fMRI COIL BUILDING AND QUANTIFICATION

By

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ABSTRACT:
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This work focused on research conducted in the Biophysics Department at the Medical College of Wisconsin, where tools and techniques for functional Magnetic Resonance Imaging (fMRI) were studied. Various tribulations took place to understand the fundamentals and concepts in fMRI. In fMRI, there are many components to take into consideration and the ones studied in this research were transmit and receive coils. In the study, a receive coil was simulated, designed and created to obtain the signal response for a site-specific area of a brain, primary somatosensory cortex, forelimb region. Bench testing and images from scans with a Sprague-Dawley rat provided information to determine whether the coil was successfully functioning as a receive coil. The scans were conducted on a Bruker Biospec 9.4 T (Tesla) Scanner. In order to function properly, the coil was required to resonate at 400 MHz due to the 9.4 T Scanner used in the study. When changes were needed, components on the board were adjusted with different values to modify the variations in the coil resonance.

After scans were completed, calculations for the signal-to-noise ratio (SNR) were completed on the eight and fifteenth slice of each scan. The signal-to-noise ratio provided a way to analyze the image for signal intensity and clarity of the site-specific region. The image dataset obtained from the Bruker scanner was used in Matlab as a means to reconstruct the images and also yield an SNR value for each slice. These SNR values were then compared to the Bruker ParaVision values. The comparison found that the values were similar at various slices but slightly different at other slices. Reasons yielding the difference were the appearance of the area of interest differing through slices. Future work is planned to further validate the SNR values for example, using Analysis of Functional NeuroImages (AFNI). Furthermore, the coil designed in the study will also be used to build future coils that can provide even further site-specific areas of interest with greater SNR values.

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PROBLEM STATEMENT:

This work focuses on research at the Department of Biophysics at the Medical College of Wisconsin where tools and techniques for Functional Magnetic Resonance Imaging (fMRI) were studied. The opportunity to work with Phillip Bishop with guidance from Dr. Rowe provided the ability to understand the fundamentals and challenges of MRI rf coil development. A surface coil was designed; simulated, built, and tested both on the bench and images acquired with a Sprague-Dawley rat.

Two types of coils are used in the Bruker Biospec 9.4 Tesla(T) animal scanner: transmit and receive. (The transmit coil generates electromagnetic fields, while the receive coil works as an electromagnetic field detector.) In order to detect the electromagnetic fields the frequency of the receive coil needs to be associated to the static magnetic field strength of the scanner, in this case, a frequency of 400 MHz. If the coil is not tuned to the correct frequency no signal is detected. Transmit coils were not investigated as part of this research.

Surface coils are designed to enhance the resolution at specific areas of the rat. This work at MCW focuses on the rat brain. A surface coil has a higher sensitivity in the region of interest then a whole volume coil. In this project, we focused on a specific site in the rat brain. Additionally, pulse sequences were used to detect functional signals corresponding to physical stimulations. These special areas correlate to the functional aspect of MRI, where physical stimulation can be detected as signals in the brain and overlayed on an anatomical image. The availability of commercial site-specific coils is limited. This constrains the type of brain research that can be conducted. As site-specific research has become more important, the need for specialty coils has greatly increased.

A site-specific coil was developed to address this concern. During development, images are acquired and the signal-to-noise ratio (SNR) is characterized in the region of interest.

Image processing tools such as Analysis of Functional NeuroImages (AFNI) and Bruker ParaVision provide convenient ways to analyze image data. However, these tools do not provide an automated statistical analysis over a number of slices simultaneously. An alternative option, Matlab, provides the ability to automate image reconstruction and statistical analysis. This automated process will ultimately allow researchers to run the program from the convenience of their workstation with a previously acquired dataset. The output from the program will be the scan images with the necessary statistical information. The importance for this research is to analyze the SNR at any region of the brain or enhance quantitative coil development. The SNR value corresponds to the signal intensity in the area of interest. The greater the SNR, the more optimized and sensitive image is reconstructed. If the SNR meets a certain threshold, it can be concluded that the fMRI signal detection was successful.

Another concern in coil design is coverage area. If the area of sensitivity is much greater than the area of interest, the coil is not optimal for this scan. A more site-specific coil that provides coverage of the area of interest would need to be designed. On the other hand, a coil that doesn't properly cover the entire region of interest is of no use. Figure 1 shows a cross-sectional representation of the anatomical structure of the rat brain. The area of the brain labeled as S1FL is the forelimb region of the primary somatosensory cortex. A coil was designed to image a cylindrical area inside this region with a length of 2 mm and a diameter of 2 mm.

