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# 優勝作品專輯

**編號：100018**

**作品名稱**

**Charging the Miniature Electronic Components of Medical Equipment in Vivo**

**得獎獎項**

**大會獎：四等獎**

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**關鍵字：spatial charge、electromagnetic induction、electromagnetic rod**

# 作者簡介

我是邱崇恩，自幼就對科學很感興趣，個性對甚麼都感到好奇，喜歡思考。對於問題往往不喜歡看結果而是喜歡探討過程，「為什麼」也就理所當然成為了我的口頭禪。如果問我高中生活有什麼事情可以讓我引以自豪的，那我一定會說是參加科展。當我第一次與指導教授長談之後，才知道學習科學的主要目的是用來改善人類的生活。只要用心去觀察，日常生活中可以發現整個世界到處都充滿著研究題材，等待我們去探討與去解決。為了讓研究主題更具有創新性與應用性，我整整花了一年的時間才確定研究主題。在整個研究過程中非常感謝指導教授耐心的指導，給予許多新的啟發，同時也讓我學習到許多書本無法學習到的研究技術與方法。此外，也要感謝父母一路走來對我的支持與鼓勵，讓我在沒有壓力情況下專心做我喜歡做的研究。

# 摘要

世界上有許多病患，需要在體內植入電子醫療裝置，才能維持生命。然而，電池充電的問題卻一直無法克服，於是必須透過開刀重新更換電池，如此不僅增加病患的痛苦，也增加了醫療成本與環保問題。然而，過去研究以提高電池蓄電量為主，只有極少數研究著重在探討隔空充電技術，例如:動物體內電池充電。本研究主要是應用電磁感應原理，設計一套可以針對實驗兔體內體溫發射器的電池進行充電的方法，及探討充電過程所產生的電磁輻射及其影響。我們的初步研究成果顯示: (一)將 24V 與 18V 兩種電壓分別輸入電磁棒，在實驗兔動物身體表面進行充電，發現可產生的最高充電電壓值分別為 4.75 V 與 3.64V。(二)充電 30 分鐘後可讓體溫發射器每二秒發射一次訊號，為期長達 8 天。(三) 將 24V 與 18V 兩種電壓分別輸入電磁棒，在距離電磁棒 5-60cm 的範圍，最大的電磁輻射值為 179.6mG 及 0.1 mG。本研究證實我們設計的電磁棒可以對兔子體內電池進行隔空充電，並且不會對實驗兔子造成電磁輻射傷害。我們建議未來可以應用此方法解決動物體內醫療電子元件的充電問題。

# Abstract

The health of many patients is sustained by the electronic medical instruments implanted in their bodies. However, when the battery power of the instrument runs out, a surgical operation is required to replace the battery with a new one. Not only are these operations painful, but the medical expenses associated with them are a heavy burden as well. In addition, the discarded batteries are potential pollutants to the environment. To solve these problems, previous studies have explored ways to enhance the battery charging capacity, while a few studies have aimed at developing the technique of spatial charging, such as charging the battery in vivo. Therefore, in this study, we decided to investigate the charging of the battery. The purpose was to apply the principle of electromagnetic induction to charge a battery implanted in the subject rabbits. Additionally, the effects of the electromagnetic radiation incurred in the charging process were also explored. The results showed the following. (a) When an electromagnetic rod with a 24 V input was used to place a spatial charge on the battery in the subjects, the subsequent maximum charging voltage generated by the induction coils was 4.75 V; with an input of 18 V, the subsequent maximum charging voltage was 3.64 V. (b) A body temperature transmitter was set to transmit a signal every 2 s. With a 30-min charge, the signal transmission could last eight days. (c) The amount of electromagnetic radiation produced during the charging process was measured with a detecting instrument 5 to 60 m away from the rod. The maximum amount thus recorded was found to range from 179.6 to 0.1 mG. These results showed that the electromagnetic rod designed in this study could achieve the spatial charging of the battery in rabbits in vivo, and that no harm from electromagnetic radiation was done to the subject rabbits. Thus, this approach is practical and effective for charging an electronic sensor in vivo. It can also be further improved and adopted to charge miniature electronic medical components in vivo.

# 1. Introduction

Many people die of heart failure every year. To prevent such cases, researchers in the medical field have been committed to related research since long, and have invented devices like the permanent pacemaker. This pacemaker allows for significant improvements in the patients' symptoms, saving their lives. Nevertheless, this innovation has a disadvantage. Because the human body lacks a charging system, patients with heart problems need to undergo an operation every few years to replace the dead battery with a new one [1,2]. This not only causes patients more pain but also forces them to run the risk of the operation failing. In addition, many financially disadvantaged families cannot afford the associated medical expense.

Apart from a permanent pacemaker, patients may have other electronic medical instruments implanted in them, including glucose sensors, thermometers, and electroacupuncture devices [3]. Providing these instruments with electricity is a great concern and poses a big challenge to medical technology. In addition, some experiments on animals require the implantation of an electronic transmitter in vivo to conduct long-term tracking of the animal's physiological condition. In this case, the state of the battery power is the determining factor for the duration of the signal transmission. If the battery cannot be charged in vivo, the tracking will be interrupted because of power failure.

To find a better solution to the above problems, researchers first looked into some current methods to charge the battery [4,5]. As one example, based on the principle of electromagnetic induction, a varying magnetic field can induce an electromotive force in a wire. If the wire is a closed electrical circuit, it will result in electric currents and generate electricity. As another example, scientists at MIT developed the spatial charging technique by making use of electromagnetic resonance [6], which can transmit 60 W of power over a distance of 2 m. Inspired by these studies, we assumed that with electromagnetic induction, a varying magnetic field could be formed in vitro, allowing a spatial charge to be imposed on the induction coils placed in vivo [7]. If this hypothesis is confirmed by an experiment, the devised approach can be adopted in the future to solve the problem of charging an electronic sensor device in vivo [7, 8].

This study aimed to apply the principles of electromagnetic induction to establish an approach for charging a body temperature transmitter in vivo [9]. The effects of the electromagnetic radiation on animals during the spatial charging process were also explored. The experiment tools included an electromagnetic rod, electromagnetic induction coils, and body temperature transmitter.

## 2. Materials & Methods

### Subjects

The subjects of this study were three rabbits of the New Zealand species (body weight: 3.63 ± 0.32 kg). The quarantine inspection they underwent proved that they had not contracted any disease over the past three months. When the body temperature transmitters were implanted in the subject rabbits, their temperatures were maintained at 38.6℃ ± 0.3℃ (see Fig 1), with heart rates of 130.2 ± 10.5 bpm.

