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Downsizing of Coreless Coils for Transcutaneous Energy Transmission in Implantable Devices -Improvement of Coupling Factor and Efficiency between Coils-

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Abstract— **Transcutaneous energy transmission is useful for improving patient quality of life and for supplying energy to implantable devices noninvasively. To supply highly efficient energy transmission through the skin, it is necessary to increase the coupling factor between the coils and increase the inductance of each coil. In this study, the optimal shape required for the coils to increase the coupling factor was investigated.**

I. Introduction

Wireless power transmission technology for medical equipment is a vital for supplying energy to implantable devices (such as noncontact and noninvasive systems). Wireless power transmission to implantable devices is delivered by what is known as transcutaneous energy transmission systems (TETSs). Up to the present, transcutaneous energy transmission systems use electromagnetic induction. There are problems with electromagnetic induction systems, in that transmission distance is short and the efficiency is lowered if the central axis between the feeding and receiving coil is shifted. On the other hand, magnetic resonance[1] shows a lesser decrease in efficiency as the central axis of the feeding and receiving coil is shifted than electromagnetic induction. It is desirable for the coils used to be small, from the point of view of the patient's quality of life (QOL). However, it is difficult to achieve high transmission efficiency with smaller coils. To achieve highly efficient energy transmission, it is necessary to increase the inductance of the coils, the coupling factor between the coils, etc.

In this study, we have examined and compared to the optimal shape of the coil used for transcutaneous energy transmission by changing the outer diameter and inner diameter of the coil. The goal of this optimization is designing a small device with a high coupling factor.

II. Overview of TETS

Fig. 1 shows an overview of a TETS. Using a regulated DC power supply or battery, AC power is converted into a high frequency signal by a switching circuit. The resulting AC power is transmitted to the implanted device via the transcutaneous energy transmission coils; thus, no cable penetrates the skin. The transmitted AC power is converted into DC power by a rectifier and a ripple filter circuit. Next, this DC power is used to drive the implanted device and charge the secondary battery in the body.

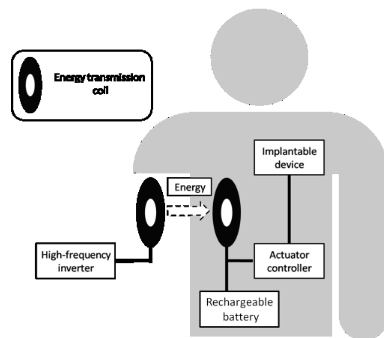

Figure 1. TETS for implantable device.

III. Coreless Coil

Transcutaneous energy transmission coils could be coreless coils[2] in an externally coupled TETS. In this study, we used coreless coils. Fig. 2 shows the equivalent circuit when the device uses a transcutaneous energy transmission coil to transmit energy.

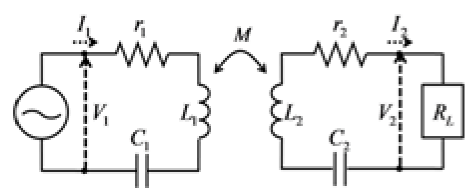

Figure 2. Equivalent circuit to evaluate efficiency.

L_1 and L_2 are the self-inductances of the primary coil (external side) and the secondary coil (internal side), respectively. r_1 and r_2 are the coil resistances of the primary coil and the secondary coil, respectively. C_1 and C_2 are the series resonance capacitors (inserted to improve the transmission efficiency). M is the mutual inductance between the coils. R_L is the load resistance representing the implantable device, rectifier, ripple filter circuit, and secondary battery. V_1 is the input voltage. V_2 is the output voltage. I_1 and I_2 are the currents flowing through the primary coil and secondary coil, respectively. The angular frequency is represented by ω.

