Development of Automatic Impedance Matching System for Resonant Cavity Applicator

YASUHIRO SHINDO^{1*}, KAZUO KATO², HIDEAKI TAKAHASHI³,
TAKEO UZUKA⁴, YUKIHIKO FUJII⁴

¹Graduate School of Science and Technology, and ²Department of Mechanical Engineering Informatics, Meiji University, 1-1-1 Higashi-mita, Tama, Kawasaki, Kanagawa 214-8571, Japan

³Niigata Cancer Center, Section of Neurosurgery, 2-15-3 Kawagishi-cho, Niigata 951-8566, Japan

⁴Department of Neurosurgery, Brain Research Institute, Niigata University, 1-757 Asahimachi-dori, Niigata 951-8585, Japan

Abstract : This paper describes a new system to match the impedance automatically for a re-entrant resonant cavity applicator during brain tumor hyperthermia treatments non-invasively. We have already discussed the effectiveness of the heating method using a manual impedance matching controller with heating experiments of an agar phantom and computer simulations. With this heating method, to generate heating power in the cavity, it is necessary to match the impedance and to tune the resonant frequency. In the initial prototype heating system, both were manually adjusted. However, it was difficult to match the impedance and to tune the frequency especially using a high resonant frequency.

To overcome this problem, we developed the automatic impedance matching system (AIMS). It is known that reflected power is generated when the impedance matching is not complete. In this system, to reduce the reflected power which is fed back to the computer, the stepping motor to turn the dial of the variable capacitors is controlled by developed software. To evaluate the developed AIMS, the heating experiments of the agar phantom, using several electromagnetic modes, were performed. The VSWRs are 1.05 and 1.01 using manual matching and AIMS, respectively. From these results, we found that the temperature rise in the agar phantom using AIMS was about 180% (with TM₀₁₂-like mode) and about 110% (with TM₀₁₀-like mode) more than using the manual type controller under the same heating condition. It was found that the proposed system was very effective for hyperthermia treatment using the resonant cavity applicator even when the resonant frequency was high.

Key Words : impedance matching, resonant cavity applicator, electromagnetic field patterns, non-invasive.

Introduction

As the human brain is protected by the skull, it is not easy to heat deep brain tumors non-invasively

with electromagnetic energy for hyperthermia treatments. Several heating methods have been proposed to heat deep tumors. Some examples are radio frequency (RF) capacitive heating applicators¹⁾, annular phased array applicators²⁾, and coaxial transverse electromagnetic (TEM) applicators³⁾. Some of these methods have been in practical use. However, all of them have advantages and disadvantages, and a successful heating method has not yet been realized.

From 1989, a non-invasive heating method using a re-entrant type resonant cavity applicator was proposed and many positive results have been generated since then^{4,6-10)}. These results show that this heating method is capable of heating deep-seated tumors non-invasively.

In the proposed heating system, different from other high-frequency heating systems⁵⁾, generating heating power inside the cavity requires not only impedance matching input and output, but also the tuning of the exciting frequency and the resonant frequency of the cavity. When the matching and tuning operations are completely performed, the electromagnetic field pattern is generated inside the cavity and the human tumors can be heated concentrically. From our current research, it is found that the resonant frequency can be estimated by computer simulations⁶⁻¹³⁾. So in this study, resonant frequencies of the cavity were calculated by the finite element method (FEM) and were used as the exciting frequencies. In the early prototype heating system, as a manual type impedance matching controller was used. It was difficult to match the impedance in high frequency electromagnetic modes (over 200 MHz) in this early stage. Especially when using TM_{012} -like mode, we could not get a sufficient temperature rise in the hyperthermia treatment with the manual controller⁹⁾. To overcome this problem, we have developed an automatic impedance matching system (AIMS).

In this paper, we propose a new matching system which can adjust the impedance between input and output power automatically.

Fig. 1. Illustration of the automatic impedance matching system (AIMS).

First, the developed matching system for a non-invasive heating system using the re-entrant type resonant cavity applicator is presented. This system feeds back the reflected power generated in the cavity to the impedance matching unit. When the impedance does not match, the unit decreases the reflected power until it matches. Second, the experimental results of heating agar phantoms using AIMS with several electromagnetic modes are discussed. Finally, from these results, it is shown that the developed system can accurately adjust the impedance automatically and is useful for non-invasive hyperthermia treatments.

Methods and materials

Development of Automatic Impedance Matching System (AIMS)

Fig. 1 shows an illustration of the automatic impedance matching system (AIMS). In Fig. 1, a human head is placed in the center of the inner electrodes, and is heated by electromagnetic fields inside the cavity without touching the human body with the applicator. The impedance matching unit is connected to the cavity, and the heating power is supplied by the high frequency amplifier. When the impedance does not match completely, the reflected power generated is fed back to the computer with the AD converter, and the motor drive unit connected with the impedance matching unit is controlled automatically to match the input and output impedance.

