2006-1950: A LABORATORY DEMONSTRATION OF SPATIAL ENCODING IN MRI

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A Laboratory Demonstration of Spatial Encoding in MRI

Abstract

The solution at hand describes a low-cost, small-scale MRI system which has been shown to demonstrate 1-dimensional spatial encoding. The main motivation for constructing the apparatus is its need for educational and demonstration purposes in biomedical engineering courses. The hardware and software is designed to be as simple as possible. A MATLAB program directly controls a microprocessor over a serial RS232 line. Our evaluation with four selected students revealed that they enjoyed completing the activity and they improved their understanding of some basic MRI concepts. Students reported that the system made the MRI concepts become visible and easy to comprehend.

1 Introduction

Magnetic Resonance Imaging (MRI) has not only become one of the most important diagnostic tools in medicine, but there are also MRI courses available at nearly all university biomedical engineering departments. The reasons for its widespread popularity are obvious. MRI is capable of producing high resolution images, see figure 1; this allows diagnosis of a large number of health problems and disorders such as tumors, abscesses, blood flow congestions, heart malfunctions and joint problems. For example, MR Angiography deals with the localization and imaging of blood vessels by observing signal amplitude changes and the resultant phase. Furthermore, there are fields other than medicine which benefit from MRI, such as psychology, in which MRI is used to study brain activity in different kinds of situations.

MRI not only provides high resolution images, but also provides significant advantages over alternative imaging modalities. A major advantage of MRI over X-ray and computerized tomography (CT) is that the patient is not exposed to ionizing radiation, which has been shown to have detrimental effects to the body. The underlying principle of MRI uses the presence of atomic spins, specifically those of ^1H protons. To obtain an image, the patient or sample is placed in a strong, highly uniform magnetic field. By applying a perpendicular magnetic field of lower magnitude, the magnetizations of the protons can be flipped. The velocity and phase shift of their following precession is used to determine the type of tissue. Since the physics and techniques used to generate images are not very intuitive, it is valuable to have an adequate means for teaching the theory and demonstrating the practical implementation of MRI. That was the main motivation to develop a small-scale MRI laboratory module. Furthermore, another potential usage for the appartus is for small-scale in vivo experiments, since cost and installation effort of such a system are significantly lower than in a hospital.

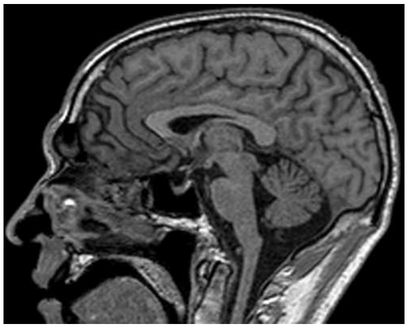

Figure 1: MRI Brain Scan

2 Previous Work

Others have developed desktop NMR and MRI systems for teaching or research use; however, these systems have a major drawback of significantly high cost, making them impractical for most university teaching laboratories. Wright et al. [4] developed a complete desktop MRI system with a 2.5 cm imaging region and 0.21 T field strength. The estimated cost of this system was 13,500 US dollars. Kirsch describes the electronic circuitry for demonstrating pulse NMR, including spin echo, although details of the magnet are not given. A commercial system is manufactured by TeachSpin Inc. for demonstrating pulsed NMR phenomena, with a list price of 13,850 US dollars.

3 MRI Technology

A single MRI spinecho experiment (figure 2) consists of a 90 degree RF pulse which makes the magnetizations flip. The concurrent application of a G_z gradient is needed to select a specific slice of the sample. The following G_y gradient field performs the phase encoding, meaning that due to the different magnetic field strengths at different positions along the y-axis, the precession frequencies are different and so the initial phase shifts. After $\frac{T_E}{2}$ seconds, a 180 degree RF pulse inverts the direction of the precessing magnetizations and ensures that they are brought together again. They had become out of phase because of the unavoidable inhomogeneity of the static magnetic field. The maximum signal strength is reached after another $\frac{T_E}{2}$ seconds. At that point of time the signal sampling starts and the A/D conversion takes place.

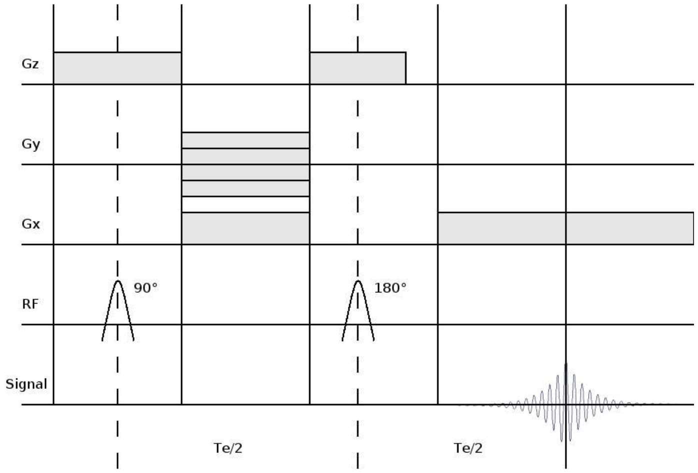

Figure 2: Spinecho Timing

4 Apparatus Hardware

4.1 Overview

Since the goal of this small-scale MRI system is to use it for demonstration and educational purposes, the hardware and software effort is kept to a minimum. A microprocessor controls the whole system, including the A/D conversion of the received signal. The PC interface facilitates ease of control via MATLAB. Figure 3 gives an overview of the different components.

