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A geometrically adjustable receive array for imaging marmoset cohorts

Kyle M. Gilbert[a,*], Joseph S. Gati[a], L. Martyn Klassen[a], Peter Zeman[a], David J. Schaeffer[a], Stefan Everling[a,b], Ravi S. Menon[a,c]

[a] Centre for Functional and Metabolic Mapping, The University of Western Ontario, 1151 Richmond St. N, London, Ontario, Canada N6A 5B7
[b] Department of Physiology and Pharmacology, The University of Western Ontario, London, Ontario, Canada
[c] Department of Medical Biophysics, The University of Western Ontario, London, Ontario, Canada

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ABSTRACT

The common marmoset (*Callithrix jacchus*) is an increasingly popular animal model for translational neuroscience studies, during which anatomical and functional MRI can be useful investigative tools. To attain the requisite SNR for high-resolution acquisitions, the radiofrequency coil must be optimized for the marmoset; however, relatively few custom coils have been developed that maximize SNR and are compatible with accelerated acquisitions. For the study of large populations of animals, the heterogeneity in animal size reduces the effectiveness of a “one size fits all” approach to coil sizing and makes coils tailored to individual animals cost and time prohibitive. The approach taken in this study was to create an 8-channel phased-array receive coil that was adjustable to the width of the marmoset head, thereby negating the need for tailored coils while still maintaining high SNR. Two marmosets of different size were imaged on a 9.4-T small-animal scanner. Consistent SNR was achieved in the periphery of the brain between head sizes. When compared to a 15-channel, “one size fits all” receive coil, the adjustable coil achieved 57% higher SNR in the superior frontal and parietal cortices and 29% higher SNR in the centre of the brain. The mean geometry factor of the adjustable coil was less than 1.2 for a 2-fold reduction factor in the left-right and anterior-posterior directions. Geometry factors were compared to the 15-channel coil to guide future designs. The adjustable coil was shown to be a practical means for anatomical and echo-planar imaging of marmoset cohorts.

Introduction

The common marmoset monkey (*Callithrix jacchus*) is becoming increasingly popular as an animal model in neuroscience, in part due to its closer homology with humans compared to rodents (Okano et al., 2012; Solomon and Rosa, 2014). The marmoset has several advantages compared to the more ubiquitous macaque monkey, such as a short duration to sexual maturity, a high birth rate, and reduced biosafety concerns (they do not carry the herpes B virus and are classified as Biosafety Level 1). Additionally, it has been demonstrated that marmosets can be trained to perform complex behavioural tasks while head-fixated (Mitchell et al., 2014). The common marmoset has therefore been used to study brain function (Belcher et al., 2013; Ghahremani et al., 2016; Hung et al., 2015; Liu et al., 2013) and anatomy (Bock et al., 2009; Helms et al., 2013) and is now evolving as a powerful transgenic primate model with strong homology to humans (Sasaki et al., 2009).

Despite the expanding use of the marmoset in translational research, few radiofrequency (RF) coils have been developed specifically for this species (Papoti et al., 2016, 2015, 2013). There are several requirements for designing coils dedicated to the marmoset. First, receive coils must have high sensitivity to provide the requisite signal-to-noise ratio (SNR) for high-resolution functional and anatomical imaging. The most efficient means to increase SNR is to place coil elements as close to the brain as possible; however, this is complicated by the marmoset anatomy, as the body and shoulders restrict the placement of coil elements near the occipital pole and large ears and temporal muscles increase the distance between the coil and the temporal lobes. Second, with a strong emphasis being placed on functional imaging, receive coils must be comprised of multiple elements (typically greater or equal to four) to allow for parallel acquisition schemes. This reduces geometric distortion in echo-planar acquisitions that are exacerbated at ultra-high field strengths—a problem caused by the increase in B_0 field distortions attributed to

Abbreviations: 3D, (three dimensional); AFI, (actual flip-angle imaging); (BOLD), Blood oxygenation-level dependent; DC, (direct current); DWI, (diffusion weighted imaging); EPI, (echo-planar imaging); FLASH, (fast low-angle shot); FOV, (field of view); MP2RAGE, (magnetization-prepared 2, rapid gradient echo); NaCl, (sodium chloride); OSFA, (one size fits all); RF, (radiofrequency); SENSE, (sensitivity encoding); SNR, (signal-to-noise ratio); tSNR, (temporal SNR)

* Corresponding author.
E-mail address: kgilbert@robarts.ca (K.M. Gilbert).

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differences in magnetic susceptibility between tissues and increased transverse relaxation rates within the head. Third, a method for immobilizing the head must be incorporated into the mechanical setup to prevent movement during scanning. These requirements, when combined with a small-bore animal scanner, place tight geometrical constraints on the coil design and have manifested in several approaches to marmoset imaging.

Generic coil solutions for marmoset imaging have made use of phased-array clinical coils (Helms et al., 2013), volume coils (Yamazaki et al., 2016), and single surface coils (Sadagopan et al., 2015). However, clinical coils are not tailored to the marmoset anatomy and therefore produce suboptimal SNR, while parallel acceleration is not feasible with volume coils or single surface coils. To this end, multi-channel receive coils have recently been developed that are tailored to the individual marmoset head. The receive coil is either mounted on the external surface of the coil former or adhered to the interior surface (Papoti et al., 2016, 2015, 2013). This places the coil in the closest possible proximity to the head to increase SNR, while also allowing for parallel acceleration: these coils have produced impressive results for blood-oxygenation-level-dependent (BOLD) functional imaging of a visually stimulated awake marmoset (Papoti et al., 2016). The drawback of such coils, however, is the requirement to create a separate, optimized coil for each animal under investigation. This can become cost and time prohibitive for studies of larger populations. An alternative is to design a fixed coil that is large enough to accommodate all animals in the study, which compromises SNR for smaller animals (Gilbert et al., 2016; Janssens et al., 2013). For the remainder of the manuscript, this will be denoted as a "one size fits all" (OSFA) coil design.

