Off-resonance and detuned surface coils for B_1 inhomogeneity correction in 7-Tesla MRI

By

Elizabeth K Zakszewski

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ABSTRACT

A problem with high-field MRI is the lack of B_1 homogeneity, particularly signal cancellation in the outer parts of the head. Here we attempt to correct this by adding surface coils. To adjust the mutual coupling, we vary the resonance properties of the added coil. A new agar-based head phantom was built, and two surface coils were built and tuned. The surface coils were placed in various configurations against the phantom to modify the B_1 field with their presence, while images were taken using a 16-rung birdcage coil to transmit and receive. Trials were taken with various spacings between the surface coil and the phantom, while the resonance of the surface coil was either shifted in frequency by changing the voltage across a varactor diode, or detuned using a resonant detuning circuit. It was discovered that with a 1 cm spacing and a surface coil tuned just above resonance, SNR near the surface coil could be improved by upwards of 400%, with the trade-off of a reduced signal in other areas on the periphery of the head. Other configurations could achieve better B_1 homogeneity at the expense of reduced SNR throughout the head. Future studies will explore the possibility of using more than one surface coil to improve SNR in more places on the periphery of the head.

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1 Introduction

Currently functional MRI, or fMRI, provides an invaluable tool to neuroscientists who wish to learn which portions of the brain are active while a subject is performing certain tasks, or to compare the functions within a "normal" brain to those of an addict's. Because of this, researchers are continually trying to develop improvements to the MRI system that will produce images of different parts of the brain that are of interest to neuroscientists with a higher signal-to-noise ratio (SNR). A higher SNR can facilitate acquiring higher resolution images, more sensitive measurements of brain activation, and faster data acquisition. These improvements to the system could be in the form of specially designed RF pulse sequences, image reconstruction programs, or system hardware. This thesis will focus on the latter, specifically radio frequency coil designs.

Two of the main coil designs in use today are surface coils (small circular coils, often overlapping with one another in carefully designed patterns that are placed as close as possible to the surface of the head) and volume coils (tubes large enough for a patient's head to fit inside). Both types of coils have benefits for certain applications. Surface coils are popular when high SNR is desired in a specific small region of the brain (or other part of the body), because they have high sensitivity in the regions that they are placed adjacent to. Birdcage coils, a specific variety of volume coil with a series of closely spaced "rungs" on the outside containing capacitors at various intervals, are desirable for imaging the entire head with a relatively uniform SNR.

An important consideration in coil design is to tune the coil by building its circuitry such that it forms an LC circuit with resonance at the Larmor frequency that a sample's protons will have when placed within the B_0 field generated by the main magnet. An RF coil must be in tune so that it can effectively deliver RF power to the sample, and thus create the desired alignment of the nuclear spins with a reasonable amount of input power to the coil.

The goal of the process is to deliver a 90-degree pulse to all regions of interest with as little transmit power as possible, while still achieving the desired SNR if the coil is being used to receive RF signal (as surface coils almost always are, and volume transmit coils sometimes are as well). This process becomes more difficult at higher B_0 fields; specifically, it becomes more difficult to achieve a uniform B_1 field in all regions of interest. The higher B_0 field means that protons within it will have a higher resonant frequency. This in combination with the dielectric properties of the head means the EM radiation in the head has a shorter wavelength in higher B_0 fields, leading to signal cancellation in the outer parts of the head.

One of the major problems of higher-field imaging is B_1 (the field generated by the RF pulses that the RF transmit coil delivers) inhomogeneity. As a result of lower B_1 on the outside of the head when imaging the brain, areas near the outside of the head generally require more transmit power to achieve the same flip angles. This effect is larger in

higher B_0 fields. According to one study,[1] the variation in B_1 field throughout the head was 23% at 4T and 42% at 7T, almost two times higher at 7T. In addition, the power required to transmit a 90 degree pulse in the center of the head at 7T was about twice that at 4T, and at 7T the power required to deliver a 90 degree pulse to the periphery of the brain is 3db higher, or two times higher, than in the center of the head. Not only is a larger transmit voltage required in general in higher fields, but the spatial inhomogeneity is also stronger.

A number of solutions have been proposed to mitigate this non-uniformity. Some of these include an algorithm for intensity correction in image post-processing[4], spiral birdcage coils[2], and dielectric pillows filled with ultrasound gel[4]. A recent study[3] showed that a standard birdcage coil tuned to the first gradient mode, rather than the uniform mode, could produce a signal with higher SNR in the outer regions of the brain, albeit at the expense of a signal null in the center of the head. This design may work well for specific studies that concentrate on the temporal lobes, parts of the occipital cortex, or the cerebellum. It has been suggested that a detunable gradient mode coil used in conjunction with a phased array receiver could achieve more uniform target flip angles with high SNR in the temporal and occipital lobes with low transmit voltage, and work on this approach is underway[3].

Another study[4] has suggested that local surface coils, in which a reactive current flow is induced during the excitation phase, could work in place of ultrasound pillows to attempt

a uniform B_1 distribution. In simulations, it was shown that the local surface coils should be tuned to a higher resonant frequency than that of protons within the B_0 field, in order to compensate for the RF eddy currents induced in the body. This study attempted various surface coil designs on a 3T body imager and compared the results to those in which dielectric pillows were used, but did not test the coil tuned to a lower frequency on a human subject due to high SAR (specific absorption rate, meaning human tissue could be burned from exposure to the RF energy) generated in phantom tests. For this thesis, I have attempted to extend this type of approach to human brain imaging at 7 Tesla.

The intent of my thesis work focuses on building a new phantom to simulate more accurately a human head than the phantoms currently in use at the lab, and then building surface coils and testing them on the phantom, using a transmit/receive volume coil to gather images with the surface coil placed near the phantom and either tuned to various frequencies or detuned at the resonance frequency. I then compare images acquired while the surface coil was adjusted to these various resonant properties, and observe changes in SNR in several locations on the phantom head.

2 Procedure

2.1 "Alien Head" Phantom Construction

In order to accurately test the effects of the surface coils to be created, a new phantom

sample needed to be built that would more accurately simulate the electrical properties of a human head. A hollow glass form of the same size and shape of a human head was used as container. When a phantom using this glass form is imaged, the image resembles the head of a cartoon "Roswell" alien, hence the term "alien head phantom".

The inside of the phantom was made from agar (Fisher Scientific AA1075236 Agar Powder) mixed with .02 sodium benzoate (as a preservative) and .07 NaCl to match the dielectric properties of the human head. The mixture was boiled for one hour, poured into the glass form, allowed to settle overnight, and then sealed with a collar, gasket, and end cap made by hand from plastic and silicone caulk.

The agar mixture did not harden to the thickness we desired overnight, as was expected from previous phantoms made from agarose by colleagues at the lab. We attributed this to lack of sufficient boiling time (2 hours would probably have been better). However, the phantom still created a B1 distribution when imaged that was more similar to that of a human head than the alien head phantoms filled with water that were already available in the lab and showed an exaggerated B1 inhomogeneity effect.

2.2 Surface coil construction

Two identical circular pieces of FR4 circuit board of diameter 10 cm were used to construct two surface coils to be used in trials. Both coils were made with capacitors at 6 evenly spaced points along the circle. One was built with a bias diode and detuning trap at the match circuit, and the other was built without a detuning trap but with a varactor diode in place of one of the capacitors. Both coils were tuned to 297.2 MHz at the bench using coupled probes and network analyzers.

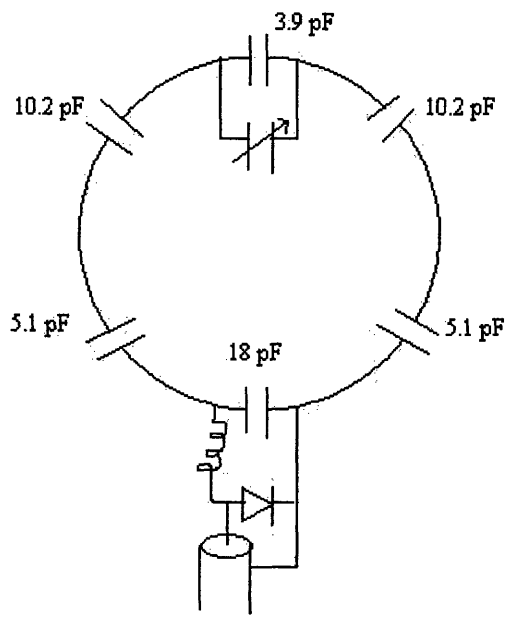


Figure 1: Circuit diagram of detuing coil with capacitor values

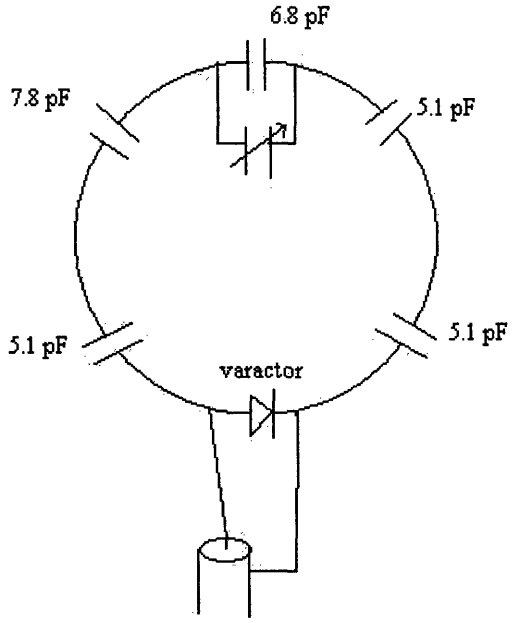


Figure 2: Circuit diagram of coil with varactor diode and capacitance values

The varactor diode changes its bias gradually based on the voltage put across it, and thus serves the purpose of a variable capacitor whose capacitance is can be changeed by varying the input voltage, rather than by adjusting the plate spacing by hand. By changing the capacitance at one location, the tuning of the entire coil could be changed by increasing voltage across the varactor. At the bench, a coaxial cable placed across the varactor was connected to a voltage source. Then the behavior of the coil in response to variations of a voltage source was measured, and the results plotted in Figure 3. The coil was also checked in the same way while loaded against the phantom, where it would be positioned during imaging, to see if loading would change the