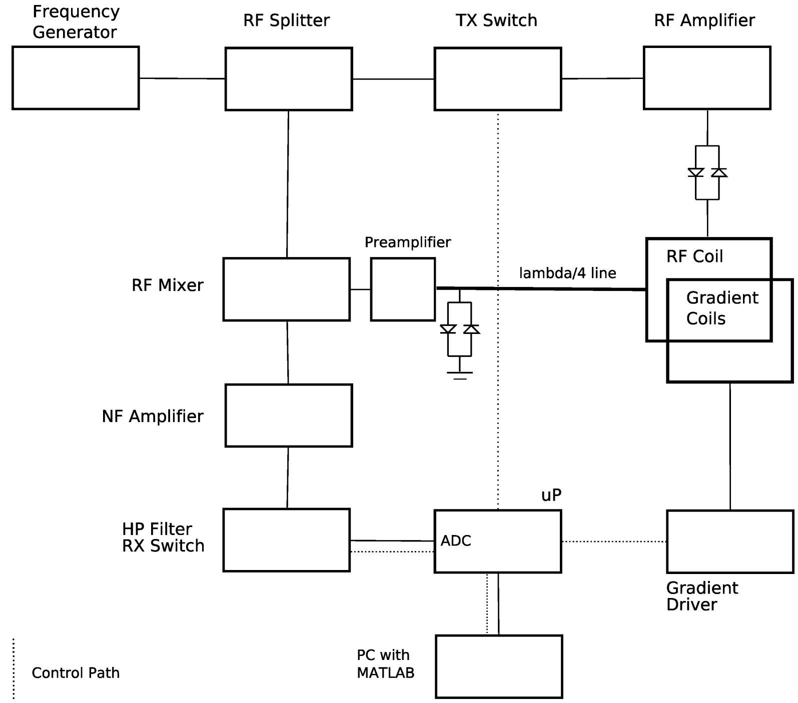

Figure 3: System Overview

The apparatus consists of the permanent magnetic field setup, the RF coil, the gradient coils, the RF circuitry, the microprocessor and power supplies. The FOV is a cube of approximately $1cm$ length wherein the permanent and the gradient magnetic fields are sufficiently homogeneous.

4.2 Magnet System

To reduce costs, a simple magnet system was developed which achieves a 0.08 T field with adequate uniformity over a $1cm^3$ volume. The field (in z-direction) originates in two 2x2x1 inch NdFeB permanent magnets having a field strength (on the 2x2 inch face) of approximately 0.6 T. The magnetic circuit uses a rectangular box made of 0.5 inch thick ASTM A-36 hot rolled steel, built using two 10 inch and two 6 inch plates, each 6 inches wide. The permanent magnets are affixed within the box opposite each other across the short dimension. On each magnet is placed a 5-inch round, 1-inch thick cylinder pole piece of hot-rolled 1018 steel, resulting in a 1.75 inch gap between the poles. In this arrangement many of the field lines originating at the permanent magnets are shunted directly around and wasted, but the field within the gap is highly uniform, particularly at the center. Small NdFeB magnets (3/8 inch square, 1/8 inch thick) are placed on the rears of the pole-piece cylinders to shim the field and attain the highest possible uniformity. Aluminum foil is used around the outside of the box for RF shielding to improve signal quality. The Larmor frequency (for protons) for this magnet system is 3.38 MHz. Figure 4 shows the permanent magnet system, the RF coil and the gradient coils.

4.3 Microprocessor

The heart of the apparatus is a 16-bit MSP430F169, which is an ultra-low power microprocessor from Texas Instruments. In addition to the pulse generation, it is also responsible for A/D conversion of the signal which is being received from the RF coil. Even though low power consumption is not of primary concern in this project, this microprocessor was chosen since its performance is sufficient for the system, and it is relatively simple to use. It allows programming in C, C++ or Assembler. The code used in this apparatus is written in C++. An evaluation board is available from TI which includes a JTAG port and the appropriate cable to connect it to the USB port of a computer. It has a flash program memory of 60 kB, a RAM size of 2048 bytes and 48 I/O pins. It includes a 12-bit SAR A/D converter and two 12-bit D/A converters. Furthermore, it allows the use of two SPI or UART channels for serial communication. It also provides two 16-bit timers and a watchdog. The maximum clock frequency is 8 MHz. The maximum A/D sampling frequency is around 150 kHz.

