A Novel Spiral Radiofrequency Coil for High Field Mouse Cardiac Imaging

C. Constantinides¹, S. Gkagkarellis¹, S. Angeli¹, and G. Cofer²

Abstract—The idea of a novel MR surface coil based on multi-turn spiral geometry is presented for use in mouse cardiac MRI. The benefits from flat, cylindrical arrangement of the coil are compared using computer simulations and MRI experiments in various cases of free space, phantom and animal loading conditions. Results show that the cylindrical case compares well with a commercially available birdcage coil offering a 50% signal intensity improvement for depths of penetration up to 6.1 mm from coil surface. There is also adequate B₁ field penetration that allows visualization of the lateral and inferior walls of the murine heart.

Keywords – Magnetic Resonance Imaging, cardiovascular system, mouse, radio frequency coils, simulations, image processing, SNR, relaxation times.

I. INTRODUCTION

The mouse has been emerging as one of the most prominent models for the study of cardiac function over the past few years. As an extension of such work, recent imaging attempts have been focusing on image-based cardiac phenotyping of normal and transgenic mice [1]. Despite the fact that a number of prior studies quantified cardiac function and mechanics with state-of-the-art imaging technology, including magnetic resonance imaging (MRI), some of such prior attempts [1-8] have not considered optimal radiofrequency (RF) designs, but have instead exploited conventional surface and quadrature transmission (TX)/reception (RX) coils, or have adopted new phased array technology for multi-channel mouse cardiac ¹H MRI [9,10]. The reduced field-of-view (FOV) acquisitions for mouse imaging, the increased cost and technical complexity of multi-channel systems, phased array complex mutual coupling effects, in addition to insignificant additional benefits in signal-to-noise (SNR) performance of such arrays, have led to an increasing use of birdcage coils (good filling factors, uniform B₁ excitation) and surface coils for imaging the mouse. Surprisingly, not much attention has been expended on the optimization of the size and geometry of surface coils employed in prior successful imaging attempts, with constructed coils having dimensions that range from 25-35 mm. Considering a distance of the infero-lateral cardiac wall from the mouse chest surface of approximately 10-14 mm, the ideal coil should be designed in such a way to evoke a B-field response with optimal penetrance.

This paper presents a novel surface coil design that allows optimal B₁ reception using multiple turns in a spiral arrangement. A comparison between the flat and cylindrical geometries is attempted (from simulations and actual MRI experiments) to establish optimal field penetration conditions (allowing infero-lateral wall imaging), with adequately high SNR, exploiting the additive effect of the transverse B-field component in the cylindrical case. Overall, this work establishes a platform for accurate, quantitative comparisons of B₁ performance of any coil design and geometry in a fully automated fashion, that includes the initial computer design, free space simulations, and simulations under realistic conditions of loading (both with phantoms and computer-generated animal biomodels) using closed form and analytical solutions of the Biot-Savart and Maxwell’s equations, accounting for the morphology, and electromagnetic property characteristics of relevant anatomic structures.

II. METHODS

Autocad Designs: Three radiofrequency (RF) coils were designed using Autocad Mechanical Desktop software (Version 2007, Autodesk Inc., San Rafael, California, USA), and included a single-loop coil with dimensions of 4.7x4.4 cm²; a three- and a four-leg spiral coils (4.7x4.4 cm²) with a 1-2 mm spacing between each spiral track, and spiral coils with the same dimensions as the flat equivalents, wrapped on a cylindrical former with an internal diameter of a commercially available quadrature coil of 32 mm internal diameter (M2M imaging corporation, Ohio, USA). Designed...
schematics were saved in standard Autocad file formats (.sat, .cad) and were exported in XFDTD (Version 7.0.2, Remcom Inc., State College, Pennsylvania, USA).

