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**Original Article**

# Designing and Fabrication of a New Radiofrequency Planar microcoil for mini-Nuclear Magnetic Resonance

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## Abstract

**Introduction**
Radiofrequency planar microcoils are used to increase the resolution of magnetic resonance images of small samples. In this study, we aimed to design and fabricate a spiral planar microcoil constructed on a double-sided printed circuit board (PCB). It has four rings with an internal diameter of 241 microns tuned and matched at 63.8 MHz.

**Materials and Methods**
To achieve the maximum signal-to- noise ratio (SNR) and quality factor of the coil, its geometry was optimized based on parameters such as width (w) and thickness (h) of the copper rings, the distance between the rings, inner radius of the microcoil ($R_i$), and the number (N) of coil rings by using COMSOL, ADS, and MATLAB software packages.

**Results**
Our findings indicated that the Q factor and SNR of the coil at resonance frequency of 63.8 MHz are 63.149 and 168.23, respectively, which are higher than the equivalent features of the pervious coils. In addition, to evaluate the function of matching and tuning circuit, reflection coefficient factor ($S_{11}$) of the coil was experimentally measured to be -48 dB at resonance frequency of 63.8 MHz, which is consistent with the simulated value.

**Conclusion**
In this study, a new microcoil was designed and fabricated to produce images of very small samples and volumes in microliter dimensions. The results showed that this new microcoil has superior capability in imaging very small samples compared to the conventional coils applied in magnetic resonance imaging devices.

**Keywords:** Nuclear magnetic resonance, Radiofrequency microcoil, Signal to noise ratio

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# 1. Introduction

Nuclear magnetic resonance (NMR) is an efficient method for sample analysis in the fields of Medicine, Biology, and Chemistry. The radiofrequency (RF) coils play a very important role in high sensitivity and high-resolution magnetic resonance imaging (MRI) systems.

In imaging small samples, the signal to noise ratio (SNR) of NMR and MRI systems is improved by reducing the detector coil's diameter. According to the previous studies [1-3], the sensitivity of coils was increased by extenuating the size of the detector coil in the range of micron. Therefore, to analyze small samples in MRI and spectroscopy planar microcoils are used to increase SNR, resolution, and sensitivity. Planar coils can produce and detect perpendicular magnetic fields [4].

When imaging small samples, magnetic fields of planar coils in receiver mode can be compared with magnetic field of volumetric coils in whole-body MRI [1-3]. On the other hand, because the planar coils are located in proximity of the sample, the SNR of planar coils would be higher than that of volumetric coils. Therefore, microscale planar coils are appropriate for providing convenient access to the anatomy locations and obtaining in-vivo signals. These coils are cost-effective and can be used in MR-probes [1-3].

Given the importance of microcoils, some studies have been performed on this issue. Hsieh et al. [5] fabricated a single loop planar coil with 5 mm diameter on typical FR4 substrate and tested it for Zebra fish brain imaging on 3T MRI. They reported the quality factor (Q-value) of the coil, as well. The Q-value of a coil is defined by the following equation:

$$Q = (2\pi f)L / R \qquad (1)$$

Where f is the coil operating frequency, R is the real part of the coil impedance, and L is the inductance of the coil. They reported the Q-value of the coil to be about 90 at RF of 125.3 MHz. Baxan et al. [6] fabricated the copper planar receiver microcoil using plating technique. It was designed in ellipsoidal geometry (1000×500 µm) with four turns, trace width of 22 µm, and trace thickness of 46 µm. It was tested on a 4.7-Tesla MRI, in which case, the SNR and Q-value of the coil were reported to be 80 and 24, respectively. Kong et al. [7] created gallium microcoils with a thickness of 375 microns. The structure of microcoil consists of three layers, namely, the spiral channel, interconnection, and lead-out channel for putting the sample. The microcoil was characterized for 0.5 T proton magnetic resonance relaxometry (MRR) measurements. At resonance frequency of 21.65 MHz, Q-value and SNR of the coil were 30.4 and 80, respectively. In the current study, we aimed to improve SNR and magnetic parameters. To this end, a new planar microcoil was designed and fabricated and the effect of this planar microcoil on output parameters (SNR and magnetic parameters) was examined.