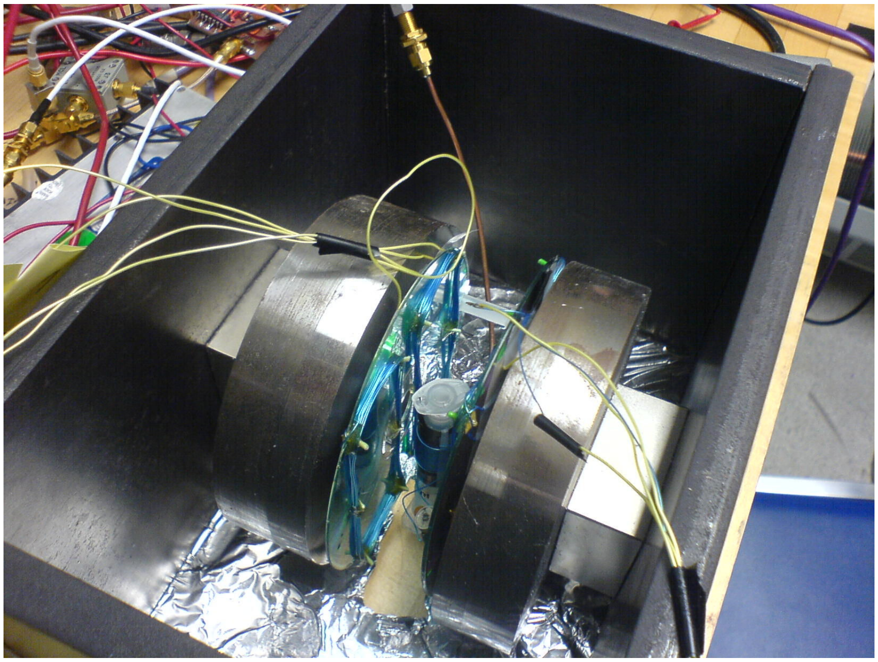

Figure 4: Magnet System

4.4 RF Electronics

The TX channel must be switchable in order to allow an application of TX pulses at specified points of time. The requirements for a switch are a high impedance when open and a good conductance when closed. The RF switch chosen in this project is a MSWA-2-20. Two HF amplifiers (class A) are used in series in the TX path, a 30 dB Avantek amplifier with 1 W output and a 10 dB Hexfet amplifier which raises the TX power to approximately 10 W. The RX channel, on the other hand, needs to amplify the received weak signal from the coil to an appropriate level for further signal processing. This is done by using an Avantek preamplifier (50 dB gain, 3.5 dB noise figure). Since the same antenna, the RF coil, is used both for transmitting and receiving, a mechanism is needed to prevent the TX signal from reaching the RX electronics. The measures to do so are two pairs of crossed diodes, a $\lambda/4$ line and a switch in the RX filter network. The characteristic of the crossed diodes in figure 5 is shown in figure 6 [2]. According to equation 1 the $\lambda/4$ line yields a high input impedance in the case of transmitting since Z_{out}, the crossed diodes, is small.

$$Z_{in} = \frac{|Z|^2}{Z_{out}} \tag{1}$$

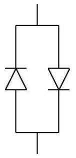

Figure 5: Crossed Diodes

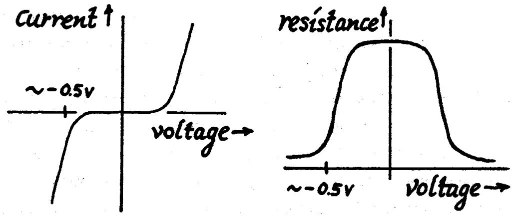

Figure 6: Crossed Diodes Characteristic

After the amplification of the RX signal, a filter and switching network prepares the signal before it reaches the A/D converter. A CD4066AE chip makes sure that the channel is only open during the readout phase and closed otherwise. The high pass filter flattens the signal. The circuit is shown in figure 7. When the switch is closed no signal gets to the A/D converter. During RX phase the switch is open and the high pass filter with the 1.5nF capacitor and the 1MΩ resistor is used to get frequencies above the corner frequency of $\approx 100Hz$ only. The two resistors after the standard operational amplifer add a constant DC voltage to the signal not to confront the A/D converter with a negative voltage input.

4.5 RF Coil

The RF coil fulfils two tasks, the generation of the magnetic field perpendicular to the permanent field and the receiving of the weak signal from the precessing magnetizations. The applied magnetic field causes the magnetizations of the ^1H