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$$V_1 = \left\{ r_1 + j\left(\omega L_1 - \frac{1}{\omega C_1} \right) \right\} I_1 - j\omega M I_2 \qquad (1)$$

$$V_2 = j\omega M I_1 - \left\{ r_2 + j\left(\omega L_2 - \frac{1}{\omega C_2} \right) \right\} I_2 \qquad (2)$$

$$V_2 = R_L I_2 \qquad (3)$$

The resonant angular frequency is ω_0.

$$\omega = \omega_0 = \frac{1}{\sqrt{L_1 C_1}} = \frac{1}{\sqrt{L_2 C_2}} \qquad (4)$$

η is the transmission efficiency.

$$\eta = \left| \frac{V_2 I_2}{V_1 I_1} \right| = \frac{(\omega_0 M)^2 R_L}{r_1 (r_2 + R_L)^2 + (\omega_0 M)^2 (r_2 + R_L)} = \frac{R_L}{\dfrac{r_1 (r_2 + R_L)^2}{(\omega_0 M)^2} + (r_2 + R_L)} \qquad (5)$$

Based on (5), it is necessary to satisfy $(\omega_0 M)^2 >> r_1(r_2 + R_L)$ to increase the transmission efficiency. Therefore, it is important to increase the mutual inductance and frequency. However, the coupling factor between the coils and the self-inductance can be reduced by downsizing the coils. Therefore, we have examined coils with a high coupling factor between them, so as to maintain high transmission efficiency.

IV. Method of Measuring the Coupling Factor

Fig. 3 shows an equivalent circuit for measuring the coupling factor between coils. The secondary side voltage V_2 is the open circuit voltage.

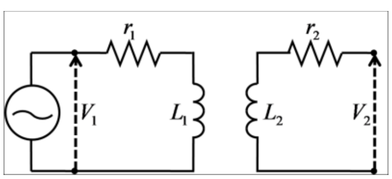

Figure 3. Equivalent circuit to evaluate coupling factor.

$$M = L_1 \frac{V_2}{V_1} = k\sqrt{L_1 L_2} \qquad (6)$$

$$k = \frac{V_2}{V_1} \sqrt{\frac{L_1}{L_2}} \qquad (7)$$

In this study, we calculated the coupling factor using (7).

V. Determination of the Transmission Coil

A. Outer Diameter of the Coil is 50 mm

It is desirable that the implanted secondary coil be small from the point of view of the patient's QOL. Therefore, the outer diameter of the coils is kept constant at 50 mm. The inner diameters of the coils are 0, 10, 16.7, 20, 30, and 40 mm, called A, B, C, D, E, and F. Fig. 4 shows the prototype coils. The primary coil and secondary coil were fabricated to have the same inductance, outer diameter, and inner diameter. Taking into account the skin effect, the windings are made of litz wire (0.05 mmϕ, bundle of 120).

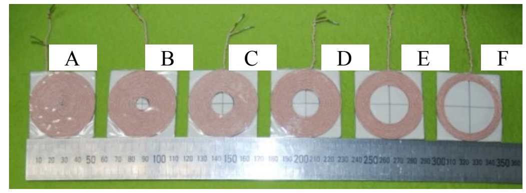

Figure 4. Appearance of coreless coils.

The voltage on the secondary side was measured for various distances d between the coils from 0 mm to 30 mm in increments of 5 mm. The coupling factor was calculated using (7). Fig. 5 shows the calculated results for the coupling factor.

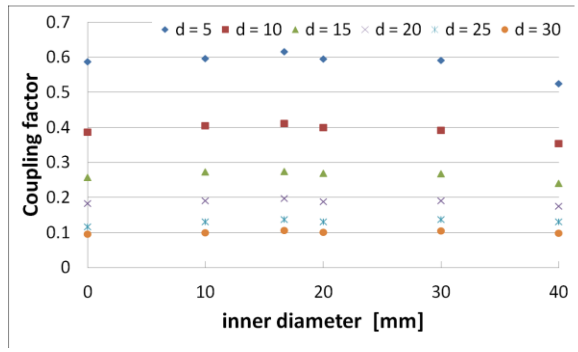

Figure 5. Coupling factor (outer diameter 50 mm).