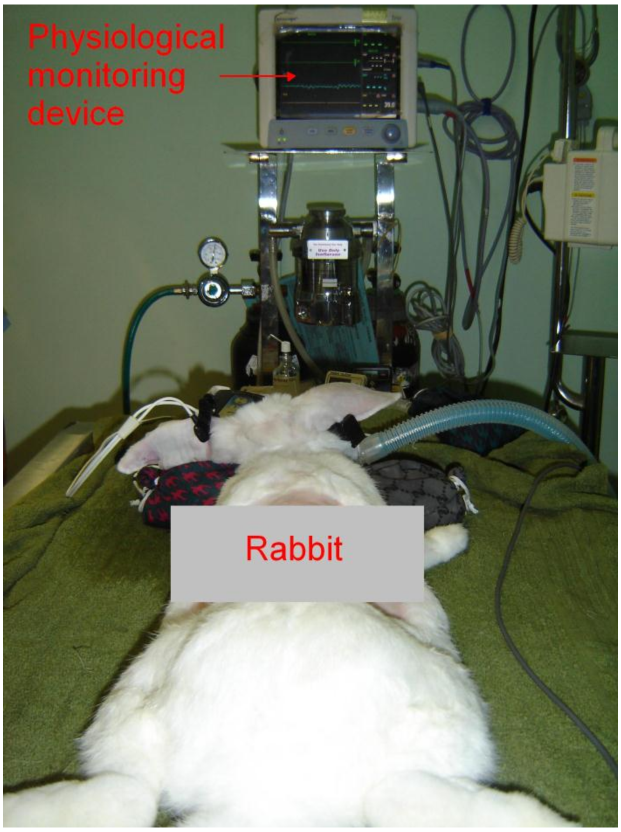


Fig. 1 Operating table and medical physiology monitor used in this study.

## Charging Device

(1) First, a 200-turn coil (0.11 mm) was wound around an iron rod (length: 13.5 cm) to obtain the desired electromagnetic rod, which was connected to a transformer and a switch (Fig 2A). The input voltage of the transformer was 110 V (60 Hz), and it had two output voltages: 18 and 24 V (electric current: 1 A).

(2) Next, 2,000 turns of wire (0.09 mm) were used to make induction coils with radii ranging from 3.9 to 1.2 cm. These induction coils were connected to a full-wave rectifier, which can convert alternating current to direct current and in turn charge the battery in vivo (Fig 2B). The electricity of the battery was intended to power the RFID body temperature transmitter (brand: Summit AR245) to send signals.

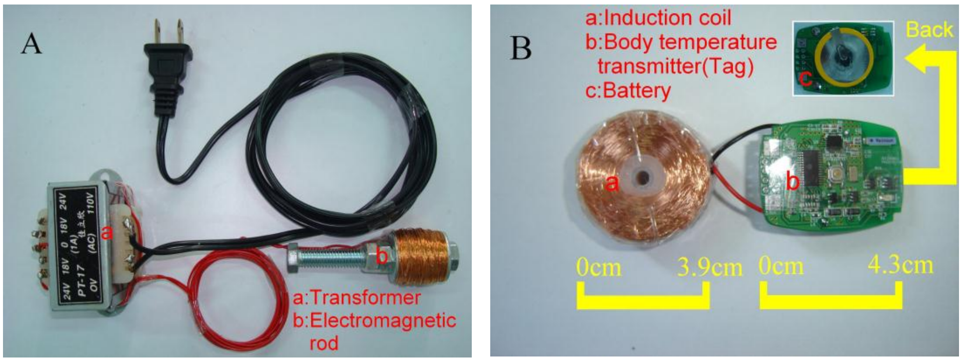


Fig. 2(A) Devised electromagnetic rod and transformer. (B) Self-made induction coil and body temperature transmitter.

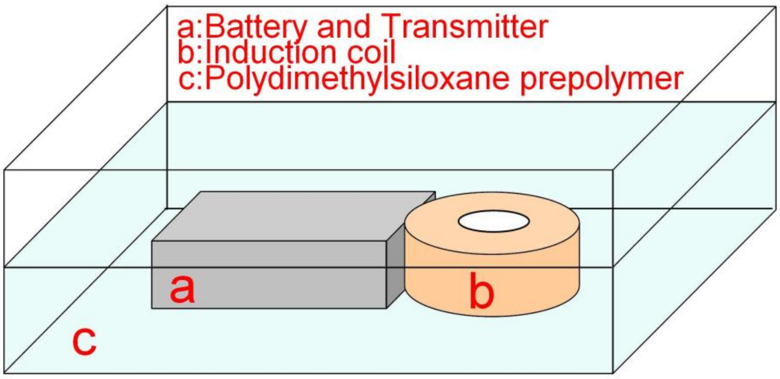


Fig. 3 Formation of covering film.

(3) The self-made induction coils and body temperature transmitter (ICTT) were placed in a plastic mold (Fig 3). Next, a curing agent

(polydimethylsiloxane prepolymer) was poured into the plastic mold. The mold was then placed in a heat preservation box (60℃) for an hour so that a covering film could form on the surface of the ICTT (Fig 4A). This covering film was intended to prevent the ICTT from contacting cells in vivo.

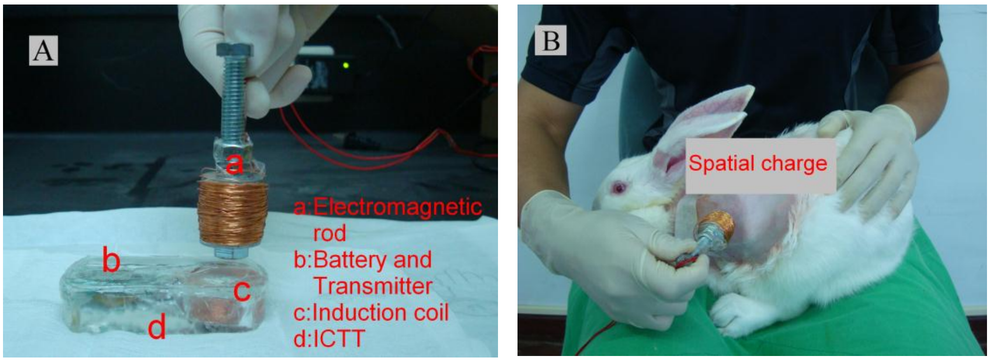


Fig. 4(A) Charge test before implantation. (B) Spatial charging conducted after implantation.

