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HPC-BASED HIGH-RESOLUTION QUANTITATIVE MRI

Allocation: Illinois/100 Knh
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EXECUTIVE SUMMARY

Newly emerging high-resolution, quantitative magnetic resonance imaging techniques are powerful tools for clinicians and researchers to apply to study problems in neurology, neurosurgery, and neuroscience. For example, magnetic resonance electrography enables mapping the structure, function, and health of the human brain by measuring the mechanical properties of neural tissue. However, such techniques are hampered by excessive image reconstruction and analysis times that limit their adoption into standard practice. Software developed for the unique Blue Waters architecture that leverages the combination of CPU and CPU–GPU resources allows for reconstructions and analysis at a scale commensurate with data collection at the Beckman Institute and Carle Neuroscience Institute. In a cohort of mesial temporal lobe epilepsy patients, magnetic resonance elastography (MRE) has shown it can identify affected regions as stiffer than similar regions in healthy controls. Since surgical resection is the most viable treatment, MRE has shown potential as a specific biomarker of disease.

RESEARCH CHALLENGE

Quantitative magnetic resonance imaging (MRI) techniques provide an added dimension to standard neuroimaging routines: they allow researchers and clinicians to measure the physical characteristics of the human brain. Over the last few years, our team has become a leader in MRE development and application, enabling the study of the mechanical properties of the brain. Indeed, the research team has made significant advances in developing high-resolution methods for MRE based on the advanced image acquisition and reconstruction approaches [1–3] and robust mechanical inversion schemes [4–5]. Through these developments, we have been able to map the brain at unprecedented resolution and probe specific neuroanatomical structures, including white matter tracts [6,7] and subcortical gray matter [8].

Additionally, the pathogenesis of neurodegenerative diseases such as dementia and Alzheimer's disease (AD) are not well understood, but there are indications of microvascular changes being an important biomarker. To understand the changes in the microvascular architecture that accompany AD, investigators have been limited to sophisticated histological and immunohistological methods to laboriously document changes in postmortem (after death) samples [8–11]. These histological techniques, while capable of visualizing the degradation of the microvasculature, one microscope field at a time, fundamentally lack the scale to be incorporated in prospective studies tracking individuals at risk of developing AD or other forms of dementia, or to incorporate information about functional measures of blood flow. In light of these limitations, the need for a quantitative set of noninvasive measures for brain microvascular architecture that can scale to population-level studies is clear.

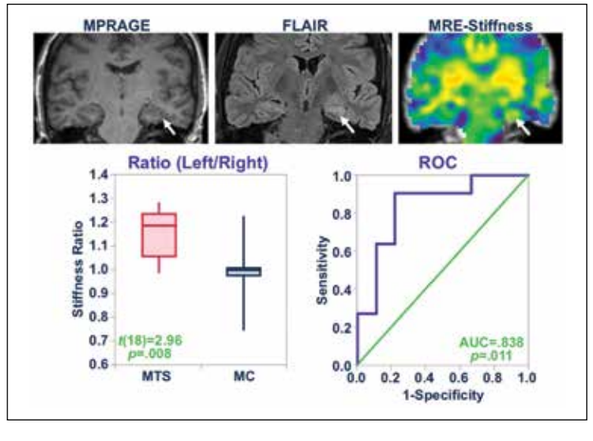

Figure 1: (Top) MPRAGE, FLAIR, and MRE-Stiffness images from a patient with mesial temporal lobe sclerosis. (Bottom) The ratio of stiffness of epileptogenic to nonaffected hippocampus (HC) is significantly greater compared to controls. The ROC curve indicates that the ratio of HC stiffness dissociates patients from controls with high accuracy.

METHODS & CODES

We used two codes in this work: PowerGrid for iterative MRI image reconstruction [12] and nonlinear inversion for iterative MRE property reconstruction [4,5].

PowerGrid is an open-source platform developed by our group for performing iterative MRI image reconstruction [12], and is a flexible, GPU-based MRI reconstruction platform that includes support to model and correct for several common data artifacts. Implemented with initial assistance from NVIDIA and NCSA, PowerGrid has shown good scaling across multiple GPU nodes on Blue Waters via MPI for performing the reconstruction of a single subimage from a single subject.