# 2. Materials and Methods

## 2.1. Geometry of Planar Micro-Coil

Figure 1 demonstrates the geometry of microcoil designed in this study. The geometry of the coil was optimized using MATLAB, COMSOL, and ADS packages based on parameters such as the width (w) and thickness (h) of copper rings, distance between rings (s), inner radius of microcoil ($R_{in}$), and number of coil rings (N).

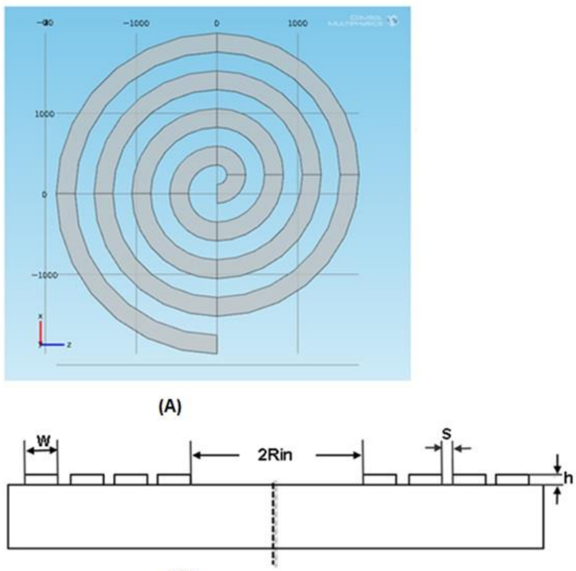



Figure 1. Geometry of designed microcoil. (A) Spiral planar microcoil; (B) cross-section of microcoil: width (w) and thickness (h) of the copper rings; distance between the rings (s); inner radius of the microcoil ($R_{in}$); and the number of the coil rings (N)

