Solenoid coil for mouse-model MRI with a clinical 3-Tesla imager: body imaging

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A solenoid coil was built for magnetic resonance imaging of the mice. A coil prototype composed of 5 turns, with a length of 4 cm and 2.5 cm radius was developed to acquire (whole) body mouse magnetic resonance images at 130 MHz and an insertable gradient coil set. Coil performance was measured using the *Q* factor for both the loaded and unloaded cases were 161.67 and 178.03, respectively. These *Q* factors compare very well with those values reported in the literature. The images were acquired with a clinical 3 T system equipped with a custom-built gradient insert coil and gradient echo image sequence. Both phantom and in vivo images showed good signal-to-noise ratio and uniformity. The electromagnetic interaction between the insertable coils and the solenoidal coil is poor, and no image artefacts are present in the whole-body image of the mouse. This preliminary experience has shown that consistent high quality MR images of the mice can be obtained using this particular hardware configuration, making it a promising method for acquisition of high-spatial resolution MR images of mice. Volume coils are still a good choice when combined with high field MR imagers and standard gradient echo sequences for the magnetic resonance imaging of the mouse.

Keywords: mouse MRI; solenoid coil; electromagnetic simulation.

Una antena del tipo solenoide fue construida para generar imágenes por resonancia magnética de ratones con un sistema de cuerpo entero de 3 T de uso clínico y un arreglo de antenas de gradientes insertable. El prototipo de antena consistió en 5 vueltas con una longitud total de 4 cm y un diámetro de 2.5 cm. El desempeño de la antena se midió usando el factor *Q* para los casos cargado y sin carga cuyos resultados fueron 161.78 y 178.03 respectivamente. Estos valores concuerdan muy bien con los reportados en la literatura. Se obtuvieron imágenes de un maniquí construido específicamente para este propósito con isletas marcadas con un agente de contraste, usando una secuencia gradiente-eco. La interacción electromagnética entre el conjunto de gradientes insertables y la antena solenoide es pobre, y no hay evidencia de artefactos de imagen en las imágenes de cuerpo entero del ratón. Esta experiencia preliminar muestra que esta clase de antena ofrece una alta calidad de imágenes de ratón que es posible obtener con un sistema de 3 T. Las antenas de volumen son una buena elección para obtener imágenes de alta resolución espacial en investigación preclínica de ratones a campos magnéticos altos.

Descriptores: IRM de ratones; antena solenoide; simulación electromagnética.

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1. Introduction

Magnetic resonance imaging (MRI) of the mouse is an imaging modalitiy with great potential for studying human diseases through animal models [1]. Small animals can be imaged directly using the coils supplied with clinical imagers [2]. However, the spatial resolution attained (approximately 1 mm) provides very little anatomical information in a mouse. Improved spatial resolution can be obtained provided a significant gain in the signal-to-noise ratio (SNR) is achieved. For small animals, considerable gain in SNR is achieved with the use of Radio Frequency (RF) receiver coils designed to fit the dimensions of the animal.

Imaging of whole-body specimens can be performed with RF volume coils such as the traditional birdcage [3-4], the saddle coil and the solenoid coil [5]. Volume RF coils like the traditional birdcage coil are known to have good field uniformity but relatively low SNR. With the advent of the high field MR systems, an improvement on SNR for volume coils can be gained. These three RF coil designs have been extensively used in small-animal MRI.

Solenoids were the mainstay of NMR receiver coils in the early days for a very simple reason: they permit the highest SNR when sample losses are not dominant and B_0 (external magnetic field strength) homogeneity is not critical [6]. The solenoid coil design has been studied for different applications and its advantages reported elsewhere [7-10]. Dedicated small-sample solenoid coils provide improved SNR efficiency for small specimens.

In this work, a solenoid coil was developed for body-mouse magnetic resonance imaging. Imaging experiments were conducted on a clinical 3 T imager equipped with an insert gradient coil set. The custom-built gradient insert coil was built using the method of constrained current minimum inductance, with the solution for the minimum inductance current density satisfying a set of field constraints, subject to a set of constraints on the current density itself. The current constraints are defined by the region over which the current is allowed to flow and therefore specify the design's aspect ratio, defined as the ratio of the coil's length to its diameter. This gradient coil has an inner diameter of 17.5 cm, a maximum gradient strength of 600 mT/m and a slew rate greater than 2000 T/m/s [11]. In addition, a specially designed gel phantom containing isolated pancreatic islets for in vitro studies, and a mouse model of transplanted pancreatic islets into liver for in vivo studies were also used. The experimental and uniformity results showed that this coil design is able to generate high quality phantom images with fast scanning techniques such as standard gradient echo sequences.

