Non-Invasive Measurement of the Temperature Using Scanning Small Coils

SATOSHI ANDO 1*, HAJIME MONZEN 1, MORIKAZU AMANO 1, HIROBUMI ONO 1, TOMOAKI SUZUKI 1, KAYOKO MAEDA 1, ATSUSHI FUKUYAMA 1, TOHRU TAKAHASHI 2, ITSUO YAMAMOTO 3, TAKEO HASEGAWA 1

1 Department of Medical Imaging and Information, Graduate School of Suzuka University, Suzuka, Mie 510-0293, Japan
2 Department of Radioisotope Research Center, Kansai Medical University, Moriguchi, Osaka 570-8506, Japan
3 Department of RF Research Center, Yamamoto Vinita Co, Tennoji-ku, Osaka 543-0002 Japan

Key Words: antenna, hyperthermia, non-invasive, RF current, temperature

Abstract: The temperature measurement of tumor is very important for hyperthermia. A temperature is measured by inserting a thermocouple thermometer into a living body. The fault of this method is that it can get only partial temperature and it has large invasive to the patient. Therefore, it method can't know even if a part of temperature rises. We researched the matter whether temperature measurement could be done without stabbing a thermometer by using the small coils. A magnetic field is generated when the radio-frequency is charged with electricity of the high frequency to the objects. Magnetic field is caught with the coil which put this magnetic field on making it stand opposite to each other. The electric fields decrease by 1/(2πr). Then, we can calculate the profile of the electric fields using this equation. There are strong correlation between the radio frequency current and temperature in this object. Therefore, we can estimate the temperature distribution in the heating object non-invasive. The results of this study confirmed, there was strong correlation between temperature distribution using thermography and distribution of RF currents from our methods.

Introduction

In hyperthermia for tumors, the effect in vivo increases greatly with an increase in the tissue or cell temperature of 1°C above 42.5°C. Therefore, monitoring of the tumor temperature is an important in hyperthermia. Thermocouple sensors are usually utilized for temperature monitoring hyperthermia. They consist of constantan wires, which are coated with Teflon to reduce noise and connected to a multi-point sensor. These sensors allow simultaneous measurement at five points arranged at 1cm
intervals from the tip. The temperature in the heated area is measured by inserting two or more sensors into and around the target area. This causes pain and injures the patients and may affect the prognosis of hyperthermia. With this method, however, temperature monitoring at every treatment may be difficult depending on the site.

We report the development of a new technique for non-invasive and repetitive temperature measurement during hyperthermia. Using small coil antennas, we measured the intensity of the magnetic field by radio-frequency currents flowing through a phantom target during radio-frequency hyperthermia. The aperture consists of a parallel of small coil antennas. The temperature can be estimated from the two-dimensional distribution of radio-frequency currents based on the intensity distribution profile of the magnetic field which can be measured non-invasively by using the coil antennas.

Materials and Methods

Materials

Two 6.0 µH coils were prepared by winding a 0.18 mm enamel copper wire 40 times around a plastic pipe 5.1 mm in diameter. These coils arranged parallel (to one another). These coils were covered with magnetic protection materials. The signal wires from the coils enter a conversion circuits consisting of a rectifier circuit, an impedance matching circuit, and a voltage dividing circuit. The radio-frequency output from each coil antenna is led to a voltage conversion circuit, and all outputs were connected to a voltmeter. The sensitivity of each coil antennas was adjusted to a uniform level by controlling the output voltage from each antenna with a variable resistance placed on the input side of the voltmeter. (Fig. 1)

The heating apparatus was RF-8 (Yamamoto Vinita Co.), and a 4% agar phantom (30×30×40 cm) was used as a model of hyperthermic treatment site. The temperature distribution in the phantom after heating was examined by thermography (Themotracer TH1106, NEC Sansei), and it was compared with the two-dimensional distribution of the radio-frequency currents measured with the coil antennas.

Methods

Measurement of intensity of magnetic field

A 4% agar phantom (30×30×40 cm, the shape of a rectangular column) was sandwiched by heating electrodes 30 cm in diameter. Radio-frequency energy of 200 Watts was applied between the heating electrodes. The coil antennas to detect the magnetic field were placed on the both side of the agar phantom perpendicular to the radio-frequency current during the radio-frequency heating. Attenuation of the magnetic field was measured at various distances between the phantom and the antenna. Also
theoretical values of the intensity of the magnetic field were calculated at various distances. (Fig.2, Fig.3)

Radio-frequency currents and temperature increases

A 4% agar phantom was sandwiched between heating electrodes of 10, 14, 25 cm in diameter respectively. Radio-frequency energy at 8 MHz and 1,000 Watts was applied, and the output of the coil antenna and the increase in temperature every minute were measured. The relationship between the radio-frequency current in the phantom and the temperature increase was studied.

Agar phantom heating test

The radio-frequency energy was applied at 1,000 Watts. After radio-frequency heating for about ten minutes, middle of the phantom was cut horizontally, and the temperature distribution in the agar was examined by thermography (Fig. 4). The thermograms were compared with reconstruction images of the radio-frequency current intensity distribution obtained from the output voltage (intensity of magnetic filed) from the coil antennas arranged around the agar phantom. A hot spot was created in the phantom by inserting an iron rod 1.5 cm in diameter and 10 cm length into the agar phantom. The two-dimensional current distribution reconstructed form the voltage output from the parallel coil antennas was compared with the two-dimensional temperature distribution in the agar by thermography.