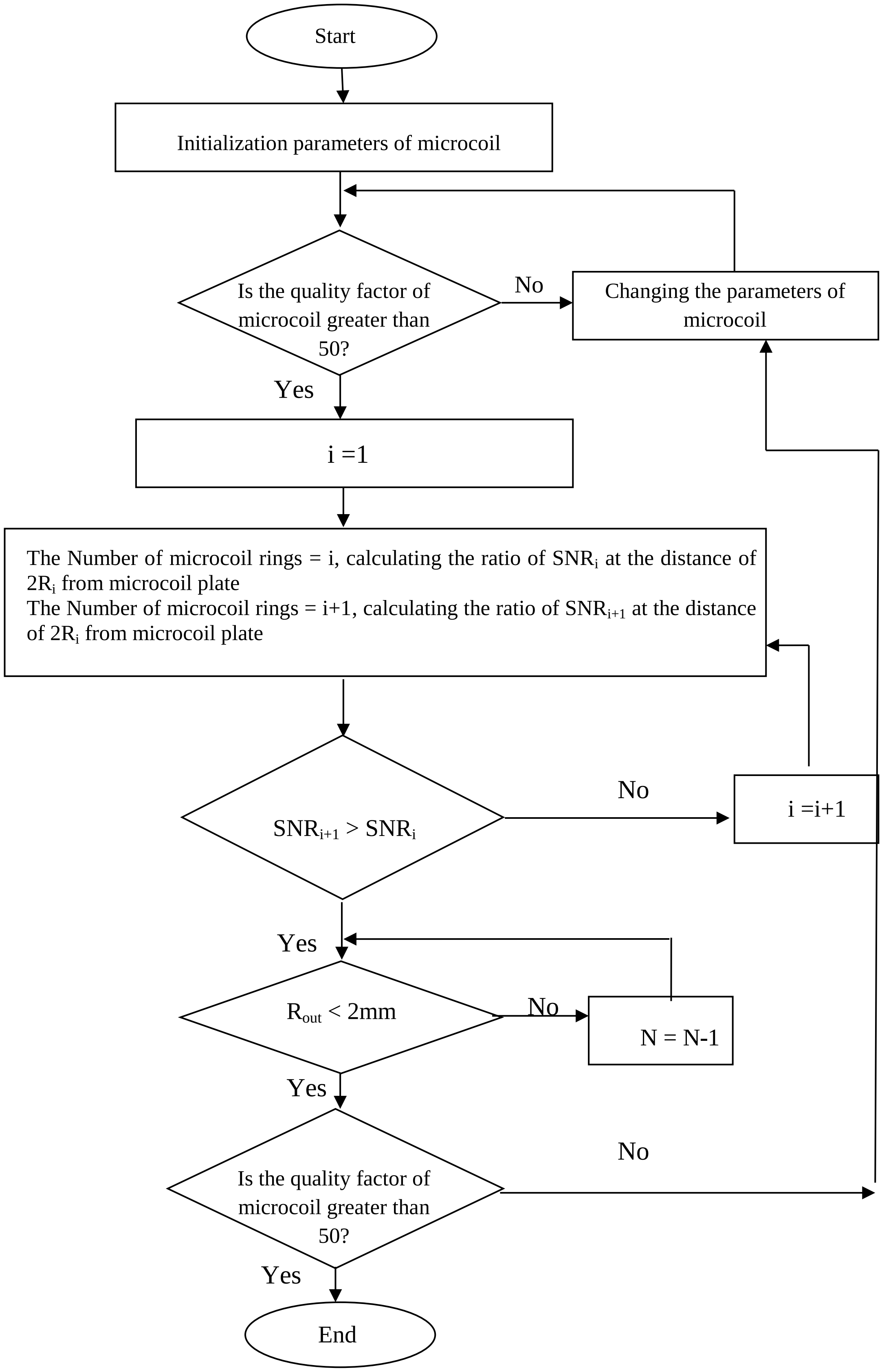



Figure 2. Block diagram showing the steps performed to optimize the designed microcoil

Figure 2 exhibits the block diagram employed for micro-coil optimization. For running the optimization algorithm, initial parameters of the designed coil were set as the number of turns= 4, gap between the turns= 200 µm, turns thickness=18 µm, and inner radius of the coil= 100 µm. However, regarding the high inductance value of the designed coil compared to the previously presented coils (Table 1), the minimum Q-value of the proposed coil was assumed to be 50. Calculations using MATLAB, COMSOL, and ADS packages indicated that the SNR and Q-value were maximized at $D_i$= 241 µm, W= 233 µm, S= 235 µm, N= 4, and h = 35 µm.

## 2.2 Geometry Optimization of Microcoil

### *2.2.1 Signal to Noise Ratio*

SNR, as an important parameter in designing microcoils, is defined using the following equation [8]:

$$SNR = \frac{k_0 (\frac{B_1}{i}) V_s N \gamma \hbar I (I+1) \frac{\omega_0^2}{3\sqrt{2} k_B T_s}}{\sqrt{4 k_B T R_c \Delta f}} \quad (2)$$

where $k_0$ is a proportionality constant for correction of non-uniformities in the RF field, $B_1$/i is the sensitivity of the coil, $V_s$ is the sample volume, $N$ is the number of spins per unit volume, and γ is the gyromagnetic ratio, which has a characteristic value for each chemical species (for a proton, $\gamma$ is equal to 42.58 MHz/Tesla). Likewise, $\hbar$, $k_B$, $I$, $\omega_0$, and $T_s$ are Planck's constant, Boltzmann's constant, nuclear spin quantum number (which is equal to 1/2 for a proton), the operating frequency, and absolute temperature of the sample, respectively. Moreover, observed resistance at the coil input due to sample and coil is represented by $R_s$ and $R_c$, respectively. Moreover, $T$ is the coil temperature and $\Delta f$ is the bandwidth of the receiver.

According to Equation 2, for a constant volume of sample, $B_1$ and $R_c$ are determinant factors for coil SNR. Therefore, Equation 2 is simplified as [8]:

$$SNR \propto \frac{B_1}{\sqrt{R_c \Delta f}} \quad (3)$$

In the present study, Equation 3 was used to determine the optimal number of coil rings in COMSOL. For this purpose, various geometries of MR coils were generated by the optimization process in COMSOL. Afterwards, to compute the SNR of each coil and find the optimal coil geometry, a current of 1 A was applied to each coil input, and magnitudes of $B_1$ and $R_c$ parameters were computed using COMSOL and ADS, respectively. As illustrated in Figure 3, the optimal number of coil rings should range between 2 and 4. The chart of SNR versus normal distance from surface of coil is used to determine the exact number of coil rings. Figure 4 illustrates that the coil with 4 turns of wire has higher SNR in comparison to other coils at a large distance range from the coil's surface. Accordingly, the optimal number of turns to achieve the maximum SNR equals 4.