In all cases, regardless of the distance between the coils, the coupling factor of prototype coil C is larger than that of the other prototype coils. Therefore, the coupling factor is determined to be largest when the inner diameter is 1/3 of the outer diameter.

To confirm this result, we measured coils of different outer diameters.

B. Outer Diameter of the Coil is 40 mm

In this case, the outer diameter of coils is keep constant at 40 mm; The inner diameter of the coils is 0, 8, 10, 13.3, 16, 20, 24, 30, and 32 mm. Fig. 6 shows their coupling factors.

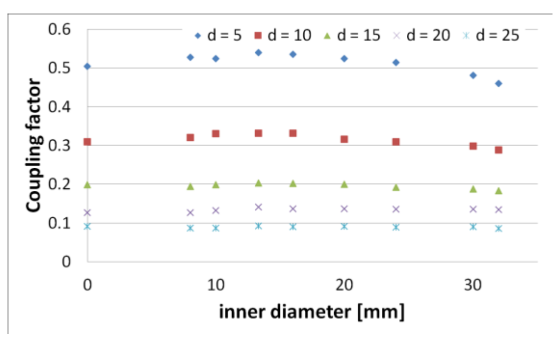

Figure 6. Coupling factor (outer diameter 40 mm).

Even for an outer diameter of 40 mm, the coupling factor is found to be the largest when the inner diameter is 1/3 of the outer diameter.

C. Outer Diameter of the Coil is 60 mm

In this case, the outer diameter of coils keep constant at 60 mm; the inner diameter of the coils is 0, 10, 12, 20, 24, 30, 36, 40, 48, and 50 mm. Fig. 7 shows their coupling factors.

Even for an outer diameter of 60 mm, the coupling factor is found to be the largest when the inner diameter is 1/3 of the outer diameter.

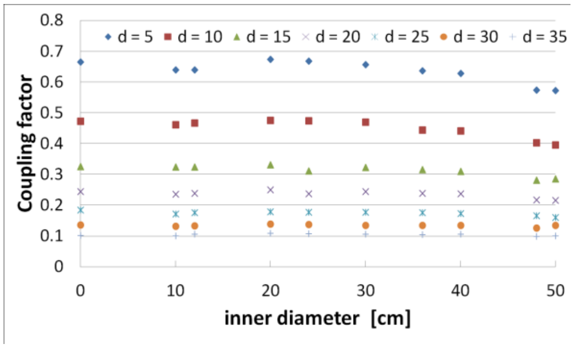

Figure 7. Coupling factor (outer diameter 60 mm).

D. *Outer Diameter of the Coil is 100 mm*

In this case, the outer diameter of coils is keep constant at 60 mm; the inner diameter of coils is 0, 10, 20, 30, 33.3, 40, 50, 60, 70, 80, 90, and 100 mm. Fig. 8 shows their coupling factors.

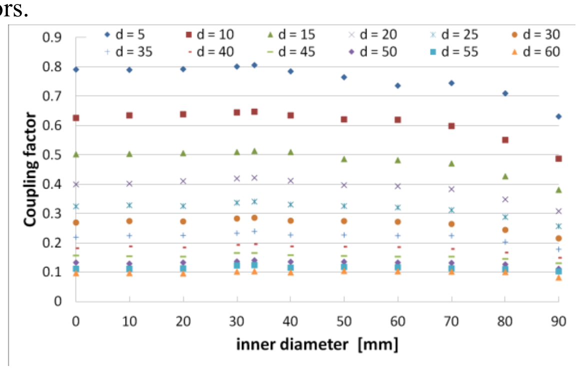

Figure 8. Coupling factor (outer diameter 100 mm).

Even for an outer diameter of 60 mm, the coupling factor is found to be the largest when the inner diameter is 1/3 of the outer diameter.