Reconstruction Two-dimensional Radio-frequency current distribution image

Profile data were collected between two antennas arranged parallel. The distance between the antennas was 40 cm. We supposed

![Fig. 2. The output of antennal is expressed as X1, that of antenna2, the maximum output as D, and the intensity of the magnetic field at a given point as Xn. The distance between the two opposite antennas was 30.0 cm. Xn is 1/(2πr) less than D.](image1)

![Fig. 3. This picture shows profiles of electric field and distribution of RF current.](image2)

![Fig. 4. This picture shows coil antennas and phantoms.](image3)
that a profile showing a decrease of \(1/(2\pi r)^4\) and a profile with a width identical to the maximum distance between two antennas (Fig. 3). We scanned magnetic field profiles between antennas vertically, and obtained magnetic field distribution profiles mountain ranges. It data like prepared by scanning profile data between all combinations of antennas were added up. The threshold of the profile data was the 7% and 15% of the maximum. Smoothing was quadric, and a reconstruction image of two-dimensional radio-frequency currents was show a display.

**Results**

When an agar phantom was sandwiched between heating electrodes, and a single channel coil antenna was moved away from the surface of the agar at 1 cm intervals during heating, the signals decreased from the distance at a rate of \(1/(2\pi r)\) \[r: \text{distance from the current}\] (Fig. 5). Near the phantom, difference of these profiles was occurred by the performance of volts meter.

**Fig. 5.** This graph shows the output signals \([V]\) from the phantom. The triangle show output signals from the coil antennas. The line indicate theoretical values \([V = A/(2\pi r)]\).

**Fig. 6.** This graph shows the temperature increase every minute along the vertical axis and the radio-frequency current on the surface of the heated material along the horizontal axis.

**Fig. 7.** The left picture is calculated by our technique. The right picture is temperature by thermography. There looked like at each other.
When the applied power was unchanged, the temperature increased as the radio-frequency current increased during heating. Also, the radio-frequency current and temperature increased with increasingly larger heating electrodes. (Fig. 6).

The radio-frequency current increased in proportion in response to the temperature increases, and the rate of temperature increased with larger heating electrodes. The linear relationship of radio-frequency current to temperature suggests that temperature monitoring may be possible by measuring the radio-frequency current. When a hot spot was produced with 1.5 cm in diameter and 10 cm iron rod inserted to a depth of 9 cm from the surface of the agar phantom, a high temperature hot spot was observed near the iron rod (Fig. 7). A hot spot was also observed at the same location in the radio-frequency current distribution profile obtained from the parallel coil antennas.

Discussion

Radio-frequency currents flowing in an object were measured non-invasively by two dimensions by parallel coil antennas. The distribution of temperature in the heating object correlated with the distribution of radio-frequency currents. Especially, the hot spot was detected. This suggests the possibility of non-invasive temperature monitoring through measuring distribution of radio-frequency currents. However, the system examined in this study has some fault to solve. For example, profile of the periphery of the phantom was different because the radio-frequency current image was reconstructed in 1 cm. And the temperature could not be measured in absolute terms. The permittivity, which represents the energy absorption of the heating tissue, specific heat, specific gravity, heat diffusion associated with increased blood flow, heated volume, input electricity, and heating time must be known to convert the distribution of radio-frequency currents into the temperature distribution. The system used in this study is capable of determining an area of high temperature during radio-frequency heating. It may have clinical value, because it allows non-invasive and repeated temperature monitoring unlike existing invasive monitoring methods. The use of superimposed CT and MRI over the two-dimensional current distribution profile and modifications to allow serial graphic representation of approximate absolute temperatures are other future enhancements.

Attempts of non-invasive temperature monitoring using magnetic resonance signals have been reported 6-8). Recently, the temperature was measurements from diffusion factor, T1 relaxation time, proton resonance frequency, spectroscopy and temperature sensitive contrast agent. Especially, measurement of the proton resonance frequency was good results 9). But magnetic resonance has a fault of narrow space, loud sound and long time. Our system for temperature monitoring requires simpler equipment and is much less expensive that the method using MRI. With refinement, it is expected to be of major clinical importance.

In clinical, our method does not have yet enough space resolution and temperature resolution, but these improvements, this system has the potential to make significant clinical contributions to hyperthermic therapy.

References

高周波加温治療時における非侵襲的温度測定モニター

安藤聡志†・門前一†・天野守計†・小野博史†・鈴木友昭†
前田佳子子†・福田篤司†・高橋徹²・山本五郎³・長谷川武夫†

† 鈴鹿医療科学大学 大学院 保健衛生学研究科医療画像情報学専攻
² 関西医科大学 RIセンター
³ 山本ビニター 高周波研究所

要 旨: hyperthermia において温度を測定することは重要である。生体の温度を測る方法として、熱電対温度計がある。熱電対温度計を使う問題として、部分的な場所のみしか温度が測定できないこと、患者を大きく侵襲することがあげられる。そのうえ、ホットスポットを知ることができない。そこで我々はコイルを使って温度を測ることを研究した。

被加温体に高周波電界をかけると、周囲に高周波磁界を生じる。その磁界的減衰は 1/ (2πr : rは距離) である。そのプロファイルから電流密度を計算した。高周波電流と温度の上昇には相関が見られた。実際に加温を行い、サーモグラフィで撮像したものと、本研究によって得られた結果は相関が見られた。よって、被加温体の電流密度を測定すれば、非侵襲的に、温度が測定できることがわかった。