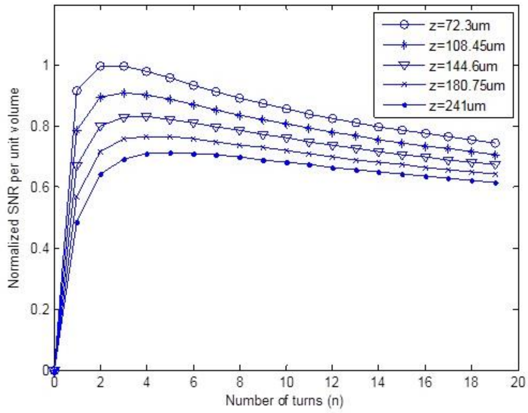



Figure 3. Normalized signal-to- noise ratio per unit volume versus the number of the coil rings; Z is axial distance from the microcoil surface

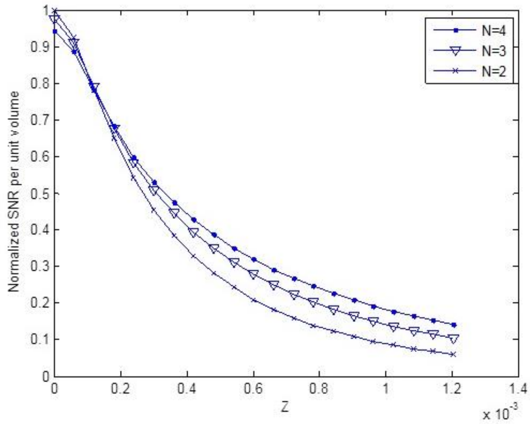



Figure 4. Normalized signal-to- noise ratio per unit of volume versus normal distance from surface of the microcoil (Z); N is the number of the coil rings

### *2.2.2 Quality Factor*

Figure 5 illustrates the electrical model of a microcoil. In this model, the series resistor $R_c$ is the finite conductivity of the metal, L is inductance of the coil, and the capacitance C shows the parasitic capacitance between the coil's turns according to reference [7].

For a planar spiral coil, resistance is calculated using the following equation [9]:

$$R_C = \frac{\rho l_c}{S_{eff}} \quad (4)$$

Where ρ is equal to $1.68 \times 10^{-8}\ \Omega m$ and is the bulk resistivity of copper, and $S_{eff}$ and $l_c$ are the effective surface and length of the coil wire, respectively. The length, $l_c$, can be expressed as:

$$l_c = N\pi(r_i + r_e + w) \quad (5)$$

Where N is the number of turns in the coil and $r_i$ and $r_e$ are the internal and external radiuses of the coil, respectively. For a wire in rectangular profile, $S_{eff}$ is expressed as:

$$S_{eff} = wh - (w - w_{eff})(h - h_{eff}) \quad (6)$$

Where *w* and *h* are the geometrical width and thickness of the wire, respectively. The $w_{eff}$ is the analogous relations for the effective wire's width. The $h_{eff}$ is the effective wire's thickness defined as:

$$h_{eff} = 2\delta \frac{ch(h/\delta) - \cos(h/\delta)}{sh(h/\delta) + \sin(h/\delta)} \quad (7)$$

With

$$\delta = \sqrt{\frac{2\rho}{2\pi f \mu}} \quad (8)$$

Where μ is permeability of the material and f is the resonance frequency of microcoil (i.e., 63.8 MHz) in this study.

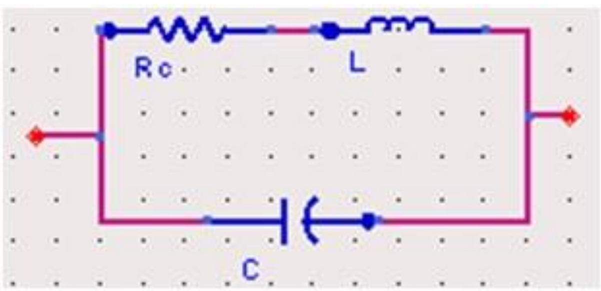



Figure 5. Electrical model of planar microcoil

The inductance L can be calculated using Wheeler's formula [10] for spiral planar coils:

$$L = 14 \times 10^{-7}\left[\frac{H}{m}\right] N^2 \frac{(r_e + r_i + w)^2}{2.14 r_e - r_i + 0.57w} \quad (9)$$