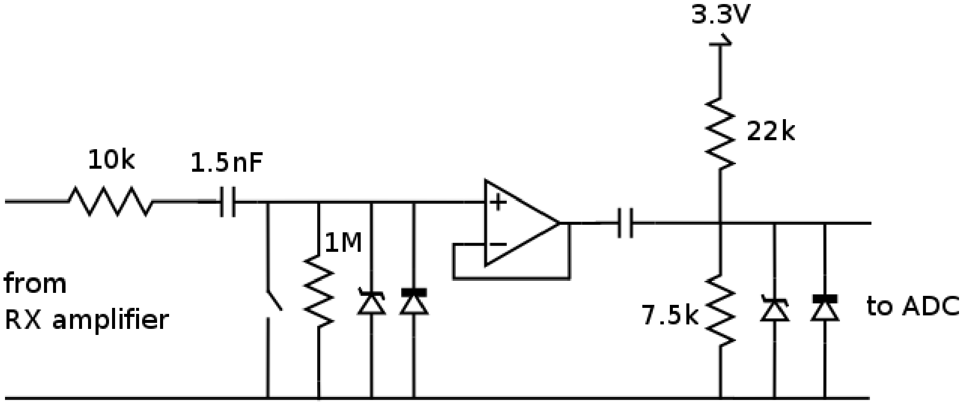

Figure 7: RX Circuit

protons to flip. The flip angle depends on the length of the pulse and its amplitude. With a RF power of 10 W the pulse length has to be around $7\mu s$ for the 90 degree pulse. The quality factor of the coil must be high enough in order to achieve a reasonable SNR. The quality factor is

$$Q = \frac{\omega L}{R} = \frac{2\pi f L}{R} \tag{2}$$

It is therefore important to keep the inductance L high enough.

$$L = \frac{n^2 a^2}{23a + 25b} \tag{3}$$

where a is the coil diameter (cm), b the length (cm) and n the number of turns. The coil used in this system is a two-layer 60 turn coil which tightly encloses the sample volume in order to minimize generated noise. The matching network is depicted in figure 8.

4.6 Gradient Coil System

The goal of using gradient coils is to establish a magnetic field gradient along the three axes. These fields are used in addition to the permanent magnetic field and allow a spatial encoding since the Larmor frequency depends on the magnetic field strength and so on the position in this case. The x-, y- and z-gradient fields are all in the direction of the permanent field which is the z-axis, but they vary

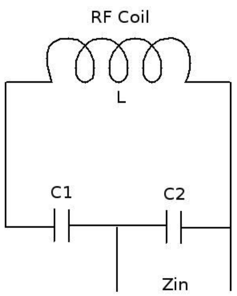

Figure 8: Matching Network

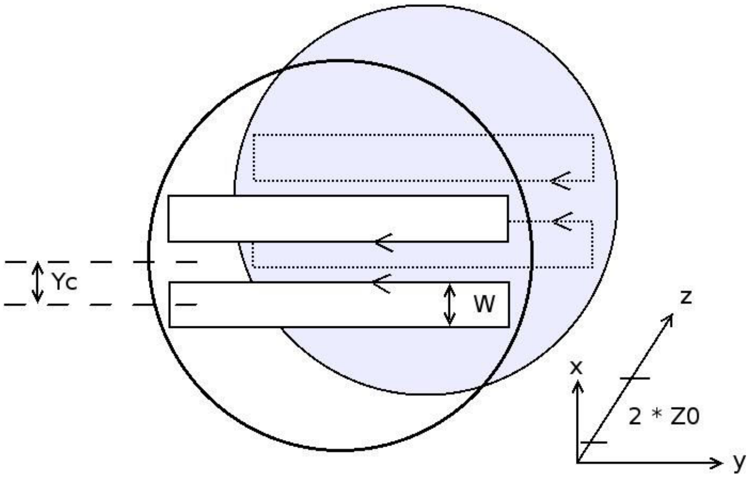

Figure 9: x-Gradient Coils

with either the x-, y- or z-coordinate. For the z-gradient, a Maxwell coil pair can be used. For the other two axes, either saddle coils or rectangular coil pairs are used. This system currently uses a 1-dimensional encoding in the x-direction with rectangular coil pairs as shown in figure 9. The distance between the two plates in the z-direction is $2 * z_0 = 4cm$. By choosing the values such as $W/z_0 = 1.55$ and $Y_c = 1.19 * z_0$, the largest possible gradient is achieved. To add a second dimension of encoding (the y-gradient), another set of similar coils can be used again, just rotated by 90 degrees. The strength of the gradient is

$$G_x \approx 0.46 \frac{\mu_0 i N}{{z_0}^2} \frac{Tesla}{m} \tag{4}$$

where i is the current flowing through the coils, N is the number of turns ($N = 10$ in this case) and z_0 is half of the distance between the two planes. The gradient coil driving circuit is found in figure 10. It shows the use of a high current operational amplifier, the Burr-Brown OPA541 which is capable of driving a 10 A peak current. The microprocessor's output is used as control input to the OPA541's negative input after adjusting its voltage level. The $0.1\ \Omega$ resistor mainly determines the ratio between input voltage and output current, so $I_{out} \approx \frac{V_{in}}{R_{out}}$. The gradient coils are connected in series in order to achieve a sufficiently high current for the gradient field. For ease of construction the gradient coils are mounted on Compact Discs.