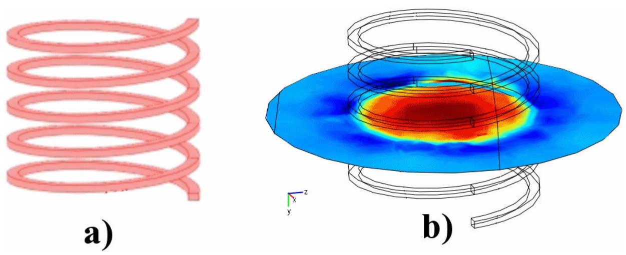

FIGURE 1. Three-dimensional model to perform the electromagnetic simulations of the solenoid coil using Eq. (1a), and numerical simulation of the solenoidal coil magnetic field computed with the commercial software tool (b).

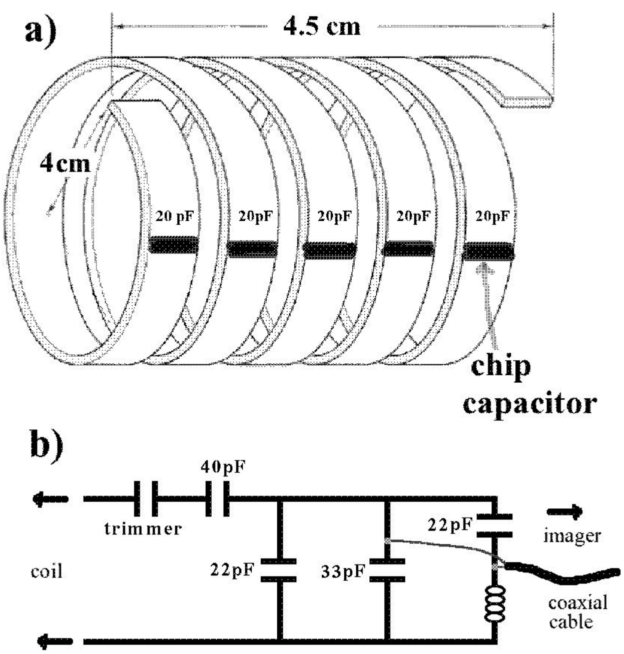

FIGURE 2. Illustration of the solenoid coil showing dimensions and electronics components in a) and the BALUM circuit in b).

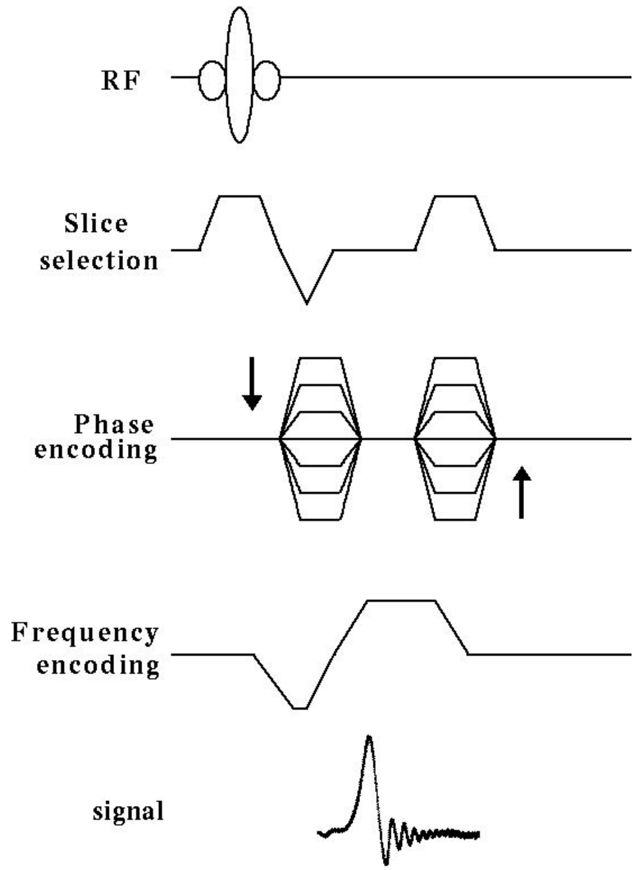

FIGURE 3. Timing diagram of the pulse sequence fast imaging steady-state acquisition (FIESTA).