resonant frequencies. Foam squares each 1cm thick were used to provide spacing between the coil and the phantom. As can be seen in Figure 3, it was determined that with at least 1cm of spacing, the behavior of the coil did not change significantly with loading.

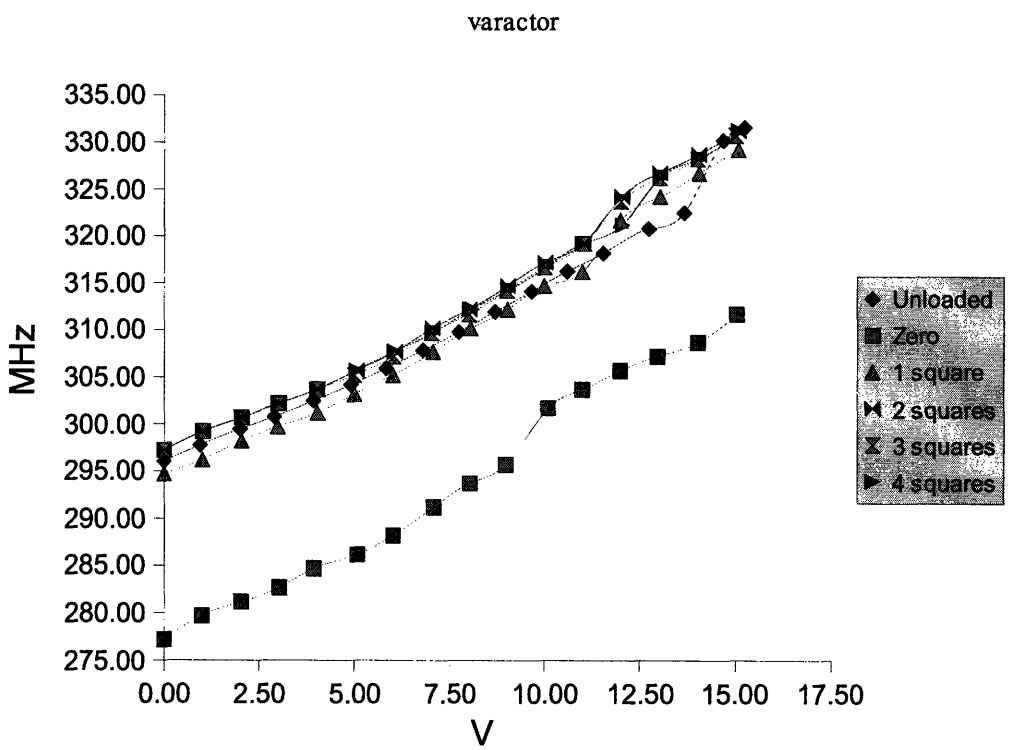


Figure 3: Frequency response of coil with varactor diode in response to voltage

The coil with the detuning trap changes the magnitude of its resonance depending upon the current going across it. By varying the current, the trap detunes gradually. Again using a coaxial cable in the detuning trap attached to a the the voltage source, the

response of the resonance to varying the current coming from the voltage source was measured and the results are plotted logarithmically in Figure 4. Again the behavior was tested with the coil loaded against the phantom, and it was noted, as can be seen in Figure 9 and Table 1, that the detuning process is significantly more sensitive to current while loaded.

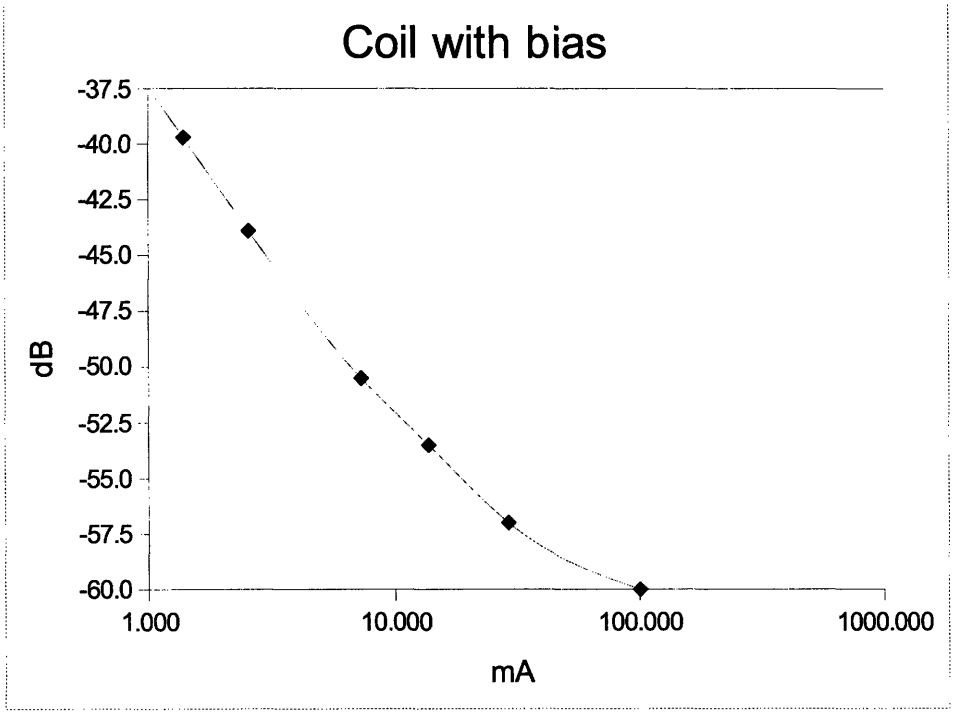


Figure 4: Resonance magnitude in response to current of coil with detuning trap

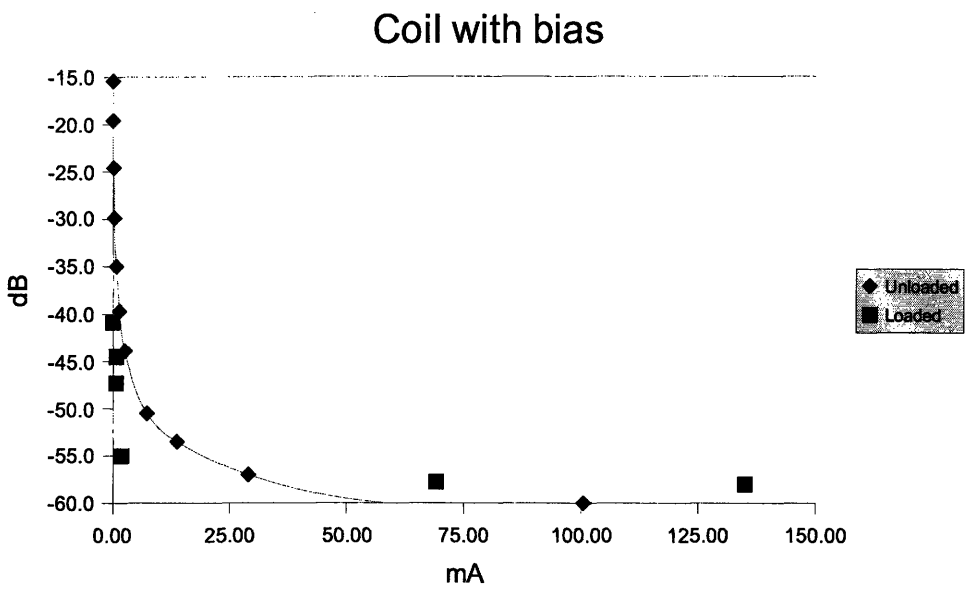


Figure 9: Resonance behavior of coil with bias circuit while unloaded or loaded

mA	Unloaded (dB)	Loaded (dB)
0.00	-15.4	-40.9
0.04	-19.6	
0.14	-24.6	
0.33	-29.9	
0.70	-35.0	-44.5
1.39	-39.7	
0.70		-47.3
1.80		-55.0
2.55	-43.9	
7.28	-50.5	
13.70	-53.5	
29.00	-57.0	
69.10		-57.8
100.50	-60.0	
135.00		-58.0

Table 1: Resonance of coil with bias circuit while unloaded or loaded

2.3 Image Acquisition

A prototype 7T human scanner (Siemens Medical Solutions, Erlangen, Germany) was used for image acquisition. The coil used for transmit/receive was an open, unshielded hybrid birdcage design, with a diameter of 28cm, length of 20cm, 16 rungs and four segments to each rung. The coil was tuned while loaded with the phantom, and positioned and fixed in the scanner so that the surface coils and foam pads could be interchanged without disturbing the orientation of the birdcage coil between trials. A voltage source was placed outside the scanner area (to avoid the force pull from the magnetic field) and attached to the surface coil via a sufficeintly long coaxial cable.