## Procedure

(1) Pre-test prior to ICTT implantation

***Measuring electromagnetic radiation:***

The electromagnetic rod was placed at the 5-cm mark on the ruler. Two different voltages were applied to the rod—18 and 24 V (current: 1 A). The location of the rod was set to be the origin, and the instrument for detecting the electromagnetic radiation was moved from the origin at 5-cm intervals. Thus, the electromagnetic radiation at different points on the rod was measured. (The radiation at every point was measured three times.)

***Charging the induction coils:***

The surface of the induction coils was set to be the origin (Fig 4A). The 18- and 24-V electromagnetic inputs were applied at different distances to spatially charge the rod; this was done to determine the charging efficacy of the coils.

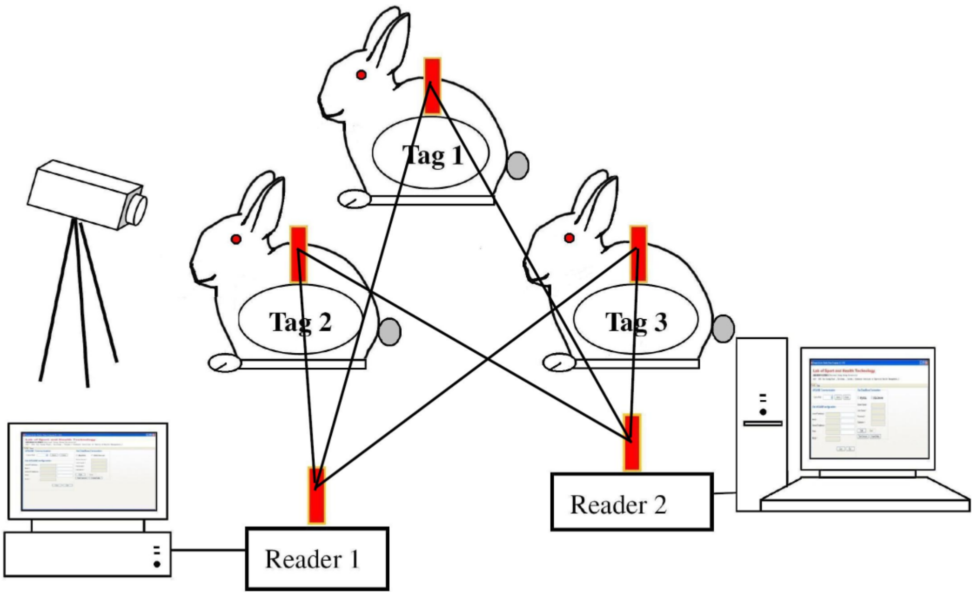

Fig. 5 Signal transmission of RFID body temperature transmitter and reception of reader.

(2) Three subject rabbits were implanted with ICTTs [9] at depths of 0.4 to 0.7 mm beneath the skin on their backs (veterinarians from NCHU were entrusted to perform these operations). First, each rabbit was soothed before a needle was inserted in its ear vein. The rabbits were then injected with a liquid mixture of 0.1 ml Rompun (xylazine, 2%) and 0.1 ml ketamine (50 mg/ml) intravenously. After each rabbit was anesthetized, a tube connected to a physiological monitor was inserted into its body. Meanwhile, a mask, which provided a mixture of isoflurane and oxygen, was used to cover the face of each rabbit and keep it anesthetized. We kept each rabbit in a prone position, shaved the fur on its back, cleaned the skin with alcohol and 2% chlorhexidine, and covered it with an aseptic towel (Fig 1). To perform the implantation, we made a 5-cm long incision on each rabbit's back using a sterile surgical blade such that the subcutaneous tissue could accommodate the ICTT. After the implantation of the ICTT, the wound was sutured and iodine ointment was applied. After the operation, the rabbits were given 3 mg/kg of ketoprofen to ease the pain and 0.4 ml of Baytril (2.5% enrofloxacin) to prevent infection.

(3) The electromagnetic rod was placed above the back of each rabbit (Fig 4B). Without touching the skin, the 18 and 24V electromagnetic inputs were used to charge the implanted ICTT at different distances.

(4) After the ICTT battery power ran out, the rod was held 0.0–0.2 cm away from each rabbit's back to conduct spatial charging. This charging continued for 30 min; simultaneously, the rabbits were monitored using a camera (Fig 5). After the charging, the ICTT was activated to transmit a body temperature signal every 2 s. The signals were received continuously [9] (Fig 5).