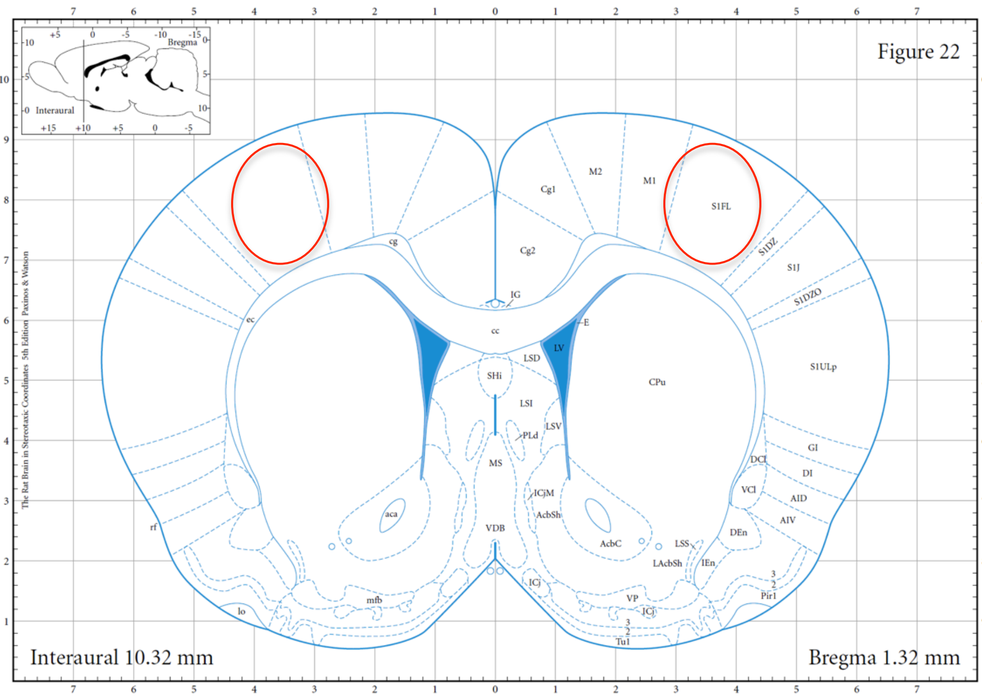

Figure 1: Anatomical structure slice of rat brain at Bregma 1.32mm, area of interest labeled as S1FL[1]

BACKGROUND:

It is desired to precisely simulate and design a surface coil that is able to obtain optimal information for the S1FL area of interest. The goal is to create a coil to be placed directly above the S1FL region; however, the coil tested in this research was only used above the center of brain. This was primarily tested to see if the site-specific area could be imaged.

As mentioned in Gareis et. al paper, *Mouse MRI using phased-array coils,* the implementation of phased-array allows an efficient approach to increasing the signal-to-noise ratio (SNR) in a functional magnetic resonance imaging scan.[2] This increase is due to having more centralized coils that are decoupled from the each other, providing a greater signal. Otherwise a standard single coil may provide a smaller SNR leading to

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1 (Paxinos and Watson 2005)
2 (Gareis 2007)

unusable results. This research serves as the basis for an array of coils that will allow imaging both the left and right S1FL regions.

Several sources exemplify the importance of the design of the coil with accurate size and orientation for sensitivity measurements. Boskamp mentions, “Sensitivity measurements are the most important component to the reception process. Large coils have much lower sensitivity than small ones. If one takes a small coil and uses it in a single-coil transmit-receive mode, the useful field of view is a relatively small part of the active coil volume because of the excitation non-uniformity.”[3] Boskamp further illustrates, “The applications of surface coils in MRI present a powerful method in spatial resolution of various anatomical regions.”[4] As Boskamp studies show there is a tremendous difference in the intensities with sensitivity and SNR measurements between surface coil and volume coil reception, resulting in a desire to create smaller surface coils that provide optimum sensitivity for a specific region.

Other papers also demonstrate the significance of specialized animal coils. The motivation for this work is to further develop site-specific coils development due to the importance of increasing SNR to attain the highest resolution images.

COIL CONSTRUCTION:

The goal was to create a copper alloy 101 coil that was thin, small and duplicable on the left and right side of brain. The design is a simple circular loop with 5 mm inner diameter, 6 mm outer diameter and a height of 2 mm. The circular copper loop was connected to the circuit board that held the necessary components: diodes, inductors,

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[3] (Boskamp 1985)
[4] (Boskamp 1985)

capacitors, resistors, and a low noise amplifier (LNA). The conductor thickness is 0.5 mm, with a height of 2 mm and a gap 0.381 mm wide. Initial values for components can be seen in the table below.

Type	Name	Value
Capacitor	Coil (C_c)	17 pF
	Trimmer (C_c)	0.25-0.7 pF
	Match (C_M)	22 pF
	Balance (C_B)	47 pF
	Out (C_O)	100 pF
Resistor	Detune	100 ohm

Table 1: Circuit board component values

The design tools used in simulation were: Ansys High Frequency Structure Simulator (HFSS), Ansys Designer, and AutoDesk Inventor. HFSS provides the ability to accurately design high-frequency components such as antennas, RF/microwave components and biomedical devices.[5] HFSS provided electromagnetic fields simulation on the coil structure. This allowed the appropriate capacitor to be chosen to achieve the correct resonant frequency. The coil was simulated in HFSS EigenMode to predict capacitor values. ANSYS Designer provided the ability to predict component values for the board. AutoDesk Inventor was primarily used for the mechanical design and simulation. For example, the case that housed the board and coil was designed in Inventor. This case was designed to securely fit the board and expose the coil without causing any issues with scanning.

[5] (Ansys HFSS n.d.)

Figure 2 below shows the diagram of the coil along with all components. The wiring between components has been omitted.