**Hardware Development:** Construction and preliminary testing was conducted in the Laboratory of Physiology and Biomedical Imaging at the U. Cyprus (LBI-UCY), and MRI testing was performed on phantoms and two mice (one post-mortem and one in vivo under anesthesia) at the Center for In Vivo Microscopy (CIVM) at Duke University, according to the National Institutes of Health and the Veterinary Services ethical rules and directives. The coils were designed and constructed with thin (0.02 mm thickness) single-sided copper sheets, using standard photo-etching technology. For the technical construction, coil lithography/etching materials were also used that included professional photo-resist lamination of microwave substrates (Kepro Bench-Top Laminator Model BTL-212, Total Systems Concept Inc., Fenton MO, USA) customized CAD/CAM design software for translation of coil patterns to masks (Inventor Pro, Autodesk Mechanical Desktop), using high intensity photo-resist exposure (Gralab 600, Dimco-Gray Co, Centerville Ohio, USA), and hardware tools.

**Coil Implementation:** The coils were implemented with resonant circuitries using 0.25 and 0.5 inch copper tape (3M Inc., USA) wherever necessary, high breakdown voltage (>1000 V) ceramic capacitors (ATC Inc., USA), and shielded RG58/59 co-axial cable (Belden Inc., USA). Electrical losses were minimized by distributing the total capacitance, through the introduction of a number of copper-track breaks. Variable matching and tuning capacitors were used to account for the coil assembly coupling loading during placement inside the scanner gradient insert and due to sample loading. Coil tuning and matching was achieved with a state-of-the-art 1.5 GHz Network Analyzer (Model E5061A, Agilent Inc., USA). Interface of constructed probes with the scanner and measuring electronics (Network analyzer, digital oscilloscope, sweep generator) was achieved with standard BNC non-magnetic 50 Ω termination connectors.

**Electrical Performance:** Electrical response was assessed with the measurements of unloaded and loaded parameters on phantoms and animals, and included values of the reflection coefficient (ρ), single port reflection parameter (S11), and composite impedance. These parameters were measured using the Network analyzer by sweeping the frequency from low values to the Larmor frequency at 7.1T (fL=300.5 MHz). Assessment of the coil performance also included B-field simulations of the transverse and total field components in free space using the Maxwell's and Biot-Savart equations [11] with Matlab (Matlab Inc., Natick, MA, USA). Simulation of lossy conducting media (adipose tissue, skeletal musculature, lungs, blood cavities, and cardiac tissue) in a real-life animal model and in phantoms were carried out using an electrical/magnetic property compartment/organ model with XFDTD, using finite element mesh computations as described below.

**Simulations:** For XFDTD simulations, the coil conductors were defined as perfect electric conductors (PEC). A 1 V sinusoidal feed was applied, with 1 A excitation current and a conductor impedance set to 50 Ohms. Excitation was emulated using broadband and modulated gaussian pulses centered at the Larmor frequency of 300.5 MHz at 7.1 Tesla. The distribution of the magnetic field was simulated at the mid-axial, the mid-sagittal, and at a coronal slice placed 5 mm above each of the three coils in the: (a) free-space case; (b) under loading conditions with a 50 ml gel cylindrical phantom (having an external diameter of 3.2 cm and a length of 11.7 cm); and (c) under loading conditions with a rat-mesh model scaled to the dimensions of a typical 25-30 g mouse (with approximate superior-inferior, anterior-posterior, and lateral-medial-lateral dimensions of 8.9 cm, 4.5 cm, and 2.5 cm, respectively). To validate the free-space simulations, the computed XFDTD results were compared with corresponding results from routines written in Matlab (Version 7.1, Mathworks Inc., Natick, MA, USA), assuming infinitesimal wire segment widths. For the simulation, the Biot-Savart law was numerically solved for all the straight (or cylindrical) wire elements of each of the three coils. The reconstructed B-field grid with Matlab was spatially matched to that of the XFDTD simulations and encompassed [133-168]x[84-142] axial grids, [102-133]x[84-190] sagittal grids, and [136-145]x[83-419] grids for coronal slices (with cell sizes of 0.25-1 mm² in all cases), for quantitative comparison purposes.

