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High-resolution whole-brain dynamic contrast-enhanced MRI using compressed sensing

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MRI sparse sampling and constrained reconstruction techniques enable high-resolution images of the entire brain with no increase in scan time or apparent loss of diagnostic information.

Dynamic contrast-enhanced (DCE) MRI is a powerful tool that maps the spatial distribution of vascular parameters in the brain, including blood-brain-barrier (BBB) permeability, interstitial transit times, and interstitial volume. DCE-MRI is widely used to assess BBB leakage in brain tumors and multiple sclerosis lesions, and it has potential applications in Alzheimer's dementia, vascular cognitive impairment, migraine, epilepsy, and neuropsychiatric disorders such as depression. It involves intravenous administration of a paramagnetic contrast agent and continuous MRI acquisition of images to track the passage of the contrast through the volume of interest. Due to conventional Nyquist sampling requirements, most brain DCE-MRI scans have 5-second temporal resolution, 8-slice coverage, and relatively poor spatial resolution. Using MRI sparse sampling and constrained reconstruction techniques, we showed order of magnitude improvements in spatial resolution and coverage. Our recent work demonstrates the potential for improved clinical assessment of primary and metastatic brain tumors.

Current clinical DCE-MRI protocols sacrifice spatial resolution and slice coverage to achieve the temporal resolution of 2–5s required to characterize contrast agent kinetics. A typical spatial coverage is 5cm, with spatial resolution $0.9 \times 0.9 \times 7.0\text{mm}^3$, and a temporal resolution of 5s. The restricted coverage and spatial resolution make it difficult to fully characterize large tumors or scattered metastatic lesions that may be present throughout the brain. MRI methods that involve sparse sampling and constrained reconstruction, including compressed sensing (CS—acquiring and reconstructing signals based on principles of sparsity), have emerged as a powerful tools to address this challenge.[1,2] They allow for significant reduction in the amount of data needed to form images, which directly translates to increased speed, finer resolution, and/or broader spatial coverage. In brief, this framework makes use of prior knowledge about the characteristics of the image or image series to enable high-quality reconstructions from under-sampled k-space data. These methods leverage parsimonious image models with few degrees of freedom to enable noise suppression and sampling well below the traditional Nyquist rate. Several groups have applied constrained reconstruction and CS to speed up DCE-MRI. Notably, Wang et al.[3] used reference image-based compressed sensing and achieved an acceleration factor of 10× without de-

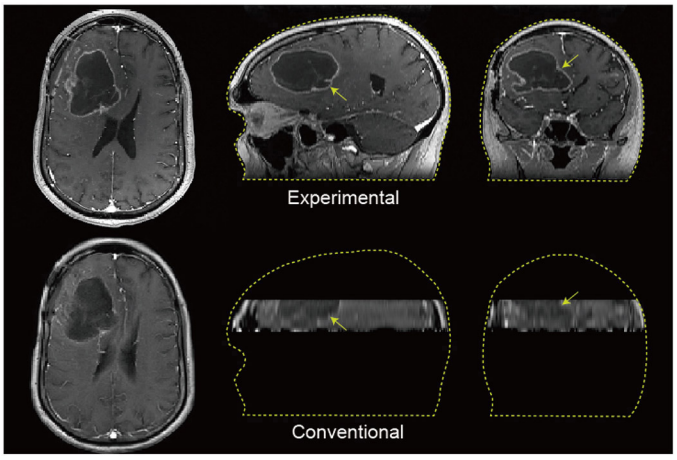

Figure 1. *Spatial coverage of the experimental and conventional brain dynamic contrast-enhanced (DCE) MRI scans. The experimental scan provides high nearly isotropic spatial resolution over the entire brain, and allows for arbitrary reformatting. This patient had a large 6cm glioblastoma multiforme that was completely captured by the experimental scan.*