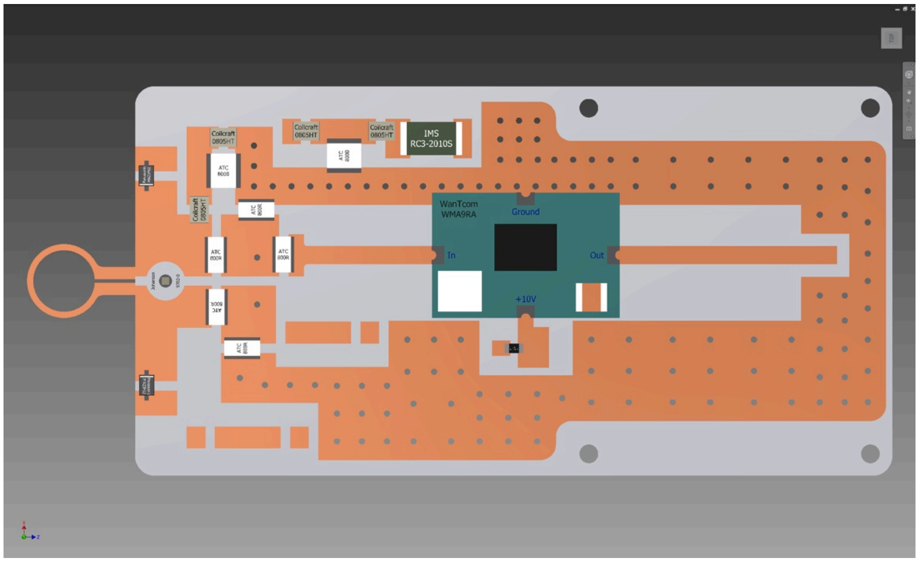


Figure 2: Top view of circuit board design with coil placed on board, with exposed capacitors, diodes and LNA

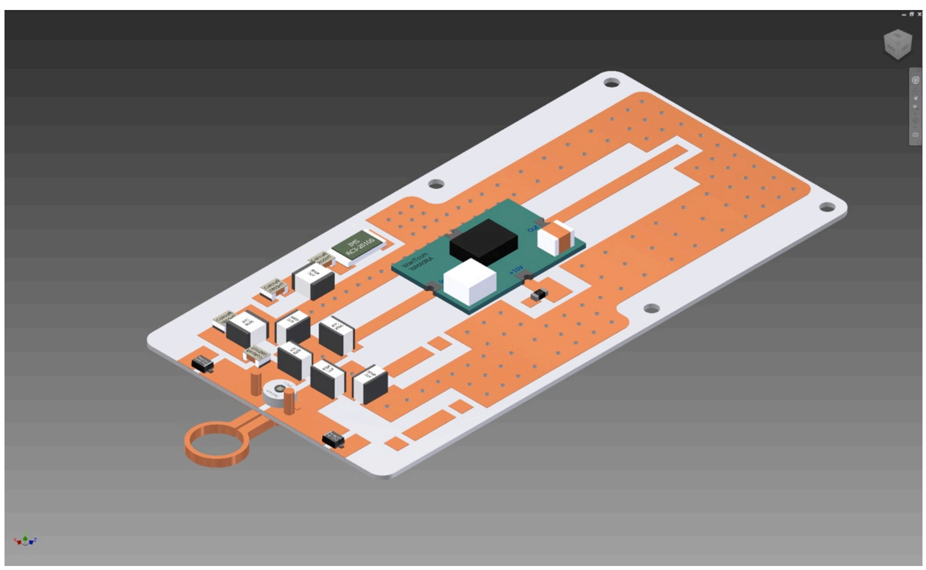


Figure 3: Front side view of circuit design with coil placed on board, with exposed capacitors, diodes and LNA

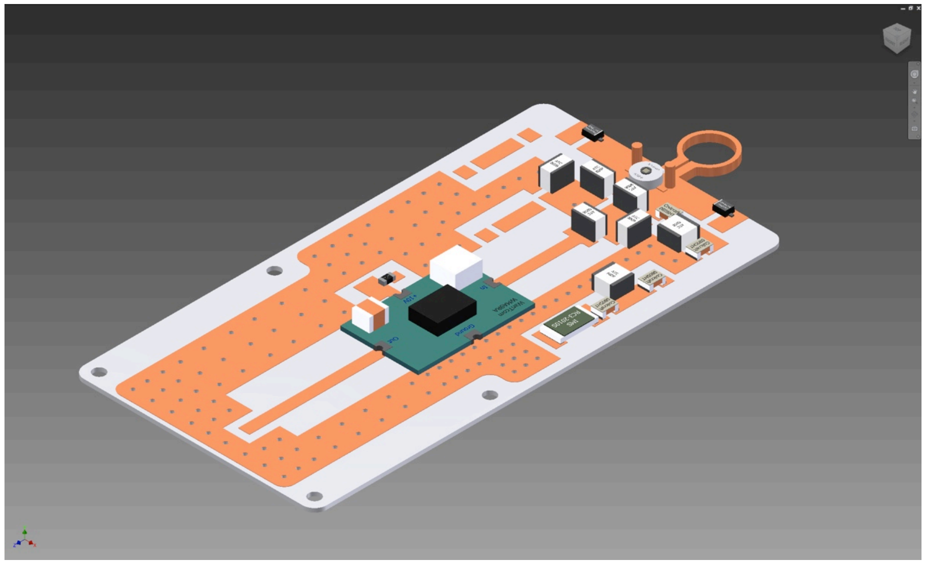


Figure 4: Backside view of circuit design with coil placed on board, with exposed capacitors, diodes and LNA

