A Volume Conduction Approach to Operate a Passive RFID Tag on Metallic Implants

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***Abstract*— This paper presents a method of using volume conduction for communication with implanted passive RFID tags. Based on electrode coupling, this method uses mainly electric field to transmit signal through tissue, and therefore can reduce the interference with metallic implants when RFID tags are attached to the implants. Exterior and interior electrodes are designed for efficient energy and signal transmission. Experiments with a saline box are conducted to study the signal attenuation through biological tissue and the feasibility of using volume conduction for RFID tags close to in vivo metallic materials.**

Keywords-implanted RFID; volume conduction; metallic interference

I. Introduction

Radio frequency identification (RFID) technology is a wireless communication technology that uses electromagnetic field at radio frequency for information exchange. Typical RFID systems include interrogators (readers) and tags and the link between them is wireless. The major application of RFID technology is for identification and tracking purposes such as “Wal-mart” type tags [1]. Due to its small size and low cost, one potential application of RFID tag is embedding on body implants such as artificial joints (Fig. 1) for identification. Such application can provide a convenient way for doctors and surgeons to reduce counterfeiting and obtain information from patients who have experienced joint replacement surgeries, with little concern about the loss or error in searching information. Furthermore, if integrated with sensors, such implanted RFID tags can also be used for monitoring the status of the joints, and thus help doctors to diagnose. The demand for such implanted RFID tags has grown rapidly in recent years. Such demand will increase as the population ages. By the year 2030, it is estimated that the number of knee replacements will increase from 450,400 to 3.48 million [2].

One major concern is the tag performance with current RFID systems, since most artificial joints are made of metal. There has been considerable research discussing the interference between RFID systems and metallic materials [3] [4]. How interference affects the RFID systems is a case by case problem depending on position, size and structure of the material as well as the material itself. For studying the possibility to operate an implanted RFID tag using traditional inductive coupling method in such a condition, experiments on reading a knee implant with embedded RFID tag are reported in this paper. The experiment is performed using a Magellan MARS-2 reader with the setup as shown in Fig. 2. The tag has a dimension of 20 mm by 10 mm with 1 mm plastic substrate. The distance between the tag and the antenna is 10 mm. We observe that no reading of the tag is seen to be recorded when the tag is placed at the center of the knee. Even when being moved 30 mm away from the knee, the embedded tag is only able to be read with low efficiency meaning that during n number of times reading only a small fraction is successful. The reading distance could be improved by re-tuning the antennas as in [5]; however, to maintain the same coupling as without the metallic joint, a much larger antenna has to be applied. Because the limited space on the implant makes it impossible to design a relatively large tag, we believe that the traditional inductive coupling method to operate an RFID tag embedded on metallic materials is not suitable for the application proposed. An alternative approach is required to operate the RFID tags in such a condition.

Studies have shown that ionic fluids within biological tissues are capable of conducting electrical current which, when intentionally manipulated, can be used to transmit information and energy. This method of using the body as a conductor, known as volume conduction, has been used to transmit information from a sensor implanted within the leg of a cadaver to perform mechanical measurements [6], and send information using a body bus described in a Microsoft patent [7]. It has also been used experimentally to recharge the battery of an implantable device to eliminate battery replacement surgeries [8]. Since volume conduction uses mainly electric field in conducting power, it has fewer chances to induce large eddy current in metals, and therefore can be more power efficient and has less interference in metallic environment than using inductive coupling. This interference can be further mitigated by insulating the metallic surface using non-conductive materials. Using volume conduction also eliminates the need of antenna, which in turn makes it more flexible in the size and shape of design.

Based on the above research results and implementations, we propose a method of using volume conduction to power and communicate with a passive RFID tag that is embedded with in vivo metallic materials. In this paper, we focus on creation of an RFID volume conduction system and discussion about its feasibility in use with metallic environments. Three sections are on the design of the system including the volume conduction system overview, electrode design and impedance matching. Finally, in section V, the experiment of successfully reading a passive RFID tag that is embedded on a real artificial joint has shown the feasibility of using our proposed method in reducing interference with metallic environments.