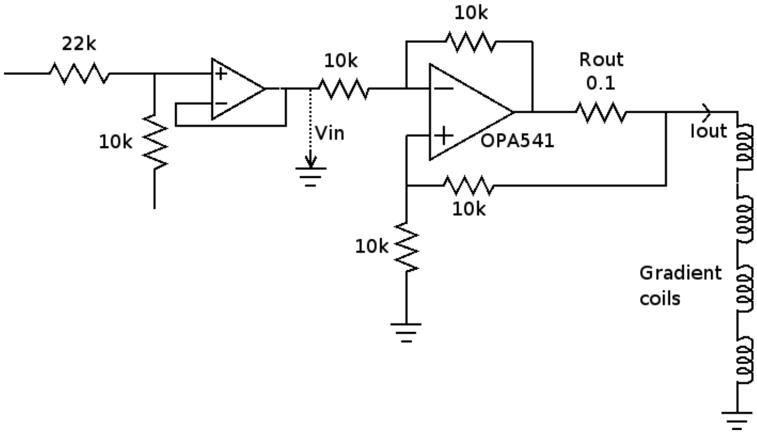

Figure 10: Gradient Driving Circuit

5 Apparatus Software

5.1 Overview

The software consists of two parts. The first one is the code on the microprocessor which receives the timing parameters from MATLAB, generates the pulses and performs the A/D conversion of the received signal. The second part is the MATLAB code which sends the timing parameters to the microprocessor and does the signal processing on the received data, including the FFT.

5.2 Microprocessor

Texas Instruments includes a limited version of IAR Embedded Systems with their MSP evaluation board. This software facilitates generation of code, which may then be downloaded to the flash memory of the microprocessor. The only constraint is the limited maximum size of downloadable code; however, this limit was not reached in this project. An on-chip debugging function is also given. The written C++ code is an interrupt driven event system. Interrupts either arise from signals on the RS232 line from the PC or from internal timers when the next step in the flow of an MRI experiment should occur. Figure 2 shows the timing of a spin echo experiment.

5.3 MATLAB

Over the serial interface the timing parameters like T_E, T_R, the length of the pulses and the number of cycles are being transferred to the microprocessor. Specific signals start and stop the MRI experiments. The data which is transferred back from the microprocessor to MATLAB is already averaged over a number of cycles, typically 10. MATLAB normalizes the data and performs the FFT. In the 1-dimensional case using only one gradient, the frequency space contains peaks whose frequencies correspond to different positions within the sample area along the gradient axis.

6 Results

For the experiments a sampling frequency of around 97 kHz was used which is high enough to cover the whole bandwidth. Figure 11 shows a shift of the peak in the frequency domain when the sample liquid (gylcerine) is moved from one end of the gradient field to the other. This clearly shows the spatial encoding in one dimension. The current through the gradient coils is about 3 A which results in a gradient strength of $\approx 420\mu T/m$. This corresponds to a spatial resolution of about 1 mm.

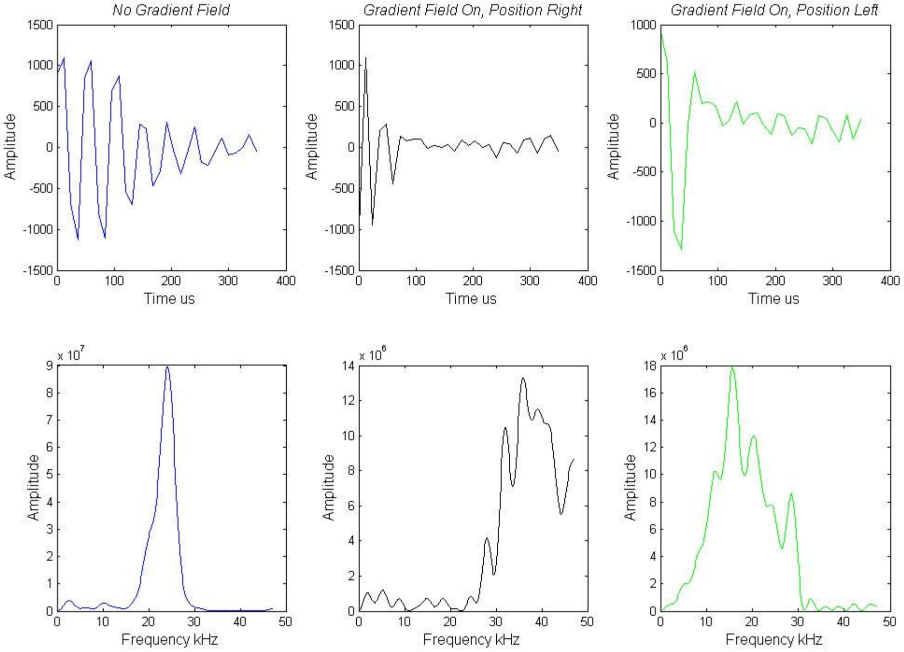

Figure 11: Different Sample Positions

Another experiment shows how the frequency domain peaks become wider when the gradient strength is enlarged. Figure 12 shows this phenomenon. The first image is an experiment without gradients. The second one comes from a high gradient where the third one is the result of applying a low gradient.

7 Student Evaluation

In this section, we discuss the effectiveness of this MRI setup as an education tool for university students.

