Suppression of Heat Generation in Magnetic Stimulation Coil
Applied for Treating Dysphagia

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The authors are developing magnetic stimulation coils for use in the treatment of dysphagia. The prototype coil manufactured in our previous research can induce large contraction of the suprahyoid muscles, which should be trained for normal swallowing. In this study, the heat generation in the coil during magnetic stimulation is investigated and suppressed. A numerical analysis showed that the main cause of the generated heat is the eddy current in the coil conductor induced by magnetic flux from the tip of the magnetic core. The analysis also showed that a parallel coil with a cross connection has an ideal current distribution in the coil conductor and thus best suppresses heat generation during magnetic stimulation. The heat-suppressing coil has parallel divided coil conductors and an appropriate connection between the conductors to level the current in each conductor. Moreover, measurements of the temperature rise in prototype coils during magnetic stimulation confirm that heat generation can be greatly suppressed by dividing the conductor and using an appropriate connection between the divided conductors.

Key words: magnetic stimulation, dysphagia, suprahyoid muscles, eddy current, parallel coil

1. Introduction

Dysphagia, or difficulty swallowing, is mainly caused by cerebrovascular disorders and aging. In Japan, a super-aged society, the number of people with dysphagia is rapidly increasing. When food enters the trachea or bronchi due to inappropriate swallowing motion, it can cause aspiration pneumonia1,2. Pneumonia is the 3rd leading cause of death in Japan. More than 70% of pneumonia cases in elderly people are related to aspiration3,4. Recovery from dysphagia is thus important for protecting the elderly.

Neuromuscular electrical stimulation (NMES), a stimulation method that uses electrodes that are stacked directly on the epidermis above swallowing-related muscles such as the suprahyoid muscles, has recently been used for the treatment of dysphagia. Several studies have shown that treatment with NMES promotes swallowing recovery5,6,7. NMES is frequently recommended by therapists in the United States8. However, when NMES is applied to the suprahyoid muscles using an intensity that does not cause pain or discomfort, the induced contraction of muscles is smaller than that in usual swallowing9,10. This occurs because the current intensity required to stimulate the motor point of the suprahyoid muscles deep below the epidermis is also sufficient to stimulate nociceptors just under the epidermis. In addition, it is difficult to adhere electrodes to the lower jaw epidermis of the elderly because of slack skin, leading to insufficient electrical contact. Moreover, for men, beards make electrode contact more difficult.

To overcome these problems, a method that uses magnetic stimulation has been proposed9,10. Magnetic stimulation excites motor nerves via a current induced by rapid changes of the magnetic flux of a coil; this current induces contraction of the target muscle. Magnetic stimulation only slightly stimulates nociceptors, so there is little pain or discomfort during stimulation11. Moreover, contact with skin is unnecessary for stimulation, so beards and slack skin do not cause problems. In our previous studies, numerical analysis showed that a coil with a U-shaped magnetic core (U-core coil hereafter) is the most suitable coil for stimulating the motor point of the suprahyoid muscles12. The figure-8 coil developed by Ueno is widely known for local magnetic stimulation13. A U-core coil consists of a figure-8 coil and a magnetic core. It focuses a strong magnetic flux to stimulate the motor point of the suprahyoid muscles but not the lower alveolar nerve. A clinical test on healthy humans confirmed that magnetic stimulation with a U-core coil can induce contraction of the suprahyoid muscles. Figure 1 shows the placement of a coil for stimulating the motor point of the suprahyoid muscles. Contraction of the suprahyoid muscles upon stimulation can be monitored by imaging the movement of the hyoid bone connected to the muscle using X-ray fluoroscopy. Figure 2 shows X-ray fluoroscopy images of the region near the lower jaw before and during stimulation. Upon stimulation, the
Fig. 1 Placement of coil for stimulating the motor point of the suprahyoid muscles.

Fig. 2 Measurement of hyoid bone movement using X-ray fluoroscopy. The shaded region indicated by the black triangle is the hyoid bone. (a) Before and (b) during stimulation.

The hyoid bone significantly moved in the anterior and superior directions, indicating that the suprahyoid muscles greatly contracted. It has been shown that a contraction comparable to that in swallowing by a healthy person can be obtained using magnetic stimulation, significantly exceeding that induced by NMES, without great pain or discomfort\(^{14}\).