**MRI Tests:** After successful implementation, the probe performances were tested on the MRI scanner (CIVM-Duke), first on phantoms and then on mice. New coil

---

![Autocad coil designs and imported XFDTD cylindrical design](image)

**Fig. 1.** Autocad coil designs and imported XFDTD cylindrical design; [Top] (Left to Right) single loop, three-leg flat, and three-leg cylindrical spiral coils; [Mid] XFDTD mouse model superimposed on the cylindrical spiral surface coil; [Bot] constructed prototype four-leg spiral RF coil.
configuration files were generated on the scanner with appropriate cable and reflection coefficient losses for testing. Testing included a series of phantom and cardiac image comparisons that allowed assessment of the best probe performance, in magnitude, single-receiver, sum-of-squares reconstructed images from the flat and cylindrical spiral coils.

Quantitative comparisons were based on image signal-to-noise ratio (SNR) [12,13] and contrast-to-noise ratio (CNR) values, effective field-of-view (FOV), field homogeneity, and depth of penetration of transverse field components in stationary phantom and mouse cardiac studies.

**Gel Phantom Construction:** Saline solutions (154 mEq/L NaCl) were heated to boiling temperatures. Agarose powder (Sigma-Aldrich, Missouri, USA) and copper sulfate (CuSO₄) were added at various % and molarity concentrations to attain desired T₁ and T₂ relaxation parameters, according to a pre-existing state-phase diagram (unpublished work – Dr. E. McVeigh cited on the web-site: www.mri.jhmi.edu/MedImgLab) and indicative relaxations values published previously [14]. Upon dilution, the solution was poured into 50 ml plastic cylindrical vials and was allowed to solidify.

**MR Imaging: Phantom Imaging:** Work was performed at the 7.1 T MRI scanner equipped with a GE EXCITE console (EPIC 12.4). A conventional Carr-Purcell Meiboom Gill (CPMG) pulse sequence with 16 echoes was employed for single slice T₂ imaging. The acquisition parameters were: Field of View FOV=5 cm, repetition time TR=6 s, echo time, bandwidth BW=31.25 kHz, slice thickness ST=2 mm, and a 128x128 acquisition matrix. For T₁ imaging, a conventional saturation recovery (MEMP) pulse sequence was employed with FOV=5 cm, ST=2 mm, BW=31.25 kHz, number of averages NEX=1, and a 256x256 acquisition matrix. Sixteen different images were reconstructed at equal time intervals, every 375 ms.

For B-field penetration comparative studies (flat and cylindrical spiral coils), a conventional multi-slice spin echo sequence was used in axial, sagittal, and coronal orientations, with FOV=5 cm, ST=2 mm, BW=31.25 kHz, phase FOV=1.0, 128x128 matrix, TE=8 ms, Number of slices=19, NEX=1, at fully relaxed conditions (TR≥3T₁).

**Mouse Cardiac Imaging:** Further to the successful implementation and testing of the probes, they were subsequently tested on one mouse (post-mortem) and compared with the commercially available birdcage coil on one mouse under anesthesia using a conventional multislice, single cardiac phase, gated spin echo pulse sequence with the following parameters: FOV=5 cm, ST=1 mm, NEX=8, TE=3.7 ms, TR=150 ms and a spoiled gradient echo sequence with TR=100 ms, NEX=2, FOV=5 cm, ST=2 mm, and BW=15.63 KHz. One male C57BL/6J mouse (weight=35.8 g; age=32 weeks) was imaged using MRI post-mortem and one mouse (weight=22.8 g, age=9 weeks) using 1.5% isoflurane anesthesia.

**MR Processing: Phantom images were saved in standard .raw or DICOM formats and were exported and read in Matlab. Custom-made Matlab routines were written that allowed further processing and visualization. Relaxation parameter estimation was achieved by region-of-interest estimation of mean signal intensities from phantom images at the various TR or TE frames followed by subsequent curve-fitting using standard mono-exponential rise or fall curves (Logger Pro, Version 3.5.0, Vernier Software and Technology, Beaverton, OR, USA). SNR and CNR estimates were obtained using standard methodology, according to prior reports in the literature.