When loaded with the phantom alone (and no surface coil), the scanner required a transmit voltage of 315V with. Using a long TR GRE (gradient echo) sequence it was noted that that to achieve a 90° pulse in the center slice required a flip angle of approximately63°. It was therefore calculated that a transmit voltage of 220.5V (63/90 x 315) should be used to achieve a good base image.

At each configuration of surface coil, three tests were performed. The first was a 3-axis localizer sequence. The second was a gradient echo sequence with a low flip angle and fft factor of 8. The third was a B1 mapping sequence that could be used to compare field homogeneity.

These test were performed under various configurations, including phantom alone with no surface coil, and each of the two surface coils with both various spacings away from the phantom and various adjustments of voltage or current to test various resonance values for each coil.

2.4 Data Extraction

After all tests were performed and all images acquired, the images from the low flip angle GRE sequence were analyzed at the Siemens console. From comparing the signal intensity of the images, a comparison of the B1 homogeneity can easily be inferred, since for small flip angles using a transmit/receive coil, the B1 field scales as the square root of the image intensity. For each image, values of the signal at three locations were recorded: the bright spot at the center of head, the null at outside of the head near the surface coil position, and a null slightly above the original null (on the image) that was often generated when signal increased near the surface coil. If no "new" null appeared in an image, then this measurement was taken at an estimated area of lowest signal nearest to the location of this null on other images. In addition, measurements of the standard deviation of noise were recorded at four points near the outside corners of the image area and averaged to represent a measurement of the background noise, so that SNR could accurately be calculated for each image.

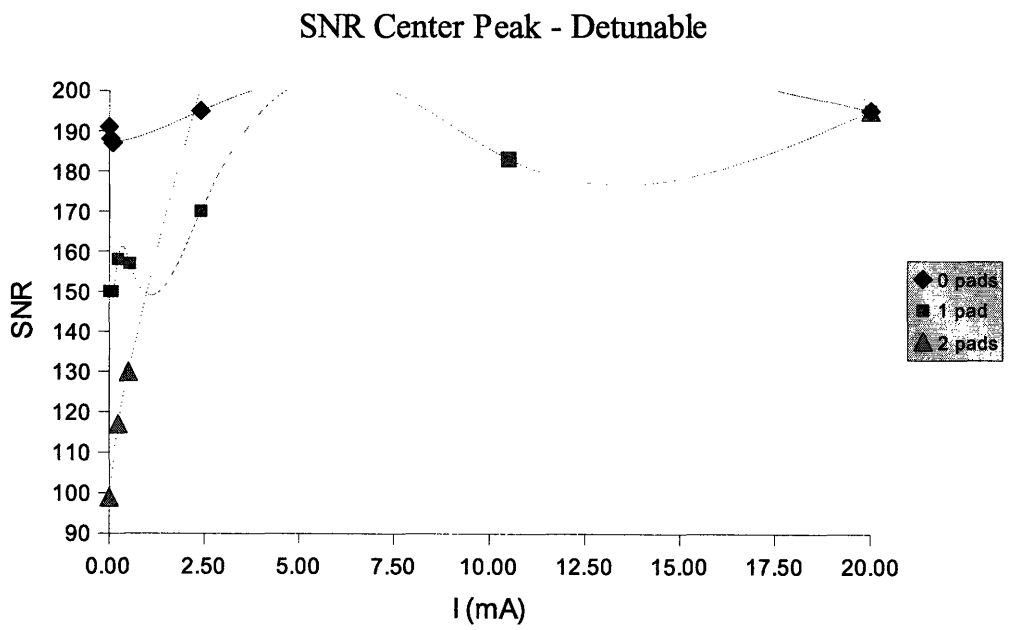
3 Results

Measurements taken of signal at each of the three locations of interest and of noise from the image of each coil configuration are presented in Table 2.

Coil	Pads	V or I (V or mA)	Average S. D. of noise	Mean @ center peak	SNR peak	Null of interest	SNR null	"new null"	SNR "new null"
None	None	None	12.3	2367	192	103.8	8.0	402.7	32
De	0	0.00	12.0	2293	191	314.8	26.0	44.9	3
De	0	0.04	12.3	2321	188	331.0	26.0	116.0	9
De	0	0.10	12.3	2308	187	291.5	23.0	104.9	8
De	0	2.40	11.9	2329	195	157.6	13.0	283.2	23
De	0	100.00	12.2	2387	195	169.2	13.0	359.4	29
De	1	0.00	12.9	1935	150	526.7	40.0	74.7	5
De	1	0.04	12.8	1922	150	510.1	39.0	67.7	5
De	1	0.10	12.7	1907	150	461.0	36.0	95.9	7
De	1	0.23	12.2	1931	158	401.8	32.0	71.1	5
De	1	0.54	12.6	1989	157	302.5	24.0	108.5	8
De	1	2.40	12.4	2112	170	150.3	12.0	288.2	23
De	1	10.50	12.1	2225	183	115.9	9.0	349.3	28
De	1	100.00	11.8	2309	195	103.7	8.0	437.6	37
De	2	0.00	12.7	1268	99	190.9	15.0	60.3	4
De	2	0.24	12.6	1478	117	152.8	12.0	57.8	4
De	2	0.50	12.3	1599	130	135.7	11.0	47.5	3
De	2	100.00	12.2	2387	195	169.2	13.0	359.4	29
Var	0	0.00	11.9	2262	190	309.0	25.0	68.8	5
Var	0	2.50	12.2	2327	190	404.7	33.0	151.2	12
Var	0	5.00	12.5	2380	190	448.5	35.0	262.1	20
Var	0	7.50	12.2	2430	199	451.2	36.0	328.8	26
Var	0	10.00	12.3	2466	200	422.8	34.0	395.0	32
Var	0	12.50	12.1	2465	203	381.3	31.0	423.9	35
Var	0	20.00	12.4	2449	197	313.0	25.0	447.3	36
Var	1	0.00	12.4	1837	148	414.9	33.0	75.4	6
Var	1	2.5	12.4	1998	161	533.4	43	69.1	5
Var	1	5.00	12.9	2194	170	536.2	41.0	339.3	26
Var	1	7.5	12.7	2314	182	449.9	35	464.5	36
Var	1	10.00	12.8	2373	185	368.1	28.0	508.7	39
Var	1	18	12.4	2423	195	228.1	18	461.1	37
Var	2	0.00	12.8	1290	100	115.3	9.0	61.0	4
Var	2	1.70	12.7	1247	98	221.5	17.0	65.4	5
Var	2	4.20	13.3	1500	112	331.5	24.0	216.0	16
Var	2	6.70	13.1	1929	147	343.1	26.0	545.7	41

Table 2: SNR calculations for all surface coil arrangements at three locations of interest

To compare SNR based upon resonant frequency and spacing of the coil from the phantom, Figures 10-15 plot SNR vs. resonant frequency determinant for each of the three locations of interest.