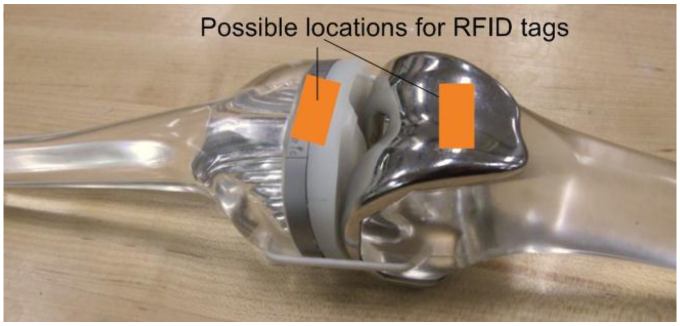


Figure 1. A knee implant with possible locations for RFID tags.

Figure 2. Reading an embedded tag placed on a knee implant using inductive coupling.

II. SYSTEM OVERVIEW

A. Volume Conduction System

The proposed volume conduction system in this paper relies on the same principle as in previous references [6-8]. The system is illustrated in Fig. 3. The source is connected to the body through two external electrodes attached to the surface of the tissue. An electric field is generated when a voltage is produced across the external electrodes. Two internal electrodes connecting the RFID chip are implanted to interact with the electric field to capture the signal. The signal captured by the internal electrodes is used to power the RFID chip as well as for communication. The RFID tag backscatters information through the inverse path but with the same principle.

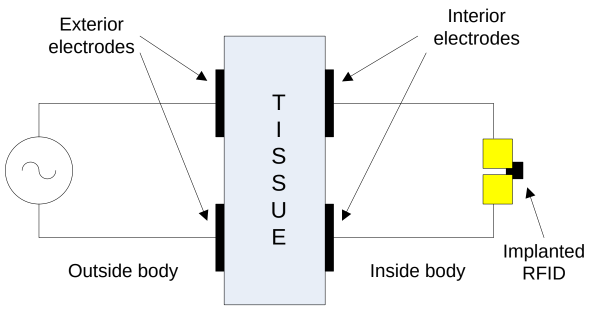


Figure 3. Volume conduction system.

B. The saline box

The saline box is built for studying signal attenuation through biological tissue where volume conduction is implemented. The box is shown in Fig. 4. The box is made from 9 mm thick acrylic boards. The dimension of the box is made to be 30 cm x 30 cm x 28 cm in order that sufficiently large transmission ranges can be covered. The exterior body electrodes are attached on the inner side of one of the walls making them contact the surface of the saline. The interior electrodes are attached to a movable panel that produces the distance to the exterior electrodes. Stainless screws are used for fastening the electrodes to the box and the panel, and also serving as external terminals.

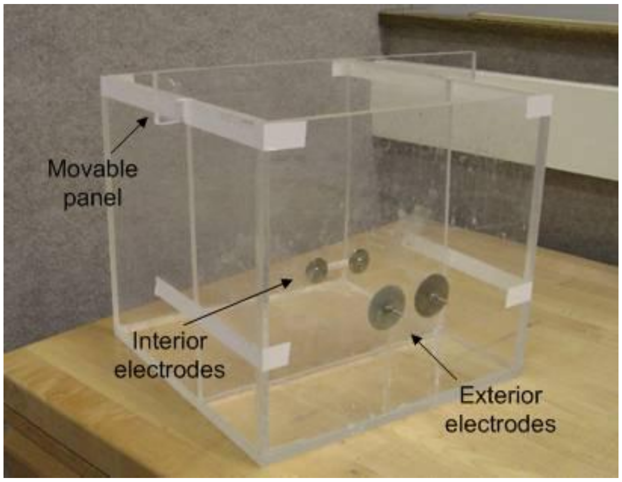


Figure 4. The saline box.

C. Electrodes

Electrode design is one of the most important considerations for volume conduction systems. Various electrodes in shape, size and patterns are designed to fulfill different applications [9] [10]. In this paper, for simplicity, electrodes with a round shape are used. The electrodes are made of stainless steel to prevent corruption in saline. The sizes of the electrodes range from 40 mm to 10 mm in diameter, with a through hole for screws at each center (Fig. 5). The thickness of the electrodes is 1mm, making it suitable for implantation.

Figure 5. Electrodes in different sizes.