**III. RESULTS**

Figure 1 presents diagrammatical representations of the designed coils using Autocad and custom made coils. Electrical performance characteristics yielded unloaded and loaded gains in the flat spiral coil of -14 and -17.3 dB, total impedances of 57.8+j21.1 Ω, and 55.0+j13.2 Ω; and corresponding values of -20.0 and -30.0 dB, 58.1+j10.4 Ω and 49.5-j3.5 Ω for the cylindrical four-loop spiral coil. The reflection coefficient was <10% in all cases. In all cases, the prominent noise source was due to the sample as observed from the significant change of the resonance peak upon loading. Figure 2 presents comparative free-space simulation results between Matlab and XFDTD at axial, sagittal, and coronal slices. The percentage difference of simulated B-field distribution (Matlab, XFDTD) was quantified in a total central volume of 45x41x11 mm³, at a depth of penetration from the coil-conductor surface of 3-13 mm. Percentage differences (means±SD) in axial, sagittal, and coronal orientations were 5±2.7, 7.2±3.8, and 2.7±0.9 %,
respectively, with noted maximum (and minimum) percentage differences in the three cases of 16.9 (1.3), 21.7 (2.0), and 17.1 (0)%, respectively.

Figure 3 shows prominent improvement in performance for the cylindrical spiral coil in comparison to the flat equivalent, both in terms of the increased field-of-penetration, but also in terms of the increased B-field response in regions where the mouse heart is typically positioned in unloaded and loaded cases (with a 50 ml cylindrical phantom). Figure 4 presents typical MRI results from $T_1$ and $T_2$ phantom imaging. Table 1 lists the estimated quantitative results for the various gel phantoms constructed. Qualitative and quantitative comparisons of $B_1$-performance of the tested four-loop flat and cylindrical spiral coils under loaded conditions (gel phantom) using $^1$H MRI are depicted in Figure 5, indicating a 50.3% increase in signal intensity performance on the spiral cylindrical coil surface compared to the birdcage coil, and overall increased performance for penetration depths up to 6.1 mm from surface. Also shown are actual MRI cardiac images from the flat and cylindrical spiral (post-mortem imaging), and a commercially available birdcage coil (in vivo imaging).

**IV. DISCUSSION**

This conference paper describes the design, implementation and construction of a novel spiral radiofrequency coil for optimal mouse cardiac MRI. It shows improved performance in the cylindrical case in comparison to the flat case, in a similar fashion to prior published attempts for human imaging [15]. The cylindrical coil has increased field of penetration that allows visualization of the entire lateral/inferior wall with adequate SNR. Additionally, it compares well with a commercially available birdcage coil. Simulations yielded accurate results in the free-space case (as compared with closed form or analytical solutions of the B-field using Matlab), and yielded results that compared well in the phantom and scaled-down mouse model. Future work will focus on the combined use of the novel spiral coil and the commercially available birdcage coil.

**TABLE I**

<table>
<thead>
<tr>
<th>Gel</th>
<th>$T_1$ Estimated (ms)</th>
<th>$T_1$ Measured (ms)</th>
<th>$T_2$ Estimated (ms)</th>
<th>$T_2$ Measured (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1000</td>
<td>966</td>
<td>38</td>
<td>30</td>
</tr>
<tr>
<td>2</td>
<td>1000</td>
<td>972</td>
<td>50</td>
<td>32</td>
</tr>
<tr>
<td>3</td>
<td>2000</td>
<td>1361</td>
<td>56</td>
<td>55</td>
</tr>
<tr>
<td>4</td>
<td>-</td>
<td>-</td>
<td>40</td>
<td>55</td>
</tr>
</tbody>
</table>

Table 1. Estimated and measured $T_1$ and $T_2$ relaxation values for the constructed gel phantoms.

**ACKNOWLEDGMENT**

Work was performed at the Duke Center for In Vivo Microscopy [CIVM], an NIH-NCRR National Biomedical...
Technology Research Center, and at the Laboratory of Physiology and Biomedical Imaging (LBI) “Hippocrates” of the University of Cyprus. We thank Remcom Inc. (Mr. S. Langdon, Mr. M. Hinks, Mrs. L. Smith) for their invaluable support and Dr. John Nouls for his advice and help in the construction and fabrication of coils. We also thank Mr. Atul Sancheti, a visiting undergraduate student from the Indian Institute of Technology for his help with the initial simulations.

REFERENCES