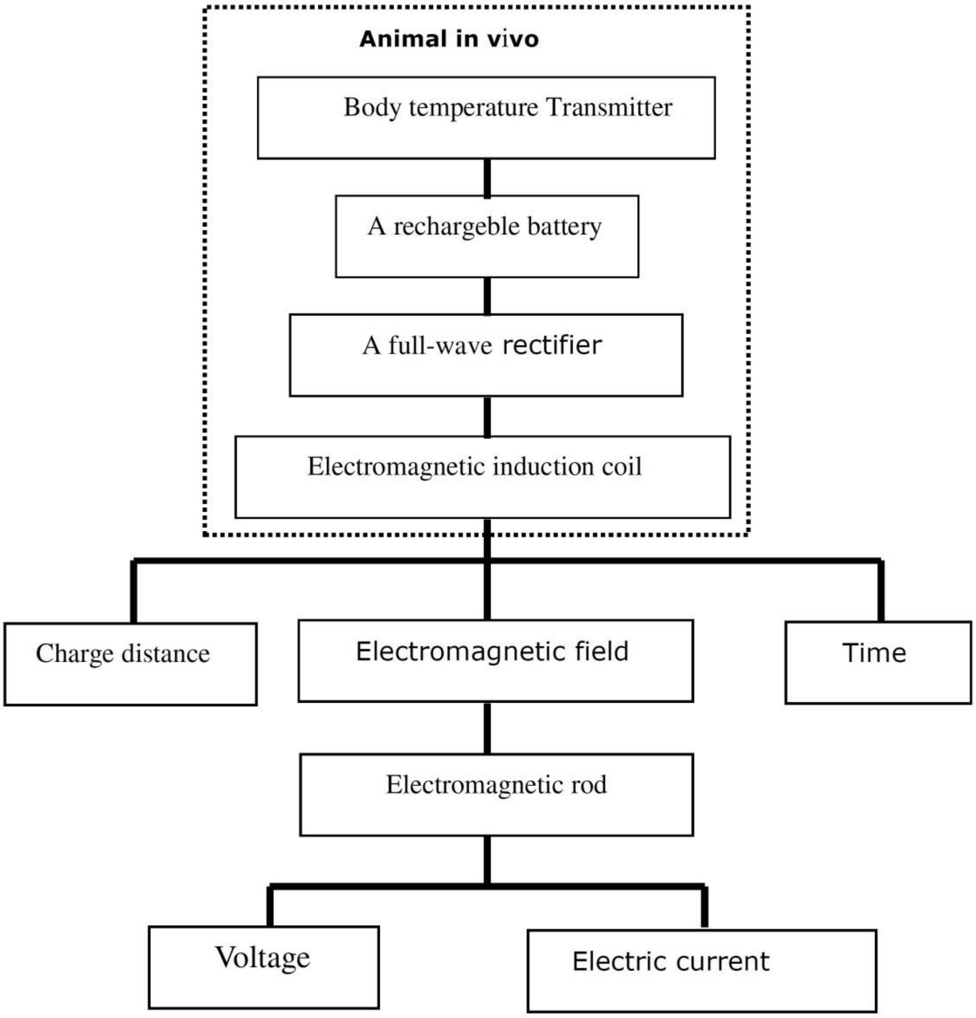


Fig. 6 Testing procedure for charging.

The procedures of this study are shown in Figure 6. It was hypothesized that spatial charging could be conducted successfully and safely, and that the in vivo transmitter could be initiated to transmit signals to the in vitro receptor.

## Electromagnetic induction

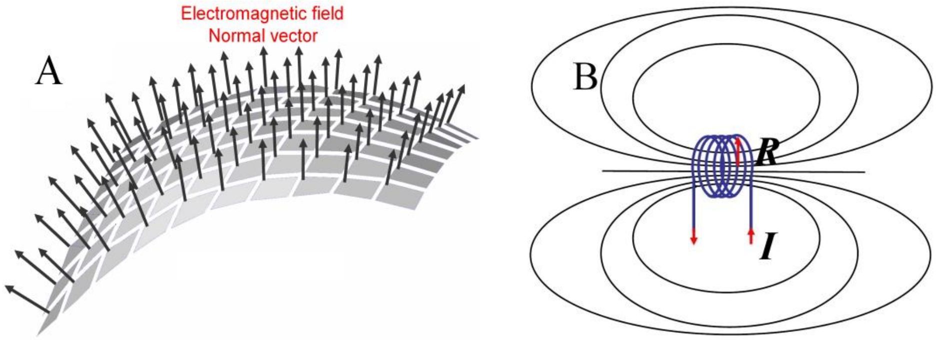

Fig. 7(A) Normal vector on curved surface. (B) Magnetic field formed by a circular coil.

According to principles of electromagnetic induction, when a voltage was imposed on the rod, a magnetic field was formed. The incurred magnetic field changed according to the input voltage, thereby stimulating the implanted induction coils to generate a varying electromotive force [10]. According to Faraday's law of electromagnetic induction, the formula for calculating the induced electromotive force is as follows:

$$\varepsilon = -\frac{\Delta \Phi_m}{\Delta t} \qquad (1)$$

In this equation, $\varepsilon$ stands for the electromotive force, $\Delta \Phi_m$ refers to the magnetic flux, and $\Delta t$ is a very short time.

According to Faraday's law of electromagnetic induction, the voltage generated by an induction coil of ***N*** turns can be calculated using the following formula:

$$\varepsilon = -N\frac{\Delta \Phi_m}{\Delta t} \qquad (2)$$

The amount of magnetic flux is directly proportional to the number of magnetic lines of force that cut through the curved surface (Figs 7A and 8). When an even magnetic field **B**, cuts through a plane at any angle, the magnetic flux is equivalent to the dot product of the magnetic field multiplied by the plane area, **a** [10]:

$$\Phi_m = B \cdot a = B \cdot a\cos\theta \qquad (3)$$

In this equation $\boldsymbol{\theta}$ is the angle between the magnetic field **B**, and the normal vector of the plane area **a.**

***Magnetic force of the electromagnetic rod***

The magnetic field produced by a single circular coil is presented in Figure 7B. If we suppose that the coil radius is R and the magnetic field at the coil's center is vertical to a section of the coil, the size of the magnetic field can be calculated using the formula: $B = \frac{u_0 I}{2R}$ ($I$: electric current; R: radius of the circular coil). In this study, the self-made electromagnetic rod was covered with spiral coils. The rod's magnetic field could be calculated by multiplying the fraction in the above equation by N (N, the turns of wire on the rod): $B = N\frac{u_0 I}{2R}$, where $u_o$ stands for the value of a constant.

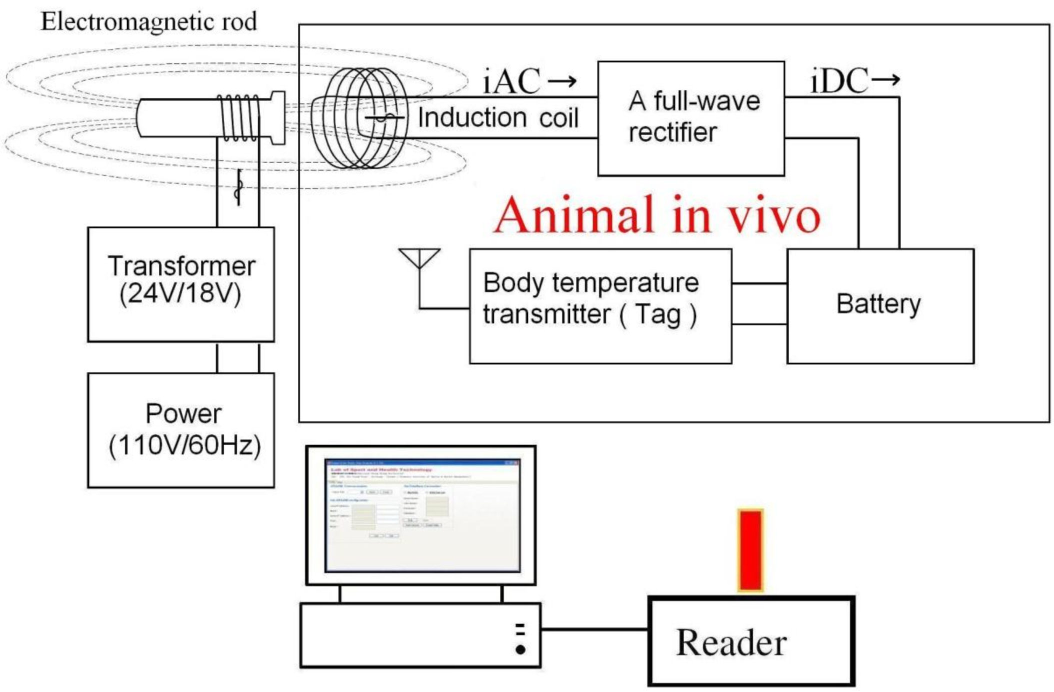


Fig. 8 Induction coils generated electricity, which was converted to direct current by a rectifier and was used to charge the battery. The battery then provided electricity to the active RFID body temperature transmitter.