III. SIGNAL ATTENUATION

One major concern of volume conduction is that biological tissue attenuates signals, especially at higher frequencies [11]. The more signal it attenuates, the less power that an implanted RFID tag can receive. Therefore, it is crucial to know how much signal is attenuated when using different sizes of electrodes with different distances in between electrodes. Such experiments are conducted using the saline box in Fig.4.

Due to the limitation of the surface area of skin, the exterior electrodes are selected to be 40 mm in diameter with 50 mm between each center. The exterior electrodes are placed and fixed as a pair at the center of the wall at one side of the saline box (as shown in Fig. 4). This makes them equal in distance to the side walls of the box and the bottom. The interior electrodes are aligned with the exterior electrodes in such a manner that their flat surfaces are in parallel and they have the same height to the bottom of the saline box from their centers. Since the in vivo space is limited for embedding implantable RFID tags, the sizes of interior electrodes are then selected to be in the range between 25 mm to 10 mm in diameter with 5 mm decrement. The distance between the interior electrodes has a maximum of 50 mm.

The electrical signal source is an RF function generator which connects to the exterior electrodes through a coaxial cable. The function generator outputs an 18 dBm sine wave at 13.56MHz, the operating frequency of the RFID reader. The RMS voltage across the exterior electrodes and the RMS voltage across the interior electrodes are measured using a digital oscilloscope. The experiments use 0.18% saline, which is the type of saline that follows the requirement specified in [12]. The measurement results are shown in Fig. 6 and Fig. 7 where the signal attenuation is defined as in equation (1). The letters "L" and "D" in the figures represent the distance between the center of the interior electrodes and the diameter of the interior electrodes respectively. The saline thickness is the thickness of saline that RF signal goes through in the experiments, i.e. the distance between the exterior electrodes and the interior electrodes.

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

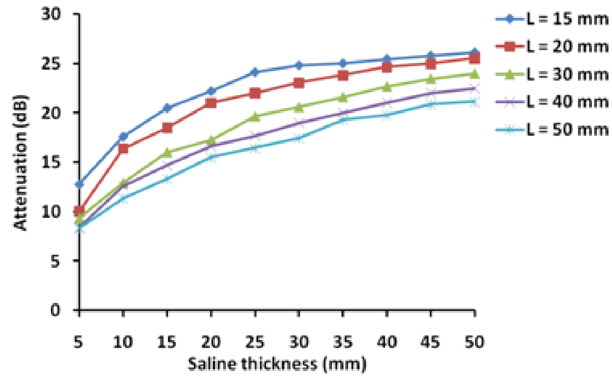


Figure 6. Signal attenuation through saline (D=10 mm).

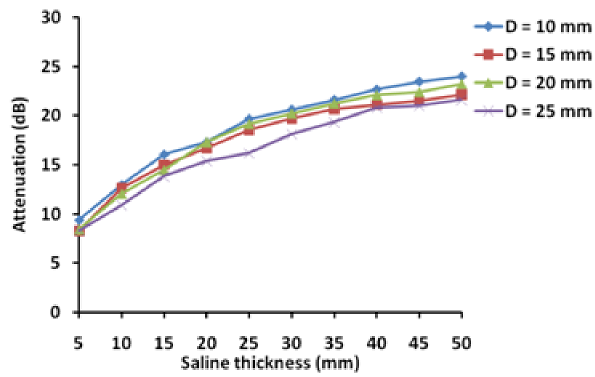


Figure 7. Signal attenuation through saline (L=30 mm).

As can be seen from the above figures, the larger interior electrodes with larger distances between them tend to reduce the signal attenuation as the thickness of saline increases. However, as the saline thickness increases, say to 50 mm, significant attenuation occurs. This is because the electric field is extremely weak at greater thicknesses making larger electrode sizes and distances not able to capture sufficient flux. At such thicknesses, not enough power can be transmitted to the implanted RFID tags.

Fig. 8 and Fig. 9 show signal attenuation with metallic interference. The interference is introduced by placing a 50 mm by 80 mm rectangular metal plate behind the interior electrodes. The interior electrodes are located at the center of the metal plate to maximize the inference. We observed an average of 24% voltage drop with the metal plate, which is affordable for signal and energy transmission, and is a proof of rationality of the proposed method.

