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RFID for Medical Applications

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RFID for Medical Applications

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Abstract

Osteoporosis and osteopenia are common conditions in adults over fifty, however x-ray based screening is not always feasible. This project is a part of a larger investigation attempting to use RFID technology to detect osteoporosis. The contribution of this project to the investigation consisted of developing a proof of concept for an RFID based osteoporosis screening device. The proof of concept was used to perform measurements on cadaveric arms. Data was collected to see if a correlation could be found between RF propagation and whether the bones were osteoporotic or not. The measurements were taken successfully and the data was used to establish a correlation in the greater investigation.

Executive Summary

Osteoporosis is a disease characterized by loss of bone density, leading to fragile bones. It affects approximately 10 million people in the USA according to data from 2010[3]. It is typically diagnosed after a fracture has occurred, which means that people with osteoporosis who have not yet been diagnosed may not be taking appropriate preventative measures and treatments. The current method of detecting osteoporosis involves using x-rays to measure bone-density. The cost of this procedure is prohibitive in less developed countries, and in developed countries limits preemptive screening. If the propagation of microwaves through the body can be used to detect osteoporosis or osteopenia, screening for the condition could be safer and less costly.

Ongoing research is being conducted to develop a method of detecting osteoporosis using RFID technology. This project consisted of contributing to that research. On beginning, it had to be established that RFID readers can be used to measure RF propagation in some way. This was done by assembling a test bed consisting of a COTS RFID reader, custom software to view the various parameters reported by the reader, and various arrays of RFID tags. The two promising parameters were 1) received signal strength indicator (RSSI) and 2) the phase.

Once the capabilities of the RFID reader were determined, an experiment was developed with the goal of using RSSI to detect the differences in RF propagation through a wrist, caused by osteoporosis. To accomplish this, an RFID reader with its antenna was placed on the underside of the wrist, and an array of 5 tags was placed radially around the wrist and centered opposite the reader's antenna. Measurements were performed on cadaveric arms that had either normal or osteoporotic bones. The data collected from the experiment was used to establish a correlation between the average RSSI of the 5 tags and the bone density of the subject.

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1. Introduction

Osteoporosis is a significant risk to the health and well being of the 50 and over population. In this population, a third of women and a fifth of men will suffer from osteoporotic fractures, and after one fracture the risk of further fractures increases to 50% [1]. This is also a significant economic burden as the cost of fragility fractures in the USA in 2015 was estimated at over $20 billion. [1].

Osteoporosis is diagnosed with a bone mineral density (BMD) test. Currently, a dual-energy x-ray absorptiometry (DXA or DEXA) test is typical [2]. While these tests are not particularly costly in developed nations, the cost would still be problematic for those with little to no income or no health insurance, and in developing nations the cost would be a significant issue for a large part of the population.

A lower cost method of diagnosing osteoporosis could increase the rate at which at-risk populations are screened. An attempt to use microwaves to detect osteoporosis by mapping the permittivity of the bone is currently being studied. [4]. A simpler and potentially lower cost solution may be possible however.

RFID technology is common and inexpensive with UHF RFID tags (300MHz-3GHz) operating in the microwave range (300MHz-300GHz). Passive tags are very inexpensive to the point where they can be considered disposable (less than 10 cents per tag). If these can be used to detect changes caused by osteoporosis, detection could be made much cheaper and available in more areas.

2. Objectives

2.1 Objective 1

Objective 1: Measure RF propagation with as much accuracy as possible using an RFID reader. Ideally the RSSI and phase of the received signal from an array of RFID tags could be combined to form a low resolution image of the space between the reader’s antenna and the array of tags. Objects in that space which cause the absorption, diffraction, and reflection of of the signal would reduce the RSSI and phase differently for the tags, depending on which paths between the reader and the tags are intercepted by the object.