From the above results, the coupling factor is the largest when the inner diameter is 1/3 of the outer diameter. This means that the interlinkage flux is the largest for an inner diameter of a certain size (in this case 1/3 of the outer diameter). Table 1 lists the coupling factor between the coils (diameters in each case: 50 mm and 100 mm) when the different distances between the coils, the outer diameter, and inner diameter have a similar relation of 1:2.

TABLE I. COUPLING FACTORS

	d = 10	d = 15
0	0.3861	0.2576
10	0.4047	0.2727
16.7	0.4119	0.2741
20	0.3999	0.2695
30	0.3912	0.2679
40	0.3538	0.2409

Outer diameter 50 mm

	d = 20	d = 30
0	0.3998	0.2697
20	0.4102	0.2730
33.3	0.4216	0.2784
40	0.4115	0.2723
60	0.3935	0.2716
80	0.3484	0.2447

Outer diameter 100 mm

Table 1 shows that when the ratio between the coils, the outer diameters, and inner diameters is 1:2, the coupling factor has approximately the same value. The distance between coils, outer diameter, inner diameter, and coupling factor all have similar relations.

The graph below shows the normalized coupling factor of the distance between the coils. Fig. 9 shows the results for an outer diameter of 50 mm. Fig. 10 shows the results for an outer diameter of 10 mm.

From Figs. 9 and 10, a larger inner diameter coil results in a more gradually reduced coupling factor with an increase in distance between the coils. To confirm this result, Fig. 11 shows the same results as in Fig. 9 with a logarithmic x-axis.

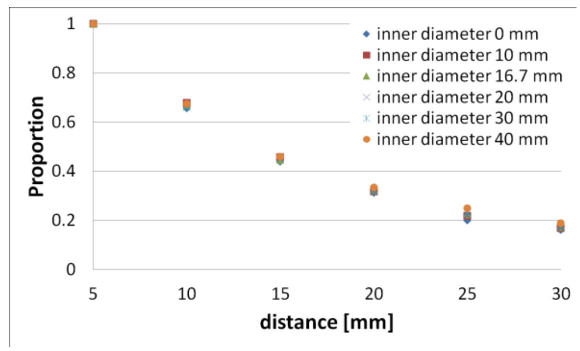

Figure 9. Normalized coupling factor (outer diameter 50 mm).

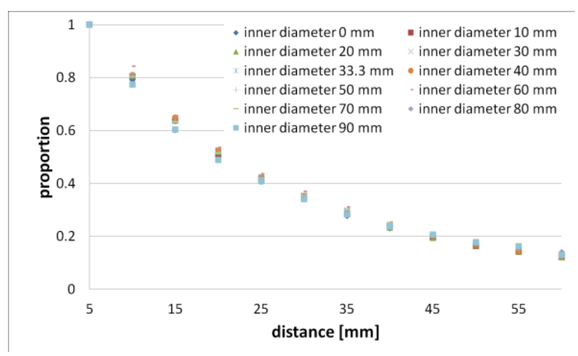

Figure 10. Normalized coupling factor (outer diameter 100 mm).

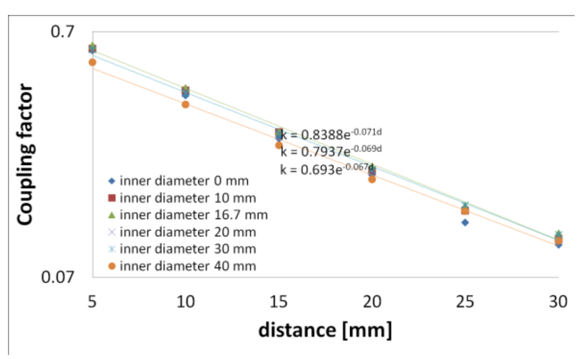

Figure 11. Normalized coupling factor (outer diameter 100 mm).