2. Method

2.1. Electromagnetic simulation

Before building the solenoid coil, its magnetic field was studied via numerical electromagnetic simulations. All simulations were conducted using the finite element method on a PC operated on a Windows platform. The commercial software tool, COMSOL (COMSOL V3.2, Burlington, MA, USA) that uses the finite element method to obtain the magnetic field distribution was used due to its ability to model complex geometric structures with acceptable accuracy. The three-dimensional model is shown in Fig. 1a. The numerical simulation runs were performed using the following electrical considerations: the solenoid coil was designed using the copper electrical properties (specific conductivity and relative permittivity for copper are 5.998×10^7 S/m and 1 respectively) taken from the COMSOL software. The following simulation parameters were used: 4030 degrees of freedom, 476 mesh points, 2523 elements, 2523 tetrahedral elements, 684 boundary elements, 684 triangular elements, 330 edge elements and 50 vertex elements. In addition, the magnetic field was also calcualted using the quasi-static approach for comparison purposes. The magnetic induction is derived from the Biot-Savart law [15]:

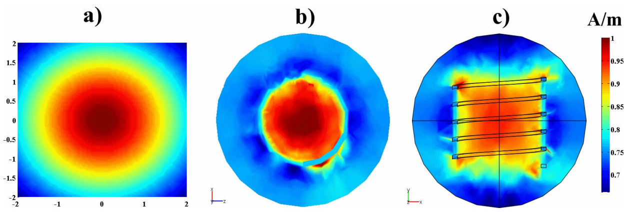

FIGURE 4. Numerical simulations of the magnetic field for the solenoid at 130 MHz for (a) axial and (b) coronal and c) saggital orientations.

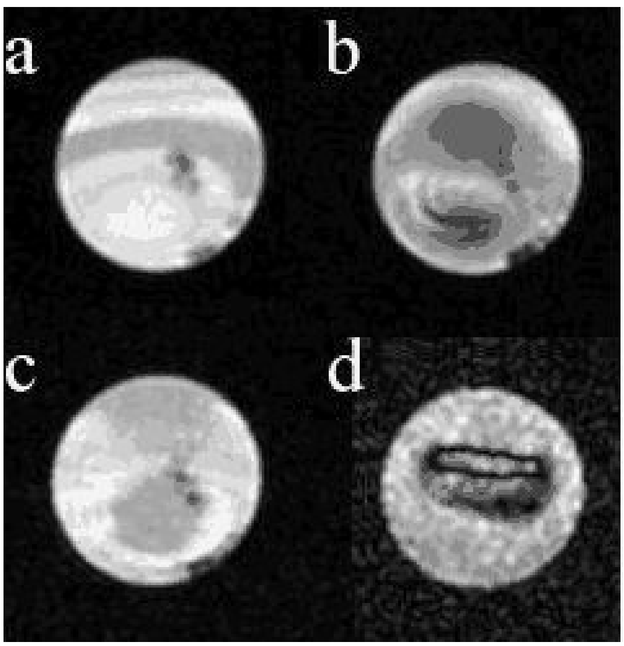

FIGURE 5. Phantom axial images acquired with the solenoid coil designs. All images are T1-weighted with a FIESTA sequence at 20MHz (a), 30MHz (b), 80MHz (c) and 140MHz (d).

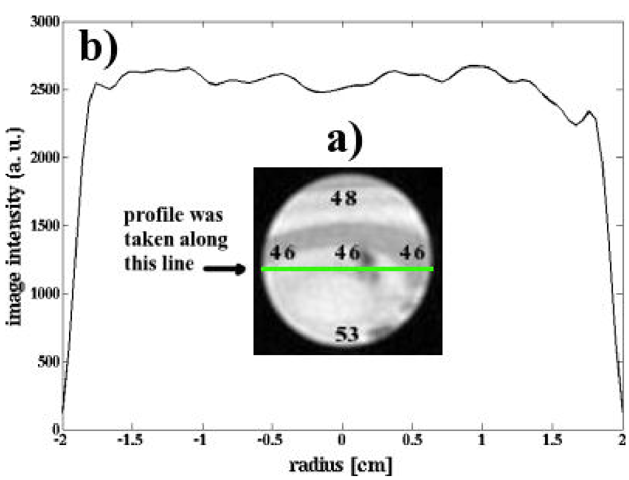

FIGURE 6. a) Experimental estimates of SNR from a standard phantom image were computed along two orthognal directions to study behavoiur of image quality. b) Uniformity profile computed along the phantom diameter.

$$B_1 = \frac{\mu N I}{\sqrt{4R^2 + l^2}} \tag{1}$$

where μ is the magnetic permeability, N the number of turns, I the current, R the radius of the solenoid and l is the length of the coil.