Finally, using resistance and inductance at certain frequencies, the quality factor of microcoil (Q) is obtained from Equation 10:

$$Q = \frac{\omega L}{Rc} \quad (10)$$

### 2. 3. Finite Element Method Simulation

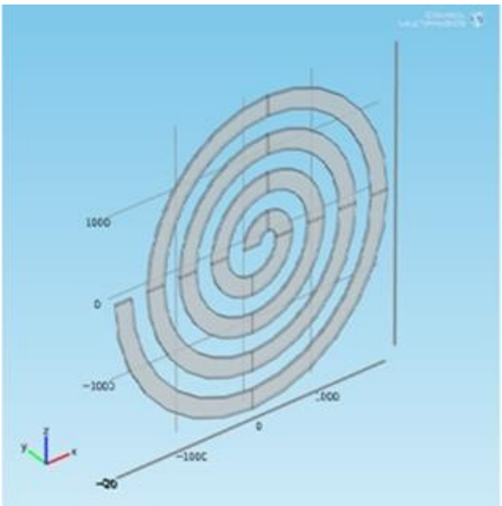
To investigate the theoretical calculation, SNR was calculated by COMSOL. This software calculates $B_1$ datum of Equation 3 by solving Maxwell equations for a defined coil geometry using the finite element method [11].

Figure 6 illustrates the simulated geometry in COMSOL. Dimensions of a cylindrical phantom were adapted to the microcoil's dimension. The sample contains normal saline with electrical conductivity of $\sigma =$0.6 S/m and relative permittivity of $\varepsilon_r$=72; the microcoil was made of copper.

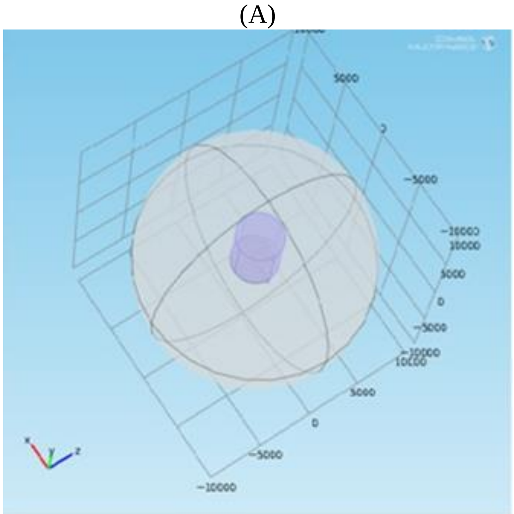
The micro-coil SNR, designed in this study, was compared with that of gallium microcoil, fabricated by Kong et al. (Figure 7) [7]. As indicated, the result of simulations are consistent with theoretical calculations. SNR of copper microcoil is ten times higher than gallium microcoil.

### 2.4. Micro-Coil Fabrication

Figure 8 presents the microcoil fabricated on PCB using the materials made of fiberglass, which were 1.6 mm in diameter and 35 micron in thickness. The microcoil was tuned at resonance frequency of 63.8 MHz. The microcoil was connected to 2 SMD capacitors, one parallel with the microcoil and the other in series with it. These capacitors are used for tuning and matching the microcoil. The scattering parameter ($S_{11}$) of microcoil was calculated using network analyzer.



(A)



(B)

Figure 6. Simulated geometry of microcoil by COMSOL (dimensions based on the micron scale). (a) Copper microcoil and (b) copper microcoils with a saline sample and its surroundings

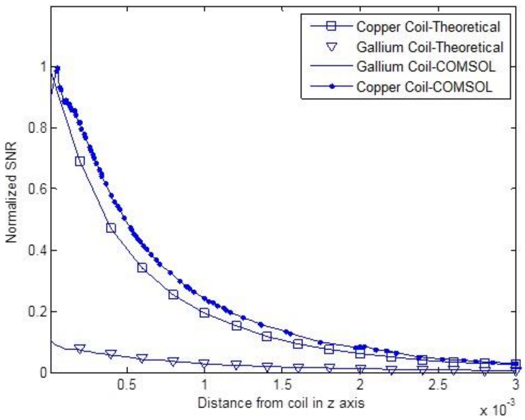



Figure 7. The comparison of normalized signal-to- noise ratio between the designed and gallium microcoils versus normal distance of microcoil's surface