A linear approximation of the results in Fig. 11 was made for the cases of inner diameters of 16.7, 30, and 40 mm. For these three lines, the large inner diameter coil has a gradual slope. Therefore, the large inner diameter coil has a high coupling factor, even if the distance between the coils increases. Magnetic fields tend to extend to the far side, as seen when the large inner diameter coil is compared with the small inner diameter coil.

From these results, we find that if the distance between the coils is long, it is more effective to have a coil with a large inner diameter. If the distance between the coils is small, the coupling factor is the largest when the inner diameter is 1/3 of the outer diameter.

VI. Improvement of Efficiency

A. Efficiency Calculation

Table 2 shows the efficiencies obtained by substituting the measurement result of the coupling factor, in case of an inner diameter of 16.7 mm and an outer diameter of 50 mm, into (5).

TABLE II. Efficiency [%]

d	5	10	15	20	25	30
η	95.8	91.5	82.9	71.8	55.2	42.3

In the case of r_1 = 0.191 Ω, r_2 = 0.189 Ω, R_L = 50 Ω, coupling factor k = 0.2741, and frequency f_0 = 300 kHz, the self-inductance of the coils must be at least 27.2 μH to obtain more than 95% efficiency when the distance between the coils is 15 mm.

B. Study of Winding

To increase the coupling factor, we prepared coils whose inner diameter is 1/3 that of the outer diameter; the coil structure is two-layered to increase inductance, and the winding changes direction. Fig. 12 shows the two coils. The coil was prepared using two primary sides and two secondary sides of the same dimensions.

Both α and β have the same direction of current flowing in the first layer and second layer.

α is wound with a second layer after the first layer is finished. On the other hand, in β the first layer and second layer are wound at the same time, with one turn of the second layer after one turn of the first layer. Table 3 shows the results for coils α and β.

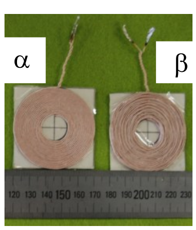

Figure 12. Appearance of coreless soils.

TABLE III. Inductance and Efficiency

	f [Hz]		L [μH]	r [Ω]
α	300 k	1	49.99	0.4429
		2	49.66	0.4387
	1 M	1	53.38	2.284
		2	52.89	2.294
β	300 k	1	40.94	0.3678
		2	42.89	0.3854
	1 M	1	41.71	1.356
		2	43.43	1.411

		d [mm]	η [%]
α	300 k	10	96.7
		15	94.6
	1 M	10	94.7
		15	93.8
β	300 k	10	97.2
		15	94.6
	1 M	10	96.5
		15	95.6

1 refers to the primary coil and 2 refers to the secondary coil. β has higher efficiency than α. β achieves over 95% efficiency when the frequency is 1 MHz and when the distance between coils is 15 mm. β has a lower apparent resistance than α. This lower apparent resistance is the reason for the improvement in the efficiency. The capacitance of each coil causes β to have a lower apparent resistance than α. Table 4 shows each capacitance measured using a network analyzer.

TABLE IV. Capacitance [pF]

	α–1	α–2	β–1	β–2
C [pF]	0.479	0.503	0.340	0.356

Table 4 indicates that β has a smaller line capacity than α; thus, the apparent resistance of β is low, improving the efficiency.

VII. Conclusion

In this study, we prepared and examined coils of different inner and outer diameters with the goal of improving the coupling factor of coreless coils used in TETSs. Our results indicate that the distance between coils, outer diameter, inner diameter, and coupling factor all have similar relations. If the distance between the coils is large, it is more effective to have a coil with a large inner diameter. If the distance between the coils is small, the coupling factor is the largest when the inner diameter is 1/3 of the outer diameter. Finally, we measured different coil windings. The results showed that coil arrangement β achieved over 95% efficiency, when the frequency was 1 MHz and when the distance between coils was 15 mm.

References

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