2.2. Coil design and construction

A solenoid coil was built in our laboratory with only 5 turns. Figure 2 shows an illustration of the coil prototype. The coil prototype was 5 cm long with a 4 cm diameter. The 5-turn solenoid coil was assembled with a 3 mm diameter copper wire. The coil prototype was designed to operate for the reception-only mode. The coil prototype is big enough to accommodate mice weighing 40 g. To tune the coil to 127.74 MHz, 5 chip fixed-value series capacitors were soldered to the coil. To transmit the MR signal to the imager, a $1/4\lambda$ coaxial cable was attached to the coil prototype. The resonant frequency of protons was measured as the reflection coefficients (S_{11}) by using an HP network analyzer and S-parameter test set (Model 4396A, Agilent, Palo Alto, CA, USA). The quality factor Q of the solenoid coil was determined experimentally by measuring the resonant frequency of the coil divided by the 3-dB bandwidth $\Delta\omega$.

2.3. Gradient echo pulse sequence

A pulse sequence is a series of events involving RF pulses, gradient waveforms, and data acquisitions. The purpose of the pulse sequence is to manipulate the magnetisation in order to produce the desired signal. In this work, the fast imaging steady-state acquisition (FIESTA) pulse sequence [12] was used for all imaging experiments. FIESTA is the commercial name for a common gradient refocused echo (GRE) pulse sequence. This type of sequence is typically used for fast imaging that allows significant changes in FIESTA signal amplitude for voxels containing a contrast agent [13]. A timing diagram for a FIESTA pulse sequence is shown in Fig. 3.

2.4. Imaging experiments

All MR imaging experiments were performed on a 3T whole-body MR imager (Signa Excite, General Electric, USA). A gel phantom was built using a cylinder with contrast agent-filled microcapsules to mimic pancreatic islets (PI). All islets were labelled with ferumoxides injectable solution (Feridex: Bayer HealthCare AG). All isolated PI were magnetically labelled with superparamagnetic iron oxide (SPIO) nanoparticles in order to detect them on MR images as hypo-intense regions. Isolated PI were incubated overnight in CMRL-1066 medium (370°C, 5% atm. CO_2; HyClone, USA) with the SPIO MRI contrast agent Feridex (Berlex Laboratories, Canada) with 5.0 μg/ml of iron complexed with poly-L-lysine (15 μl/ml) (PLL, Sigma-Aldrich, USA) and then transplanted the into liver of BALB/c mice according protocol described in [14].

Phantom images were acquired with the standard FIESTA pulse sequences provided by the manufacturer. The coil prototype was placed in the isocentre of the imager. Imaging experiments were performed on a 3T MRI scanner (GE Medical Systems, USA) using a custom-built, high-performance gradient coil insert and a customized whole mouse body solenoid radiofrequency coil (3 cm in diameter, 5 cm in length). Images were acquired using a 3D fully refocused (steady-state free precession) gradient-echo sequence FIESTA. The following parameters were used: the repetition and echo times were 3.8 (TR) and 1.8 ms (TE), respectively, together with a flip angle of 25° and, a 62.5 kHz bandwidth, all within a FOV of 4×4 cm^2. The scanned resolution was 200×200×200 mm^3. Zero filling was used to give an interpolated voxel dimension of 78×78×100 mm^3. The scan time was 25 min for mice (3 min for gel phantoms). In addition, a number of experiments were conducted for different bandwidths to investigate the behaviour of the SNR image.

3. Results and discussion

Figure 1a shows the solenoid geometry and Fig. 1b the B_1 field homogeneity as a function of the resonance frequency at 3T (130 MHz) for *x-z* projection at the midsection of the coil. Figure 4a shows an *x-z* projection of the magnetic field obtained by the Biot-Savart law, Fig. 4b shows the *x-z* projection of the magnetic field and Fig. 4c shows an *x-y* projection of the magnetic field, both obtained by COMSOL. The B_1 field simulation demonstrates that the solenoid produces a good region of homogeneity useful for MRI. Although a reduced number of turns were used in this solenoidal coil, the uniform region of the magnetic field ensures that the Region of Interest (ROI) is big enough to get high quality images of the mouse. Fig. 4a and 4b allow us to compare the simulated B_1 field generated by COMSOL and the field obtained by the Biot-Savart law. There is fairly good agreement between the numerical calculation of the magnetic field using the Biot-Savart law and the finite element approach used with the commercial package. These numerical results show that the solenoid is able to generate a good region of homogeneity along the coil diameter and coil length. This confirms those results reported in the literature [6-9].

The performance was measured using the *Q* factor for both the unloaded and loaded cases. For the loaded case (Q_l), a saline-solution cylindrical phantom was placed inside the coil to mimic the biological sample to be imaged and was 161.67. The *Q* factor was also measured for the unloaded case (Q_u) and was 178.03. Finally, the quotient of the unloaded case over the loaded case was 1.10. This a pretty common result, taking into account that a saline solution phantom with small dimensions was used. There is a very good concordance with those values reported in the literature for this type of coil design [8,9].