Continuous stimulation using a U-core coil generates heat around the tip of the magnetic core, which increases the temperature of the surface in contact with the patient's skin. In particular, for the small stimulation coil used for patients with a small jaw, because the heat capacity is small (i.e., it is easy to heat), the surface temperature rises to an unsafe value. Fig. 3 shows a thermographic image of the surface of a small coil after 600 continuously generated magnetic pulses. It can be seen that the coil is overheated from the tip side of the magnetic core: the temperature of the coil reaches about 75 °C. Although the coil is covered with a resin cover for insulation, there is a danger of burning the patient via the heat transmitted through the resin cover. The cover itself may also be damaged by the heat.

In this study, to reduce the temperature of the coil surface during magnetic stimulation, the current density distribution inside the coil during magnetic stimulation is obtained using numerical analysis to clarify the mechanism of heat generation. Based on this information, a method for suppressing heat generation is developed. A temperature test using prototype coils is used to validate the proposed heat suppression method.
2. Numerical Analysis

2.1 Model and conditions

The software ANSYS Electromagnetics Suite 19.1 was used for numerical analysis and Eddy Current Solver was used for AC steady state analysis. For numerical analysis, various coil models were prepared. Figure 4 (a) shows a conventional coil model with the same shape and size as those of a prototype U-core coil. The U-core coil is composed of a U-shaped magnetic core made of a silicon steel sheet and a pair of coils. As shown in Fig. 5 (a), the coils are manufactured by winding an insulated copper flat plate (thickness: 0.9 mm; width: 8 mm) with double pancake winding. This model is denoted as the single-coil model.

We also prepared a model in which the coil conductors are divided to suppress the eddy current (Fig. 4 (b)). The coils are manufactured by winding five flat copper plates (thickness: 0.9 mm; width: 1.6 mm) in parallel. This model is denoted as the parallel-coil model. As shown in Fig. 5 (b), the coils wound around one tip of the core are denoted as A1, A2, ... A5 starting from the layer on the tip side. Similarly, the coils wound around the other tip of the core are denoted as B1, B2, ... B5. For analysis of the parallel coil, two methods for connecting coils were applied. As shown in Fig. 6, one connection method (straight connection) is to connect the coils of a given layer (A1-B1, A2-B2, ... A5-B5). The other connection method (cross connection) is to connect a coil from the tip-side layer to a coil from the base-side layer (A1-B5, A2-B4, ... A5-B1). The parallel-coils with straight and cross connections are denoted as parallel coil (straight) and parallel coil (cross), respectively.

The current density distribution in the conductor when a 1.1 kA, 2.35 kHz sinusoidal current is supplied to these coils was analyzed. The value of current is for each coil layer. The current condition was determined by measuring the waveform of the actual current flowing through the prototype coil during magnetic stimulation. The current supplied to a coil used for treatment is an intermittent biphasic pulse. However, the results of an analysis with a continuous sinusoidal current are applicable to coil development.

2.2 Results of numerical analysis

Fig. 7 shows the current density distribution inside the conductor of each coil on line C shown in Fig. 5. The current density distribution shown in the figure was obtained at the phase at which the current density inside the conductor was maximum. The level indicated by "Ideal" shows the current density for a current flowing evenly through the conductor.

The results for the single coil in Fig. 7 show that the current density is biased toward the tip side of the core. The current density reaches a value nine times the ideal density. This current density distribution is equivalent to a state in which a current is flowing through a conductor that is thinner than the actual one and the effective resistance of the conductor increases, greatly increasing heat generation. In addition, because Joule heat is proportional to the square of the current density, the region of the coil close to the tip of the core generates particularly strong heat. It is found that the direction of the current density is opposite to that of the supply.
current in the region of the coil apart from the tip of the core. This opposite current density reduces magnetic flux in the core and generates unnecessary Joule heat.

The cause of this bias is considered to be the eddy currents inside the conductor induced by the magnetic flux generated from the tip of the core. Fig. 8 shows a vector diagram of the magnetic flux calculated under a forced condition where eddy current does not occur in the coils. It can be seen that a strong magnetic flux passes through the coil portion between the tips of the core. The induced eddy current flows to cancel out this magnetic flux.