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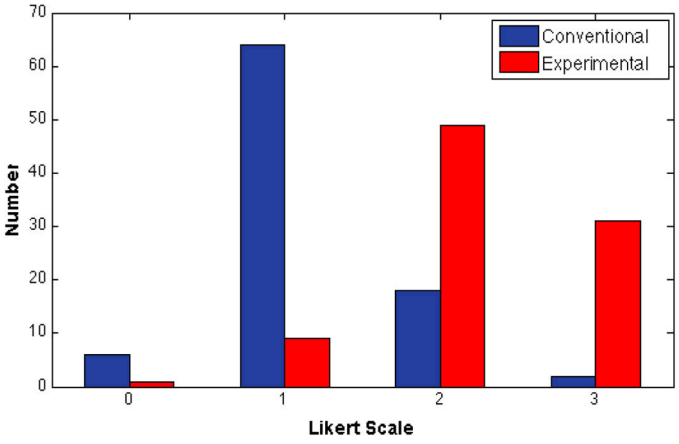

Figure 2. *Histogram of quality scores for the conventional and the experimental sequences from our clinical pilot study (15 patients). The scale represents 3 = good, 2 = average, 1 = poor, and 0 = non-diagnostic.*

grading spatial resolution for DCE-MRI of the breast. Feng et al.[4] used CS, parallel imaging, and golden-angle radial sampling to achieve fast and flexible DCE-MRI. Wang et al.[5] used parallel imaging and spatio-temporal total variation constraints to accelerate DCE-MRI of the brain by 6×.

Our team has been developing advanced CS techniques for various research and clinical applications. For DCE-MRI of the brain, we were able to speed up the imaging by 36× and realized a whole-brain near-isotropic resolution DCE-MRI protocol with no change in scan time relative to the current conventional approach. We demonstrated coverage of $22 \times 22 \times 20\text{cm}^3$ with spatial resolution $0.9 \times 0.9 \times 1.9\text{mm}^3$ and temporal resolution of 5s.[6] We adapted a CS scheme with multiple sparsity constraints in the spatial and temporal domain, including spatial wavelet, spatial total variation, and temporal finite difference.[6–8] The novelty of our approach is to use multiple sparsity constraints, each with low weight, to mitigate potential bias from any one constraint, thus achieving higher acceleration rate and better image quality.[5]

We highlighted the advantages of our experimental DCE-MRI protocol in the clinical imaging of brain tumor patients. Figure 1 illustrates the improved spatial coverage in a patient with a 6cm glioblastoma. Our approach offered a detailed, crisp depiction of the entire tumor body and boundary. Conversely, the conventional scan provided limited spatial coverage, and the sagittal and coronal reformats have extremely low resolution in the slice encoding direction. We used radiologists' ratings to evaluate the quality of the images from these two scans. We used a four-point Likert scale to score the image quality, where 3 = good, 2 = average, 1 = poor, and 0 = non-diagnostic. In the 15 clinical cases we have performed thus far, the experimental scans consistently provided more clear and crisp depiction of all lesions seen. Figure 2 contains a histogram of overall scores, showing that the experimental scan received higher image quality scores than the conventional approach, with average ratings of 1.2 ± 0.6 and 2.2 ± 0.7, respectively. This difference was statistically significant, with $p<0.001$ for all image sets.

In conclusion, high-resolution whole-brain DCE-MRI using CS is clinically feasible in brain tumor patients. It provides characterization of all abnormal tissues, a significant advance over the current clinical approach. This method also provides superior image quality and no apparent loss of diagnostic information compared to the conventional technique. We envision several ways in which we could further advance this technology. We could optimize temporal constraints (which proved to be the most powerful constraints in this study) by more directly incorporating pharmacokinetic models.[9,10] This could also obviate the need for tuning parameters. We could also augment the proposed DCE-MRI imaging sequences to include several forms of auto-calibration and yield multi-parametric information from a single scan.[11] Finally, we could use tools from estimation theory to optimize the acquisition itself, for improved reproducibility of derived kinetic parameter maps.

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