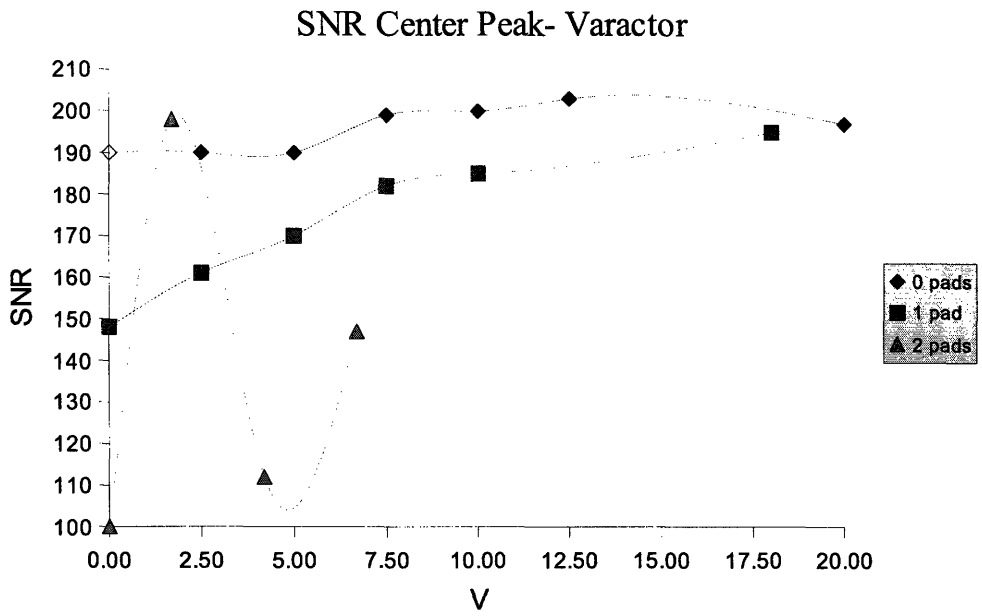
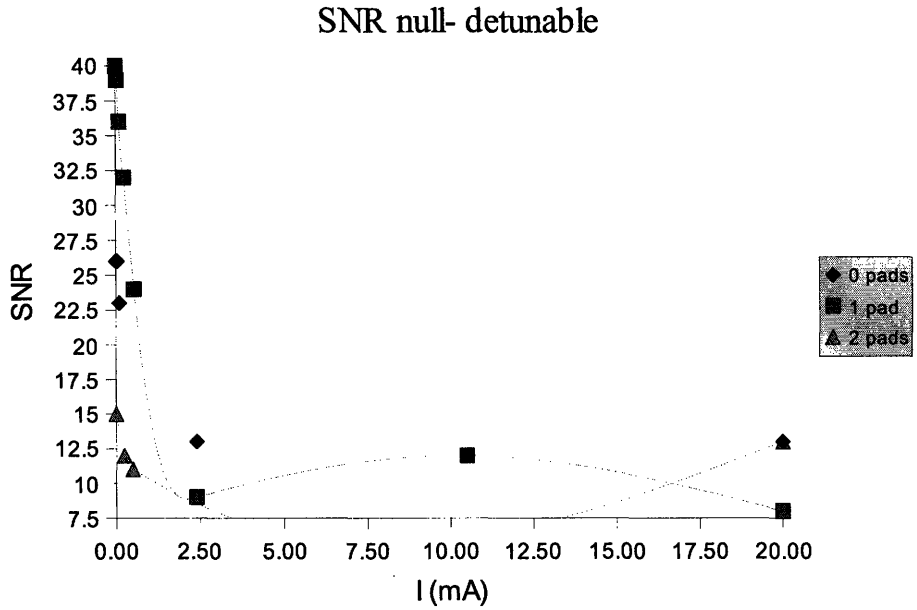
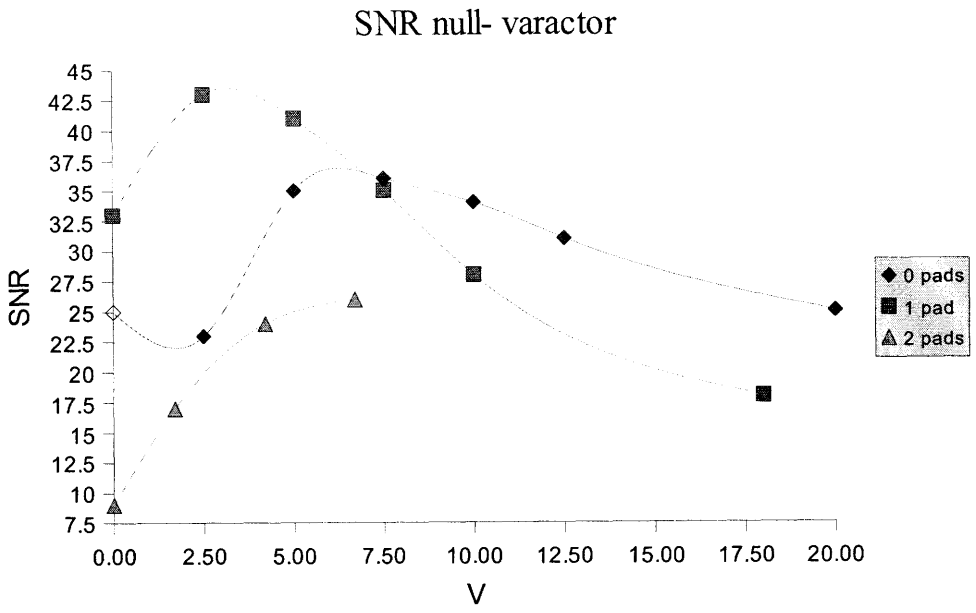
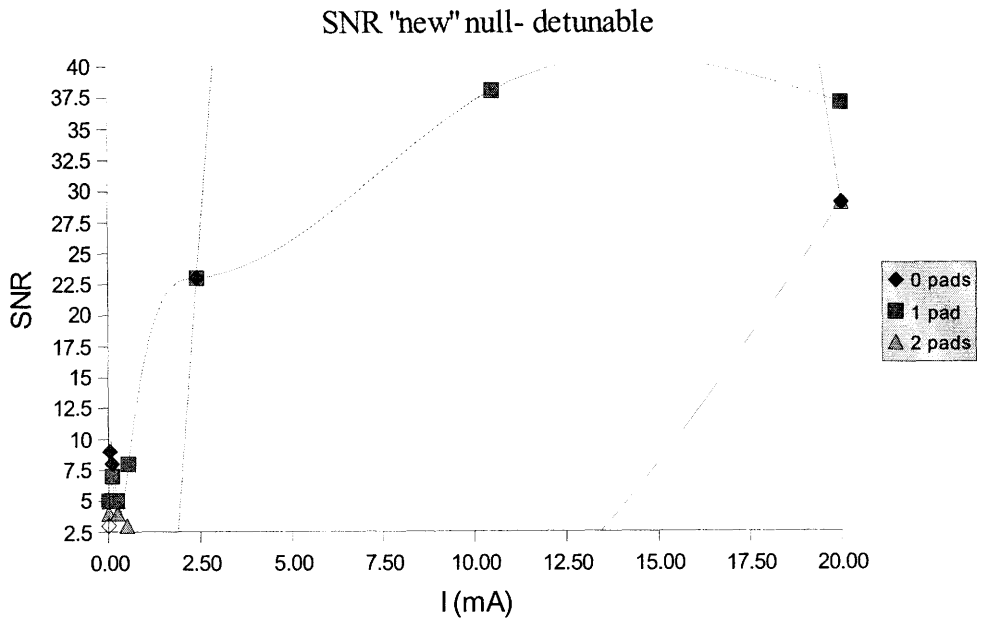


Figure 11: SNR dependence on voltage across varactor at center peak




SNR null- varactor
SNR
V
0 pads
1 pad
2 pads


SNR "new" null- detunable
SNR
I (mA)
0 pads
1 pad
2 pads

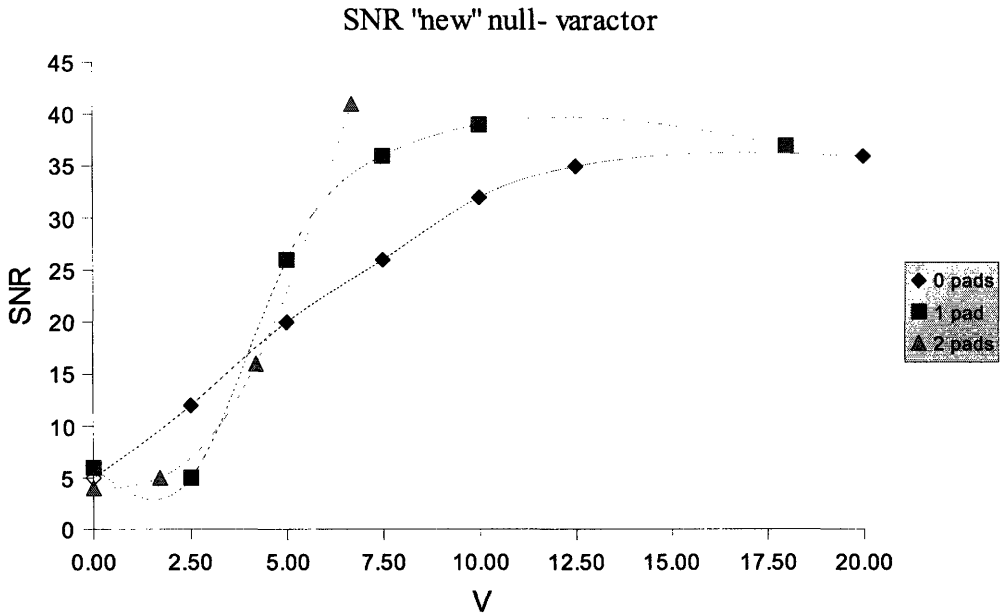


Figure 15: SNR dependence on voltage across varactor at "new" signal null

Next are presented plots of the configurations which achieve the most SNR at the null of interest, in each case comparing the SNR at this null to that of the other two locations for the same configuration.