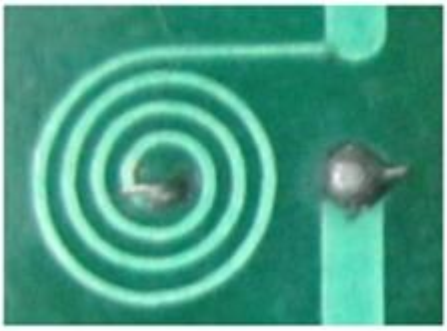


Figure 8. Spiral planar micro fabricated coil

## 3. Results

Figure 9 illustrates the resistance, inductance, and quality factor calculated by ADS[1] for the fabricated microcoil. Table 1 depicts a comparison of the geometries and resulting parameters of the previously presented planar microcoils accompanied with the fabricated microcoil in this study. Figure 7 verifies that the simulated and theoretical SNR results of the designed and fabricated copper coil in this study are consistent with each other.

Network analyzer was employed to investigate the efficiency of copper microcoil. Scattering parameter ($S_{11}$) shows the returned power loss. The microcoil was tuned at resonance frequency of 63.8 MHz and the scattering parameter was calculated to be -48 dB.

Figure 10 illustrates the results of scattering parameter ($S_{11}$) in ADS simulation and Network Analyzer measurement. In comparison with the measured value, the relative error of simulation is equal to 10%.

To obtain the SNR of the fabricated microcoil and evaluate its capability in recognition of micro sample, MRI (Model: GE) 1.5 Tesla was used. The sample was put in a sample holder and was fixed above the coil using the PCB.

Figure 11 (a) shows the axial image of a saline sample drop, acquired in seven minutes using the fabricated coil. The distance between the image plane and coil surface was set to 1 mm. To calculate the SNR, MATLAB software and equation 11 were used.

[1]Advanced Design System

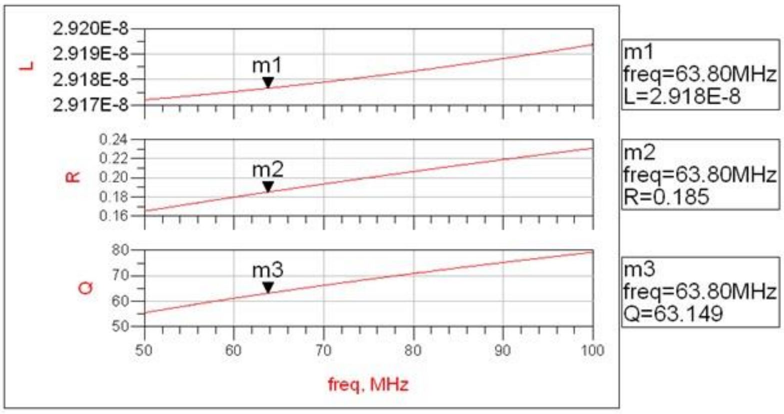
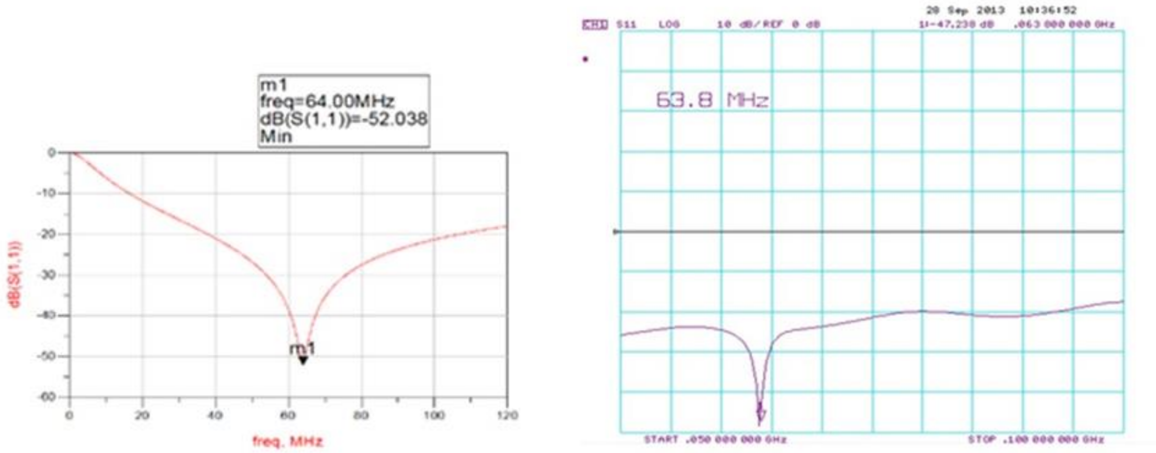
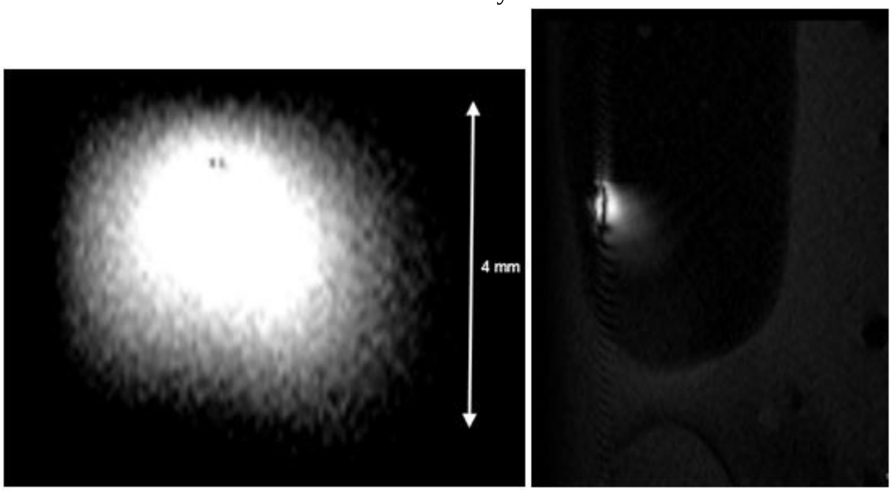



