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Design and Implementation of a Volume Conduction Based RFID System for Smart Implants

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Abstract— **As the population ages, knee and hip replacement surgeries are more and more popular, and embedding an RFID (radio frequency identification) tag on these implants for identification becomes an important issue. Traditional operation of an RFID tag by wireless means will not work on the implantable knees or hips which are made of metal because of the interference caused by metallic objects degrading the field strength near the RFID tag. This paper proposes a method of operating an RFID tag using volume conduction while avoiding the RF interference in a metallic environment. To increase the efficiency of power transmission, electrodes in this paper are designed and optimized for a real knee implant. Experiments using saline have been conducted and the results have shown that volume conduction has a better performance than wireless methods in that signal attenuation is far less in metallic environments. Finally, the experiment on reading an implanted RFID tag through pig skin shows that volume conduction is an effective method to operate an RFID tag embedded on a metallic implant.**

I. Introduction

A. The Smart Implant

Knee and hip replacement surgeries have become common for people with severe diseased knee or hip joints in recent years. As the average age of the population goes higher, it is estimated that the total knee and hip replacement surgeries will hit 3.48 million by the year of 2030 [1]. Such a large potential market forces researchers and manufacturers to improve the quality of the knee and the hip implants by making them smart. The reasons include monitoring of implants for improving outcomes research. One method of making an implant smart is embedding biosensors and an RFID device inside or on the surface of the implant for identification and monitoring purposes. The RFID device serves as a medium for communication between the biosensors and the interrogator (reader). The biosensors, placed inside or on the surface of the replaced implant, transmit the status of the implant such as pressure and PH level to the RFID device by wired connection. The RFID device then transmits data collected from the sensors to the interrogator through the tissue. The RFID device also stores the information of the implant as well as the information of the patient who has had knee or hip replacement surgery to eliminate counterfeiting, with little concern about the loss or error in searching information from a paper enabled database.

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The design of a smart knee implant is shown in Fig. 1, where a passive RFID tag is attached to the side surface of the bottom knee implant and the biosensors are placed on the surface of the white poly layer for obtaining information from the knee joint without obstructing its movement.

B. Volume Conduction

Because most knee and hip implants are made of metal for durability considerations, which causes interference [2] with an RFID tag and causes huge field degradation around the tag, traditional methods of operating an RFID tag embedded on metallic implants wirelessly is non-efficient and will not work [3]. An alternative method of operating an RFID tag on metallic implants is volume conduction, a method that uses human tissue to conduct electricity to power the tag.

Volume conduction was first invented to capture EEG signals from the human body, and was later demonstrated to be able to transmit small amounts of power [4]. By using mainly the electrical field to transmit a signal, volume conduction reduces the eddy currents in the metallic implants to only a small degree, and therefore avoids the interference between the RFID tags and the implants. Furthermore, there is more flexibility in making the tags including the shape and the size, because no antenna is needed.

The proposed volume conduction system consists of two pairs of electrodes, one placed on the exterior surface of tissue and the other under the tissue but on the surface of the knee implant (Fig. 2). The source is applied to the exterior electrodes from the RFID interrogator, and the power is transmitted through tissue to the interior electrodes. The RFID device and the biosensors are connected to the interior electrodes for power. With proper selection of the shape, size and location of the electrodes and with the electrodes being well aligned, the power transmission efficiency from the exterior electrodes to the interior pair can be maximized, which can guarantee enough power to turn on the RFID device and the sensors.

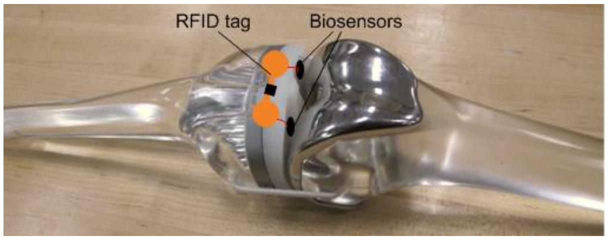

Fig. 1. The proposed smart implant.