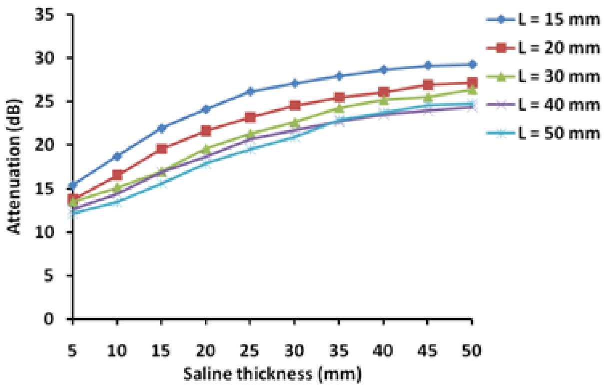


Figure 8. Signal attenuation through saline with metal plate inteference (D=10mm).

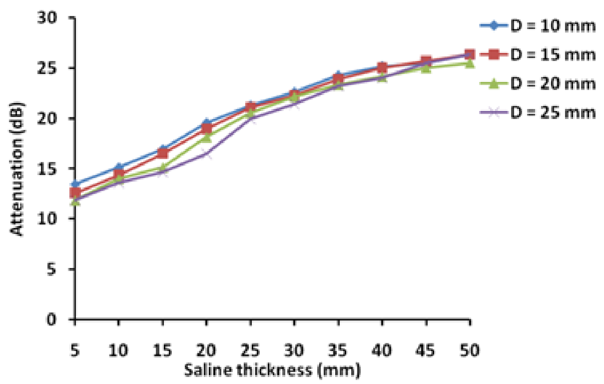


Figure 9. Signal attenuation through saline with metal plate interference (L=30 mm).

IV. Matching Circuit

Impedance matching is important in electrical circuits to obtain maximum power transfer between a source and a load. In order for maximum power transfer to occur, the impedance of the source and load are required to be complex conjugates of each other, i.e., R +jX and R – jX, where R is the real part and X is the imaginary part of the impedance. Matching networks are also required in RF systems for maximizing power and signal transmission efficiency. In this volume conduction system, matching circuits are used at both the external and internal sides for optimum performance. The diagrams of the matching circuits are shown in Fig. 10.

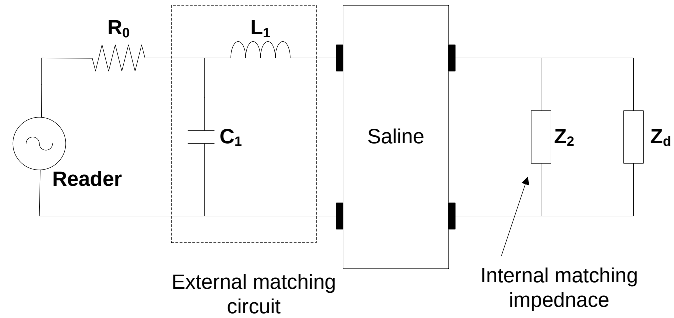


Figure 10. The matching circuit for volume conduction system.

A. *Matching the saline to the reader*

Matching the impedance of the saline to the reader is required to reduce the signal reflected back to the reader due to any impedance mismatches, thus maximizing the energy transmitted to the saline and the load. The impedance of the saline is the impedance seen from the exterior electrodes into the saline, which depends on the conductivity of saline and the size of the exterior electrodes. An LC circuit [13] is added between the reader and the saline as indicated in Fig. 10.

Solving the equation that the equivalent impedance seen from the external matching network is equal to the impedance of reader, the values of the inductor and capacitor that can match the saline to the reader can be calculated from the following equations:

$$C_1 = \frac{1}{\omega R_0}\sqrt{\frac{R_0 - R_L}{R_L}} \quad (2)$$

$$L_1 = \frac{\sqrt{R_L\left(R_0 - R_L\right)} - X_L}{\omega} \quad (3)$$

where ω is the angular frequency, R_0 is the impedance of reader (50 ohm), and R_L and X_L are the real and imaginary part of the saline impedance. The saline is measured to be 21.6 – j0.61 ohm by a network analyzer, which in turn gives a 270 pF capacitance and 280 nH inductance for the matching network.

