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Ex vivo mouse brain microscopy at 15T with loop-gap RF coil

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ABSTRACT

The design of a loop-gap-resonator RF coil optimized for ex vivo mouse brain microscopy at ultra high fields is described and its properties characterized using simulations, phantoms and experimental scans of mouse brains fixed in 10% formalin containing 4 mM Magnevist™. The RF (B_1) and magnetic field (B_0) homogeneities are experimentally quantified and compared to electromagnetic simulations of the coil. The coil's performance is also compared to a similarly sized surface coil and found to yield double the sensitivity. A three-dimensional gradient-echo (GRE) sequence is used to acquire high resolution mouse brain scans at $(47\,\mu m)^3$ resolution in 1.8 h and a $20 \times 20 \times 19\,\mu m^3$ resolution in 27 h. The high resolution obtained permitted clear visualization and identification of multiple structures in the ex vivo mouse brain and represents, to our knowledge, the highest resolution ever achieved for a whole mouse brain. Importantly, the coil design is simple and easy to construct.

1. Introduction

Magnetic resonance microscopy (MRM) is a tool for microscopic imaging of ex vivo soft tissue samples. Unlike histology, MRM allows imaging of multiple tissue contrasts (T_1, T_2, diffusion-weighted, etc.) in addition to morphometric measurements. Moreover, because it is non-invasive, MRM preserves structural spatial relationships that can be lost during the sectioning process used in histology. Nevertheless, achieving micron-scale resolutions in reasonable scan times remains a technical challenge given the intrinsically poor signal to noise ratio (SNR) of MRI and the rapid degradation of SNR with increasing magnification. Overcoming this limitation requires the use of strong magnetic fields and special consideration in the design of the RF coil. One possible way of mitigating the low SNR intrinsic to smaller voxels is through reduction of the coil size [1]. This has led to development of micro-coils used to obtain in-plane resolutions as small as 3 μm [2]. However, the increased signal per pixel comes at the cost of reduced spatial coverage that prevents the use of micro-coils for experiments with large field-of-views (FOV). Instead, volume coils must be used with the added benefit of homogenous RF transmission and reception. Solenoid coils in particular are a popular choice and have been used with different configurations and field strengths in the quest to reduce the achievable voxel size. Huang et al., [3] reported scan times of 11 h imaging fixed mouse brains at 14T, achieving $25 \times 25 \times 37\,\mu m$ in a $512 \times 512 \times 256$ matrix, and $37 \times 37 \times 37\,\mu m$ in a $400 \times 256 \times 256$ matrix. An in-plane resolution of 39 μm was obtained in an ex vivo mouse brain in a 10 h scan at 9.4 T using a custom made solenoid coil [4]. More recently, 22 μm resolution was achieved, with the long scan time offset by partial acquisition of Fourier space though at the cost of some blurring [5]. Similar resolutions were obtained at a lower, 7 T, field strength with a solenoid coil but with a longer (13h) scan time [6].

In this work we propose an alternative to the solenoid coil and describe the construction of a remotely-tunable bridged double loop-gap resonator (LGR) RF coil optimized for fixed mouse brains at 15T. The loop-gap resonator design was chosen for its simple construction, large frequency tuning range, good filling factor and excellent RF homogeneity [7–10]. In particular, this double LGR design is based on that reported by Koskinen and Metz [8]. Because of the difficulties in tuning multi-turn loops at 15T, we compare the sensitivity of our design to that of a similarly sized, single turn surface coil. The combination of high field strength and optimized RF coil allowed acquisition of $20 \times 20 \times 19\,\mu m^3$ voxels that, to our knowledge, represent the highest resolution yet achieved in whole mouse brain MR imaging.

2. Material and methods

2.1. Coil construction

Coaxial cylinders made of polypropylene (outer cylinder) and quartz (inner cylinder), with dimensions as shown in Fig. 1a, were used as formers for the coupled resonator devices. The cylindrical conductors and bridge were formed from self-adhesive copper foil tape (Scotch