2.2 Objective 2

Objective 2: Design and carry out an experiment to measure the differences between a population with normal bone density and one with osteoporosis. It was hoped that the differences in RF propagation between the two populations would be well enough defined that the individual samples could be sorted back into their population based on the measurements.

3. Background

3.1 Osteoporosis Effects on RF Propagation

The medical term ‘osteoporosis’ stems from roots meaning ‘porous bone’, with the porosity of the bone increasing as the disease progresses. The pores become filled with yellow bone marrow and fat, which changes the dielectric constant of the bone at microwave frequencies [4][6]. This change increases the ratio of dielectric constants (dielectric contrast) between the bone and surrounding muscle tissue. This contrast would scatter microwaves, reducing the strength of any microwave signals along a path that goes through the bone. In his research, Professor Sergey Makarov (WPI) was able to simulate the projected strength of a microwave signal when transmitted through a thigh, as measured at various angles from the reader antenna using the finite element method (FEM) [5]. See Figure 2 for a plot of received signal strength vs. angle and see Figure 1 for a diagram of the simulated thigh.

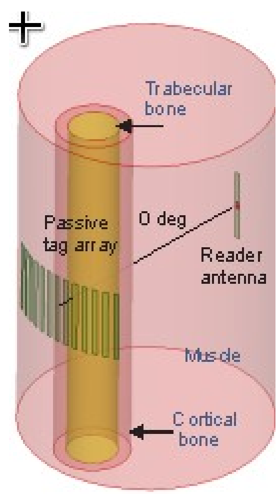

Figure 1: FEM Thigh Diagram

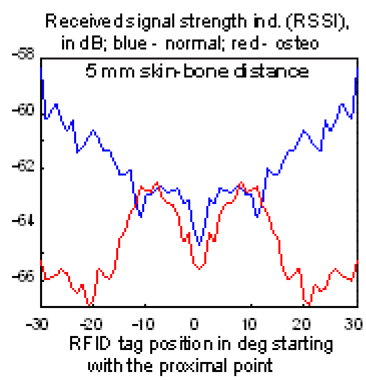

Figure 2: FEM Plot

3.2 Hardware

There are a variety of RFID readers and tags on the market. The differences to be measured are present at 900MHz which is a common frequency used by RFID readers and tags. Because of this, a 900MHz UHF RFID reader and tags were necessary. An Impinj Speedway R420 RFID reader was initially chosen for the project because of its availability (see Figure 3).

Figure 3: Impinj Speedway R420 RFID Reader. Taken from [16].

In an attempt to overcome problems obtaining phase shift information using this RFID reader, a zebra FX7500 was also used in project (see Figure 4). It has similar capabilities to the Impinj unit.

Figure 4: Zebra FX7500 RFID Reader. Taken from [15].

General Purpose disposable 900MHz RFID tags were used with both of these RFID readers. These consisted of paper with adhesive backing, with the IC and antenna embedded within.

3.3 Software

When using the Impinj RFID reader, an open source software called sllurp [7] was utilized to interface with the RFID reader through a network based protocol, called the low level reader protocol (LLRP). This software was used to build an application in Python to the RSSI and phase angle of each tag in an array, and to graphically display this data in real time. When the switch was made to the Zebra RFID reader, externally developed software with similar capabilities was used.

4. Preliminary Investigation and Experimentation

4.1 RFID Reader Tests

Upon beginning this project, it was necessary to establish that RFID readers could be used to measure RF propagation, as this isn't the intended use. While RFID readers typically indicate the strength of the signal received by the reader, it wasn't known how accurate the RSSI would be, and what effect many RFID tags in close proximity would have on the reading.

To accomplish this, the capabilities of the RFID were determined using the sllurp software package mentioned in 3.3 Software. Through the use of this software, which communicates with the RFID reader, it was discovered that the reader could apparently report the relative phase angle of the received signal from each tag. For this project, the software was modified to open a list of identifiers for the tags to be read, and to display the RSSI graphically. Using this software, experimentation was performed to see how the RSSI and phase would behave when the tags were held at different distances from the reader's antenna, and when objects were placed in between. The RSSI behaved as expected and appeared to be accurate and consistent, decreasing as the distance was increased and objects were placed in between. However, attempts to read the phase from the RFID reader were unsuccessful.

