. Although the part of the tomographic image around the circuit was blackened, the surrounding part was clearly imaged enough for diagnosis.

3.2. Frequency modulation in MRI

The waveform of RF magnetic field is modulated sinc wave pulse in order to observe recovery and decay of hydrogen nuclei magnetic moment. Its frequency is distributed as to match the nuclear magnetic resonance (NMR) frequency, also called the Larmor frequency, for each position. Figure 4 shows the waveform of RF pulse and its frequency distribution. They are related to each other in Fourier and Fourier inverse transformations. In order to collect tomographic images, information depending on the position under gradient dc magnetic field corresponds to information depending on NMR frequency. In MRI equipment used in this study, the frequency shift of 0.1 MHz can be obtained by the position shift of 70 mm by employing an appropriate sequence. The temperature rise of the resonant circuit depending on the position in the MRI stage was investigated as shown in Fig. 5. The resonant circuit was placed at distance of 0, ±70 and ±140 mm from the center position and its temperature rise of measured at each position. The frequency at the center was 63.9 MHz. Figure 6 shows the temperature rise measured at 30 sec and 300 sec after irradiating the RF pulse. It was confirmed that temperature rise was maximum at the center position, where the excitation frequency was matched to the resonant frequency of the circuit of 63.9 MHz. From this result, it is suggested that...
the temperature of the resonant circuit implant can be controlled by its position as well as by pulse duty ratio of MRI sequence.

3.3. Resonant circuit using core-coil

In case that size of implants is as small as 1mm, it is possible to deliver them to a tumor through a catheter as illustrated in Fig.7. This delivery method offers a cancer treatment with less scar, which can not be achieved by surgical operation including endoscopic resection. A risk of infectious disease can be also reduced. A resonant circuit is one of the promising implant from the viewpoints of its size and high heat efficiency.
Recently miniaturization of the resonant circuit implant has been achieved as shown in Fig. 7. Previously, the inductor was air-core type. The Ni-Zn ferrite core of a cylindrical shape was employed for the inductor in order to enhance the induced electromotive force from the external ac magnetic field. As a preliminary result, it was found that the diameter of the resonant circuit implant using a core-coil could be reduced to a tenth of that using an air-coil. The reduced size less than 1 mm in diameter allows delivery of the implant into the body using an injector as a lower invasive process.

4. Conclusions
The cancer therapy of hyperthermia using a resonant circuit implant was discussed. The implant consisting of a closed connection of an inductor and a capacitor was efficiently heated by an external ac magnetic field. It was found that normal MRI equipment of clinically used in hospital system could rise the temperature of the resonant circuit. The temperature rise was up to 30 deg. C by an applied magnetic field of RF pulse under a normal diagnosis procedure of the MRI system. It is advantageous that the commercial MRI equipment can be used for the hyperthermia because the therapeutic procedure can be repeated after confirming results from the MRI diagnosis. The size of the implant could be reduced by using the core-coil. This recent improvement is expected for delivery of the implant through a catheter or an injector.

References
[1] W. C. Dewey, L. E. Hopwood, S. A. Sapareto, L. E. Gerweck, *Radiology* **123**, 463-474 (1977).
[2] Q. A. Pankhurst, J. Connolly, S. K. Jones and J. Dobson, *J. Phys. D: Appl. Phys.*, **36**, R167-R181 (2003).
[3] I. Tohnai, Y. Goto, Y. Hayashi, M. Ueda, T. Kobayashi and M. Matsui, *Int. J. Hyperthermia*, **12**, 37-47 (1996).
[4] M. Jojo, A. Murakami, F. Sato, H. Matsuaki, and T. Sato, *IEEE Trans. Magn.*, **37**, 2944-2946 (2001).
[5] Y. Kotsuka, K. Orii, H. Kojima, K. Kamogawa, and M. Tanaka, *IEEE Trans. MTT*, **47**, 2630-2635 (1999).
[6] M. Morita, T. Inoue, T. Yamada, Y. Takemura, T. Niwa, and T. Inoue, *IEEE Trans. Magn.*, **41**, 3637-3675 (2005).
[7] T. Niwa, Y. Takemura, T. Inoue, H. Kurihara, T. Hisa, *British J. of Radiology*, **81**, 69-72 (2008).