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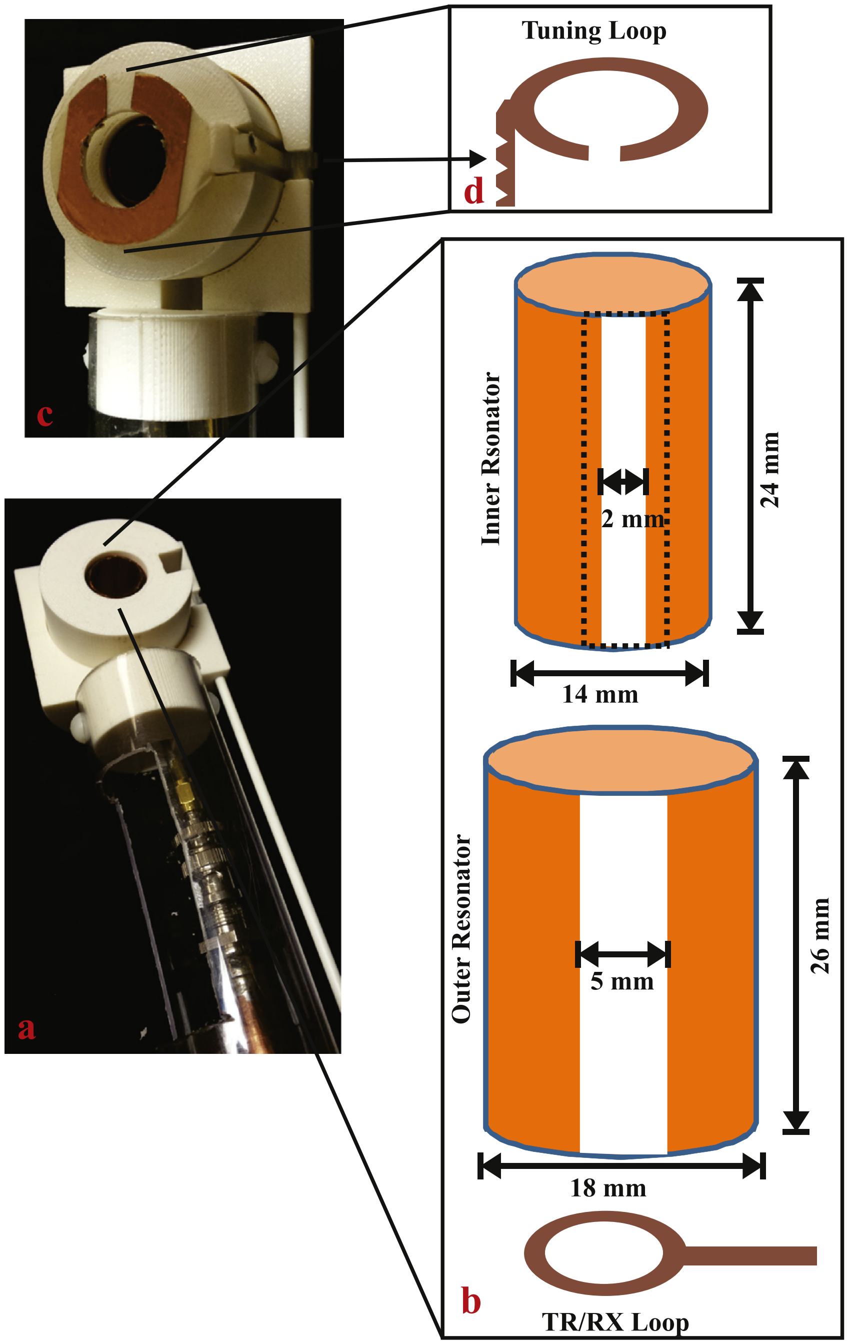

Fig. 1. Photographs of the double LGR RF coil design (a), (c) along with exploded view illustrations (b), (d). Relative rotation of the concentric resonators provides gross tuning of the frequency of the coil by varying the overlap across the capacitive gaps in the copper foil covering the resonators, in effect varying the capacitance in series with the coil inductance. Note that no discrete capacitors are needed for tuning. An additional piece of copper foil (dotted rectangle), insulated from both cylinders and rotating with the inner cylinder, was used to bridge the gap on the inner resonator and improve the RF homogeneity. Adjusting the height of the loop above the coil with the gear and rack mechanism (c) allowed fine tuning of the resonance frequency of the coil while inside the scanner. Coupling to the scanner was achieved using the TR/RX loop shown.

Brand Foil Tapes, 3M, Inc., Minneapolis, MN, USA) with gaps of 2 and 5 mm in the inner and outer cylinders respectively. The gap widths were chosen to adjust the resonance frequency of the resonator to that of the 619 MHz scanner. Adhesive Teflon tape was used to secure the copper tape, allow smooth relative rotation of the two cylinders and to increase the dielectric constant of the inter-cylinder space. The gap in the inner cylinder was bridged by a 24 mm long × 8 mm wide copper tape to improve the magnetic field homogeneity [9]. The coil size was selected to maximize the filling factor given the size of the ex vivo mouse brain samples. An initial estimate of the required inductance and capacitance was made with Eqs. 2 and 3 of Ref. [8] and was validated using electromagnetic simulations as described in the Simulation section below. Rotating the resonators with respect to each other allowed gross tuning of the resonance frequency of the coil over a 400 MHz range which was more than sufficient to overcome the ~6 MHz frequency shift upon insertion of the coil into the MR bore caused by the imperfect shielding.

Since the small diameter of the magnet bore permitted limited access to the coil when inside the magnet, a gear and rack system was used to adjust the distance of a separate flat gapped tuning loop from the end of the resonator to achieve fine tuning of the coil [7]. Coupling to the scanner for transmission and reception (TR/RX) was accomplished with a coaxial loop placed at the opposite ends of the resonators from the fine tuning loop, and connected to a 50 Ω coaxial cable. Adjusting the separation of the coupling loop from the resonator achieves impedance matching. In an alternative design, impedance matching may be achieved by adjusting a variable capacitance in series with a fixed coupling loop. In both coupling alternatives, the use of inductive coupling between the scanner and the resonator makes the resonator and specimen electrically balanced with respect to ground. This reduces the effect of parasitic capacitance of the resonator and specimen to ground, and further reduces the tendency of the resonator to radiate.

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