As the phase angle could prove to be useful, it was decided to utilize the Zebra FX7500 RFID reader. As mentioned in section 3.3 Software, software was used that was developed externally to this project. It has similar capabilities to the software developed for the Impinj reader, and has phase information available as well.

4.2 Experiment on Thigh Analog

An experiment was conducted to determine if the predicted propagation through a thigh from the FEM analysis shown in Figure 2 could be reproduced using RFID tags. An imaging phantom was created from a cylinder filled with a gel made of water, sugar, salt, and TX-151 powder along with a 3d-printed bone analog. The bone analog was offset in order to match the diagram in Figure 1. The RFID reader's antenna was fixed to the cylinder opposite the bone, and an array of RFID tags were attached with their adhesive backing to the cylinder opposite the reader's antenna as in Figure 1.

The results were similar to what was predicted in an individual with normal bone density. See Figure 5 for the results and Figure 6 for a picture of the test setup. The wide spacing of the tags reduces the possible resolution and accuracy of this approach, however it was necessary to prevent overlap between the tags which would have interfered with their function, as was discovered during a previous test.

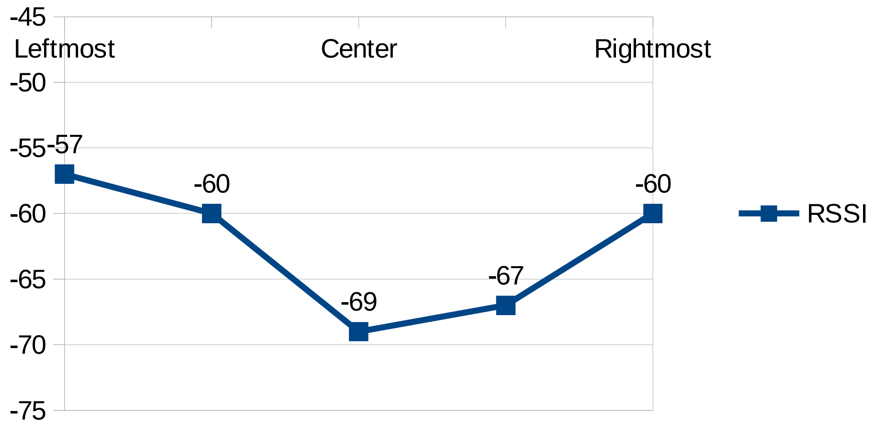

Figure 5: Thigh Analog Experiment Results

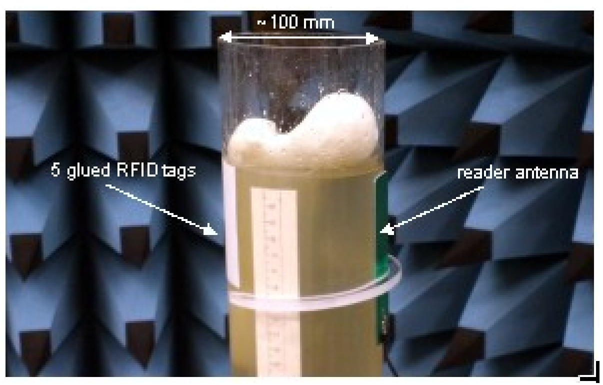

Figure 6: Thigh Analog Experiment Setup

5. On Body Measurements

The final stage of this project was an experiment attempting to detect osteoporosis. As the project was progressing, an idea of how to conduct the experiment was already forming. Ultimately, results and insights gained from the experiment on the thigh analog drove changes to the design. Rather than using an array of RFID tags to form a graph such as in Figure 5, the RSSIs of all the tags would be averaged. This was due to the fact that the tags could not be spaced closely enough to produce an accurate graph of the signal strength. The simulation in Figure 2 predicts that the average signal strength should be lower with osteoporotic bones. Finally, it was decided to test on a wrist rather than a thigh. This is because the simulation predicted that the difference between osteoporosis and normal bone density would be most pronounced when the distance between the bone and skin is minimized.