The circuit board was laid out in AutoDesk Inventor for precise component placement. It was etched by Streamline Circuits (Santa Clara, CA). The board was etched for proper placement of components. An open-bottom fiberglass G10 case was used to secure the board and expose the coil; the case was a similar case as used in prior coil designs. The coil was wrapped in a number of layers of Teflon tape to prevent the coil itself from coming in contact with the rat.

TESTING:

The 9.4 T scanner yields to a 400 MHz resonance frequency due to Hydrogen atoms that align with the Bruker magnetic field and with the transmit coil. The transmit coil, B_1, provides the Hydrogen atoms to be rotated a certain number of degrees. These atoms want to then return to equilibrium. This torque in the atoms to return to equilibrium in the magnetic field of the scanner is returned at a certain frequency called the Larmor frequency. This phenomenon takes place as the transmit coil is removed. As there no longer is a magnetic field for this alignment, the Hydrogen atoms return to equilibrium. In order to achieve equilibrium, a release in energy is needed with the atoms in the 9.4 T scanner where 1 T yields 42.546 MHz. This shows that the frequency for equilibrium in the 9.4 T is approximately 400 MHz. Hence, the coil needs to resonate at precisely 400 MHz to receive the signal in this scanner.

The bench of the coil was tested on a vector network analyzer (VNA) using loop coupling. The low-noise amplifier (LNA) that is seen in figures 2, 3, and 4 is the green icon. Once bench and rat scans presented frequency values that the coil was resonating at 400 MHz it could be said that the coil was working, the LNA component was placed on the board. The LNA served the purpose of increasing the SNR.

Table 2 shows the results for the coil tested on a bench in free space where the coil was attached directly to the board with all components placed and cables attached. LNA was not attached in the S_{11} signal is used to measure the radiating frequency of a coil. The S_{11} measurement is defined as a single cable transmitting a signal and the same single cable receiving the signal that is reflected by the coil. The reference Microwaves101 explains the S parameters as "S11 refers to the ratio of signal that reflects from port one for a signal incident on port one. Parameters along the diagonal of the S-matrix are referred to as reflection coefficients because they only refer to what happens at a single port, while off-diagonal S-parameters are referred to as transmission coefficients, because they refer to what happens from one port to another."[6] The network analyzer shows where the coil radiates the signal by a dip at the frequency, f_c. The dip is

[6] (Microwaves101 2009)

the frequency centered (f_c) and the frequencies to the left and right are the lower (f_L) and upper (f_U) frequencies respectively. The lower and upper frequencies were found by taking the frequency measurements at the 3dB cross intersection point on the network analyzer.

f_C (MHz)	f_L (MHz)	f_U (MHz)	SWR	Q_L	Q_o
418.375	415.0	421.0	1.75 – overcoupled	77.48	213.1

Table 2: Free space S_{11}, no loading present, no LNA

The table above shows results in free space but its more important for a coil resonate at 400 MHz when loaded. Since the rat cannot be loaded for simple tests, a finger was used in the table below.

f_C (MHz)	f_L (MHz)	f_U (MHz)	SWR	Q_L	Q_o
415.0	409.6	419.6	1.02 – critically coupled	41.5	83.0

Table 3: Finger loaded S_{11}, no LN

The range in the f_c could be present because of a mechanical trimmer capacitor, where the capacitance then could have a range of 0.5 – 2.5 pF. The capacitance was set with a 12 pF capacitor plus a trimmer set at 1 pF. This showed the F_c to be rather high at 426 MHz. The capacitor values were increased to decrease F_c. It was then set at 15.3 pF. The results are tabulated below in free space.

SWR (Standing Wave Ratio) illustrates whether the coil system is undercoupled, critically coupled or overcoupled. The Q_L and Q_o represent the ratio of energy stored over energy dissipated, where Q_L is Q loaded, is calculated with the measured frequencies and Q_o and is calculated with the coupling state. Q_L is found by the following equation:

$$Q_L = \frac{f_c}{f_U - f_L}$$

From Ginzton, the equation for Q_o is illustrated below.[7]

Equation 9.9: $Q_L = \frac{Q_o}{1+\beta}$

where β is:

Equation 9.41: undercoupled $\beta = \frac{1}{SWR}$

Equation 9.42: overcoupled $\beta = SWR$

Critically coupled $\beta = 1$

Tables 2 and 3 show that the resonant frequency of the coil should be around 400 MHz, ideally in free space slightly higher and when loaded as close as possible to 400 MHz. When the rat's head is loaded the frequency will decrease slightly as the coil will resonate at 400 MHz.

Following the bench tests, the coil was tested on a 500 g rat. The coil was found to resonate at approximately 408 MHz at the lowest trimmer capacitor setting and the SWR was 1.50. To compensate for the high frequency and overcoupled condition the C_c values were changed to 18 pF + 0.5-2.5 pF C_T. Also, the C_B capacitor was changed from 30 pF to 39 pF; everything else was left the same. This gave a range of 18.5 – 20.5 pF. The table below shows the bench test results.