Phantom images were first acquired with a fixed bandwidth value and depicted in Fig. 5, and showing distinctly between soft masses and islets. The image SNR was computed using a rough estimate, and specific regions of interest were taken from the image as shown in Fig. 6 Additionally, a uniformity profile was computed from the same phantom image. The profile in Fig. 6b shows very good uniformity generated by the solenoid coil developed by our group. These results allowed us to reliably scan the whole body of a mouse. Induced currents can be generated by the insertable coil set; however, phantom images of Fig. 5 did not show artefacts or distortions affecting the image quality. This is an important result since the insertable coil set was in close proximity to the coil and did not cause a great deal of distortion on the field uniformity.

In vitro images can distinctly show a good SNR and contrast, allowing easy visualisation of the islets and using relatively short acquisition times. Phantom images were then acquired with the gel-phantom for different bandwidths with a FIESTA sequence at 20 MHz, 30 MHz, 80 MHz and 140 MHz as shown in Fig. 5. These experiments were conducted to investigate the coil performance with this islet-filled phantom design. Uniformity profiles were then computed from these images for various bandwidths and plotted in Fig. 7. There is a clear dependence of the uniformity quality on the bandwidth size. Extra care should be taken when

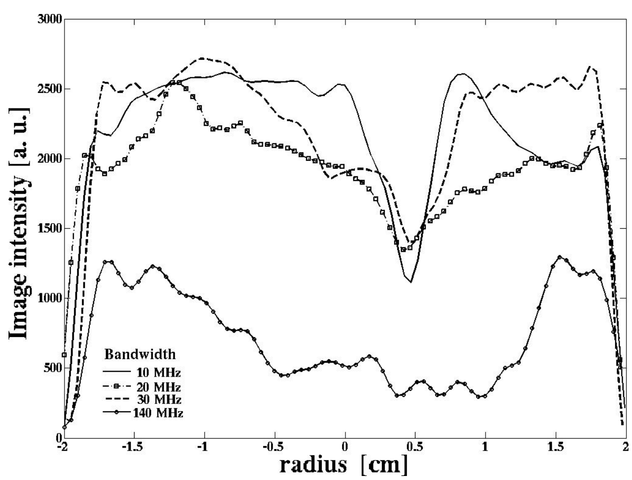

FIGURE 7. Uniformity profiles acquired from phantom images of Fig. 5 for different bandwidths.

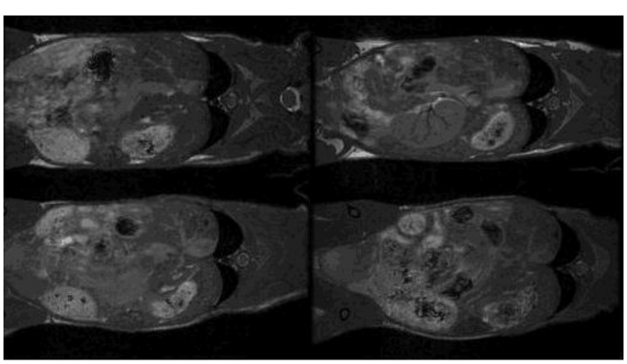

FIGURE 8. Coronal body images of implanted-islet mouse acquired with the solenoid coil. All images are T1-weighted. Arrows indicate the location of the pancreatic islets.

choosing the correct bandwidth to avoid losing good image quality. Finally, whole-body mouse images were acquired based on the acquisition times obtained with the phantom images. Figure 8 depicts coronal images of the pancreatic islets. In vivo imaging experiments demonstrated the ability of this coil design to discriminate between types of tissues and its compatibility with standard pulse sequences, although it is important to consider the MRI parameters such as pulse sequence, timings, and image resolution that are relevant in detecting the mouse anatomy.

4. Conclusion

The solenoid is a useful tool for obtaining MRI anatomical and functional images with high quality. The region of uniformity produced by the solenoid is good enough to scan a mouse, although the compromise with optimal parameters such as the selection of the pulse sequence, timings, and spatial resolution are still important to improve the quality of the image. COMSOL is a good tool for obtaining the magnetic field distribution useful in building a good solenoidal coil. The solenoid coil developed is fully compatible with clinical scanners and pulse sequences. It has been demonstrated that the solenoid coil is a good candidate coil design to be used in conjuction with a clinical scanner and an insertable gradient coil set to improve the quality of images small rodents.

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