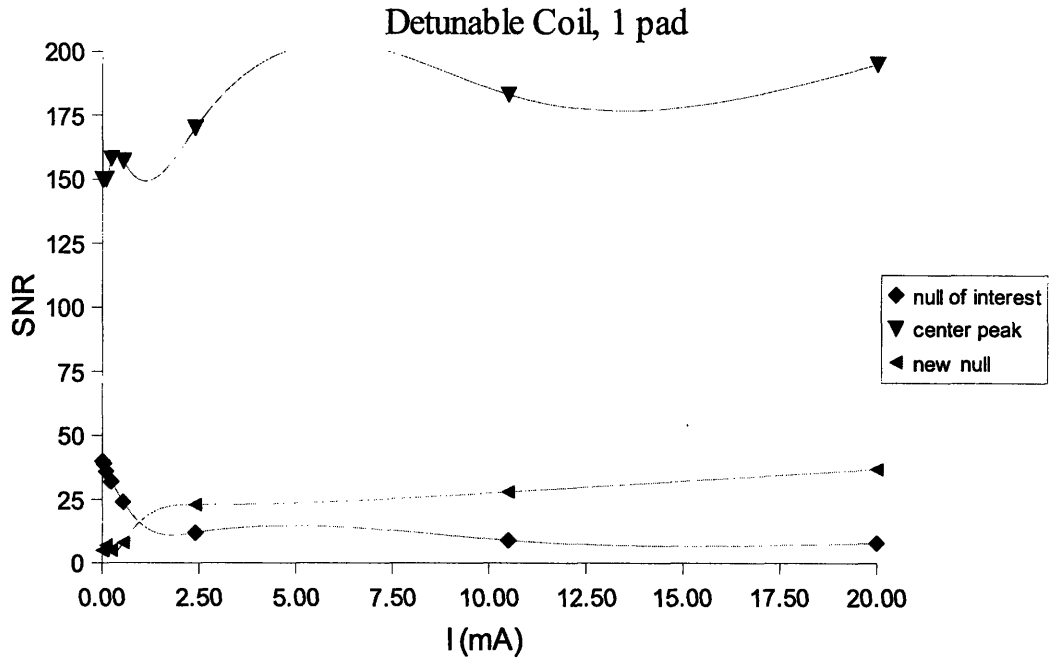


Figure 16: SNR of detuable coil with 1 pad spacing at three locations of interest

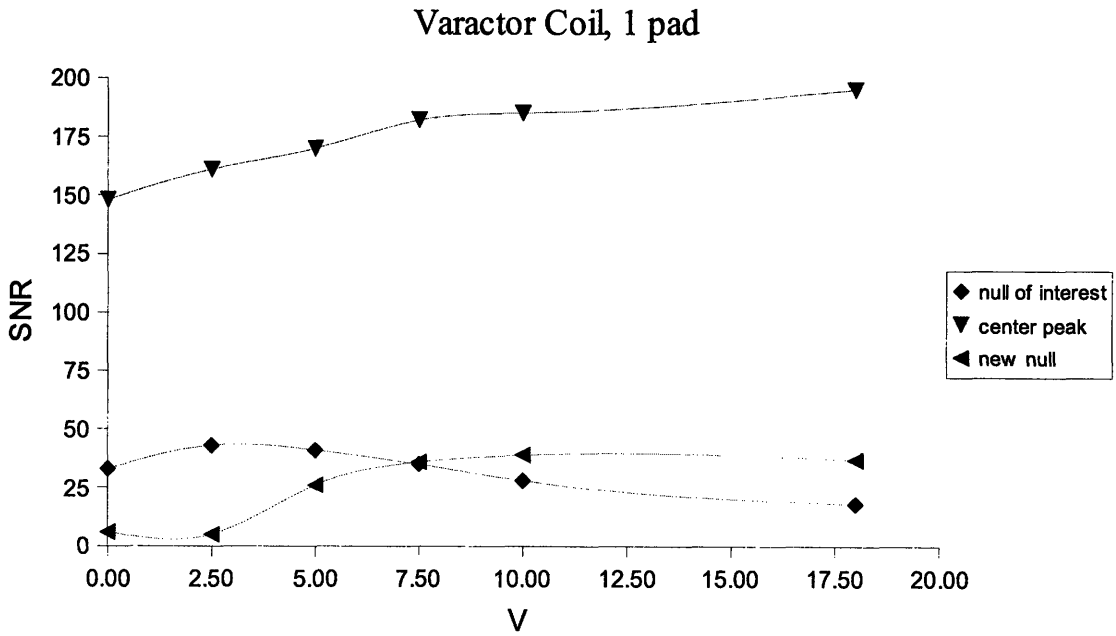


Figure 17: SNR of coil with varactor with 1 pad spacing at three locations of interest

The following figures present samples of the images that were analyzed to obtain the SNR data. Of note is how the location of the second null (dark spot) changes with changing configurations.

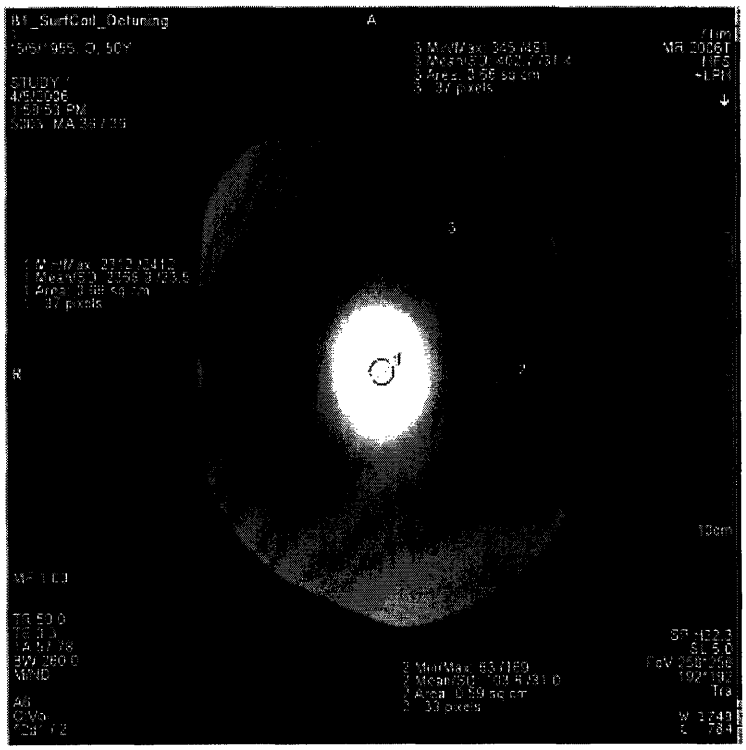


Figure 18: Image taken with no surface coil present. Note familiar "bullseye" signal pattern

Figure 18 is an image taken of the phantom with no surface coil present. The two dark spots on either side are the signal nulls that we are trying to eliminate. The locations of these nulls are consistent with the B_1 maps calculated in previous studies[1]. Figures 22 and 23 show visually the images from which the data for Figure17 was taken. Figures 19 through 21 illustrate the images from which the data for Figure 16 was taken.