[7] (Ginzton 2012)

f_C (MHz)	f_L (MHz)	f_U (MHz)	SWR	Q_L	Q_o
399.875	397.6	402.0	1.38 – overcoupled	90.9	216.3

Table 4: Free space S_{11}, no LNA

f_C (MHz)	f_L (MHz)	f_U (MHz)	SWR	Q_L	Q_o
399.0	401.8	402.0	1.04 – overcoupled	68.8	140.3

Table 5: Hand loaded S_{11}, no LNA

As seen with the results in table 4 and 5 the centered frequency is much closer to 400 MHz. With the trimmer present the coil can be tunable to a frequency range of 394-409 MHz.

A S_{21} measurement was also taken; this showed how sensitive a coil is when the frequency is 400 MHZ, while being detuned. The result showed the coil coupled to only 1% of all power, if not less. Concluding that the coil was fairly isolated at that frequency.

Finally, the coil was tested on a 300 g rat to determine loading characteristic, and the result showed it being overcoupled. The C_B was changed from 39 pF to 47 pF and the C_c of 18 pF was removed leaving just the trimmer capacitor. The results from the coil placed on a 259 g rat are shown below in table 6.

f_C (MHz)	f_L (MHz)	f_U (MHz)	SWR	Q_L	Q_o
400.04	397.76	402.37	1.082 – overcoupled	86.78	180.7

Table 6: 259g rat loaded, no LNA

Although the results show the coil being well matched, the coil was not very well loaded by the rat head. The images showed this with poor SNR gain and noise, and general band depth. This was caused due to the 1mm spaced between the coil and rat. Next step was to remove this space and cover the coil in Teflon tape, which showed the dominant load of the coil and provide images with a much higher SNR. The coil was placed into an open-bottom case allowing the coil to be exposed. The coil was wrapped in Teflon tape to prevent the coil itself from touching the rat. This coil system was tested on a 300 g rat where the coil was exposed with no spacer and only a few layers of Teflon tape. Results of this test are shown in the table below.

f_C (MHz)	f_L (MHz)	f_U (MHz)	SWR	Q_L	Q_o
400.64	398.02	403.08	1.02 – critically coupled	79.18	158.36

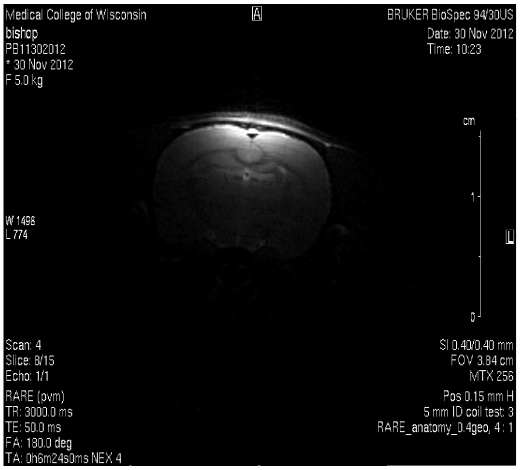
Table 6: 300 g rat loaded, no LNA

This final test shows the precise and accurate values for loading and matching. The images were clear with a high SNR.

SCAN RESULTS:

Scans taken on November 30, 2012 in both techniques of Rapid Acquisition with Relaxation Enhancement (RARE) and Echo Planar Imaging (EPI) can be seen below.

Eight images are shown from four scans: RARE 0.3 mm, RARE 0.4 mm, EPI 0.3 mm and EPI 0.4 mm. These slice sizes are typical for MRI scans. Fifteen slices were taken for each slice; the images below show the middle and last slice in the coronal orientation. Slice 8 represents the scan at the center of the coil and slice 15 represents the outside of the coil.



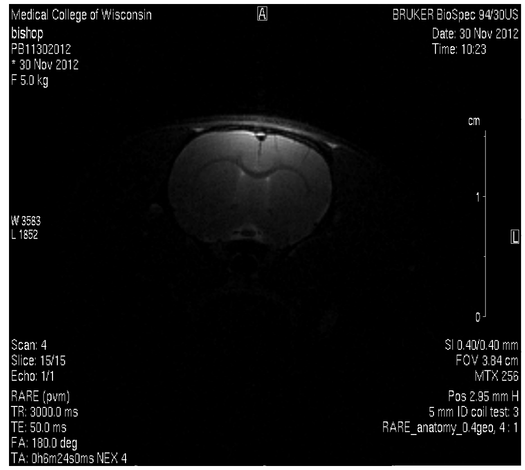
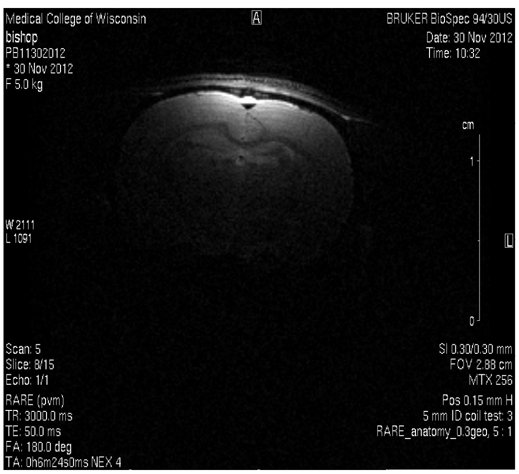