7.1 Study Purpose

The purpose of this evaluation was twofold. First was to assess students' conceptual understanding about the selected MRI concepts and capture the extent to

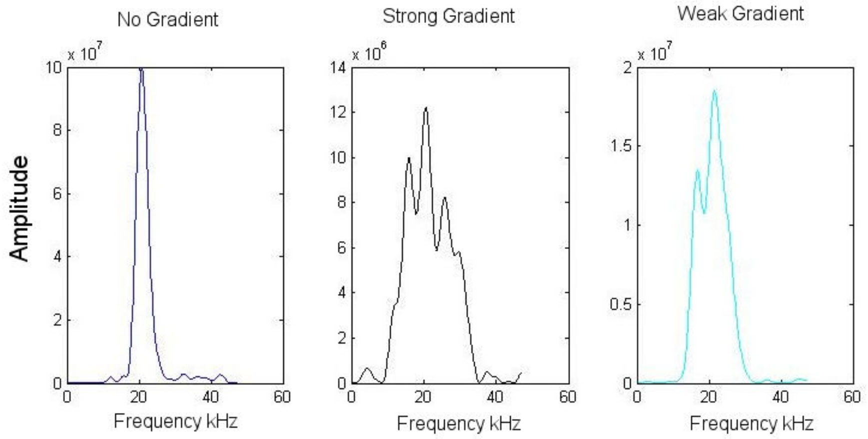

Figure 12: Different Gradient Strengths

which the MRI setup activities help students improve their understanding. Second was to explore the students' experiences with the MRI setup.

7.2 Methods of Inquiry

7.2.1 Participants

In order to explore the effectiveness of the MRI experimental setup, we worked with four university students who volunteered to participate in this student evaluation. Two of these students were undergraduates (both were male) and two were graduate students (both were female). We purposely chose the students as graduate and undergraduate [13] because we wanted to capture whether students' grades have an impact on their self-reported experiences as well on their conceptual understanding of the MRI concepts. At the time this evaluation took place, Matt and Eden (both pseudonyms), the two undergraduate students, were in their senior years in Biomedical Engineering department at a Midwest Research 1 University. Mary (a pseudonym) was a M.S. student and Terry (a pseudonym) was a Ph.D. student, both in Biomedical Engineering at the same university.

7.2.2 Design

Students participated in a pre-interview, an experiment session including both theoretical and practical parts, and a post-interview. The interviews lasted around 20 to 30 minutes per student, and all were audio-recorded. The experiment session lasted around one hour. Students completed the interviews and the experiment within one and a half hours. Students from the same levels grouped into two, and they performed the experiment together. Two of our research team members interviewed the students one-on-one before and after the experiment sessions. We followed the Institutional Review Board (IRB) regulations in recruiting participants and collecting data. We asked students to review the IRB approved consent forms and sign their consent before we began the interviews. Students were not compensated for the participation in this evaluation.

7.2.3 Context

The unguided theoretical tasks made the students familiar with the basics of MRI whereas the guided practical part helped them to visualize the basic MRI concepts. The practical part consisted of the following three steps: (1) setting the timing parameters in MATLAB, (2) adjusting the Larmor frequency and (3) observing the signals in time and frequency domains of MRI experiments with and without a magnetic gradient (only 1-dimensional encoding). When a magnetic gradient field was present, it was shown that placing the sample at different positions along the encoded axis resulted in peaks at different frequencies in the spectrum. Furthermore, a broadening of the peak in the spectrum could be observed by increasing the gradient strength.

7.2.4 Instruments

To capture the students' conceptual understanding and their experiences with the setup activities, the research team designed a pre- and a post-interview protocol, see appendix A. We designed the interview protocol semi-structured, that is, the interview questions mostly guided the conversations; however, the discussions were left open-ended and directed by the interviewees' responses to the protocol items [14]. At the conversations, interviewers asked emerging questions as they provided a richer context to explore the students' perspectives.

7.2.5 Analysis

The audio-recorded interviews were transcribed, and the transcripts were analyzed utilizing the constant comparative method [12]. Three members of our research team analyzed the transcribed verbatim individually. In the analysis, the common themes were coded, and categories were crafted. Within and across case analyses were performed. The research team met a few times to discuss the analysis and to write the study report. In the next section, we present the findings as an ongoing discussion that is a characteristic of a discussional theory building strategy [12].

7.3 Findings

7.3.1 Students' Pre-conceptions about the MRI Concepts

To explore the students' preconceptions about the MRI topics, we asked them to define the following concepts in their own words: ”spin echo”, ”spatial encoding”, and ”the Larmor frequency” (See appendix A for details).