The results for the parallel coil (straight) in Fig. 7 show that the maximum current density is suppressed compared with that for a single coil. This suppression is likely due to the subdivision of the conductor, which interrupts the eddy current flow. More specifically, the current density in the A1 layer is high, and the current flow in the A5 layer is opposite to the supply current. It is considered that the magnetic flux through the coil induces a positive electromotive force in the A1 (B1) layer and a negative electromotive force in the A5 (B5) layer. The eddy current induced by the electromotive force overlaps the current from the current supply, and the current density distribution shown in Fig.7 is appeared. In Fig. 9, the behavior of the eddy current flow in the parallel coil (straight) is simplified and illustrated. In the figure, each layer of coil is expressed as one turn coil to make it easy to understand. All layers of coil are connected in parallel at the points where the pulse current is supplied from a pulse current supply. So there is an eddy current path through A1–B1–B5–A5 layer.

Focusing on the surface bordered with the closed curve of the eddy current path, the surface has a large area, and all white arrows that indicate the direction of magnetic flux are incident on same face of the surface. It means that, when a magnetic flux is generated from the core, a large amount of eddy current is induced on the eddy current path. Therefore, the results of this numerical analysis show that it is impossible to sufficiently flatten the deviation of the current density by merely subdividing the conductor.

Moreover, the results for the parallel coil (cross) in Fig. 7 show that the current density is suppressed to a level close to the ideal distribution. This suppression is likely due to the electromotive force in the A1 (B1) layer, which makes the current flow in the positive direction, and the electromotive force in the B5 (A5) layer, which makes the current flow in the reverse direction; these currents cancel each other out.

Table 1 shows the heat generated by various types of coil after one pulse of magnetic stimulation calculated in the numerical analysis. The values for the single coil, 5.5, and 3.4 J, respectively. Compared to the single coil, heat generation is suppressed by 52% using the parallel coil (cross), parallel coil (straight), and parallel coil (cross) are 7.1, 5.5, and 3.4 J, respectively.

The results of the numerical analysis show that the main cause of the heat generation in a U-core coil is the eddy current induced inside the coil conductor via the magnetic flux generated from the tip of the core. It was shown that dividing the coil conductor and using a cross connection between coils provides a current density distribution close to the ideal level, suppressing heat generation.

Moreover, Table 1 shows the heat generated by various types of coil after one pulse of magnetic stimulation calculated in the numerical analysis. The values for the single coil, 5.5, and 3.4 J, respectively. Compared to the single coil, heat generation is suppressed by 52% using the parallel coil (cross), parallel coil (straight), and parallel coil (cross) are 7.1, 5.5, and 3.4 J, respectively.

Table 1 Solid loss for various types of coil

| Coil Model              | Quantity of heat generated by 1 pulse (J) |
|------------------------|------------------------------------------|
| Single Coil (Conventional coil) | 7.1                                      |
| Parallel Coil (Straight)                      | 5.5                                      |
| Parallel Coil (Cross)                        | 3.4                                      |
| Ideal Coil (Uniform current density)         | 1.9                                      |
Because the cause of heat generation is an eddy current induced by the magnetic flux passing through the coil, heat generation could be reduced by suppressing the eddy current using litz wire manufactured by twisting a thin enameled wire. However, in general, litz wire has a space factor of about 50% to 60%, and thus it is expected that the effective direct current resistance of the coil will roughly double when litz wire is used. Even if the current of each strand flows evenly and an ideal current distribution is obtained, because heat generation is proportional to the resistance value, it is expected to roughly double. Therefore, it is thought that the heat generation is the same as or greater than that in the parallel coil (cross). In addition, for litz wire, each fine element wire is insulated by a resin coating film, so for the heat inside to be dissipated to the outside, it must pass through several layers of the insulation film. When the temperature rises, it is thus difficult to decrease the temperature inside the coil.

3. Temperature Test using Prototype Coils

3.1 Method

The three types of coil used in the numerical analysis were manufactured and their temperature rise was measured. The temperature rise over the entire coil surface was measured using thermography. In addition, two K-type thermocouples were installed at the upper and lower ends of the coil, respectively, and the temperature was recorded with a data logger. The temperature measurement points are shown in Fig. 10.

The conditions for pulse current conduction were set to those that obtain the highest frequency assumed to be used for subjects. Specifically, a cycle in which 30 pulses were generated per second for 2 seconds and then stopped for 2 seconds was repeated. The waveform of each pulse is 1 cycle of sinusoidal wave. The coil surface temperature was measured during the cycle. The supplied pulse current was set so that the amplitude would be 1.10 kA. The value of amplitude was for entire coil not for each coil layer. The pulse current was supplied from a pulse current supply using capacitor discharge. The wavelengths of pulse current were 422-434 µs and the inverse of the wavelengths are equivalent of 2.30-2.38 kHz of frequency.

