NeuroImage 125 (2016) 153–161

Contents lists available at ScienceDirect

NeuroImage

journal homepage: www.elsevier.com/locate/ynimg

Optimized parallel transmit and receive radiofrequency coil for ultrahigh-field MRI of monkeys

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ARTICLE INFO

Article history:
Received 21 April 2015
Accepted 19 October 2015
Available online 20 October 2015

Keywords:
Transmit coil
Receive coil
Monkey
Parallel transmit
Echo-planar imaging

ABSTRACT

Monkeys are a valuable model for investigating the structure and function of the brain. To attain the requisite resolution to resolve fine anatomical detail and map localized brain activation requires radiofrequency (RF) coils that produce high signal-to-noise ratios (SNRs) both spatially (image SNR) and temporally. Increasing the strength of the static magnetic field is an effective method to improve SNR, yet this comes with commensurate challenges in RF coil design. First, at ultrahigh field strengths, the magnetic field produced by a surface coil in a dielectric medium is asymmetric. In neuroimaging of rhesus macaques, this complex field pattern is compounded by the heterogeneous structure of the head. The confluence of these effects results in a non-uniform flip angle, but more markedly, a suboptimal circularly polarized mode with reduced transmit efficiency. Secondly, susceptibility-induced geometric distortions are exacerbated when performing echo-planar imaging (EPI), which is a standard technique in functional studies. This requires receive coils capable of parallel imaging with low noise amplification during image reconstruction. To address these challenges at 7 T, this study presents a parallel (8-channel) transmit coil developed for monkey imaging, along with a highly parallel (24-channel) receive coil. RF shimming with the parallel-transmit coil produced significant advantages—the transmit field was 38% more uniform than a traditional circularly polarized mode and 54% more power-efficient, demonstrating that parallel-transmit coils should be used for monkey imaging at ultrahigh field strengths. The receive coil had the ability to accelerate along an arbitrary axis with at least a three-fold reduction factor, thereby reducing geometric distortions in whole-brain EPI.

Introduction

Neuroimaging of monkeys is an important means for investigating neuronal anatomy and function, including connectivity between neural networks and the blood-oxygenation-level dependent (BOLD) response (Barazany and Assaf, 2012; Dubowitz et al., 1998; Ekstrom et al., 2008; Logothetis et al., 1999, 2001; Moeller et al., 2008; Vanduffel et al., 2001). To discriminate the BOLD response originating from disparate locations in the brain, high-resolution functional imaging, as well as high-resolution anatomical references, are required (Chen et al., 2012, 2013; Goense et al., 2012; Logothetis et al., 2002). To resolve such fine anatomical and functional detail places stringent demands on the performance characteristics of the radiofrequency (RF) coil. Most notably, the RF coil must be highly sensitive, equating to a high signal-to-noise ratio (SNR). The most effective method to improve sensitivity is to situate the coil in close proximity to the head; however, in monkeys, this is made difficult by the presence of head-fixation posts, recording chambers (used for electrophysiological measurements), and external hardware affixed to the skull. The large lateral muscles on the monkey head further distance the coil from the brain. A common method to improve the SNR of the MRI experiment is to increase the strength of the static magnetic field. Although it is an effective solution, an increase in field strength is accompanied by several challenges, most notably a non-uniform, and potentially inefficient, transmit field and the presence of susceptibility induced geometric distortions.

At ultrahigh field strengths, the magnetic field pattern of a surface coil becomes increasingly asymmetric in a dielectric medium (Wiesinger et al., 2004). This complex wave behavior, coupled with the non-uniform shape of the monkey head, causes the most efficient mode of a cylindrical transmit coil to deviate from an equally distributed 2π phase accrual about its circumference. This is further complicated when the wavelength of the transmit field approaches the width of the head (λ/2 ~ 7–8 cm *in vivo* at 7 T), causing a central-brightening effect due to the destructive interference of the transmit field in the periphery of the head. The combination of these effects can reduce the

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http://dx.doi.org/10.1016/j.neuroimage.2015.10.048
1053-8119/

transmit-field efficiency and uniformity. A variance of flip angle across the head can reduce the contrast between tissues, while a lower efficiency can restrict the amplitude and duty cycle of RF pulses due to constraints imposed by the power amplifier or specific absorption rate (SAR). To mitigate these problems, multi-channel transmit coils have been developed (Adriany et al., 2010a; Gilbert et al., 2010). The magnitude and phase of each transmit channel can be chosen to improve the efficiency and/or uniformity of the transmit field, a process known as RF shimming (Mao et al., 2006; Van de Moortele et al., 2005).

A second problem at ultrahigh field strengths occurs when magnetic-susceptibility gradients at tissue–air interfaces cause large inhomogeneities in the local magnetic field. Magnetic-susceptibility gradients are particularly prevalent in the monkey brain due to the presence of large nasal cavities and the potential for external hardware to be affixed to the skull. This, in turn, causes geometric distortions in echo-planar imaging (EPI)—a technique that is ubiquitous in the acquisition of fMRI datasets. Geometric distortions can be mitigated by shortening the echo train with parallel imaging (Pruessmann et al., 1999; Sodickson and Manning, 1997) and with partial-Fourier encoding. Therefore, effective functional imaging at ultrahigh field strengths requires an array of receive elements that produce low noise amplification during reconstruction of under-sampled data. To minimize noise amplification, receive elements must be highly decoupled and have independent field profiles.