***Body temperature transmitter in vivo***

In this study, a USB reader was adopted to receive the signals sent by the implanted active RFID body temperature transmitter (voltage of the battery: 3.6 V). First, the transmitter was set to send a signal every 2 s. Next, the IP address of the USB reader was set. The reader could detect and collect the signals' hexadecimal data. With the conversion of the hexadecimal data, information about the body temperature was available. The farthest distance the signals could reach was 50 m.

***Processing data:***

Microsoft Excel 2010 was adopted to analyze the statistics and chart graphs.

# 3. Results and Discussion

### *Effects of electromagnetic radiation on subjects*

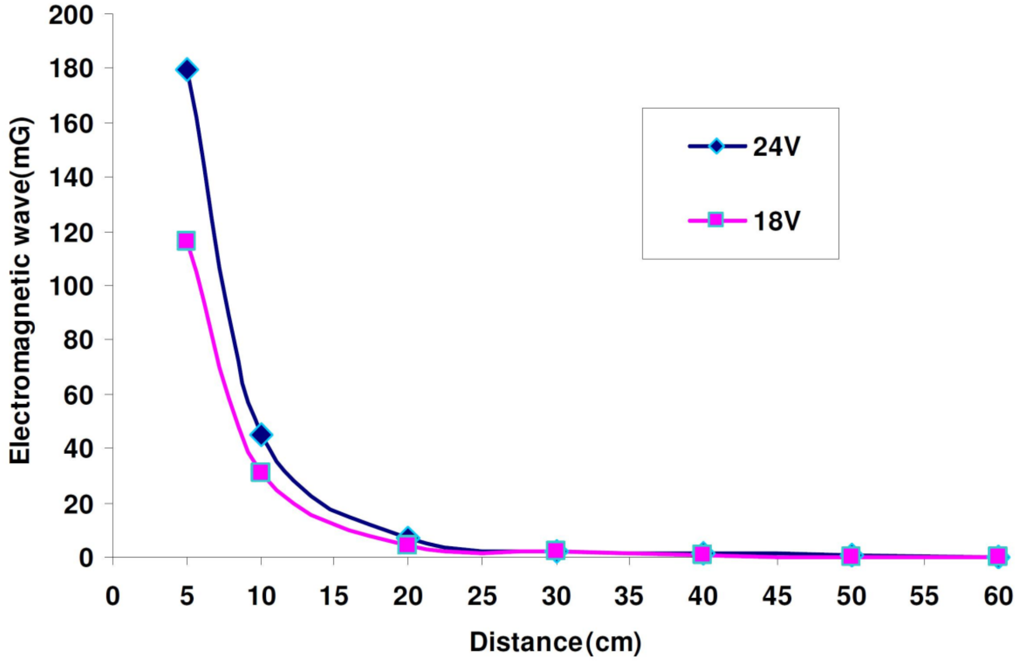


Fig. 9 State of electromagnetic radiation changed with distance variation between rod and rabbit.

Figure 9 shows the state of the electromagnetic radiation incurred by the in vitro electromagnetic rod [11]. It was found that irrespective of the voltage of the rod (18 or 24 V), with an increase in its distance from the subjects, the electromagnetic radiation attenuated in a nonlinear manner. When the distance ranged from 5 to 20 cm, there was a significant margin between the amounts of electromagnetic radiation produced by the two voltages. The higher voltage gave rise to a higher amount of electromagnetic radiation. When the rod was over 20 cm away, the amount of radiation approximated 0 mG. When charging was conducted 5 cm away, the radiation was the strongest, with 116.1 mG for 18 V and 179.0 mG for 24 V (Figs 9 and 10). Either intensity was below the 195-mG radiation emitted by a hair dryer (detected near the mouth of a 1500-W hair dryer) [11, 12]. As a result, the experiment proved that the amount of electromagnetic radiation produced in the charging process was less than that produced by electric appliances. As long as the charging was performed at a short distance, and was not done frequently or for a long time, it did little harm to the animals.

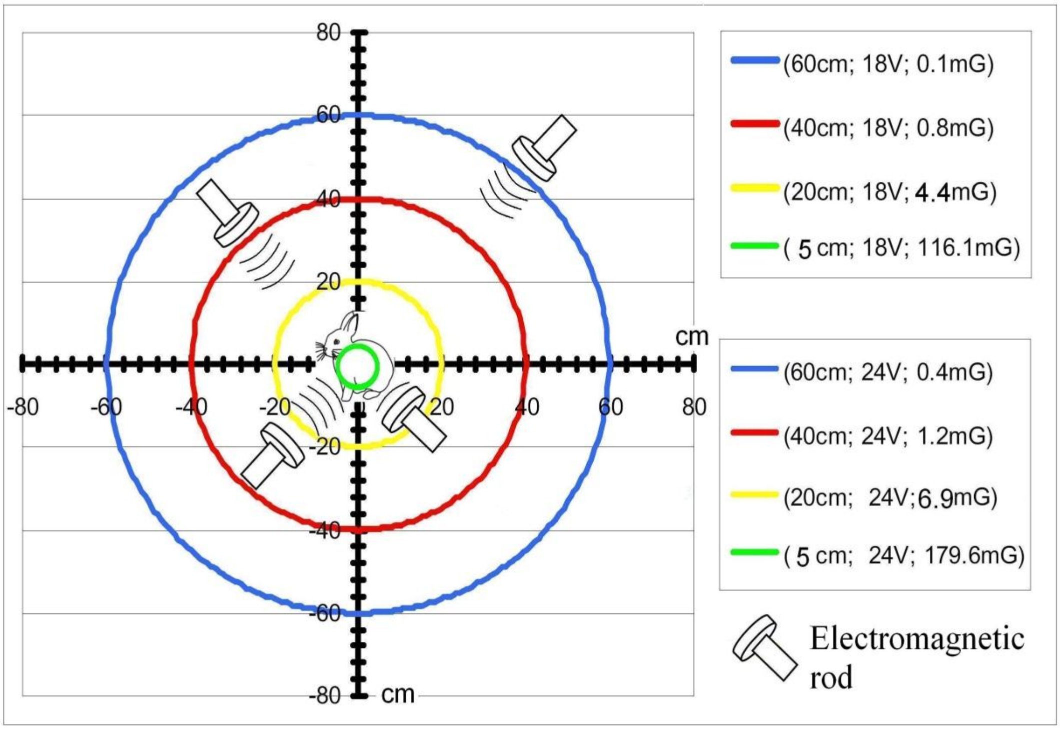

Fig. 10 State of electromagnetic radiation generated at different charging distances.