Figure 9. The simulated values of resistance, inductance, and quality factor of the copper microcoil by ADS




(A) (B)

Figure 10. Scattering parameter ($S_{11}$) of planar spiral micro-fabricated coil. (a) simulated by ADS and (b) measured by Network Analyzer




(A) (B)

Figure 11. Axial image of a saline sample acquired by (a) the fabricated microcoil, Imaging parameters were: Spin Echo, TE= 17 ms, TR= 1500 ms, FOV=4 cm, Slice thickness= 1 mm, Matrix size= 192×160, Number of slices= 1, Number of excitations (NEX) = 2, (b) a conventional surface coil of MRI 1.5T. Imaging parameters were: Spin Echo, TE= 17 ms, TR= 1500 ms, Field Of View = 8 cm, slice thickness= 1 mm, matrix size= 256× 192, Number of slices= 24, Number of excitations (NEX) = 2

Table 1. Comparison of electrical performances for the pervious planar micro-coils. (Inner diameter ($D_{in}$), number of the coil rings (N), Inductance (L), Resistance ($R_c$), Resonance frequency (f), Quality factor (Q) and Signal to Noise Ratio (SNR))

| Reference | Baxan, et al. [6] | Peck, et al. [12] | Massin, et al. [9] | Stocker, et al.[13] | Kong, et al. [7] | Kratt, et al. [14] | This research |
|---|---|---|---|---|---|---|---|
| Geometry of micro-coil | Planar elliptical | Planar rectangular spiral | Planar spiral circular | Planar rectangular spiral | Planar spiral circular | Spiral volumetric | Planar spiral circular |
| Type of micro-coil | Copper | Gold | Copper | Gold | Gallium | Copper | Copper |
| Year | 2006 | 1994 | 2002 | 1997 | 2012 | 2010 | 2014 |
| $D_{in}$(μm) | 708 | 97.5 | 500 | 60 | 500 | 300 | 241 |
| N | 4 | 4.5 | 3 | 3.5 | 5 | 5 | 4 |
| L(nH) | 7.5 | 4.3 | 8.7 | 5 | 7.48 | 14 | 29.18 |
| $R_c$(Ωm) | 0.62 | 8.6 | 0.7 | 5 | 0.3 | 2.2 | 0.185 |
| f(MHz) | 200 | 300 | 300 | 250 | 21.65 | 400 | 63.80 |
| Q | 24 | 0.9 | 23.5 | 1.57 | 30.4 | 52 | 63.149 |
| SNR | 80 | 20 | 20 | 25.5 | 80 | 53.89 | 168.2306 |

$$SNR = \frac{\text{Mean Of Signal}}{\text{Standard Deviation Of Noise}} \quad (11)$$