The method that was decided upon would consist of measuring the RSSI from five RFID tags placed on top of a cadaveric wrist, with the reader antenna placed on the bottom of the wrist (see Figure 7). Eight wrists were measured in total, with four coming from individuals with osteoporosis, and 4 without. The RSSI from each wrist was recorded along with the wrist diameter.

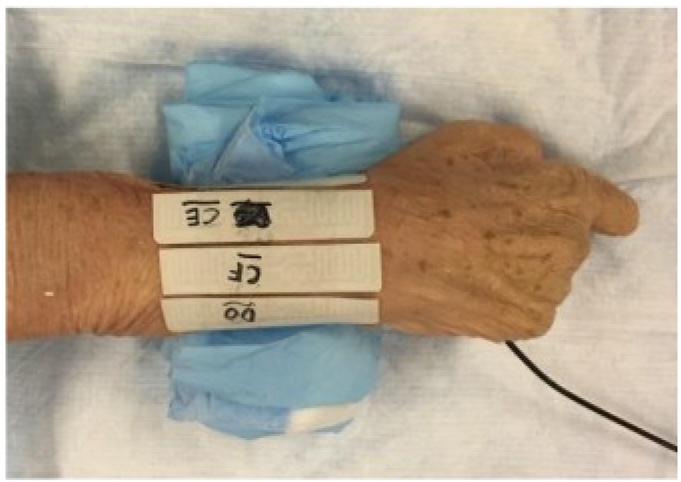

Figure 7: RFID Tags and Antenna on Cadaveric Wrist

The obtained data was processed by first converting the RSSI from dBm to watts as noted in the following equation.

$$P(w)=\frac{10^{\frac{P(dBm)}{10}}}{1000} \tag{1}$$

What will be referred to as the bone signature was calculated for each wrist as follows: the received signal power among all tags was averaged; each average was then multiplied by the square of the wrist circumference. This was done because it appeared that the power would be reduced in proportion to the cross sectional area of the wrist as in the following equation.

$$BS = C^2 \frac{1}{N} \sum_{i=1}^{N} P_i, \quad N = 5 \tag{2}$$

As can be seen in Figure 8, the results of the final experiment showed a correlation between bone signature and the areal bone mass density (aBMD).