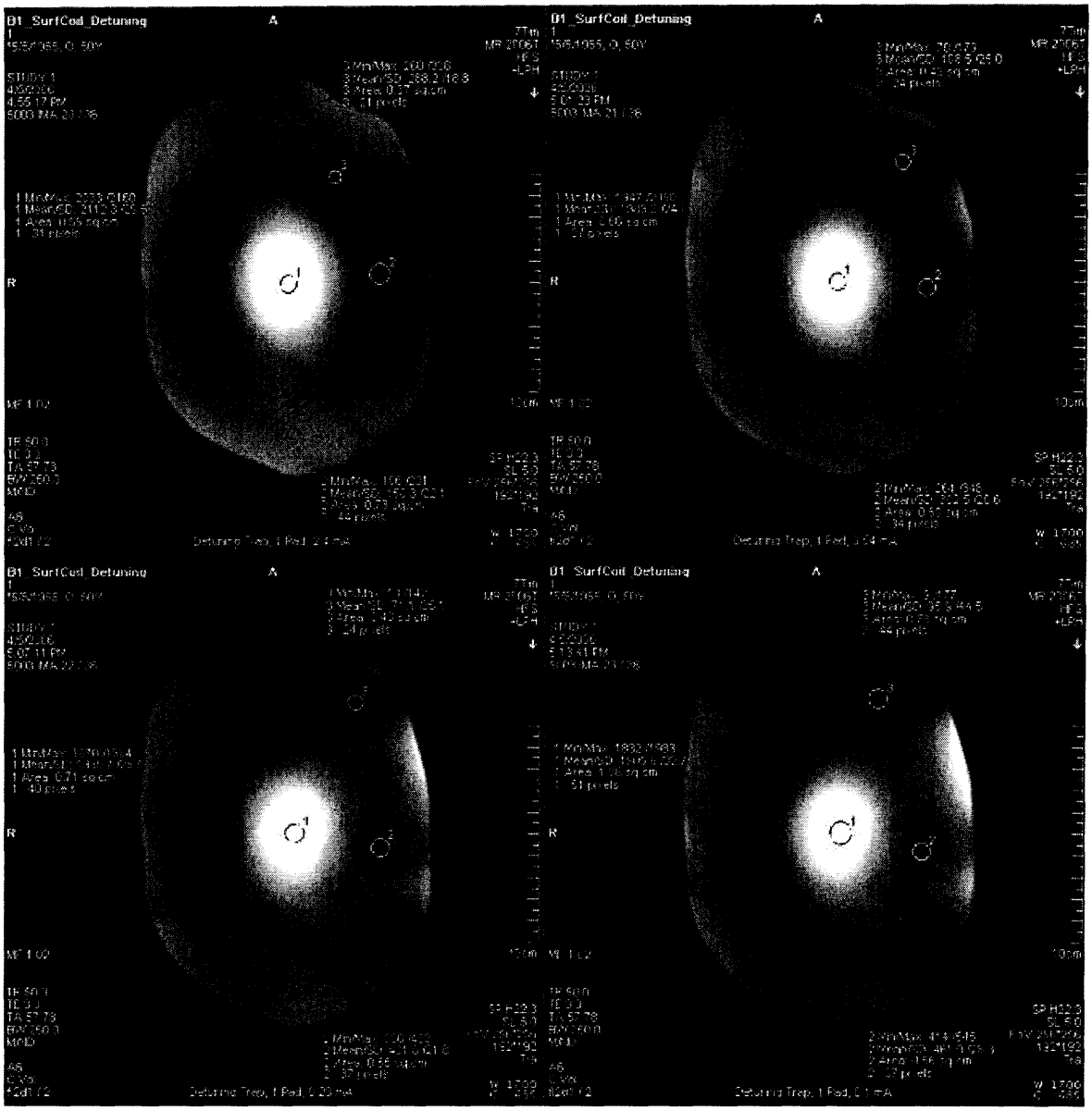


Figure 19: Images taken with presence of detunable coil with one pad spacing and currents of (top to bottom, left to right) 2.4, 0.54, 0.23, and 0.1 mA

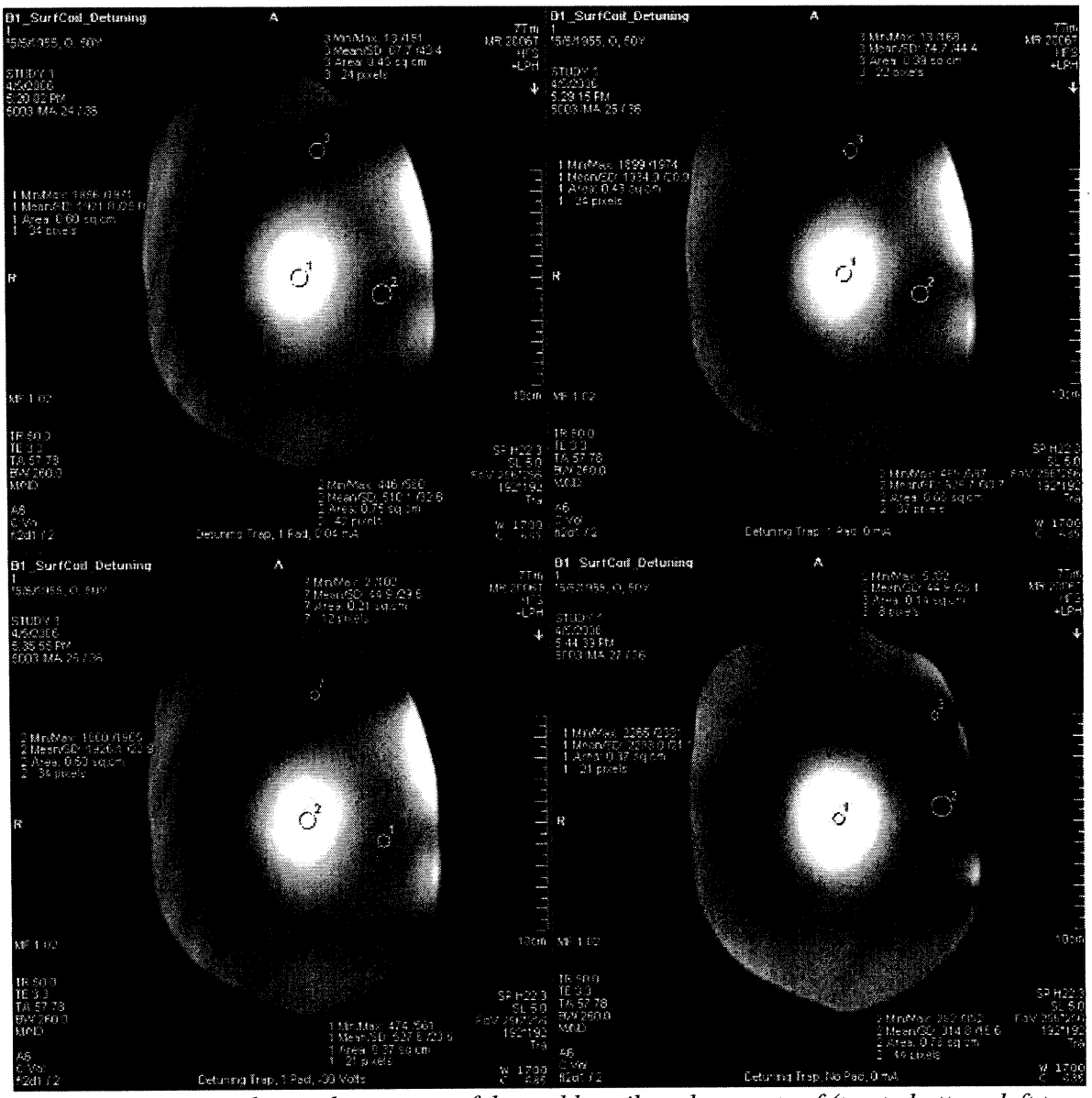


Figure 20: Images taken with presence of detunable coil and currents of (top to bottom, left to right) 0.04 mA, 0 mA, -30 V, and 0 mA. The first three images are with 1 pad spacing, the last is with 0 pads spacing.

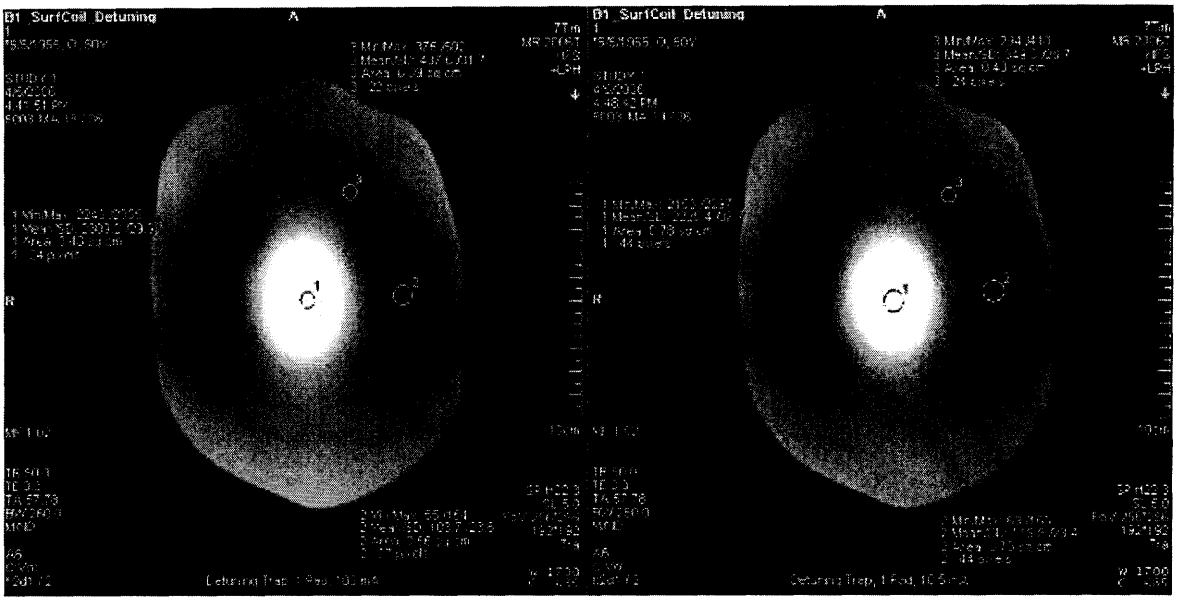


Figure 21: Images taken with presence of detunable coil with one pad spacing and currents of 100 and 10.5 mA