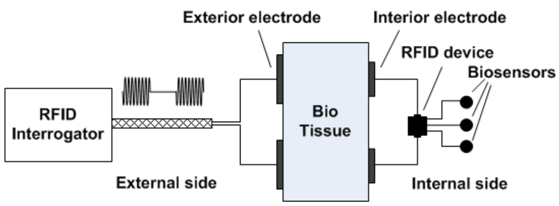

Fig. 2. The proposed volume conduction RFID system.

II. Signal Attenuation

A. Experiment Platform

It is well known that attenuation occurs when signal is going through biological tissue [5]. Therefore it is of great importance to know how much signal is attenuated when going through different thickness of tissue with electrodes differing in size and location. Instead of using real tissue, saline solution with 0.18% NaCl concentration, recommended in [6] for implantable medical device-electromagnetic compatibility test is used in the experiments. A saline container is built as a box with dimensions of 300 mm by 300 mm by 280 mm to hold the saline. Two holes were drilled through the center of the front side of the saline container so that the exterior electrodes can be fastened to the front wall using metal screws. A movable panel with a slot is also used to hold the interior electrodes. A 5mm thick stainless steel sheet with size of 50 mm by 80 mm is attached between the movable panel and the interior electrodes for studying the metallic interference using volume conduction as seen in Fig. 3. To insulate the interior electrodes from the metal sheet, another 0.4 mm plastic sheet is placed between them to avoid interior electrodes shorting.

The source signal is added to the exterior electrodes through an RF cable. An HP function generator is utilized as the source of signal and a Tektronix DPO 7254 digital phosphor oscilloscope is used for measuring the voltages at both the external and the internal sides. The attenuation is then calculated from equation (1):

$$A = 20\log_{10}\left(\frac{V_{\text{input}}}{V_{\text{output}}}\right) \tag{1}$$

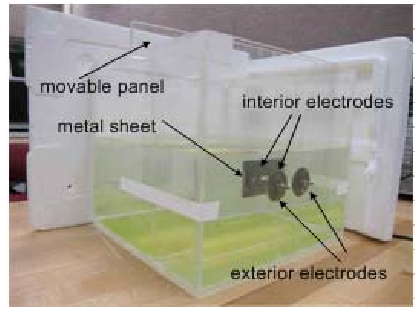

Fig. 3. The saline container.

B. Operating Frequency

Even though most volume conduction systems use low RF frequencies as operating frequencies [7], modern RFID systems prefer higher frequencies such as HF (13.56MHz) and UHF (915MHz) because of higher data rate and larger range [8]. Some literature compares signal attenuation at different frequencies [9]. From the existing literature, tissue/saline absorbs more RF signal at UHF than HF, if with the same electrode installation and with the same thickness of tissue for signal going through, resulting in a much larger attenuation. It then can be concluded that the transmission range for same amount of power at UHF is much smaller than that at HF, limiting its application to power the implantable RFID devices installed in people with thick skin. Therefore in this paper, HF (high frequency, 13.56MHz) is adopted as the operating frequency for the implantable RFID device.

C. Attenuation With and Without Metallic Interference

In the experiments, the two exterior electrodes are chosen to be round with 40 mm diameter and 50 mm between each other. The interior electrodes have diameters ranging from 25 mm to 10 mm with the distance between each pair fixed at 30 mm. The thickness of saline the signal goes through (saline depth) is adjusted to be from 5 mm to 50 mm, the common range of skin/tissue for most people, including those with obesity. The experimental results without the metal sheet are shown in Fig. 4 and Fig. 5.