***Efficacy of in-vitro spatial charging***

Before the implantation of the ICTTs in the rabbits (Fig 4A), the electromagnetic rod with the two input voltages, 18 and 24 V, was placed in contact with the covering film of the ICTT. The distance between the rod and induction coils was gradually changed, and the corresponding output voltages were measured. The results showed that with an increase in the distance between the rod and induction coils (Fig 11), the output voltage attenuated in a nonlinear manner. From a distance of less than 1 cm, the 24 V applied voltage induced a maximum effective voltage of 7.8 V; while at 18 V, the maximum effective induced voltage was 5.9 V. When the distance was more than 2.5 cm, the maximum voltages for 24 and 18 V were 5.0 and 3.8 V, respectively. The above statistics (Fig 11) indicated that the input voltage from the rod was nonlinearly and directly proportional to the output voltage from the induction coils. Therefore, the charging voltage for the battery could be varied by slightly adjusting the input voltage of the electromagnetic rod.

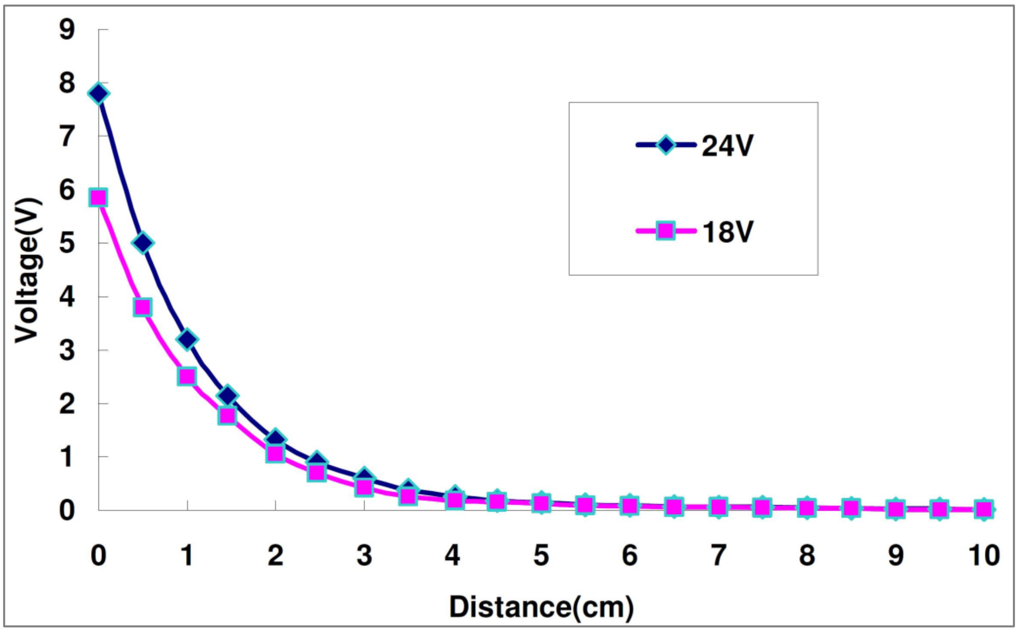

Fig. 11 Relationship between different charging distances and subsequent voltages produced by induction coils.

The charging device in this study was designed to conduct spatial charging based on electromagnetic induction (Eqs. 1–3). Nevertheless, the device did not work in the same way as a transformer, where the voltage on the primary winding is directly proportional to that on the secondary winding. Because the device did not have a closed-loop structure, the output power was not equal to the input power; in other words, some power was lost. The following factors contributed to this loss of electric power [10].

Loss of magnetic force: the failure of the induction coils to sense the magnetic field caused a loss of electric power.

Electric resistance of coils: heat was produced when current passed through the conductor, resulting in the loss of electric power.

### *Efficacy of spatial charge on induction coils*

After the implantation of the ICTTs in the rabbits, the LED would glow when the electromagnetic rod was brought close to a rabbit and would dim when the rod was taken away (Fig 12). Apparently, our device was capable of spatial charging. The rod was then gradually moved away from the rabbit's skin (Fig 5B), and the subsequent charging voltages generated by the induction coils were recorded. It was found that with an increase in distance, the charging voltages attenuated in a nonlinear manner (Figs 13 and 14). The charging voltage had to be 3.6 to 6 V to effectively charge the ICTT. When the distance was within 0.2 cm, the maximum charging voltage was 4.75 V for the 24V rod and 3.64 V for the 18-V rod. When the distance was over 0.2 cm, the corresponding charging voltage was too small to charge the battery.

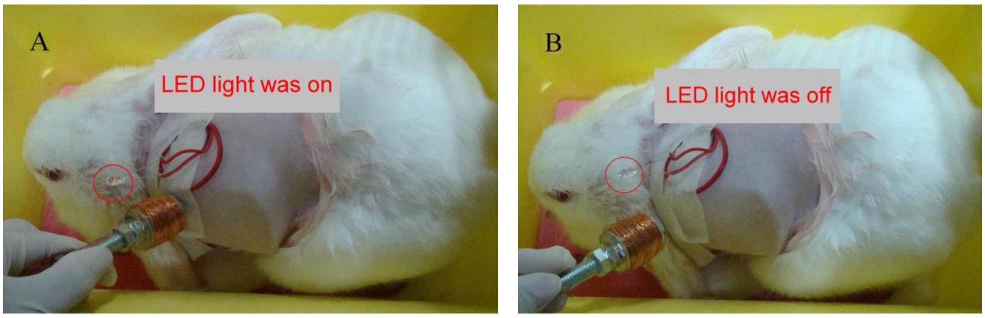


Fig. 12 (A) LED glowed when the rod was brought close to rabbit. (B) LED dimmed when rod was taken away.