In this condition, the magnetic flux densities at 1mm above tip core of single coil, parallel coil (straight), and parallel coil (cross) were 0.92 T, 0.90 T, and 0.93 T, respectively, and that at 16mm above were 0.21 T, 0.21 T, and 0.21 T, respectively. Considering 1mm of the thickness of resin cover for insulation, it means that the magnetic flux density on the patient skin exceeds 0.90T, and that at the region 15mm inward from skin exceeds 0.20 T. Because the amplitude of magnetic flux density over 0.20 T is enough to stimulate nerve, these coils can stimulate nerves at depth of 15mm.

The generation of pulses was started after the surface temperature of the coil was confirmed to be about room temperature (22 °C ± 2 °C).

3.2.1 Results of thermography test

Figures 11-13 show thermographic images taken after 600 and 1200 pulses for the three types of coil, respectively.

The experimental results for the single coil (Fig. 11) show large heat generation in the upper coil, which is consistent with the numerical analysis results. In the numerical analysis results, because the current density was strongly concentrated on the tip side of the upper coil, the temperature rise seemed to be also concentrated at the tip side. However, in the experiment, the upper and lower coils almost uniformly increased in temperature, respectively. This is thought to be caused by the coil not being finely divided and the heat being diffused throughout the upper and lower coils because of the high thermal conductivity of copper.
The experimental results for the parallel coil (straight) (Fig. 12) show that the top layer of the upper and lower coils generates strong heat, consistent with the numerical analysis, which showed that the current density concentrates on the top layer of the upper and lower coils. In this coil, because the coil conductor is divided, diffusion of heat by thermal conduction is weak. The heat at the top layer is not transmitted to other layers; therefore, there is only a local temperature rise at the top layer.

The experimental results for the parallel coil (cross) (Fig. 13) show almost uniform current flow in each layer, which is consistent with the numerical analysis. Considering localized heat generation for the straight connection, the main cause of this uniform temperature rise seems to be the uniform current density, not the fast thermal diffusion in the coil.

The temperatures at the coil tip side after 1200 pulses for the single coil, parallel coil (straight), and parallel coil (cross) were 110.4 °C, 112.3 °C, and 67.6 °C, respectively, corresponding to temperature rises from room temperature (22 °C) of 88.4 °C, 90.3 °C, and 45.6 °C, respectively. These results roughly agree with the numerical analysis results shown in Table 1. Considering the amount of heat generation, the temperature rise should be lower in the parallel coil (straight). The reason of unexpected increment of temperature rise in the parallel coil (straight) is the heat in the top layer does not diffuse throughout the coil.

### 3.2.2 Results of test with thermocouples

Figure 14 shows the results of measuring the time course of the surface temperature of each coil type with thermocouples. This figure shows also the number of generated pulses. The measurements were carried out three times for each coil type. Table 2 shows the means and standard deviations of the number of pulses required for the surface temperature to increase from 30 °C to 80 °C measured at each measurement point three times.

#### Table 2  Number of pulses required for coil surface temperature to increase from 30 °C to 80 °C.

| Coil model      | Position | Average ± SD |
|-----------------|----------|---------------|
| Single coil     | A        | 635 ± 31      |
|                 | B        | 1635 ± 32     |
| Parallel (Straight) | A        | 575 ± 9       |
|                 | B        | 2000 ± 160    |
| Parallel (Cross) | A        | 1830 ± 150    |
|                 | B        | 2995 ± 262    |
As shown in Fig. 14, for the single coil and the parallel coil (straight), the temperature on the tip side of the coil (A) sharply rises, and that on the base side of the coil (B) also rises but with a delay. There is a large difference between the temperatures at points A and B, indicating that the rise in temperature is biased toward the tip of the coil. Even with the results in Table 2, for the single coil and the parallel coil (straight), the required number of pulses at points A and B are greatly different. The inverse of the required number of pulses corresponds roughly to the amount of heat generated at a point. The difference of required number of pulses thus indicates that heat generation in these coils is strongly biased.