Nonlinear Inversion (NLI) is an iterative, finite-element method (FEM)-based inversion algorithm for converting MRE shear displacement fields into shear modulus property maps [4,5]. NLI was originally developed by researchers at Dartmouth College and has been adapted for brain MRE in collaboration with the project research team. The current implementation of NLI divides the brain into smaller regions (called "subzones") for FEM meshing and optimization of properties at a local level, which are then reconstituted as a global solution. Importantly, this subzoning process allows for parallelization across CPU cores.

RESULTS & IMPACT

The codes and computational resources have been applied to several neuroimaging studies, including a mesial temporal sclerosis project (Fig. 1). Our data suggest that MRE is a useful tool for identifying patients with mesial temporal lobe epilepsy due to an asymmetry in hippocampal scarring. This project has also identified an unanticipated and intriguing outcome: Previously, based on available imaging tools, researchers and physicians have believed that the nonsclerotic hippocampus was structurally normal. However, our work has revealed significant softening of the nonsclerotic hippocampus compared to healthy controls, which may provide an important biomarker for early disease detection. Because of poor pharmaceutical outcomes but excellent surgical outcomes in this patient group, early detection is critical for successful treatment before significant and irreversible damage occurs. Thanks to the contributions of Blue Waters, we now have sufficient pilot data to write a grant to translate this technology into the clinic for early detection.

With PowerGrid and Blue Waters we have scaled reconstructions for a single subimage of a single subject to over 200 GPUs (Fig. 2) with significant speedup via MPI parallelization and the high-speed interconnect present in the Cray XE/XK system. MPI has not been widely employed in MRI imaging, and to our knowledge, has not been combined with GPU acceleration for parallelizing single-image reconstructions. Currently, MRI imaging is limited to what can be reconstructed in a reasonable time with a workstation attached to the scanner. This provides poor efficiency in using the limited time that a patient is in the scanner to obtain high-spatial-resolution images with quantitative information relevant to disease progression. We hope to develop new applications and techniques that can be made tractable by exploiting cutting-edge resources such as Blue Waters.

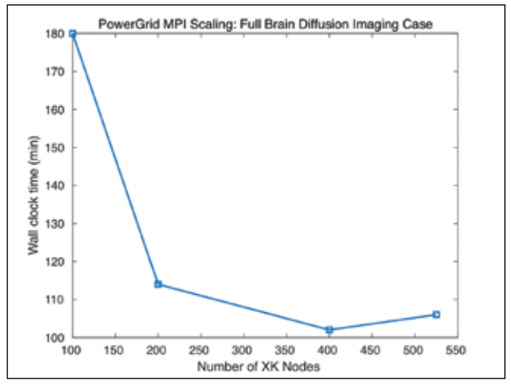

Figure 2: Initial scaling results from PowerGrid suggest acceptable speedup and efficiency when scaling to 200 GPUs (XK nodes), including communication and Shifter containerization overhead. This scaling empowers our workflow to distribute a much larger reconstruction problem across multiple GPUs.

WHY BLUE WATERS

The Blue Waters system provides a unique resource for MRE because it allows for rapid transfer of imaging data from the scanners and the low-latency memory transfers necessary for highly parallel computations. For PowerGrid, Blue Waters provides an environment with a large number of GPUs, as well as support for containerization technology, Shifter, that supports our development workflows.

PUBLICATIONS & DATA SETS

McIlvain, G., E. Telzer, and C. Johnson. Mechanical Properties of the *In Vivo* Adolescent Human Brain. *Developmental Cognitive Neuroscience*, in review (2018).

Anderson, A., et al., Multi-Excitation MRE in Aging Human Brain. *Proceedings of the 26th Annual Meeting of the International Society for Magnetic Resonance in Medicine* (Paris, France, 2018).

Anderson, A., 2018. *Magnetic Resonance Elastography and Nonlinear Inversion Problem in the Aging Brain*, doctoral dissertation, University of Illinois at Urbana-Champaign (2018), http://hdl.handle.net/2142/101335.

Johnson, C., et al., Double dissociation of structure–function relationships in memory and fluid intelligence observed with magnetic resonance elastography. *NeuroImage*, 171 (2018), DOI:10.1016/j.neuroimage.2018.01.007.