Massively Parallel MRI

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Long before today's approaches to parallel MRI were developed, early proposals envisioned massively parallel implementations in which spatial encoding using many-element coil arrays might entirely replace gradient phase encoding [1, 2]. These suggestions went largely unexplored until techniques such as SMASH [3] and SENSE [4], which share the burden of spatial encoding between coils and gradients, became available. This workshop is a testimony to the rich profusion of ingenious new techniques and applications that followed. Until recently, however, relatively modest accelerations – typically by factors of 2 to 4 or, in special cases, 6 to 8 – have been achieved with parallel imaging approaches. The large gap between these implementations and the vision of massively parallel imaging results in part from practical considerations (e.g. the complexity and expense of many-element arrays and many-receiver systems) and in part from theoretical limitations (namely, signal-to-noise ratio, which decreases in a nonlinear fashion with increasing acceleration). Based on empirical observations of the scaling of SNR with increasing acceleration factor, it has been suggested over the years that practical *in vivo* accelerations would never greatly exceed current moderate levels, at least for typical body imaging applications. Several recent developments in the field of parallel imaging have either challenged or clarified such a contention. In light of these developments, it seems appropriate, then, to reexamine an oft-asked question: "How fast can we (really) go?"

On the one hand, the elimination of phase encoding has recently been demonstrated with the SEA technique [5], which used a 64-element array [6] to acquire entire images in a single echo. This work hearkens back to the early models of massively parallel imaging, and throws down the gauntlet to an MR engineering community who might begin to contemplate large-scale designs for *in vivo* massively parallel imaging. On the other hand, numerical computations have established the existence of fundamental electrodynamic limits on parallel imaging performance, indicating that SNR will always suffer dramatic degradation for high accelerations at any appreciable depth within the imaged body [7, 8]. Indeed, the high accelerations obtained with SEA were possible only at extremely shallow depths beneath the finely-segmented linear coil array.

The conflict between the promise of massively parallel imaging and the rigorous constraints of electrodynamics raises other questions that extend beyond the realm of raw acceleration. What freedom still exists within the theoretical limits of parallel imaging performance? How can we optimize our parallel imaging apparatus to approach these limits of performance? And how should we best use the speed we can achieve?

Some leeway clearly remains. For example, the use of large arrays of small elements does not in itself constitute a limit on depth penetration, contrary to rules of thumb developed for single coil elements. High accelerations still hurt the SNR bottom line, but superposition of signals from many elements can actually improve depth penetration, as least so long as the noise from individual coil circuits can be controlled [9]. Furthermore, the use of 3D acquisitions with acceleration along two phase-encoding directions can dramatically mitigate SNR losses by spreading the encoding burden along more than one dimension [10].

Over the past two years, acceleration factors as high as 24 were demonstrated *in vivo* using 32-element arrays designed for multidimensional spatial encoding [11, 12]. With the same arrays, 12- to 16-fold accelerated acquisitions were demonstrated repeatably for 3D contrast-enhanced MRA studies over large imaging volumes [13]. Our group and others have also demonstrated high multidimensional accelerations for body imaging [14, 15], brain imaging [16, 17], and coronary artery imaging [18]. Volumetric imaging is a particularly appealing candidate for highly parallel MRI, not only because of the availability of multiple directions suitable for acceleration, but also because SNR in 3D sequences increases with the quantity of acquired data. Highly parallel MRI enables large volumetric acquisitions with otherwise prohibitive imaging times, and the resulting gains in baseline SNR serve to offset at least in part the SNR losses associated with parallel imaging. At the same time, large volumetric acquisitions allow a simplification of scan prescription, enabling, for example, visualization of full vascular trees at the press of a button, as an alterative to the careful and patient-specific planning of limited vascular studies.

The use of large highly-accelerated volumes has been somewhat controversial, since one may reasonably argue that a) more limited targeted slabs are generally considered sufficient to image many target anatomies, and b) order-of-magnitude accelerations are not practical or even necessary for such targeted slabs. Such concerns emphasize the point that the true value of highly parallel MRI is likely to be manifested less in sheer acceleration – and less in straightforward extrapolation of existing parallel imaging applications – than in overall workflow, simplicity, and clinical acceptance. As many-receiver imaging systems become more widely available, one might envision a shift in the paradigm of routine MR scanning, moving away from targeted imaging of limited regions of interest and towards rapid volumetric imaging in the style of helical CT. Studies are currently underway at our institution in an attempt to demonstrate the clinical value of such a rapid volumetric paradigm for MRI.

Recent moves by several MR manufacturers towards commercial systems with 32 or more receiver channels will clearly pave the way for such possibilities. The practical design and operational requirements of many-element arrays promise to motivate advances in conductor arrangement, cabling methods, substrate materials, and image recon-

struction hardware. Meanwhile, two areas of active research also promise to shift the SNR balance for highly parallel imaging and perhaps even to pave the way for more massively parallel approaches. First, the use of high magnetic field strengths has been shown to increase the ultimate attainable SNR for parallel MRI studies, above and beyond the effects of increased spin polarization [7, 8]. Second, the dramatic improvements in baseline SNR associated with new hyperpolarized contrast agents [19] may be synergistic with parallel imaging approaches, allowing highly accelerated acquisition of large data volumes during the comparatively short duration of enhanced polarization. In short, even in the presence of electrodynamic constraints, the vision of highly parallel MRI continues to motivate new research, and offers the prospect of rapid volumetric imaging in the style of multidetector CT while maintaining the full range of biochemical contrast options associated with MRI.

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