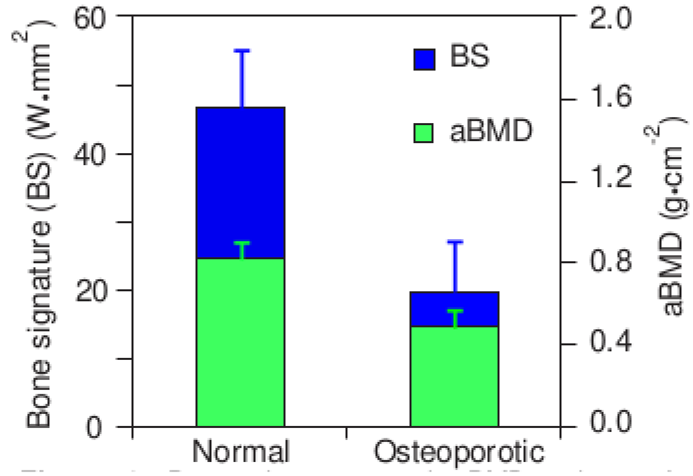

Figure 8: Results of Test using Cadaveric Wrists

6. Summary and Conclusions

With osteoporosis posing a significant health risk to a growing 50 and over population, less expensive and readily available diagnosis techniques have the potential to improve health and quality of life for those affected[1][2][3]. A method of using microwaves to image bones in order to detect osteoporosis is currently under research [4]. Prior research in the field indicated that 900MHz signals transmitted through a thigh would be affected differently depending on whether the bones were osteoporotic or not. Based on those findings, it was hypothesized that RFID technology could be used to detect these changes. This project sought to test this hypothesis by developing methods to measure RF propagation using RFID readers, and utilizing these methods experimentally with the goal of measuring the differences in cadaveric wrists with and without osteoporosis. The data collected was used along with the wrist diameter to calculate a property of each wrist called bone signature. The bone signature appeared to correlate with the areal bone mass density of the wrists. The correlation found in this project represents an important step in developing an RFID based medical device to detect osteoporosis that is less costly than the method currently used.

The results of this project support the hypothesis that RFID technology has the potential to detect osteoporosis and warrants continued investigation. Looking forward, improvements to this method and further research are suggested in order to reliably diagnose osteoporosis using RFID technology. Specifically, custom RFID tags designed for on body use in a tightly spaced array should yield more accurate results. This is because the antenna could be optimized to transmit and receive signals through the body, and more tightly spaced tags could be used to improve the resolution of a graph such as in Figure 5. An experiment using human wrists with a larger sample size would also yield more statistically significant results. Finally, while it could not be determined how to use the received phase in this project, perhaps future research could find a way to use this data to improve the results.

7. References

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Appendix: Review of RFID Technology

Origins

Radio frequency identification (RFID) technology originated with smart cards, which are devices that store identifying information in an integrated circuit (IC) [9]. Smart cards, along with other automatic identification technologies such as barcodes, were developed for the automatic identification of people and objects. This allows repetitive tasks, such as unlocking a door, logging inventory, and looking up prices to be automated.

The original form of the smart card has contacts which are used to form a galvanic connection to the smart card reader. The contacts provide power along with a clock signal to the card from the reader, and a bidirectional data bus between the card and reader [8]. Smart cards can store more data than barcodes, and a direct electrical connection can provide an advantage over optical reading in some use cases. However, by replacing the galvanic connections with a method of remotely reading the data contained in the memory on a smart card, most of the advantages of both barcodes and smart cards are combined. In accomplishing this, RFID and contactless smart card technology has become extremely prolific, with the RFID market worth $11.1 billion in 2017 [11].

RFID Signaling

The RFID reader and tag operate by replacing the power, clock, and data bus connections on a smart card with an RF signal. This is relatively straightforward with power and clock, as an RF signal already has energy and its frequency can be used to generate a clock. Transmitting data over an RF signal is nothing new and multiple methods can be used.

The cleaverness that makes RFID work, lies in the means by which data is transmitted back to the reader. For low frequency devices (LF) devices (those which operate in the frequency range of 125-135KHz), the tags are meant to operate in the near field where the tags are coupled inductively to the transmitting coil [10][12]. This means that adding a load to the receiving coil on the tag would result in an increase in the current amplitude on the transmitting coil if the voltage amplitude remains constant. This is because the reader and tag coils form a transformer. By modulating the load by the signal to be transmitted the tag can send the signal to the reader. This method is called load modulation.

Load modulation and inductive coupling is an excellent solution in the near field. However to work practically, the reader's antenna and the tag need to be significantly less than a wavelength apart from each other in order to be inductively coupled. UHF does not use this technique as its higher frequency range (860-960MHz) results in a very short wavelength of about 33cm, and because it was developed in part to satisfy demands for RFID tags that can be read from farther away than what was previously possible. Instead, a technique called backscatter modulation is used. Backscatter modulation works similarly to load modulation, however, the principle by which information is transmitted to the reader is different. An antenna can absorb and reflect different portions of the energy at a particular frequency depending on the impedance of the load that is connected to it. By modulating the impedance, and therefore how much energy is reflected by the antenna, a signal is transmitted by the tag without the need for a complicated transmitter. [10][12]

UHF RFID Protocol

Depending on the sRFID standard being used, the methods used for modulation and collision avoidance vary. The ISO18000-6C protocol is used by the RFID readers and tags in this project, and even within this single standard there are many combinations of capabilities and operations that can be performed. Instead of covering all the capabilities defined in this standard, an example reflecting this project's use case is given below.