Figure 5&6: Rapid acquisition with relaxation enhancement (RARE) Anatomy 0.4 mm slices 8/15 and 15/15



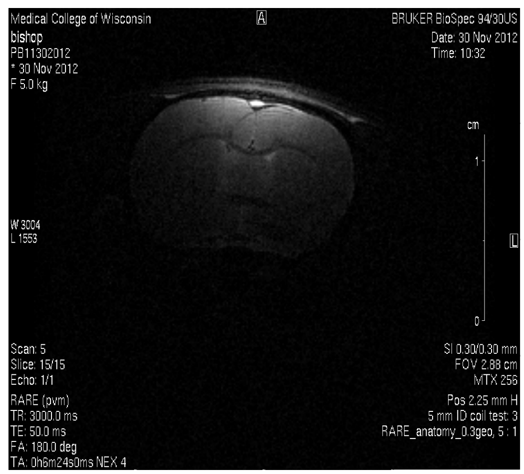


Figure 7&8: RARE Anatomy 0.3 mm slices 8/15 and 15/15

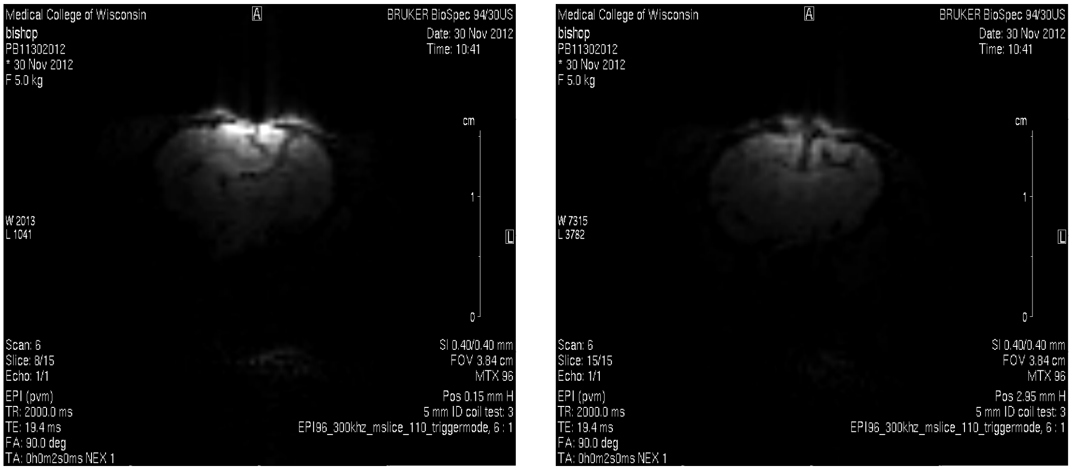


Figure 9&10: Echo Planar Imaging (EPI) Full k-space resting state 0.4 mm slices 8/15 and 15/15

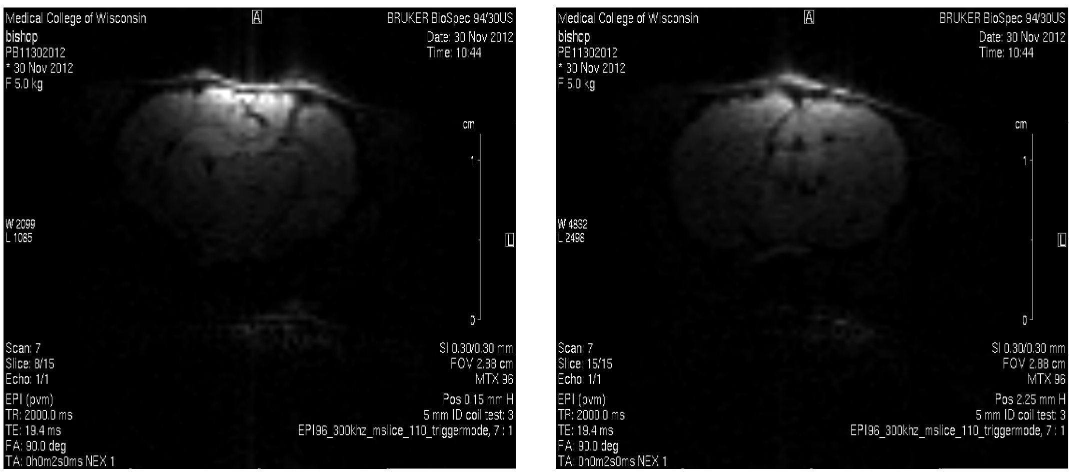


Figure 11&12: EPI Full k-space resting state 0.3 mm slices 8/15 and 15/15

Both EPI with full k-space and RARE scans were taken. RARE scan illustrates an anatomical image with high intensity resolution. In addition, the RARE slices collect voxel intensity values one voxel at a time. In comparison EPI scan illustrates a quick snapshot of the intensity values. In the EPI scans above a full k-space scan was taken, where every voxel value in each column and row was found. Other EPI scans may vary, where a half k-space scans takes the intensity values at each voxel for every other row.