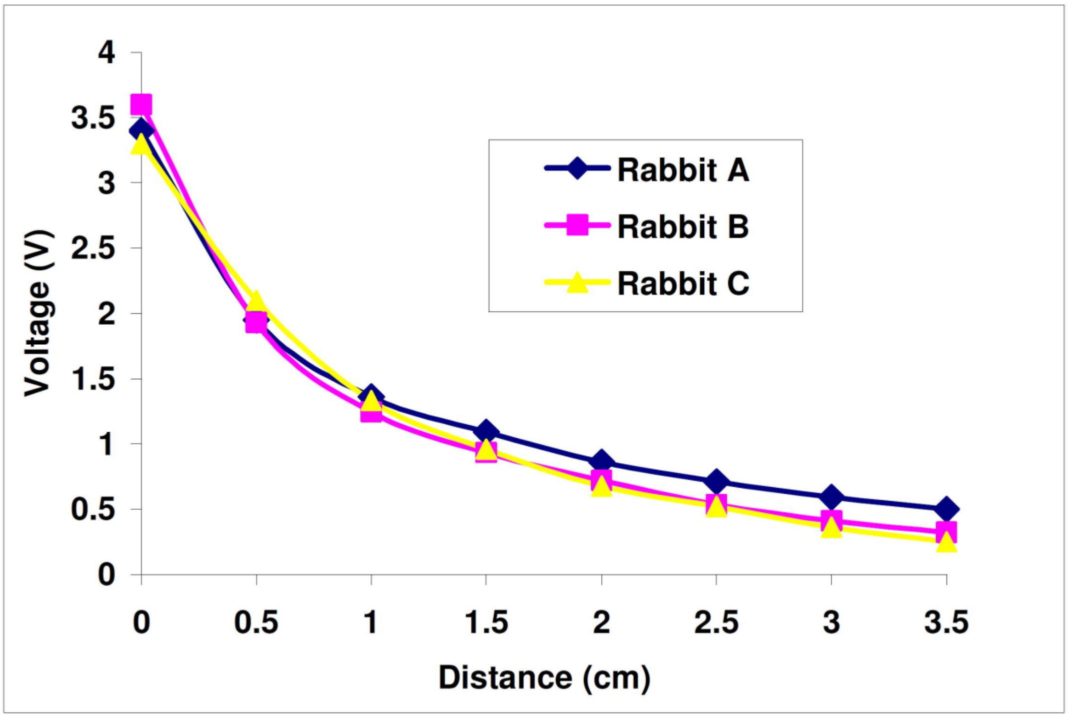


Fig. 13 Output voltages produced at charging distances of 0~3.5 cm (input voltage: 18 V).

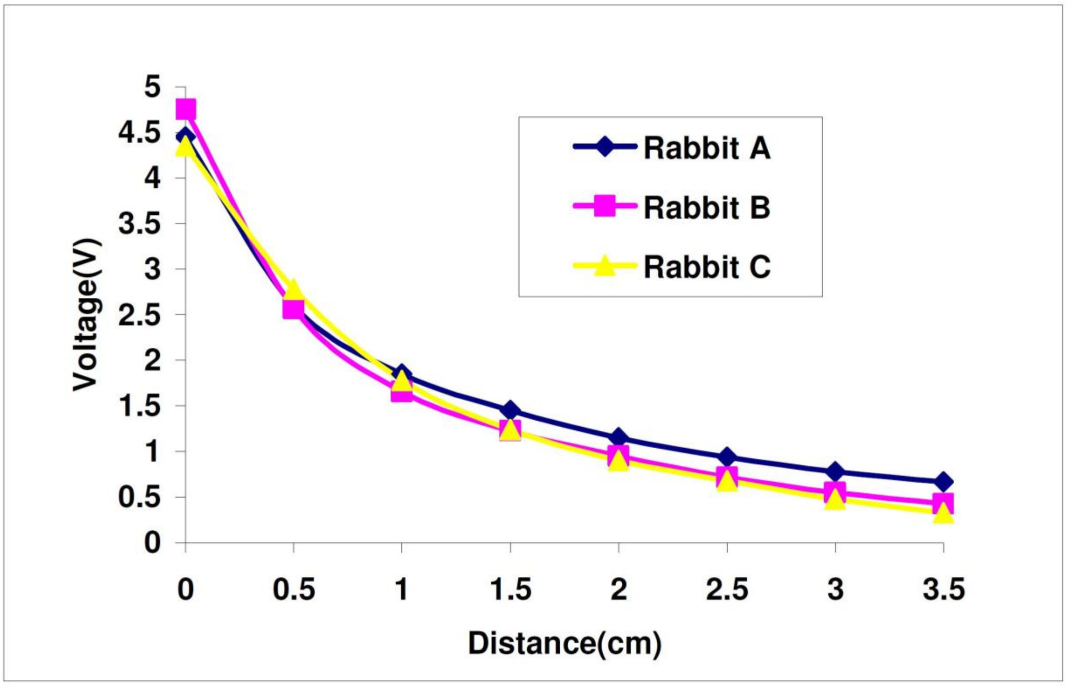


Fig. 14 Output voltages produced at charging distances of 0~3.5 cm (input voltage: 24 V).

When the distance between the rod and rabbit was fixed, the charging voltage generated by the induction coils would be increased with an increase in the input voltage of the electromagnetic rod. Apparently, the charging voltage was the highest when the rod input was 24 V. However, the electromagnetic radiation produced during the charging process was also the highest (Figs 13 and 14). Accordingly, when selecting the appropriate amount of input voltage, both the effects of the electromagnetic radiation and required minimum charging voltage must be taken into account.

***Efficacy of induction coil charging voltage on temperature body transmitter***

The electromagnetic rod was located 0 to 0.2 cm above the back of each rabbit, and the spatial charging was done for 30 min (24 V). Because the induction coils of the ICTT exhibited electrical resistance, some of the magnetic force was converted into heat and was unavailable to the transmitter. The heat produced caused the body temperature of the rabbits to rise, with the temperature of rabbit A rising from 37.8°C to 39.0°C; rabbit B, 37.2°C to 38.5°C; and rabbit C, 37.4°C to 38.8°C (Fig 15, Table

1). Although the temperature once rose to 39.0℃ in the charging process, in vivo tissues would not be damaged as long as the charging did not last for a long time. Nonetheless, to prevent the temperature from rising sharply, it is recommended that the area surrounding the ICTT be ice compressed before spatial charging in order to contain the heating of the ICTT.

After finishing spatial charging, the transmitter was activated, and the signals sent by the transmitter were received [13]. The body-temperature curves of the rabbits were obtained on the basis of the data collected from these signals (Fig 16). These charts indicate that the body temperatures ranged from 36.5℃ to 39.0℃. No regular change in body temperature was found from these temperature curves. It is possible that the rabbits' random activities contributed to the irregularity in the temperature changes [14,15]. It was also found that the ICTT was capable of constantly sending signals for eight days after being charged for 30 min (Table 1). Throughout the experiment, the rabbits remained healthy, and no significant change was found in their average weight, which reduced only slightly from 3.63 ± 0.32 kg to 3.58 ± 0.35 kg.