The RFID reader is always transmitting the carrier wave, which powers any tags within range. To inventory the tags, the reader must first use an anti-collision protocol to prevent two tag from transmitting simultaneously. The following example demonstrates how the type of anti-collision used by this protocol works, however the exact function in practice will vary based on implementation. First, the RFID reader sends a message to the tags which in turn triggers them to generate a random 16-bit number. The reader then transmits numbers sequentially in a range from 0 to one less than a power of two (such as 15). The tags listen and compare the number to the least significant digits of the 16-bit number they chose, such as the last 4 digits in the case of the range being 0-15. When the comparison is a match, the tag transmits its 16-bit randomly generated identifier, and if only one tag does so then the reader broadcasts the 16-bit number. This response from the reader triggers the tag to respond with its electronic product code (EPC). This is done for each number in the range chosen by the reader. If there is a collision during this step, the reader will repeat the process until each tag has a collision free response. [14]

The encoding and optionally the modulation methods used by this protocol vary depending the direction of the communication. The RFID reader always uses pulse interval encoding (PIE) and amplitude shift keying (ASK) when sending data to the RFID tags. PIE sends a pulse for each bit and encodes its value in the length of the pulse. For example, a "1" may be transmitted with a pulse length of 10 units of time, while a "0" may be transmitted with a pulse length of 8 units of time. Because the reader uses ASK, these pulses would consist of an increase or decrease in amplitude. [14]

When the RFID tags transmit data to the RFID reader, there are multiple options for modulation and data encoding. ASK can be used as with reader to tag communications, or phase shift keying (PSK) can be used. Phase shift keying works by changing the phase of the carrier signal. The RFID tags can use Miller Encoded Subcarrier (Miller ES) bit encoding or Bi-Phase Space encoding (FM0). These operate similarly by defining the value of a bit based on the number of transitions. Miller ES encodes a "1" bit as a transition followed by a transition back to the original state in the middle of a bit. For example, using ASK with a signal that is initially at high amplitude, a "1" would be encoded as a transition to low amplitude after a delay, and then a transition back to high amplitude after a delay. The “0” bit is more complicated in order to guarantee a minimum rate of transitions. A “0” after a “1” is encoded with no transition, while a “0” after another “0” would have an immediate transition followed by a transition back to the original state. See Figure 9 for what this looks like.

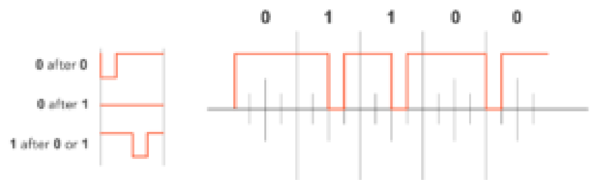

Figure 9: Miller ES Encoding. Taken from [14].

FM0 encoding is similar to Miller ES encoding, trades off simplicity for having more transitions per bit. It encodes a “0” with one transition at the start, and one in the middle, and a “1” with a transition at the the beginning only. See Figure 10 for what this looks like. [14]

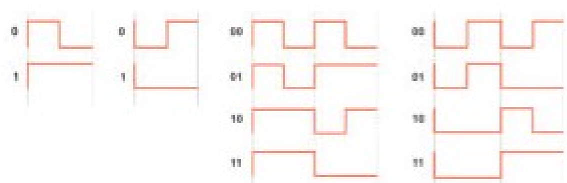

Figure 10: FM0 Encoding. Taken from [14].