The SNR values were calculated on Bruker ParaVision taking the ratio of the mean of the area of interest over the standard deviation of the noise. The region of interest was drawn in the axial place encompassing the top of the brain above the corpus callosum. The mean signal intensity was recorded from this region. Another region of similar size was drawn outside of the reception field of the coil. The standard deviation of noise was recorded from this region. The results are tabulated in Table 7.

Scan Type:	Slice #	Mean Signal	Std. Dev Noise	SNR
RARE 0.4 mm	8	1.31e5	2.35e3	55.74
	15	1.01e5	2.37e3	42.62
RARE 0.3 mm	8	6.89e4	2.36e3	29.19
	15	5.03e4	2.36e3	21.31
EPI 0.4 mm	8	4.15e4	256	162.1
	15	2.89e4	295	97.97
EPI 0.3 mm	8	2.41e4	365	66.02
	15	1.76e4	364	48.35

Table 7: Mean, Standard Deviation and SNR values for RARE and EPI slices

The SNR values were also found through creating a reconstruction algorithm in Matlab taking the ratio of the mean of the area of interest over the standard deviation of the noise. The region of interest was computationally drawn as labeled in blue in the figure below. The mean signal intensity was recorded from this region. Another region of similar size was drawn outside of the reception field of the coil also labeled in blue. The standard deviation of noise was recorded from this region. The results are tabulated in Table 8.

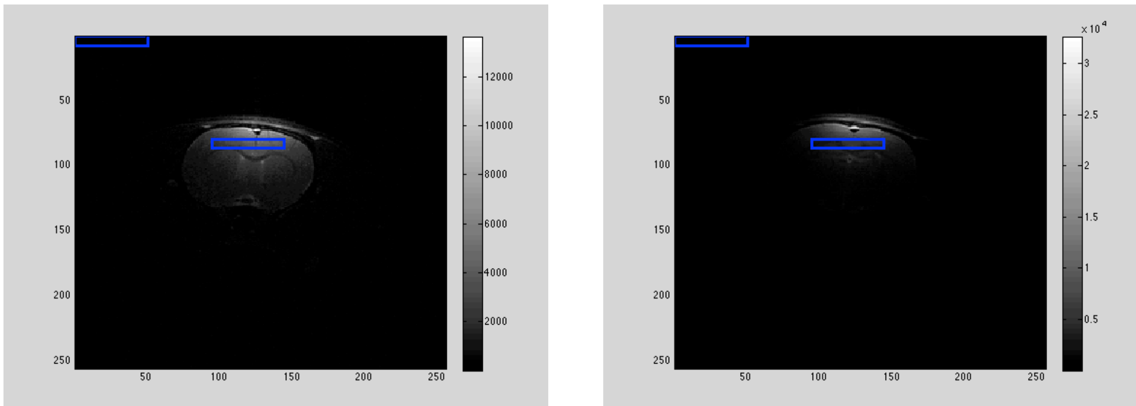


Figure 13&14: Rapid acquisition with relaxation enhancement (RARE) Anatomy 0.4 mm slices 8/15 and 15/15

