Parallel Transmission

D. C. Noll[1]
[1]University of Michigan, Ann Arbor, Michigan, United States

Introduction

Parallel transmission or parallel excitation is the excitation analogy to parallel imaging. In *parallel imaging*, arrays of RF coils are used in conjunction with an undersampled acquisition of k-space data to create an unaliased image. In a similar fashion, parallel excitation involves excitation of multidimensional patterns using undersampled *excitation* k-space trajectories [1] to produce an unaliased *parallel excitation* excitation pattern. This work was pioneered by Katcher et al. in [2] and by Zhu in [3]. While the most straight forward analogy to parallel imaging is for the excitation of multidimensional patterns, there are other related applications, including using independent excitation channels to simply excite uniformly in situations where wavelength/object interactions lead to inhomogeneous excitation, for example, at very high field strengths. Further, parallel excitation also can be used to create excitation in ways that reduce power deposition (specific absorption rate or SAR) globally or regionally. The essential feature of parallel excitation is the independent control and driving of multiple transmitter channels.

Challenges

With a focus on the design of multidimensional excitation pulses, the obvious place to start is in the small tip-angle regime with excitation k-space [1]. Here the analogy to parallel imaging is most obvious – just as undersampling results in aliasing in the image, undersampling in excitation k-space results in aliasing in the multidimensional excitation pattern. Several approaches to multidimensional pulse design have been suggested. The "transmit SENSE" method by Katscher, et al. [1] is characterized by its formulation as a convolution in excitation k-space. It allows use of arbitrary k-space trajectories and once set up, the problem is solved by matrix inversion. Grissom, et al. [4] developed an RF pulse design method that is related to Katscher's method, but is formulated in the spatial domain. It is a multi-coil generalization of the iterative pulse design method proposed by Yip, et al. [5] and can easily incorporate regions of support, peak RF and SAR constraints. Large problems, for example 3D excitation problems, can be solved by a fast iterative solver, e.g. the conjugate gradient algorithm as shown in [5]. The method introduced by Zhu [2] is formulated as an optimization problem in the spatial domain, but, as presently described, is restricted to Cartesian (e.g. echo-planar) k-space trajectories. Zhu showed that this method can allow for optimization of the excitation pattern subject to a SAR constraint. Griswold, et al. [6] proposed a k-space domain method that is analogous to GRAPPA imaging, and is unlike other methods in that it does not require prior determination of sensitivity patterns. Instead, it involves an extra calibration step in the pulse design process. All of the aforementioned design approaches are based on the assumption of small-tip-angle excitation.

Grissom et al. [4] has shown that accelerated pulses designed using small-tip-angle techniques produce distorted excitation patterns when scaled to produce large tip angles (90° or greater). Large-tip-angle accuracy degrades with increasing acceleration. New design approaches, including a spinor-domain approach and an additive angle iterative approach, will be presented. One interesting feature that distinguishes the excitation process from the imaging process is that the excitation pattern is known *a priori*. Accordingly, it may be possible to achieve reductions in pulse length, increased excitation accuracy, and reductions in SAR via k-space trajectory optimization. Several specific cases where k-space optimization has improved accuracy and SAR performance will be presented. Two issues regarding SAR arise in parallel excitation: reducing SAR relative to single-channel pulses or limiting the increase in SAR with speed-up factor [7]. Zhu [2] has suggested that SAR may be effectively controlled in the parallel RF pulse design process, and that parallel excitation may offer opportunities for SAR reduction in localized excitation, compared to single-channel excitation. In the single coil case, it has been shown that SAR can be reduced indirectly in the pulse design process by regularization on RF power, with small errors in excitation accuracy [5]. Zhu et al. [8] pointed out another analogy to the parallel imaging case: that a "g-factor", which quantifies noise amplification in parallel imaging, may be derived to quantify SAR amplification in parallel excitation.

Another major challenge for parallel excitation is determination of the excitation B1 fields (often referred to as B1+ fields). Accurate knowledge of the absolute B1+ field is necessary, especially for the large tip-angle case, though there may be some circumstances under small-tip assumptions where only relative B1+ fields are necessary. In standard amplifier/coil configurations, RF magnetic fields are influenced by the sample being excited, so that one must collect maps of the magnetic fields on a subject-by-subject basis. Thus B1+ mapping or other calibration steps may be necessary for every subject. It is critical, then, that accurate *and* fast B1+ mapping methods be developed, for example, [9]. It may be possible, however, for low and moderate field strengths, that B1+ maps might be stable across different coil loading situations with current source type RF amplifiers [10]. Finally, there are numerous other challenges, including development of software and system hardware for controlling and synchronizing multiple independent transmitter channels – most commercial systems today do not provide for large numbers of transmitter channels with synchronized carriers. As in parallel imaging, coil-to-coil coupling and amplifier interactions present a unique challenge that may be addressable, again, by current source technology [10]. Finally, given the non-uniformity of the B1+ fields for individual coils, calculating and monitoring SAR represents yet another challenge.

Demonstrations and Applications

The past 2 years have seen several practical demonstrations and parallel excitation technology [1,2,11-14]. While the technology, in and of itself, is interesting, practical applications are necessary for wide-spread implementation – a "killer app" is needed. Amongst the common applications for multidimensional selective excitation are excitation of inner volumes for reduced FOV imaging and multidimensional tagging pulses for angiography and targeted arterial spin labeling. Multidimensional RF pulses can also be used to compensate for signal dephasing in T2*-weighted functional MRI [15]. A promising application for parallel excitation is making excitation more uniform at higher magnetic fields, for example, at 3T or higher. Besides multidimensional RF pulses parallel excitation systems can also be used to adjust only the amplitude and phase of the RF channels in a process known as RF shimming. Finally, parallel excitation may have important application to reducing total or focal SAR [16].

References

1. J. M. Pauly, et al. *J. Magn. Reson.*, 81:43-56, 1989.
2. U. Katscher, et al. *Magn Reson Med*, 49(1):144–150, Jan 2003.
3. Y. Zhu. *Magn Reson Med*, 51(4):775–784, Apr 2004.
4. W. Grissom, et al. *Magn Reson Med*, 56(3):620–9, 2006.
5. C. Y. Yip, et al. *Magn Reson Med*, 54:908-17, 2005.
6. M. A. Griswold, et al. in Proc. 13th ISMRM, Miami, p. 2435, 2005.
7. U. Katscher, et al. *MAGMA*, 18(2):81–88, May 2005.
8. Y. Zhu. in Proc. 14th ISMRM, Seattle, p. 599, 2006.
9. C. H. Cunningham et al.. *Magn Reson Med*. 55:1326-33, 2006.
10. K. N. Kurpad, et al., in Proc. 13th ISMRM, Miami, p. 16, 2005.
11. P. Ullmann, at al. *Magn Reson Med*, 54(4):994–1001, 2005.
12. K. Setsompop et al. *Magn Reson Med*, 56(5):1163–1171, 2006.
13. A. Kerr, at al. in Proc. 14th ISMRM, Seattle, p. 2561, 2006.
14. P. Vernickel, et al., in Proc. 14th ISMRM, Seattle, p. 123, 2006.
15. C. Y. Yip, et al. *Magn Reson Med*. 56(5):1050-9, 2006.
16. G. C. Scott, et al. in Proc. 14th ISMRM, Seattle, p. 128, 2006.