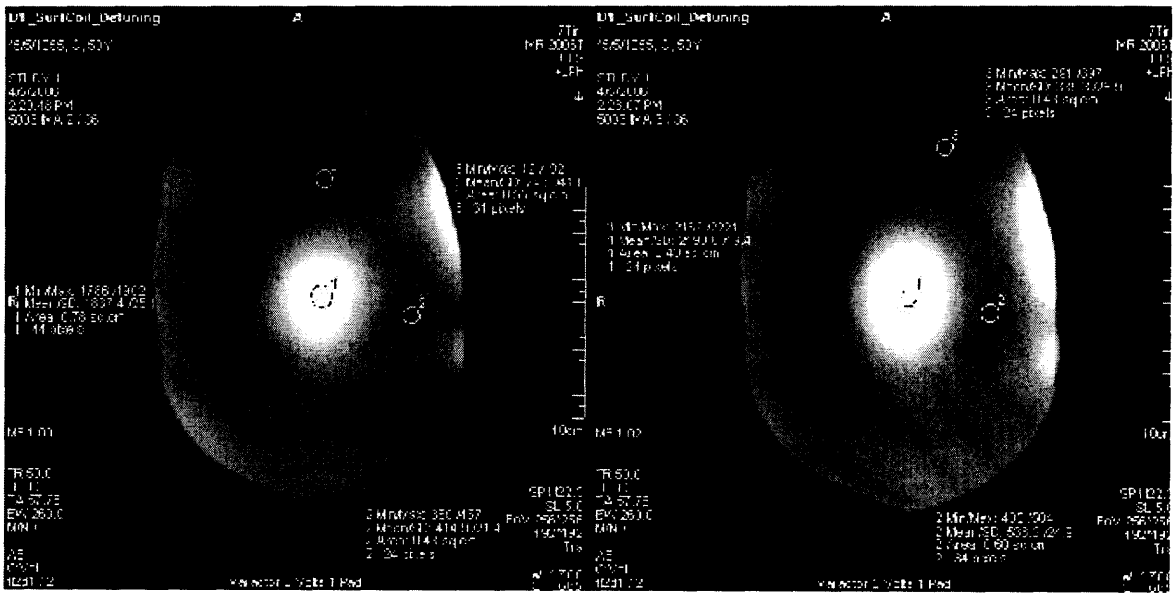


Figure 22: Images taken with presence of coil wit hvaractor with one pad spacing and voltages of 0 and 5 V

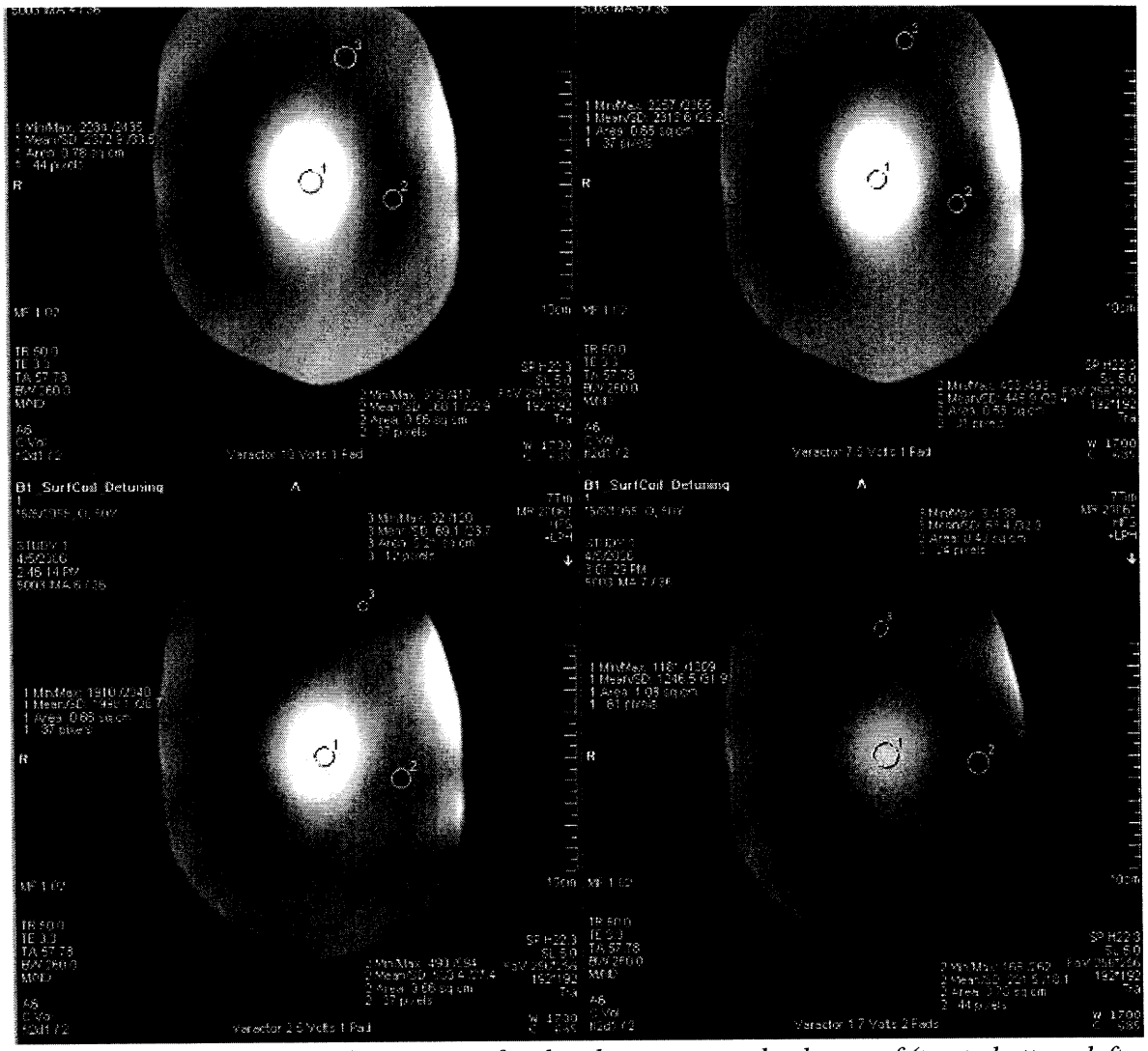


Figure 23: Images taken with presence of coil with varactor and voltages of (top to bottom, left to right) 10, 7.5, 2.5, and 1.7 V. The first three images are with a spacing of 1 pad, the last of 2 pads.

4 Discussion

By simple observation of the image data, it is clear that with certain configurations of a surface coil, an increase in SNR near the periphery of the head adjacent to the surface coil can be achieved. In the most successful configuration, using the coil with a varactor spaced 1cm away from the phantom and tuned with a voltage of 2.5V, an SNR gain of 1 - 43/8 = 438% was achieved in the signal null near the surface coil.

Of note, however, is the apparent pattern of a decrease in signal at the area more towards the back of the head that gets more severe as the signal increases in the area of interest. Figure 16 illustrates this patten, showing a near inverse relationship in the SNR at these two locations.

This phenomenon can be explained to some extent by observing the current patterns that would theoretically be generated by the volume coil and the surface coil during the excitation phase. As can be seen in Figure 24a, the volume coil alone is known to generate currents traveling left to right across a cross section of the sample in line with the slices observed in our B1 maps. In the same cross section, a surface coil with the geometry of our experiment is known to generate currents circling the coil as shown in Figure 24b. If these two current patterns are superimposed onto each other as per the geometry of our experiment, as in Figure 24c, the currents will theoretically cancel each other out, at the points noted with arrows in the figure. This could be an

explanation for the "new" signal null that was created in many cases. It is unclear at this point why only one of the two points of canceled current produced a significant signal null and not the other. Another way of thinking about the phenomenon is that the presence of the surface coil effectively "pulls" signal towards it, and away from the other side of the sample.

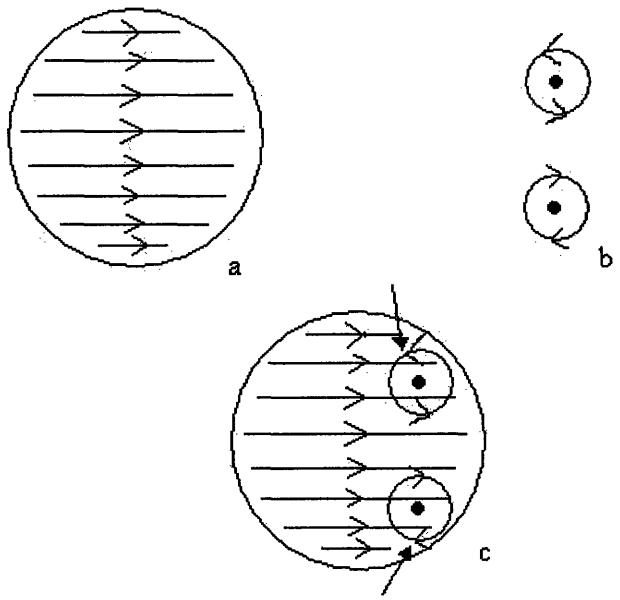


Figure 24: a) Current pattern for a standard birdcage coil. b) Current pattern for a circular surface coil perpendicular to plane of page. c) Superposition of current patterns of the two coils. Null spots are indicated by dark arrows.