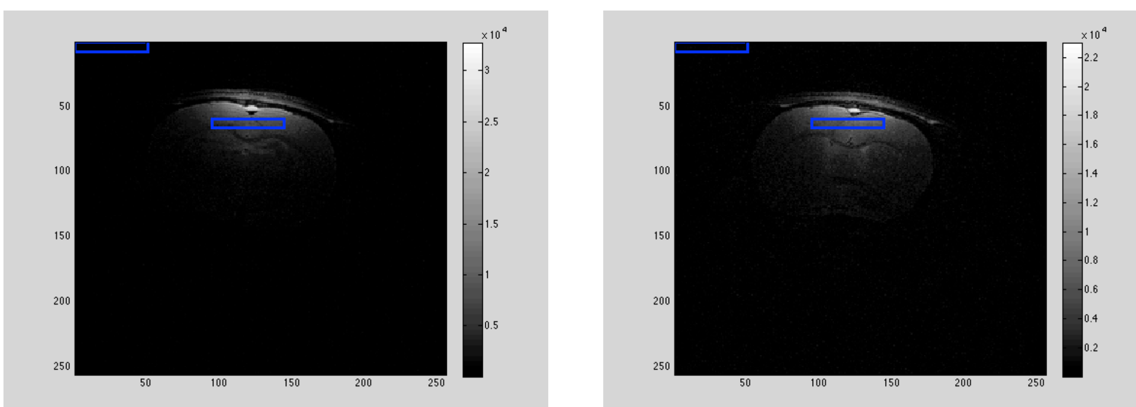


Figure 15&16: RARE Anatomy 0.3 mm slices 8/15 and 15/15

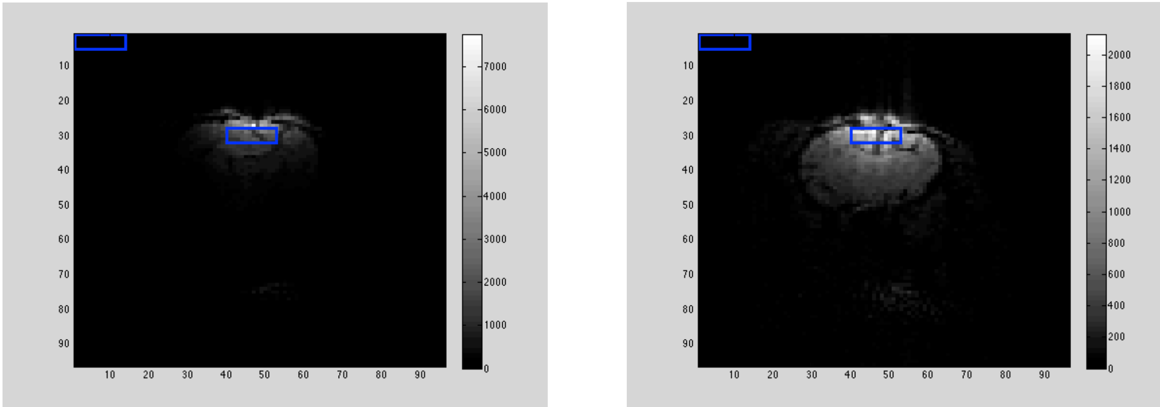


Figure 17&18: Echo Planar Imaging (EPI) Full k-space resting state 0.4 mm slices 8/15 and 15/15

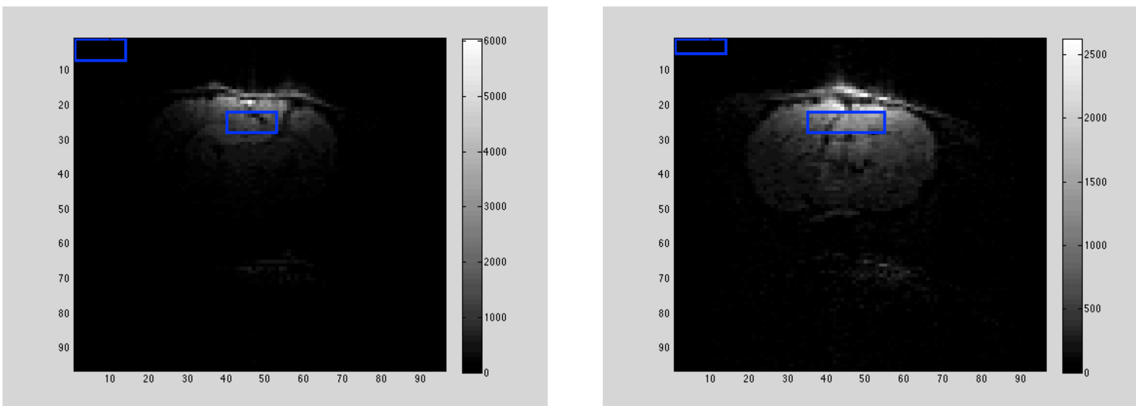


Figure 19&20: EPI Full k-space resting state 0.3 mm slices 8/15 and 15/15

The figures 13-20 display the Matlab reconstructed images similar to the output of the Bruker outputted slices.

Scan Type:	Slice #	Mean Signal	Std. Dev Noise	SNR
RARE 0.4 mm	8	4.26e3	92.68	45.96
	15	3.62e3	81.91	44.13
RARE 0.3 mm	8	6.84e3	220.95	30.94
	15	6.45e3	231.73	27.82
EPI 0.4 mm	8	1.94e3	6.95	278.79
	15	1.25e3	10.52	118.631
EPI 0.3 mm	8	1.25e3	19.92	62.81
	15	1.08e3	18.97	56.96

Table 8: Mean, Standard Deviation and SNR values for RARE and EPI slices reconstructed from Matlab

As seen in Table 8, the SNR values for each slice are relatively similar for most slices. Since the shape of the brain in the image tends to change over slices the created blue box needs to also be recreated. If the blue box were recreated in a similar way as completed in Bruker, the SNR values would be similar. Since the boxes are different, the exact values cannot always be found. More precise ways to create the boxes in Matlab is needed in order to successfully get results that are always similar to Bruker. As seen throughout, most values are very similar with only a few slices the SNR values are different due to the box size and orientation of the image.

CONCLUSION:

The overall results and the completion of the project from a design, simulated coil build to analyzed results shows that everything was completed successfully. The tangible coil along with scan images with high SNR output illustrates that the coil was successful in providing brain scans. The data was also reconstructed in Matlab yielding similar reconstructive images from Bruker. In addition, the SNR output from Matlab follows a correlation to the output from Bruker. More work can be completed where results from Bruker and Matlab can be compared to AFNI results.

FUTURE WORK:

Future work consists of building coils with this base design that can provide even further accurate and precise results. Furthermore, utilizing Matlab and AFNI to provide more precise and accurate SNR values. Additionally, through Matlab creating an automated program that could provide inputs for scans and output SNR values for slices. This would provide a way to analyze images in a much easier and convenient way.

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This is to certify that we have examined this copy of the thesis by

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and have found that it is complete and satisfactory in all respects.

This thesis has been approved by:

Dr. Daniel B. Rowe, Department of Mathematics, Statistics, and Computer Science

Approved on