The results for the parallel coil (cross) in Fig. 14 show that although the temperature rise at point A is faster, the difference between temperatures at points A and B is always smaller compared with that for the other two coil types. That is, heat generation bias on the surface of the coil is weaker than other two coil types.

Because the part in contact with the patient is on the tip side of the coil, for practical coils, the temperature rise in this part must be small. As shown in Table 2, at point A, the pulses required for the temperature to increase from 30 °C to 80 °C for the single coil and the parallel coil (straight) are about 600 pulses; that for the parallel coil (cross) is more than 3 times this value. In other words, the latter coil can generate more than 3 times the number of pulses compared with those of the former two coils.

4. Conclusion

The heat generation in a U-shaped core coil during magnetic stimulation was investigated using numerical analysis and experiments. The numerical analysis results reveal that the main cause of the heat generation is the eddy current generated inside the coil conductor by the magnetic flux generated from the core tip. Moreover, an ideal current density distribution can be obtained by dividing the conductor and using an appropriate connection between the divided conductors so that the electromagnetic forces induced in the conductors cancel each other.

Prototypes of the coil models were manufactured and tested. The experimental results were consistent with the numerical analysis, confirming that heat generation can be greatly suppressed by dividing the conductor and using a proper connection between the divided conductors.

A clinical trial on a dysphagia patient with a stimulation coil based on the proposed technology is currently underway at Fujita Health University. Considering the actual use at the rehabilitation clinic, it is desirable to generate 6,000 pulses in 15 minutes, so further improvement of the stimulation coil is required. In this study, the conductor was divided into five sections and evaluated. However, it may be possible to reduce the bias of the current density further and make a coil with lower heat generation by using finely divided parallel winding coils. However, if the division is excessive, the conductor space factor and the heat dissipation efficiency may decrease. The optimal winding parameters should thus be determined using numerical analysis.

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References

1) P. K. Lieu, M. S. Chong, and R. Seshadri: Ann. Acad. Med. Singapore, 30, 148 (2001).
2) G. C. Remesso, and M. M. Fukujima: Arq. Neuropsiquiatr, 69, 785 (2011).
3) Y. Michiwaki, and Y. Sumi: Roumehshigu (in Japanese), 28(4), 366 (2014).
4) M. Bulow, R. Speyer, L. Baijens, V. Woisard, and O. Ekberg: Dysphagia, 23, 302 (2008).
5) J. W. Park, Y. Kim, J. C. Oh, and H. J. Lee: Dysphagia, 27, 521 (2012).
6) G. D. Carnaby, and L. Harenberg: Dysphagia, 28, 567 (2013).
7) H. Kagaya, M. Baba, E. Saitoh, S. Okada, M. Yokoyama, and Y. Muraoka: Neuroumodulation, 14, 278 (2011).
8) S. J. Kim, and T. R. Han: Neuroumodulation, 12, 134 (2009).
9) R. Momosaki, M. Abo, S. Watanabe, W. Kakuda, N. Yamada, and K. Mochio: Neuroumodulation, 17, 637 (2014).
10) R. Momosaki, W. Kakuda, N. Yamada, and M. Abo: Int. J. Rehabil. Res., 39(4), 263 (2016).
11) J. Szecsi, M. Schiller, A. Straube, and D. Gerling: Arch. Phys. Med. Rehabil., 90(4), 564 (2009).
12) H. Mori, K. Yoshima, H. Kosukegawa, S. Izumi, and T. Takagi: Baiomekanizumu (in Japanese), 24, 79 (2018).
13) S. Ueno, T. Matsuda, and O. Hiwaki: J. Appl. Phys., 67(9), 5838 (1990).
14) H. Kagaya, M. Ogawa, S. Mori, Y. Aoyagi, S. Shibata, Y. Inamoto, H. Mori, and E. Saitoh: Neuroumodulation, Epub ahead of print.
15) T. Kato, M. Sekino, T. Matsuzaki, A. Nishikawa, Y. Saitoh, and H. Ohsaki: Seitaikougaku (in Japanese), 50(1), 180 (2012).
16) M. Jaritz, and J. Biela: Analytical model for the thermal resistance of windings consisting of solid or litz wire, p1-10 (2013 15th European Conference on Power Electronics and Applications, Lille, 2013).
17) S. Izumi, T. Takagi, R. Nagatomi, N. Nakazato, Y. Yoshima, T. Abe: Rinshoshinkessseirigaku (in Japanese), 37(1), 1 (2009).

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