It was also observed that the more pads were placed between the sample and the surface coil (thus bringing the surface coil closer to the birdcage), the better homogeneity was achieved in the image. However, this often came at the expense of overall SNR throughout the image. Figure 23 (lower right corner) shows a prime example of this. The standard deviation of the signal among the three locations of

interest is calculated using Equation 1 and plotted in Figures 25 and 26 for different spacings between coil and sample.

$$sigma=\sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i-\bar{x})^2}$$

Equation 1

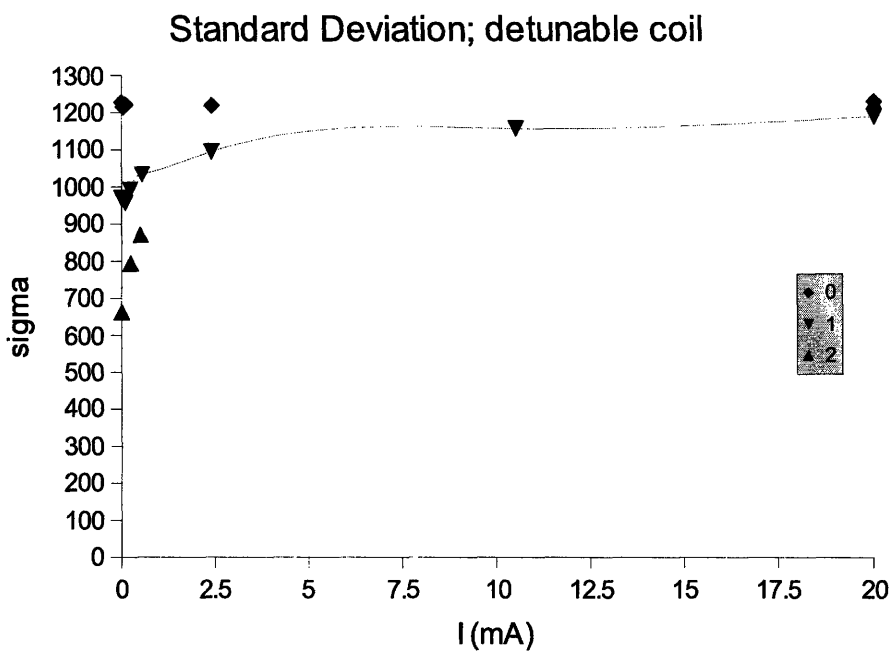


Figure 25: Standard deviation in signal among three points of interest using detunable coil with various spacings

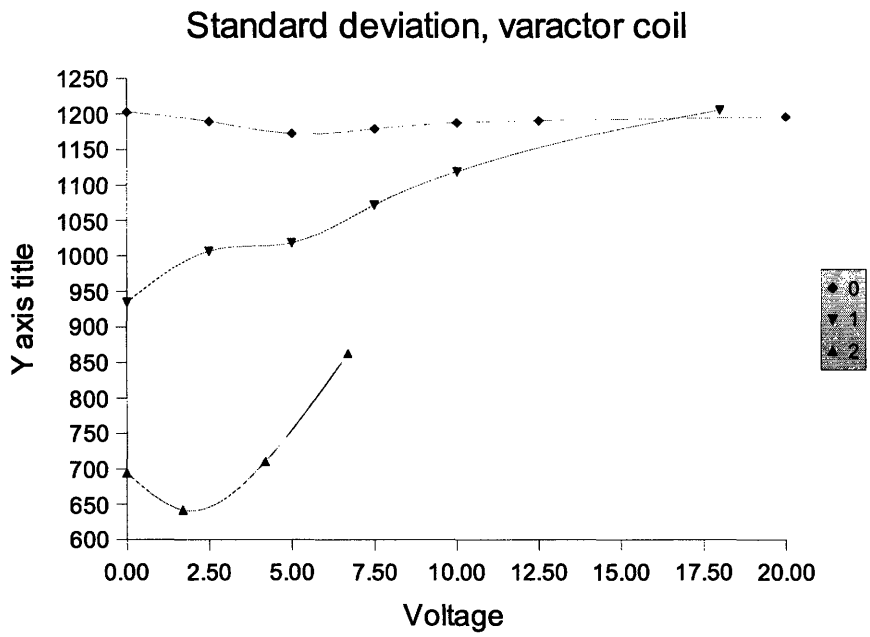


Figure 26: Standard deviation in signal among three points of interest using coil with varactor with various spacings

It is clear from these figures that the greater the spacing between the surface coil and the sample, the less the spatial deviation in signal, therefore the better B1 homogeneity. However, by comparing these two figures to Figures 4-9, it is also clear that with and increase in homogeneity also comes a decrease in SNR at each of he three locations of interest.

This phenomenon can be explained by observing the spatial dependence of the signal from the two coils, as shown in Figure 27. The signal from the birdcage begins to decrease near the periphery of the sample, which is why there is typically a null near this point. However, the signal from the surface coil begins to increase sharply near

the periphery of the sample, so that when the fields from the two coils are added, the result is a stronger signal or even a signal peak where there once was a null. Now, imagine moving the dotted line corresponding to the location of the surface coil further away from the sample. The signal from the surface coil no longer increases sharply at the periphery of the sample, rather in increases more gradually, leading to a more spatially uniform, yet not as strong, signal.

Another consideration is that the presence of the surface coil may change the

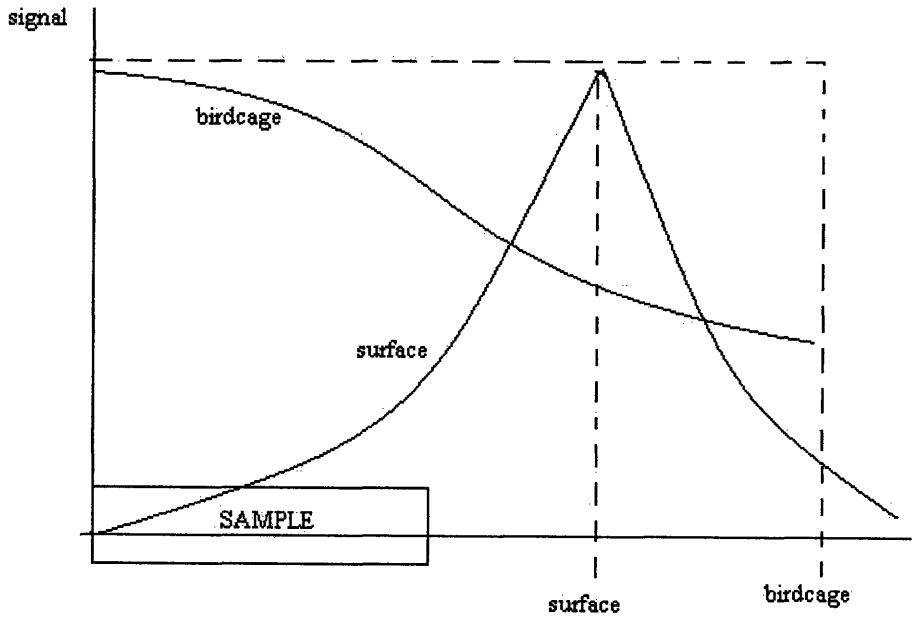


Figure 27: Signal as a function of radius from center of sample resulting from positioning of the two coils

resonance of the birdcage coil itself. If the transmit/receive coil is off resonance, flip angle will not be as expected, and the image will be affected by this. A solution to this has been proposed, that if a certain surface coil configuration is chosen as optimal, the birdcage coil could be re-tuned to account for this configuration.

Based on my observation of the data collected, it appears as though using a coil with a varactor diode is a better way to improve SNR. Not only can the resonance properties of the coil be controlled more easily (the detuning coil detunes very quickly when loaded), but the resulting images slow stronger increase in SNR in the area of interest, while the decrease in SNR at the "new" null is about the same as with the detuning coil.

5 Conclusions

By placing a surface coil tuned off-resonance near the phantom, an increase in SNR at the periphery of the phantom near the surface coil can be achieved. However, in many cases this does result in another signal null above the area where SNR is improved. Moving the surface coil further from the phantom can achieve a more uniform B1 field throughout the head, but the overall SNR will be lower. The optimum spacing between coil and phantom for improving SNR is around 1cm. The optimum surface coil to be used is one with a varactor diode tuned to between 2.5 and 5 volts. In our experiment this corresponded to around 299-300 MHz, meaning a surface coil tuned just above resonance will have the most desired effect. It is noted that the presence of a surface coil may change the resonance of the transmit/receive volume coil, therefore it is suggested that when an optimal configuration is chosen, the volume coil should be re-tuned.

6 Further Studies

It has also been noted that by placing two surface coils, one on either side of the head, the same increase in SNR can be achieved on either side of the periphery resulting in an even more uniform B1 field. The possibility of an array of surface coils used in conjunction with the birdcage coil to achieve optimum B1 uniformity. Further studies should be pursued to investigate this effect.

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