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SERIAL transmit – parallel receive (ST_xPR_x) MR imaging produces acceptable proton image uniformity without compromising field of view or SAR guidelines for human neuroimaging at 9.4 Tesla

Keith R. Thulborn [a,*], Chao Ma [b], Chenhao Sun [d], Ian C. Atkinson [a], Theodore Claiborne [a], Reiner Umathum [c], Steven M. Wright [d], Zhi-Pei Liang [e]

[a] Center for Magnetic Resonance Research, University of Illinois at Chicago, 1801 West Taylor St., MC 707, Suite 1307, Chicago, IL 60612, USA
[b] Gordon Center for Medical Imaging, Department of Radiology, Massachusetts General Hospital, 125 Nashua Street, Suite 660, Boston, MA 02114, USA
[c] German Cancer Center (DKFZ), Division of Medical Physics in Radiology, Im Neuenheimer Feld 280, 69120 Heidelberg, Germany
[d] Department of Electrical and Computer Engineering, Texas A&M University, Wisenbaker Engineering Building, College Station, TX 77843-3128, USA
[e] Beckman Institute, University of Illinois at Urbana-Champaign, 405 North Mathews Avenue, Urbana, IL 61801, USA

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Dedication: I had the good fortune to meet Joe Ackerman in 1979 when I arrived to work as a post-doctoral research fellow in the Biochemistry Department at Oxford University, UK. The laboratory, led by Sir George K. Radda, had one of the first wide bore (89 mm diameter) magnets from Oxford Instruments that fostered in the era of in vivo multi-nuclear NMR spectroscopy. Joe was working with a cardiologist on in vivo cardiac 31P NMR spectroscopy, implanting solenoidal RF coils around rat hearts. It was Joe who made the leap in RF coil design from volume coils to surface coils. Prior to his observations and insight, it was widely believed that volume RF coils, (i.e. solenoidal coils) with homogeneous B1 sensitivity profiles were mandatory for good spectra. Joe made a giant step forward when he pointed out that the end of a solenoidal coil gave excellent spectra despite the non-uniform B1 field. From this observation, he rapidly developed the concept of the surface RF coil. Such flat coils were much easier to use in vivo to localize spectra to an organ while still yielding high quality spectra despite their non-uniform excitation profiles [1]. After a highly successful fellowship, Joe returned to the USA to set up

ABSTRACT

Purpose: Non-uniform $B1^+$ excitation and high specific absorption rates (SAR) compromise proton MR imaging of human brain at 9.4 T (400.5 MHz). By combining a transmit/receive surface coil array using serial transmission of individual coils with a total generalized variation reconstruction of images from all coils, acceptable quality human brain imaging is demonstrated.
Methods: B_0 is shimmed using sodium MR imaging (105.4 MHz) with a birdcage coil. Proton MR imaging is performed with an excitation/receive array of surface coils. The modified FLASH pulse sequence transmits serially across each coil within the array thereby distributing SAR in time and space. All coils operate in receive mode. Although the excitation profile of each transmit coil is non-uniform, the sensitivity profile estimated from the non-transmit receive coils provides an acceptable sensitivity correction. Signals from all coils are combined in a total generalized variation (TGV) reconstruction to provide a full field of view image at maximum signal to noise (SNR) performance.
Results: High-resolution images across the human head are demonstrated with acceptable uniformity and SNR.
Conclusion: Proton MR imaging of the human brain is possible with acceptable uniformity at low SAR at 9.4 Tesla using this serial excitation and parallel reception strategy with TGV reconstruction.

* Corresponding author.
E-mail address: mrix@ameritech.net (K.R. Thulborn).

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his own biologically oriented NMR laboratory at Washington University in St Louis. Thanks to Joe's transformative work on the potential of surface coils more than three decades ago, this current report uses an array of surface coils as a means to facilitate safe ultrahigh field MR imaging of the human brain. The approach avoids the self-resonance limit of large volume coils at ultrahigh frequencies while reducing the non-uniform specific absorption rate (SAR) and the non-uniform excitation profile that also limit ultrahigh field imaging. Combined with the SENSE reconstruction techniques, the non-uniform but localized excitation profile of the surface coil does not compromise large field of view ^{1}H MR imaging, at least for the human brain at 9.4 Tesla.

Keywords:
Ultrahigh magnetic field
9.4 Tesla
Proton MRI
Human brain
Surface coil arrays
SENSE reconstruction
Specific absorption rate
Image uniformity

1. Introduction

9.4 T MR scanners for human imaging provide the expected signal to noise ratio (SNR) improvement for quantitative metabolic imaging of non-proton nuclei (^{23}Na, ^{17}O, ^{31}P), thereby providing access to new information about the human brain [2–5]. ^{1}H MR imaging at 9.4 T has not received the same emphasis for anatomical imaging as at 7 T where the parallel transmission approach has been the focus of efforts to overcome the non-uniform excitation that results when the transmission wavelength approaches the dimensions of the sample [6,7]. This report demonstrates the application of a previously published and patented approach, but not yet reported for in vivo human imaging, using serial excitation of individual coils within a surface coil array with parallel reception in all coils to perform proton MR imaging at 9.4 T [8–12]. Orzada published an alternative approach in which different modes were sequentially excited from different phase shifts applied to a set of eight transmit array elements [12]. That method produced excellent homogeneity at 7 T, but required additional hardware for rapidly changing the applied phase to the array elements after each acquisition. Additionally, because of the different phase shifts, there may be a small SAR penalty due to summation of the electric field from different elements. As the proton imaging is to be used to provide correction for partial volume effects in lower resolution metabolic images obtained from non-proton imaging, the full range of ^{1}H image contrast used in clinical imaging is not the goal of this approach.

We report on the feasibility of ^{1}H MR imaging of the human brain at 9.4 T (400.4 MHz) in which acceptable image uniformity across the entire brain can be achieved well below the SAR guidelines using 2D or 3D FLASH (fast low angle shot) sequences. The proposed approach uses an array of transmit/receive surface coils in which the coils are multiplexed to transmit serially (ST_x) rather than in parallel (PT_x) but all coils receive simultaneously. Although each RF coil has a very non-uniform $B1^{+}$ excitation profile, the non-transmit coils are used to form a virtual volume coil with acceptable total image uniformity. The final image is reconstructed using the SENSE method with sensitivity maps derived from the virtual coil. Although image reconstruction develops a sensitivity profile from the non-transmit elements, the data from all coils are used in the final total generalized variation SENSE reconstruction [13]. We present human brain images with significant contrast between gray matter, white matter and cerebrospinal fluid (CSF).

2. Materials and methods

2.1. Human studies

Human imaging was performed at 9.4 T under a protocol approved by the institutional review board (IRB) using an investigational device exemption (IDE) from the Food and Drug Administration (FDA). Informed signed consent was obtained from all human volunteers (N = 6).

2.2. Phantom studies

The phantom was a plastic sphere of 16 cm outer diameter (OD) with an array of solid plastic rods (5mm OD) with five rows of decreasing separation (6, 5, 4, 3, 2 mm edge to edge). The sphere was filled with aqueous saline solution (40 mM sodium chloride) with a small bubble to identify the orientation of the phantom within the FOV.

2.3. Specific Absorption Rate (SAR) power simulations

Although the low power of the FLASH sequences was not expected to produce SAR issues for either STx or PTx modes, typical SAR simulations were performed on phantoms (cylindrical and spherical) filled with normal saline (dielectric constant of 78, conductivity of 0.4S/m) using both an in-house developed 2D

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