B. *Matching the RFID chip*

Matching the impedance of an RFID chip to the saline is much more complicated because the impedance from the interior electrodes to the reader is very sensitive to the installation of the interior electrodes. The saline presents a 3 dimensional load which is thus affected by the location of the electrodes and the dimensions of the box holding the saline. To some extent, the acrylic box itself is a part of the boundary conditions which can be ignored in this case because the matching is being performed empirically. It is also difficult to measure or calculate the impedance of saline from the internal side when reader is connected. Therefore, it is impractical to match the impedance of the RFID chip to a specific value that can be calculated *a priori*.

The way we propose to determine the matching impedance is to maximize the voltage across the electrodes of the RFID tag. A larger load voltage means more power as long as there is enough voltage to turn on the RFID chip. It is important to note that while power is to be optimized, there must be sufficient voltage to turn on the transistors in the RFID chip. Thus, the actual matching circuit is assumed in this case to be the one that produces the largest voltage across the electrodes where the power is assumed to be sufficient to drive the silicon chip of the RFID tag. Such a condition can be easily satisfied due to the modern manufacturing technology which reduces the current consumption level of the RFID chips from mA to µA. From the internal to external, the part of circuit from saline to the reader can be seen as a source with impedance. The impedance is extremely large because the current at internal side to be very low. Thus, maximization of the load voltage is the method to match the load impedance to the source impedance.

Because the impedance of the RFID chip, in terms of Z_d, is capacitive, inductive impedance $R_2 + jX_2$ is added in parallel with Z_d as indicated above to produce a conjugate impedance. The problem then becomes one of optimizing the impedance at the load which is given by the following equation:

$$\max_{R_2, X_2 > 0} \frac{(R_2 + jX_2)(R_d + jX_d)}{R_2 + jX_2 + R_d + jX_d} \tag{4}$$

where; R_d and X_d are the real and imaginary parts of the RFID chip impedance. Given the Q factor of the matching impedance, one can calculate the optimal solution for X_2 as

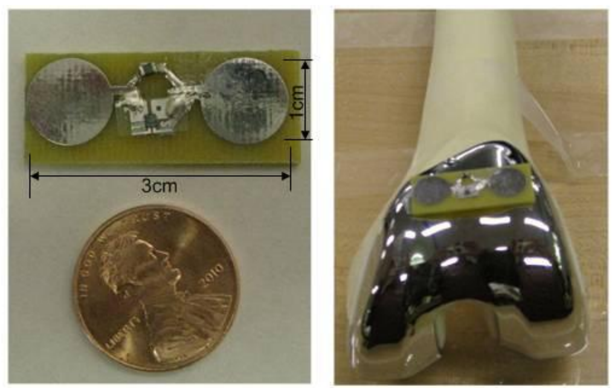
$$X_2 = -\frac{(R_d^2 + X_d^2)Q}{R_d + X_d Q} \tag{5}$$

The real part of the matching impedance is then calculated by dividing X_2 by Q, and the inductance of the circuit can be obtained from dividing X_2 by the angular frequency. The impedance of the RFID chip is 39-j800 ohm by measurement using the network analyzer. For size consideration at the implant, surface mount inductors are used. Comparing the available parts in the market, we have chosen a Q = 30 for calculation which gives an inductance of 9.4µH. In the experimental system, considering capacitance added by the electrodes and also the availability of parts in discrete units, a 10 µH inductor is used in this prototype.

V. EXPERIMENT

To test the feasibility of using volume conduction to operate an RFID tag embedded on a metallic implant, experiments in reading an RFID chip with electrodes attached is performed. First, the prototype of an embedded RFID tag is built on a printed circuit board with 1.5 mm FR4 substrate to accommodate both the RFID chip and the matching circuit. Due to the limitation of under-skin volume, the size of the PCB is required to be as small as possible. Therefore the initial size of the electrodes is chosen to be 1 cm in diameter with 2 cm between each center resulting in a total size of 3 cm by 1 cm (Fig. 11a). The prototype PCB is then placed to attach to the center on the surface of the metal (Fig. 11b).