The two graduate students (Terry and Mary) and one undergraduate student (Eden) described the ”spin echo” accurately in the pre-interview. Matt, an undergraduate student, described it as ”image recording” which was an inaccurate description. Matt said:

> Spin echo? Let's see, whenever the space is equal, it is zero. That's when you actually get an echo when you're trying to record images from magnet to magnet, like, spin echo is caused by magnetic field inhomogeneity, while the gradient is caused by the gradient fields that you're phase encoding. (Matt, 2006, pre-interview)

When they were asked, Terry, Mary and Eden portrayed a partial understanding of spatial encoding. For example, Mary told us that the spatial encoding is accomplished through:

> By having different gradients in x and y directions different points in the sample have different frequencies, are seen as frequencies. Well, because there are a lot more frequencies, it's different for different points now. (Mary, 2006, pre-interview)

Eden, an undergraduate student, defined the spatial encoding incorrectly. He said:

> Well the spatial encoding comes from the reverse transform of the frequency encoding, which is what you observe, or the data you get directly from the scanner. So they are related by the Fourier transform. (Eden, 2006, pre-interview)

Mary, Terry and Eden explained the ”Larmor frequency” accurately. Matt, an undergraduate student, portrayed the Larmor frequency as the concept of a rotating frame. He said:

> The rotating frame is at the Larmor frequency, you actually don’t see it. If you do all your calculations in the rotating frame you don’t have to worry about the resonance as much, so you have just a precession and you don’t have to worry about the rotation at that frequency, the Larmor frequency. That helps us to simplify calculations. (Matt, 2006, pre-interview)

To elicit students’ prerequisite knowledge before the experiment and to prepare them for the practical part, three more questions were asked in this regard before the experiment only. They were tailored to the subsequent practical experiments and covered the students’ expectations on how the signals in time and frequency domain will look like in different situations. These situations were experiments without a gradient field, with a gradient field placing the sample at different positions along the encoded axis and experiments with a varying gradient strength. Seven out of a total of twelve (58%) answers given before the experiment were wrong, four partially correct (33%) and one correct (9%). This finding shows a need of further educational measures to teach MRI concepts.

7.3.2 Students’ Post-conceptions about the MRI Concepts

After the students completed the MRI setup activities, we asked the same conceptual questions once again. All students described the ”spin echo” accurately. Matt, who had explained the spin echo concept incorrectly in the pre-interview, explained it almost correctly in the post-interview. He maintained that the spin echo was created because of the ”90 degree pulse and then a 180 degree pulse”. He said:

> We can use the spin echo to get a signal and form an image. You would apply the 90 degree pulse and then the 180 degree pulse would flip it and so all the inhomogeneities would be reversed. So, when you reverse precessions, you get the signal. (Matt, 2006, post-interview)

In the post-interview, all four students described the spatial encoding accurately with thorough explanations. For example, Mary, who had partially described the spatial encoding in the pre-interview, was more specific after the experiment:

> It [spatial encoding] is accomplished by using coils that apply an additional field it changes the frequency. There are more frequencies, so there is a difference among the points in the sample. (Mary, 2006, post interview)

All four students portrayed the ”Larmor Frequency” correctly in the post-interview. Matt, who explained it incorrectly in the pre-interview, answered it correctly, although not very specifically, by saying ”That’s the frequency of the resonating system”.

To sum up, eleven out of the twelve (92%) given answers after the experiment were correct and one (8%) was partially correct. This is a clear improvement to before the experiment where only seven out of the twelve (58%) answers were correct.

7.3.3 Students’ Experiences

All student participants expressed appreciation that the entire setup made the MRI concepts visible. For example, Terry, a graduate student, said that seeing the graphical representation of what happens to the signal as the x-gradient increases was ”neat”:

> I like how you can actually see graphically what happens to the signal as the x-gradient increases. For example, the FID decays much faster when the x-gradient is higher. So, these kinds of concepts were more understandable. (Terry, 2006, post-interview)

Eden, a graduate student, told us that ”the most valuable part was the demonstration of how it all works”.

When they were asked, students responded that some basic knowledge of MRI would be needed for anyone to complete the activity. The two undergraduate students, Matt and Eden, mentioned that the basic terminology should be known prior to the activity. For example, Matt said:

> I think if there was a little more theory in the introduction, a better explanation of some of the questions that you asked, it would be helpful. So I think maybe presenting the common misconceptions or the common vocabulary, even just definitions, might help. (Matt, 2006, post-interview)

Matt suggested that an introduction of the basic MRI concepts would help anyone in completing the activity. He said discussing more of the basic physics behind MRI would help before the experiment. The two graduate students, Terry and Mary, talked about the two-dimensional encoding and they suggested that it should be thoroughly integrated in this activity (which is underway). Other suggestions referred to the experimental setup. Students wanted to see more user-friendly instruments. For example, Mary said:

> If it is going to be used with a higher number of students, maybe having a user interface module, where they can press buttons and enter values, would make it more user-friendly. (Mary, 2006, post-interview)

To improve this activity, Eden recommended adding information that describes the connections between the demonstration and the medical use of MRI. Terry suggested to split the activity into two parts, one to focus on each instrument separately and the other one to focus on the entire MRI demonstration as a whole.

7.4 Discussion

Before the MRI setup activities, not all the students' responses to the conceptual questions were correct. Some students had misunderstandings about the basic MRI concepts. After the setup activities, students described the same concepts almost completely accurately with their scientific counterparts.