Fig. 2 shows a photograph of the developed system. It consists of a cavity, a high frequency amplifier, a motor drive unit, an AD converter, a computer, and an impedance matching unit.

Fig. 3 shows the cross-sectional view of the cavity. The cavity is made of an aluminum plate, and is 500 mm in diameter and 1000 mm in height. To concentrate the heating energy in the center of the cavity, inner electrodes of 100 mm in diameter and

Fig. 2. Set up of the system.

Fig. 3. Cross-sectional view of the cavity.

400 mm in height are used. We made the cylindrical agar phantom 180 mm in diameter and 130 mm in height for the heating experiments.

Impedance matching unit in comparison with the manual proto type

We used a manual type controller to match impedance in the prototype heating system⁶⁻⁹⁾. Fig. 4a shows the manual type impedance matching unit with two dials for variable capacitors (VC1 and VC2). Fig. 4b shows the circuit diagram for impedance matching. The adjustable ranges of the VC1 and VC2 are from 20 pF to 180 pF and from 6 pF to 80 pF listed in Table I, respectively. In this automatic system, we developed a motor drive type impedance matching controller to match impedance more accurately. A photograph of the developed motor drive system is shown in Fig. 4c. The

Fig. 4. Impedance matching unit. *a*, Manual type unit. *b*, Circuit diagram for impedance matching. *c*, Motor drive matching unit.

Table I. Adjustable ranges of the impedance matching unit.

Dial [rev]	VC1 capacity [pF]	VC2 capacity [pF]
0	20	6
19.9	180	80

minimum adjustment angle for the rotation of the dials for the VC1 and VC2 used in the system is 1.8 (deg/step).

Automatic control program

Fig. 5 shows the procedure for the proposed automatic impedance matching operation. First, an initial value is set for VC2 and an “All range searching” is started. In order to measure the reflected power, the VC1 motor is rotated every 10 steps roughly over the full rotation angles. After the “All range searching”, VC1 is set to around the point of minimum reflected power. Second, a “Detailed searching” was carried out. Furthermore, in order to find the minimum value of reflected power with more accuracy, VC1 is rotated by 1 step increment. When the reflected power decreases below an arbitrary threshold value, the rotation is stopped. Here, we set the threshold value to 0.1% of the heating power so that the voltage standing wave ratio (VSWR) of the AIMS becomes lower than that of the manual operation results. VC2 is also obtained as well as VC1. When the impedance matching operation was carried out by the AIMS, heating power was set to 8 W. After matching the impedance automatically, we heated the agar phantom with 30 W of heating power.

The features of the AIMS are summarized below :

- (1) During automatic impedance matching operations, changes in reflected wave power, input power and VSWRs are displayed. Therefore, the operator can operate the AIMS while checking these values so the operation does not terminate on a local minimum.
- (2) The AIMS is in a state in which the prediction results of the SAR and temperature distributions calculated by the FEM are displayed, and impedance matching operations can be carried out.

Fig. 5. Procedure for the proposed automatic impedance matching operation.

- (3) Changes of the measured temperature by the fiber-optic thermometer can be displayed, therefore the operator can operate the AIMS while checking for the target temperature.
- (4) Since the AIMS is operated by remote control, the operator can work in a safe environment.

Experimental conditions for heating a human head agar phantom with TM_{010} -like mode

To evaluate the developed AIMS when using a dominant electromagnetic mode, the heating experiments of the human head agar phantom used a TM_{010} -like mode in both matching methods.

Fig. 6 shows the set up of a human head agar phantom. The human head agar is 215 mm horizontally and 235 mm vertically¹³⁾. In order to heat the center of the brain, the human head agar is placed so that the distance from the cavity wall to the top of the head is 270 mm.

The experimental heating conditions are listed in Table II. In this experiment, heating power is 30 W, heating time is 30 min, and both resonant frequencies are 144.00 MHz.

Fig. 6. Set up of the human head agar phantom.

Table II. Experimental conditions.

	Heating power	Heating time	Resonant frequency	Impedance matching
(a)	30 W	30 min	144.00 MHz	Manual
(b)	30 W	30 min	144.00 MHz	AIMS

Results

Evaluation of Automatic Impedance Matching System (AIMS) with manual matching at TM_{012} -like mode

To evaluate developed AIMS, heating experiments using an agar phantom were performed. Here, we compare the two results of impedance matching using the manual system and the developed automatic system (AIMS). When the manual matching is finished, the reflected power is 0.8 W and VSWR is 1.055.

The operating times of the AIMS and manual matching operations are about 30 min and 60 min, respectively.