In MATLAB a region of interest (ROI) on image that covers imaging signal of the sample was selected, and then mean of the data of this window was considered. After that to calculate standard deviation of noise, a window without any data of sample's signal was selected. The measured SNR was equal to 168.2306 at the center of the image.

In another experiment, imaging was performed using a conventional surface coil of MRI and the same saline sample drop as previous experiment. Figure 11 (b) shows the axial image of sample in this experiment. Imaging was performed in nine minutes. The measured SNR was 29.9 at the center of the image. So the image SNR is poor and cannot be used in clinical studies.

The measured values of SNR in the above-mentioned imaging methods (Figures 11 (a) and (b)) are presented in Table 2. SNR of the fabricated microcoil is about 5.6 times higher than that of the conventional surface coil of MRI 1.5T.

Table 2. Experimental SNR Values

| | Signal(Mean) | Noise(RMS) | SNR |
|---|---|---|---|
| Fabricated micro-coil | 255 | 1.5158 | 168.23 |
| Conventional surface coil of MRI 1.5T | 171.4717 | 5.7329 | 29.9 |

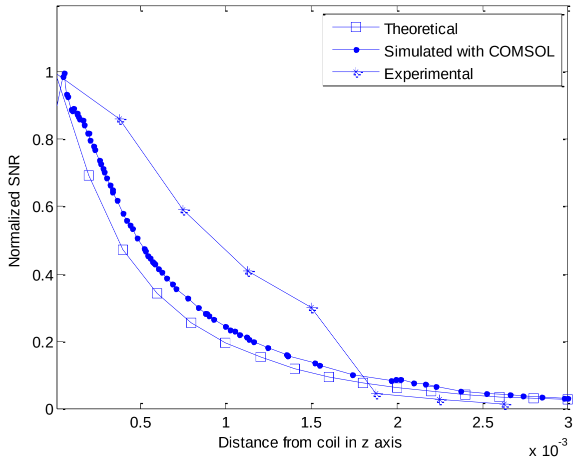



Figure 12. Analytical, simulation, and experimental results for normalized signal-to- noise ratio of the fabricated coil

Figure 12 shows the normalized SNR versus the normal distance from the fabricated coil surface, which was obtained from experiments and simulations. This figure verifies that the SNR values calculated in experiments and simulations are comparable with analytical values. By increasing the axial distance, the SNR decreases in both analytical and experimental calculations. At 1 mm distance from microcoil's plate, the microcoil has an acceptable SNR. However, at this distance, the value of SNR is about half of the obtained SNR at the center of microcoil's plate. The RMS error between simulated and experimental values was calculated to be 17%.

## 4. Discussion

This study purported to design and fabricate a new radiofrequency microcoil for MRI systems. SNR and quality factor are the most effective factors in performance and evaluation of microcoils. At a constant resonance frequency, SNR is proportional to the quality factor according to the Equations 3 and 10; therefore, the highest performance of microcoil is achieved from maximized SNR and quality factor. In this study, planar spiral copper microcoil was designed, optimized, and fabricated by ADS and COMSOL. Simulations showed that the microcoil in the present study had a better quality factor compared to the former fabricated microcoils in references [6, 7, 9, 12-14]. Moreover, the SNR of microcoil in this article was 10 times higher than the microcoils fabricated in reference [7].

## 5. Conclusion

The measurement of reflection coefficient of microcoils reflected that the power return loss of microcoil is minuscule. Results of MRI measurement showed that the SNR of fabricated microcoils was about 5.6 higher than the planar MRI coil. Accordingly, to increase the SNR, micro array coils can be applied.

In addition, the SNR is proportional to inverse square root of coil's resistor. Although the microcoil was made of copper, its purity is less than the pure copper. It leads to increased resistance of microcoil, and consequently, reduced SNR. By investigating various types of copper with high purity, the SNR of fabricated microcoil can increase.

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