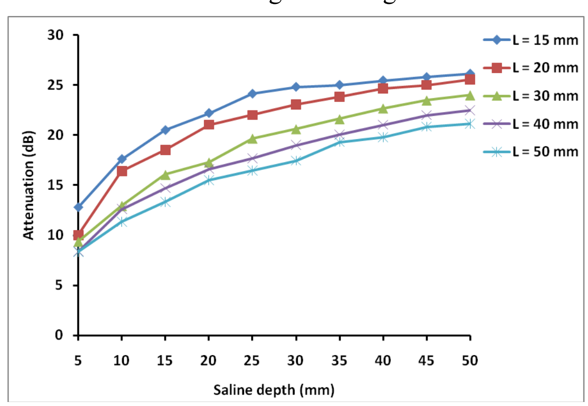

Fig. 4. Signal attenuation without metal sheet using 10 mm interior electrodes with different distances between electrode center (L).

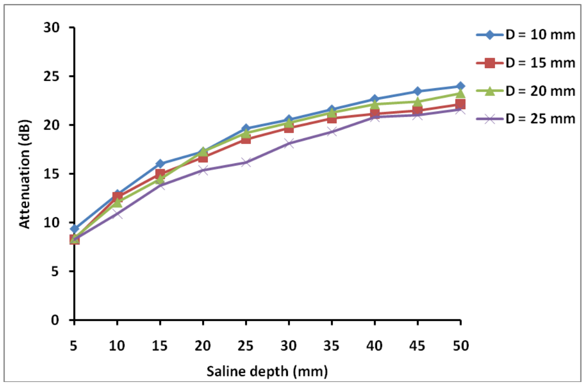

Fig. 5. Signal attenuation without metal sheet using different sizes (D) of interior electrodes with 30 mm distance between each center.

With the metal sheet placed between the interior electrodes and the movable panel, the same procedure for the experiments was repeated and the experiment results are in the following two figures. With an average increase of 2.38 dB in signal attenuation, one can believe that volume conduction does not cause a severe interference in metallic environments and will not disable the communication link between the RFID device and the interrogator.

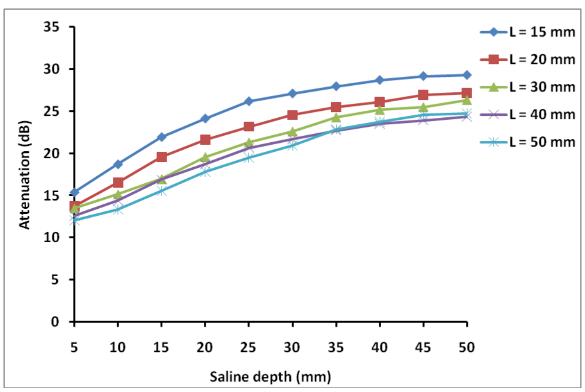

Fig. 6. Signal attenuation with metal sheet using 10 mm interior electrodes with different distances between electrode center (L).

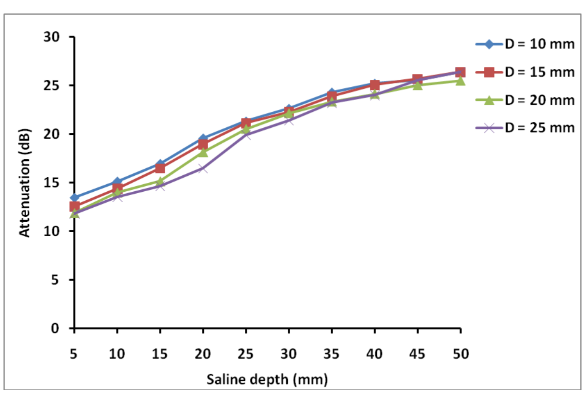

Fig. 7. Signal attenuation with metal sheet using different sizes (D) of interior electrodes with 30 mm distance between each center.

III. Electrode Design

A. Experiment Platform

The design of electrodes on the RFID tag is of great significance to the power transmission efficiency of any volume conduction system. According to [4], different patterns of electrodes including round, rectangular, triangular and ring electrodes have been studied to compare the power efficiency with conclusion that round and rectangular electrodes tend to be more efficient than the other ones. In this paper, electrodes are shaped as shown in Fig. 8, which combines the advantages of round and rectangular electrodes. The three parameters D1, D2 and D3 are control parameters that determine the distance between electrodes, the size and the shape of electrodes respectively.