In our analysis, we observed that the graduate students had a better understanding of the concepts before the experiment than the undergraduate students. Another difference we observed was on the degree to which students gave importance to prerequisite knowledge. Undergraduate students explicitly addressed that having prerequisite knowledge would be helpful. Graduate students did not state this argument as strongly as the undergraduate students. One reason that graduate students did not mention prerequisite knowledge much could be graduate students have more expertise in MRI concepts than the undergraduates.

Our data revealed that students enjoyed performing this activity. An asset of this experimental setup was to make the MRI concepts more visible to students. Students were able to visualize the MRI concepts in graphs and in real time situations.

The setup has some limitations because of the instruments it involves. Students might have had difficulties comprehending the entire structure of the system due to the number of apparatus connected. As how students reported in the post-interview, it will be beneficial to simply the instrumental setup so that the entire system will become more user-friendly for the students.

8 Conclusion

The setup presents a 1-dimensional spatial encoding with minimal hardware and software effort. The spin echo experiment produces an adequate result and represents a promising basis for further developments. It is shown that moving the sample along the encoded axis produces peaks at different positions in the frequency domain of the fourier-transformed received RF coil signal. Future work will involve a 2-dimensional readout where a second gradient system produces a y-gradient which allows an initial phase encoding. If the signal is strong enough, a Maxwell coil pair for the third dimension will be used to perform the slice selection. There might be some effort needed to make the signal stronger and the magnetic field even more homogeneous to be able to acquire slice images. Whereas the evaluation of the system involving students showed that they liked completing the activity and could improve their understanding of MRI, it would be helpful for educational purposes to design an appropriate user interface which allows the students to work more independently.

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A Interview Protocol

Note to the interviewer: Please be sure that you ask the interviewees to respond to the questions below which are numbered and marked bold. The starting questions are recommended. The alternative questions are not necessarily being posed, if the interviewee explains her response in detail, you can skip those alternative questions. You are welcome to ask emerging questions that you think they help us explore participants' conceptions. The aim is to explore the students' conceptions and the reason we list the questions below is to guide the conversations you will be recording.

A.1 Pre-Interview

Research question: What are the participants' conceptions about the selected MRI topics?

Note to the interviewer: Be sure that the interviewee signs the consent form before you start recording the conversation. Also before recording, ask the interviewee if he or she is comfortable and if the room temperature, noise, humidity or the light are bothering her. Even though she may not seem uncomfortable, asking those questions will relax the environment and ease the conversation.

Note to the interviewer: After you start recording, please also ask the interviewee the two starting questions below, just to smooth the environment. We will not be using them in our analysis, but for both parties (interviewee and interviewer) asking a few starting questions will warm up the conversation.

(a) Starting question: What is your major field of study?
(b) Starting question: What are your plans after graduation?

(1) **What is a spin echo?** Could you describe me your understanding about spin echo in your own words? Alternative questions: Where do we use it? What causes spin echo?
(2) What is spatial encoding? **How is spatial encoding accomplished in MRI?** Alternative questions: Where do we use it? What causes spatial encoding?
(3) **What is the "Larmor frequency"?** Alternative questions: Where do we use it? Why do we need to know it? What does the Larmor frequency depend on? Why is it important?

(4) Assume we have an imaging sample of only one material and we have no gradients switched on. **What do you expect the time signal and the frequency spectrum to look like?**
(5) Assume we have an imaging sample of only one material and we switch the one-dimensional encoding on (x-gradient). **What do you expect to happen when the sample is being moved along the encoding axis?**
(6) **What do you expect to happen in the frequency domain when the x-gradient is increased/decreased?**

After these introductory questions the student will be given the experiment paper (including theory and the tasks to solve). The first three tasks are of theoretical nature and help to become familiar with the topic of MRI.

A.2 Post-Interview

Research questions: What are the participants' conceptions about the selected MRI topics? What are the participants' experiences with the MRI experiment?

A.2.1 Part 1

Note to the interviewer: Tell the interviewee that you will ask again some of the questions you asked before the experiment to see if her or his understanding has changed.

(1) **What is a spin echo?** Could you describe me your understanding about spin echo in your own words? Alternative questions: Where do we use it? What causes spin echo?
(2) What is spatial encoding? **How is spatial encoding accomplished in MRI?** Alternative questions: Where do we use it? What causes spatial encoding?
(3) **What is the ”Larmor frequency”?** Alternative questions: Where do we use it? Why do we need to know it? What does the Larmor frequency depend on? Why is it important?

A.2.2 Part 2

Note to the interviewer: Tell the interviewee that you have a few more questions and that her or his answers will help us to improve this experiment.

(4) **What are the other concepts that you think this experiment might have helped you to understand better?**
(5) **What did you like most in this experiment? Why?**
(6) **What did you like least in this experiment? Why?**
(7) **Would you suggest your peers to do the same activity? Why, why not?**
(8) **How could we improve this activity? What would be your suggestions to make it more effective?** Alternative question: What would you like to do differently in this activity?

Note to the interviewer: Tell the interviewee that your questions are up to here but that you would like to know what the other things are that he or she would like to tell us about the experiment, the instruments, or his or her overall experience about today's session. Thank him or her for participation and that we appreciated it.

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