The equipment used in this experiment include an HF RFID reader with operating frequency of 13.56MHz, the saline box and its matching circuit, an actual artificial joint, the RFID chip prototype board with matching and an oscilloscope. The RFID chip is designed to allow 8K bits of memory with data rate up to 96Kb/s. This is sufficient for storing the information pertaining to the joint and relevant medical information for the patient. A small resistor is connected in series with the saline at the external side. By measuring the voltage across the resistor, the current flowing into the saline can be measured. Then the power transferred to the saline can be calculated and safety evaluation can be performed. Fig. 12 shows the experimental setup. In the experiment, the power of the RFID reader is set to be the maximum, i.e., the same level as the interference test at the beginning when using a wireless antenna. The artificial knee joint is taped onto a movable panel for test purposes allowing different saline thicknesses.



a b

Figure 11. a. The prototype RFID tag and. b. place that the RFID is attached to the implant.

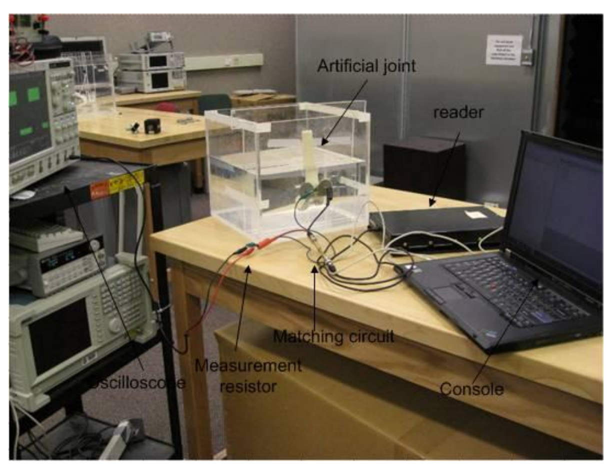


Figure 12. The experiment setup.

One of the problems with RFID with an air medium in the proximity of metal is reduced performance. This situation is being tested next with the presence of the saline as the medium of transmission with volume conduction. The efficiency with and without the knee implant is therefore measured and shown in Fig. 13. We see that with the metallic implant in the experiment, the attenuation is only a little larger than with no implant. This means that the metallic interference of RFID system using volume conduction is significantly reduced. With an average of 11.6% less in voltage efficiency (the ratio of received voltage to supplied voltage) than with no implant, the RFID tag can be read through 15 mm of saline without difficulty. The best efficiency for reading occurs within 10 mm of range which is applicable for most people.

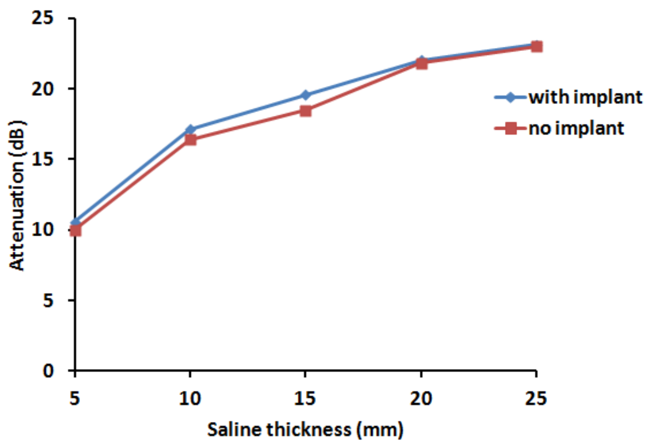


Figure 13. Attenuation with and without a metallic implant using the prototype embedded RFID tag.

It is believed that greater distances in the saline can be achieved by optimizing the electrodes on the reader side of the energy transfer. In addition, the dispersion of the energy with an actual knee implant will be considerable less than the large volume of saline used in this initial experimental setup.

The current in the saline during the test is approximately 76mA, well below the safety level specified by [14]. This also allows for increased performance within the limits of safety. At this level of current and taking into account that the reading time for the RFID tag is normally less than 1 second, we believe that the volume conduction system proposed will not cause tissue burn and is safe in human tissue.

VI. Conclusion

The experiment results show no severe attenuation increase is encountered when the RFID tag is placed in the metallic environment of an orthopedic implant using volume conduction. The success in reading the prototype embedded RFID tag proves the feasibility of operating an implanted RFID in the metallic environment of an orthopedic implant. Volume conduction is the best approach for an RFID system to reduce metallic interference when considering the human body.

Acknowledgment

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