The optimization of the electrodes follows three principles. First, larger electrodes result in more current capability because of more interference with field. Second, larger distance between each pair of electrodes results in bigger voltage because of the longer path. Third, exterior and interior electrodes should be well aligned for shortest path between each pair to minimize impedance during electrical transmission.

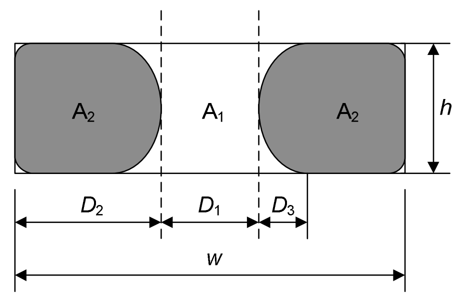

Fig. 8. Shape of electrodes with dimension control parameters.

Because there is limited space on a knee implant, the optimization of the electrodes is an optimization problem with constraints as in the following equation. The objective function to be maximized is the power received by the interior electrodes which, in this paper, is the product of the open circuit voltage and the short circuit current. The constraint is the total area for the tag being less than the area in the figure.

$$\max_{D_1, D_2, D_3} P = V_{open} I_{short}, \quad \text{where } A_1 + 2A_2 \le wh \tag{2}$$

With the help of HFSS (high frequency structural simulator), a simulation tool developed by Ansoft which can analyze the electric field and magnetic field distribution at RFID frequencies within a defined structure, field analysis between the exterior and interior electrodes are performed and the open circuit voltages and the short circuit currents are calculated by integrating the electrical field and magnet field along a certain path separately. In this paper, because the available space for a knee implant is 80 mm by 12 mm, the interior electrodes are fixed to a rectangular area of 50 mm by 12 mm. D1 is optimized within a range from 6 mm to 16 mm, with 2 mm as increment. D3 is set to be 5 mm in all simulations. By comparing the power from equation (2) with respected to D1, the optimized parameters of D1, D2 and D3 are found to be 10 mm, 15 mm and 5 mm separately.

IV. Tag Operation Through Pig Skin

Reading an implantable RFID tag through the pig skin is to demonstrate the operability of a tag using the proposed volume conduction method as well as to study the range of operation. The Magellan Mars-2 reader and the PJM ST chips are used in the experiment with a touch probe serving as the exterior electrodes as shown in Fig. 9(a). The optimized electrodes of the tag are shown in Fig. 9(b). Fresh pig skin with an average thickness of around 4 mm is used in the tag operation experiment as shown in Fig. 10. The RFID tag is made from thin copper tape, with a thin layer of insulation glue between the tag and the implant.

(a) (b)

Fig. 9. (a) The RFID reader and the touch probe; (b) The optimized tag on a knee implant.

Fig. 10. Reading the RFID tag through pig skin.

The reader has a control panel and console showing the message read from the RFID chip. When a tag is read, the tag ID and the corresponding data will be recorded and displayed on the message window, indicating a successful operation. The Magellan RFID chip has a memory of 8KB with a data rate of 96KB/s. Based on the capability of the chip, the authors first write 4KB data, sufficient in covering all the information of a patient, into the memory of the tag and then read all these data.

With the success of the read/write operation through up to 4 layers of pig skin with a high efficiency (near 100% successful rate), each taking less than one second, one can conclude that the method of operating an implanted RFID tag is suitable for most people who have their knees replaced, including some with obesity, and this method is one of the efficient ways to solve the metallic interference problems.

V. Conclusion

This paper proposed a method of using volume conduction to operate an implantable RFID tag that is embedded on metallic objects. The optimization of the interior electrodes in size, shape and the distance between the two electrodes promotes the power transmission efficiency through tissue/saline. Successful operations of an implantable RFID tag through pig skin have demonstrated that volume conduction is an efficient means of communicating with an implanted RFID tag embedded on implants made of metal.

Acknowledgment

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