To circumvent this issue in human imaging, a common solution, both commercially and in research, is to employ flexible coil arrays that target specific anatomical regions. This allows for tight coupling to the sample and commensurately high SNR. Single-channel, flexible surface coils are likewise prevalent for small-animal imaging. However, flexible coils lack the requisite rigidity for immobilizing animals during functional imaging. To this end, a semi-rigid coil that can conform to different heads is ideal.

In this manuscript, an eight-channel receive coil is described that conforms to the shape of the marmoset head, aids in immobilizing the head, and is adaptable to a range of head sizes. Two marmosets of different size were scanned, and the performance characteristics (spatial SNR, noise correlation, geometry factor, and image distortion) were evaluated. To quantify the SNR benefit of the adjustable coil, one marmoset was subsequently scanned with a 15-channel OSFA coil built in-house—to date, this is the highest channel count receive coil developed specifically for marmosets. The geometry factor was also compared to the 15-channel coil to provide guidance for future designs.

Materials and methods

Transmit coil

The transmit coil (Fig. 1a) consisted of two rectangular loops (82-mm wide by 69-mm long) overlapped by 14 mm to minimize their mutual impedance. Coil elements were mounted on an inverted U-shaped former with nominal dimensions of 82-mm wide by 49-mm high: all formers were constructed of polycarbonate and fabricated with a 3D printer. A two-channel topology, as opposed to a volume coil, was chosen due to space limitations within the 12-cm-diameter clear bore. Each transmit channel was driven independently, with the phase and magnitude of each channel adjusted through RF shimming to create a uniform transmit field over the brain (Gilbert et al., 2011).

Receive coil mechanicals

The former of the receive coil was designed to fit tightly about the head of a marmoset. Three-dimensional FLASH images were acquired of an adult marmoset's head (resolution: 375-µm isotropic). A semi-automatic segmentation tool (ITK-SNAP; (Yushkevich et al., 2006)) was used to find the surface of the head from the 3D image. The surface rendering was down-sampled and smoothed in Rhinoceros (McNeel North America, Seattle, USA) to remove subject-specific contours of the head. The smoothed surface was then imported into SolidWorks (Dassault Systèmes, Waltham, USA) and split into three pieces to create a hinged design (hence semi-rigid). The width of the coil (left-right direction) could be adjusted from 37 mm to 50 mm. Protrusions on the hinges prevented the former from being expanded beyond a critical width that would tear the coil conductors. The length (anterior-posterior direction when the animal was placed in the sphinx position) and height (superior-inferior direction) were 46 mm and 31 mm, respectively. Since the coil was intended to be fully open when placed on the animal's head, then subsequently tightened, the former was designed to taper inward at the inferior aspect of the head—a feature that is not possible with a OSFA coil—allowing for an extended field of view, as well as greater immobilization of the head.

Receive coil

Eight coil elements were machined from copper-clad garolite (1/2-ounce copper adhered to 130-µm-thick G10/FR4 fiberglass). This flexible material allowed the coil elements to conform to the inner surface of the former, an increasingly important design feature for small-animal coils where the thickness of the former may constitute a significant increase in the distance from the coil to the brain (Papoti et al., 2016). Elements were elliptical in shape. When the former was in the fully closed position, the minor and major axes of the ellipses were 21 by 23 mm (elements 1 and 6), 23 by 28 mm (elements 2 and 7), 20 by 25 mm (elements 3 and 8), and 19 by 24 mm (elements 4 and 5). Coil elements were overlapped to minimize their through-space inductive coupling and their commensurate mutual impedance (Roemer et al., 1990). Coil elements were arranged to optimize coverage of the brain. Elements at the sides of the head (elements 2 and 7) were moderately larger than those at the superior aspect of the head; this was necessary to increase the penetration depth to compensate for the greater distance to the brain caused by the temporal muscles and ears. Coil elements that spanned the hinged gaps were bridged with insulated 0.4-mm-diameter wire that consisted of a "pig-tail" loop to allow the bridge wires to expand and contract as the former changed shape. Polyimide tape was adhered to the inner surface of the receive coil to provided electrical (and some thermal) insulation between the coil conductors and the marmoset. Photographs of the receive coil are provided in Fig. 1b,c.

Holes in the former allowed 18-AWG bare wire to connect the coil elements to two surface-mount capacitors on the external surface of the former (100 series, American Technical Ceramics, NY, USA). These capacitors were then connected to matching boards (including pre-amplifier decoupling circuitry, active detuning circuitry, a fuse, and tuning and matching variable capacitors [Sprague-Goodman Electronics, Inc., NY, USA]) using 38–64-mm-long twisted pair. Choke baluns were placed at the output of the matching circuit. Active detuning consisted of a parallel-resonant circuit that was forward biased during transmit to reduce coupling to the transmit coil. A fast-blow RF fuse (Series 451, LittelFuse Inc., Chicago, USA) was placed in series with the coil element as a safety precaution in case of the rare event where an active detuning circuit fails, which could cause heating of the coil conductors and therefore the animal.

The small diameter of the clear bore (12 cm) precluded the placement of preamplifiers inside the bore near the coil. Low-input-impedance preamplifiers (Siemens Healthcare, Erlangen, Germany), operating at 400 MHz, were therefore placed directly on the front of the scanner and a 113-cm-long, high-density coaxial cable (L45466-B612-W48-EN; Leoni) connected the coils to the preamplifiers—this $n\lambda/2$