Numerous designs for RF coils have been devised for monkey imaging. At 3 T, quadrature transceive coils (Roopnariane et al., 2012), and volume transmit coils combined with receive arrays with up to 22 elements (Helms et al., 2013; Janssens et al., 2012, 2013; Khachaturian, 2010; You et al., 2007), have been used for whole-brain imaging. At ultrahigh field (7 T), whole-brain imaging has been accomplished with volume transceive coils (Gonen et al., 2008; Pfeuffer et al., 2004) and with volume transmit coils combined with receive arrays consisting of up to eight elements (Kolster et al., 2007; Mareyam et al., 2011; Papoti et al., 2013). Small-diameter surface coils have also been implemented as a means to improve SNR over a localized region for high-resolution functional imaging (Goense et al., 2010; Logothetis et al., 2002; Pfeuffer et al., 2004, 2007). Although multi-transmit coils have been more commonly implemented in combination with receive arrays for human studies, for example of the spine (Zhao et al., 2014) and head (Adriany et al., 2012), to date, only a limited number of multi-transmit studies on monkeys have been performed (Adriany et al., 2010b; Gilbert et al., 2013; Zitella et al., 2015), while most coil systems rely on quadrature or single-channel transmit coils to provide excitation.

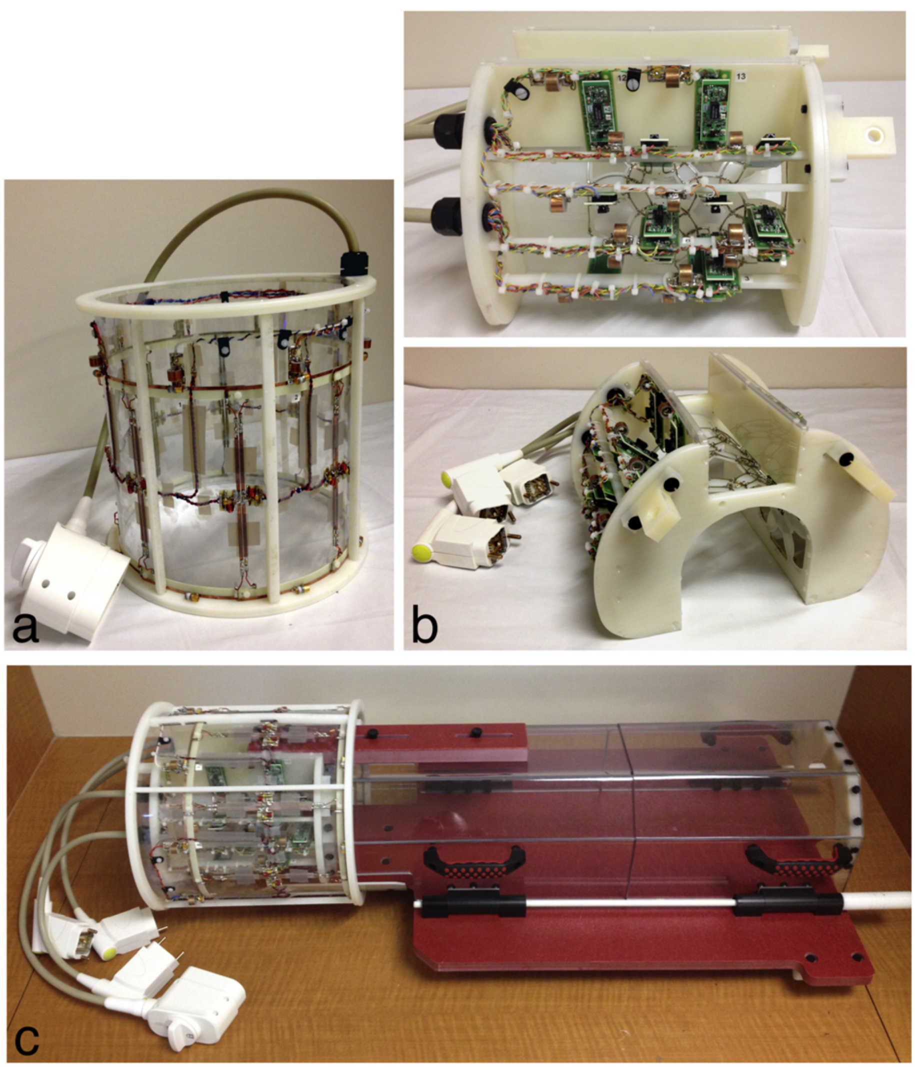

Fig. 1. Photographs of (a) the transmit coil, (b) two views of the receive coil, and (c) both coils together with the restraint system. Physiological monitoring equipment was attached to the monkey while no coil was present. The receive coil was then attached to the restraint system, after which the head-fixation post of the monkey was secured to the immobilization bar. The receive coil and restraint system were then slid into the transmit coil while on the scanner bed.