Fig. 7 shows the measured data for the reflected power under the matching operation using the AIMS when VC1 matches. In Fig. 7a, after an “All range searching”, we can see that the minimum value of reflected power exists between VC1=13 and VC1=15 rev. In Fig. 7b, after a “Detailed searching”, it can be seen that the matching value for VC1 is 13.58 rev when the reflected power reaches its minimum value (0.187 W, VSWR=1.012). We can determine the value of VC2 in the same way.

Fig. 8 shows the measured reflected power when VC2 matches. Fig. 8b shows the corresponding value for VC2 (0.01 rev) when the impedance matches.

Comparison of heating results by manual impedance matching and by the AIMS at TM_{012} -like mode

Fig. 9 shows the thermal images of a sagittal slice of the agar phantom. The thermal images were taken by an infrared thermal camera (NEC SANEI TH7102WX) after 60 min of heating using the re-entrant resonant cavity. Both of the developed AIMS and the manual type impedance matching

Fig. 7. Reflected power data of VC1. *a*, VC1 all range searching. *b*, VC1 detailed searching.

controllers were examined^{6–9)}. Experimental heating conditions are listed in Table III. From Fig. 9, both of the thermal images show that the center of the agar phantom was heated to a maximum temperature without physical contact. However, the temperature increase using the AIMS was greater than that produced when using the manual impedance matching controller. It can be seen that the developed AIMS is useful for the re-entrant type resonant cavity applicator.

Fig. 8. Reflected power data of VC2. *a*, VC2 all range searching. *b*, VC2 detailed searching.

Table III. Experimental conditions.

	Heating power	Heating time	Resonant frequency	Impedance matching
(a)	30 W	60 min	377.55 MHz	Manual
(b)	30 W	60 min	376.22 MHz	AIMS

Fig. 9. Thermal images. *a*. Manual matching. *b*. Using the AIMS.

Fig. 10. Thermal images of the human head agar phantom ($f=144.0$ MHz).
a, Manual matching. *b*, Using the AIMS.

Comparison of heating results of human head type agar phantom using the manual impedance matching system and the AIMS with a TM_{010} -like mode

Fig. 10 shows the thermal images of human head agar phantom. They are taken by an infrared thermal camera. Both of the results show that the center of the brain is heated to a maximum temperature without heating the neighboring eyeballs and nose. Furthermore, with an attention to the temperature rise, Fig. 10 shows an 8.6°C increase in the AIMS and a 7.6°C increase in the manual impedance matching system. By using the AIMS, the temperature increased more, by approximately 1°C , in comparison to the manual matching system.

Discussion

Interstitial hyperthermia has been used in clinical practice to invasively heat deep tumors^{14,15}. However, this method has both advantages and disadvantages. One of the advantages is that direct and local heating of the area around the needle is possible. Disadvantages are that this heating method has a small heating area and is an invasive heating method. In the developed prototype heating system using a resonant cavity to non-invasively heat deep tumors, the matching operations were performed manually.

If the impedance matching in the heating system with a resonant cavity is not complete, most of the microwave power will be reflected and therefore the temperature inside a targeted object will not increase.

It is not easy to completely match the impedance in the prototype heating system using the manual impedance matching controller. As shown in Figs. 7 and 8, impedance matching ranges for VC1 and VC2 are very narrow, almost all of the heating power is reflected except for these corresponding matching ranges of VC1 and VC2. It was almost impossible to manually rotate VC1 and VC2 per 0.01 rev to match the impedance. It is found that the proposed heating method, which uses the re-entrant type resonant cavity applicator with the developed AIMS is useful for deep tumor hyperthermia treatments.

As shown in Fig. 11, when comparing the temperature rise of the AIMS method to the manual

Fig. 11. Temperature rise profiles. *a*, On the x-axis. *b*, On the z-axis.

Fig. 12. Temperature profiles of the human head agar phantom (on the x-axis).

method using a manual impedance controller at TM_{012} -like mode¹²⁾, the temperature rise of the AIMS method is greater than that of the heating results using the manual impedance matching controller. The AIMS temperature rise is approximately twice that of the manual method.

Furthermore, Fig. 12 shows the temperature profiles of the human head agar phantom. From Fig. 12, the developed AIMS is effective even in the dominant electromagnetic mode (TM_{010} -like mode).

From these results, we can see that it is possible to automatically match impedance with high accuracy by using the developed AIMS.

Conclusion

We proposed the automatic impedance matching system for the developed re-entrant resonant applicator to non-invasively heat deep brain tumors.

From the experimental results, it is confirmed that the proposed AIMS is applicable to successful hyperthermia treatments.

We are now trying to develop a high speed automatic impedance matching system which contains a complete automatic tuning system consisting of both impedance matching and frequency tuning controllers. In order to confirm the safety of organic tissue within the head such as an eyeball, estimation of temperature distributions using a 3-D human head model reconstructed from 2-D medical images and animal experiments will be performed.

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