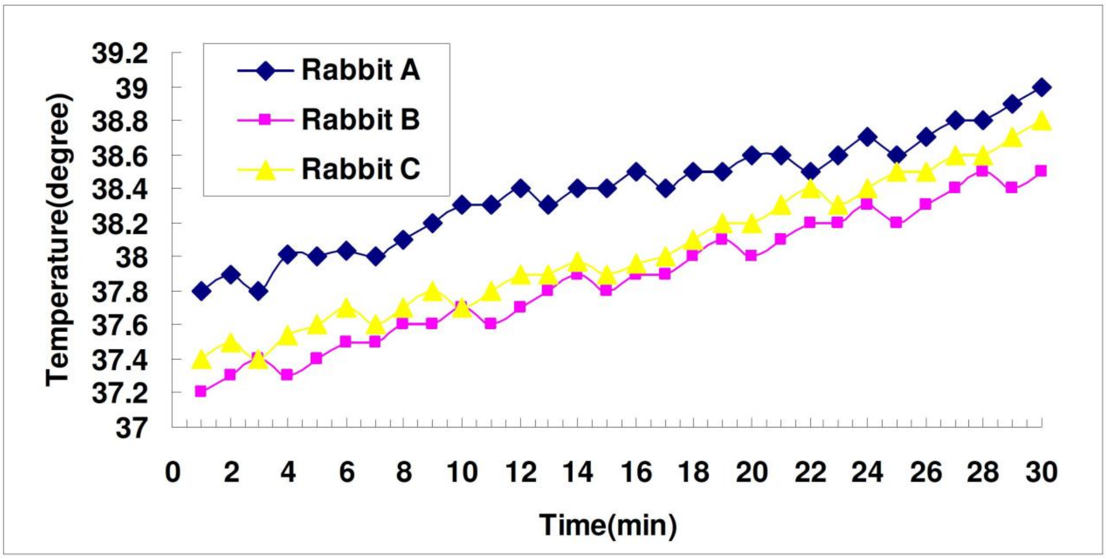

Fig. 15 Variation in each rabbit's body temperature during spatial charging for 30 min.

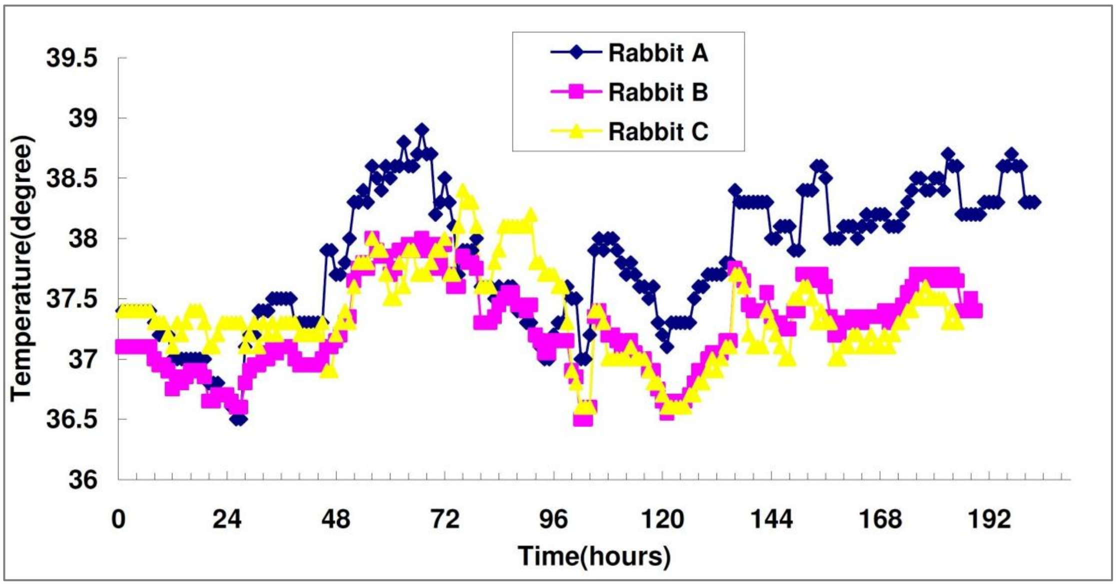

Fig. 16 The body-temperature curve for each rabbit.

Table 1. Variation in the rabbits' body temperatures and duration of signal transmission.

| Temperature rise after 30 min of charging (℃) | Duration of signal transmission (d) |
|---|---|
| 1.3 ± 0.1 | 8.0 ± 0.3 |

The above results confirmed the practicability of applying spatial charging to charge an in vivo battery. Therefore, the approach proposed in this study may be applied to solve the problem of charging electronic sensing components implanted in the human body.

# 4. Conclusions

The purpose of this study was to apply the principles of electromagnetic induction to charge a battery-run device implanted in subject rabbits by means of spatial charging. In addition, the electromagnetic radiation effects produced during the charging process were also explored. The obtained results indicated the following. (1) The self-made electromagnetic rod proved to be capable of spatial charging without causing any damage due to electromagnetic radiation. Charged fully, the in vivo battery could activate the transmitter to send signals for eight days. (2) The approach demonstrated here is an alternative for charging electronic sensing components in vivo.

# 5. Acknowledgements

I am grateful to Prof. C.H. Chiu of NCHU for his advice on the methodology of this experiment and the mathematical equations. I also appreciate the assistance of Dr. Y.W. Hung of the veterinary college, who provided great assistance in implanting the ICTTs. Thanks are also given to Dr. L.L. Weng and Ms. W. Hou for taking care of the rabbits. I am thankful to Dr. C.H. Lin who guided me while making the polydimethylsiloxane prepolymer covering film. Finally, thanks are given to the authorities of the Lab of Computer Simulation in Biomechanics in NCHU, who provided the necessary equipments and a location for the experiment.

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## 評語

這件作品利用感應發電原理，示範在活體中植入的電子裝置非接觸式充電的可行性。感應發電的原理已經是習知技術，但利用此原理來延長植入生物體的電子裝置的電路運作時間，仍不失為一個具同實質效用的概念。參賽同學口語表達清晰，研究過程及方法符合科學精神，是一件很好的作品。請繼續加油，讓作品的效益的展現更明確，更量化一點，以凸顯其應用價值。