Enabling advanced magnetic resonance imaging of diffusion and elastography of the brain through HPC-based image reconstruction

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Executive Summary

There is a large, and growing, body of evidence to support the interplay of structural attributes of the human brain being affected by and affecting the function of the brain. The ability to quantitatively assess the structural integrity of the brain using non-invasive techniques, like magnetic resonance imaging (MRI), may provide the necessary insight to understand the connection between structure and function. Clinical MRI systems are capable of advanced quantitative imaging, both in high-resolution and unique biomarkers, but require significant technological development, computational resources, and unique pre-clinical studies. The Blue Waters environment has allowed for more rapid progress in all three areas through analysis of the inversion algorithms and validation of experimental data. Two studies have been completed assessing correlations between general physical health and hippocampal mechanical properties, and two on-going studies have progressed on characterizing the connection between the structural and functional properties of the normal aging human brain.

Key Challenges

Human brains change throughout their lifetime, both in subtle and drastic ways. Subtle changes to the brain microstructure occur with lifestyle choices and normal aging. More drastic changes can come from traumatic injuries and neurodegenerative diseases. Quantitative MR imaging techniques, such as diffusion tensor imaging (DTI), magnetic resonance elastography (MRE), and intravoxel incoherent motion (IVIM), provide the opportunity to interrogate the tissue microstructure for these changes but require resolution near the same order as the smallest structures of interest. In order to accurately measure the properties of neuronal fiber bundles, DTI requires a resolution of less than 1 millimeter, see Figure 1. MRE measures the viscoelasticity of the tissue, from the very small hippocampal regions to the large corpus callosum. To understand the vasculature, IVIM exploits a similar signal as DTI, where the flow, and thus the integrity, of the vasculature supply is characterized. Achieving adequate imaging resolution and signal-to-noise ratio with these techniques is challenging but we have shown it can be accomplished using clinical imaging systems coupled with advanced imaging methods and reconstruction algorithms. The reconstructions are computationally expensive and utilized the high-speed data transfers and distributed computing coupled with acceleration from GPUs.

Why It Matters

Experimental Studies

Four separate human studies were completed, or are underway, and focus on two areas of brain health: understanding the links between tissue mechanical properties and brain performance[1,2] and effects of normal aging on the microstructure of the human brain (MRE and IVIM, in progress). MRE of the brain has been developed at Illinois on Blue Waters, providing the highest resolution studies of the brain and most reliable measures of mechanical properties of brain tissue to date. It is a new measure and it is showing significant promise in terms of its sensitivity to changes and relationship to brain functional performance.

Algorithmic Study of NLI-MRE

Further development of the algorithms to improve the capabilities of quantitative imaging require a careful characterization of the effects of inversion parameters on the reconstructed properties. Magnetic resonance elastography (MRE) is a non-invasive, quantitative technique for measuring the mechanical properties via the response of the tissue to externally applied shear waves. The full 3D mechanical waves are captured using synchronized motion encoding imaging, then the material properties are estimated using a nonlinear inversion (NLI-MRE) of the steady-state Navier equation. The NLI-MRE problem requires a decomposition of the full human brain domain across multiple processes but allowed for larger problems per processor, which has allowed a large inversion parameters study. The NLI parameter study builds on the success of the previous human studies while reducing the potential dependence of reconstructed properties on inversion parameters.

Why Blue Waters

The Blue Waters system provides a unique resource for MRI because it allows for rapid transfer of imaging data from the scanners and the low-latency memory transfers necessary for highly parallel computations. This is especially critical for quantitative, high-resolution MRI that inherently involves very large datasets and extensive computation. Blue Waters has enabled the refinement of these techniques and their translation in research by significantly reducing computational burden.

Accomplishments

Four separate human studies were completed, or are underway, and focus on two areas of brain health: understanding the links between tissue mechanical properties and brain performance[1,2] and effects of normal aging on the microstructure of the human brain. We have built on previous findings with MRE in studies run at the Beckman Institute exploring the relationship between tissue viscoelasticity and memory to include an analysis of fitness effects, which are known to improve brain health. The positive relationship between hippocampal structure, aerobic fitness, and memory performance has been demonstrated at either end of the lifespan in children and older adults; but evidence of this relationship among young adults, for whom the hippocampus is neither developing nor atrophying, is less consistent. Studies have typically relied on hippocampal volumetry (a gross proxy of tissue composition) to assess individual differences in hippocampal structure. Microstructural differences in hippocampal integrity may exist even among healthy young adults when volumetric differences are either absent or not diagnostic of tissue health or cognitive function. In the current study, we investigated the relationship between hippocampal viscoelasticity from MRE and cardiovascular health, and their mutual effect on relational memory in a group of healthy young adults. An example of the MRE results pre- and post-intervention is shown in Figure 2. We replicated our previous finding that hippocampal viscoelasticity correlates with relational memory performance. We extended this work by demonstrating better aerobic fitness, as measured by VO2max, was associated with hippocampal viscoelasticity that mediated the benefits of fitness on memory function. In contrast, hippocampal volume did not account for individual differences in memory. Therefore, these data suggest, for the first time, that hippocampal viscoelasticity may provide a more sensitive measure of microstructural tissue organization and its consequences on brain performance among healthy young adults.

We followed up on the findings of relationships between hippocampal viscoelasticity, memory performance, and fitness by using MRE in a study of exercise training in persons with multiple sclerosis (MS). Five subjects with MS completed three-month exercise training and we observed this intervention significantly improved their hippocampal viscoelasticity. Further, we observed the change in viscoelasticity correlated with the improvement in memory performance with training, see Figure 3. These results highlight the sensitivity of the MRE measures of brain health as they relate to cognitive performance. By using a highly sensitive neuroimaging battery that includes MRE to monitor therapy, we can better understand the mechanisms contributing to brain health and recovery.

Finally, Blue Waters enabled a parameter study of NLI to further develop the NLI algorithms to improve the capabilities of quantitative imaging via a careful characterization of the effects of inversion parameters on the reconstructed material properties[3,4]. Using the capabilities of Blue Waters' network and local memory, the size of the subzones was increased up to 15 times the previous subzone size, previously impossible on other systems. Additionally, processor speed afforded an investigation into increasing the number of conjugate gradient estimations at the subzone-level to ensure proper convergence of the material property estimates. This study was the first of its kind in the breadth and depth of inversion parameter characterization.

Next Generation Work

A next generation system will allow our algorithms to scale to even higher resolution imaging and faster reconstructions with novel GPU accelerators. These advances in hardware and software will result in efficient reconstruction of images for studies being performed at the Carle Neuroscience Institute and the Beckman Institute. The ultimate goal of this line of research is the development of solutions for real-time, on-line reconstructions based on seamless integration of the MRI scanner and Blue Waters that can be efficiently incorporated into the workflows of clinicians and brain researchers. The computational requirements of a single subject's data is large, but large-scale studies will require hundreds of subjects to be run and analyzed in order to provide definitive answers of the role of the mechanical properties of the brain on overall brain health.

References

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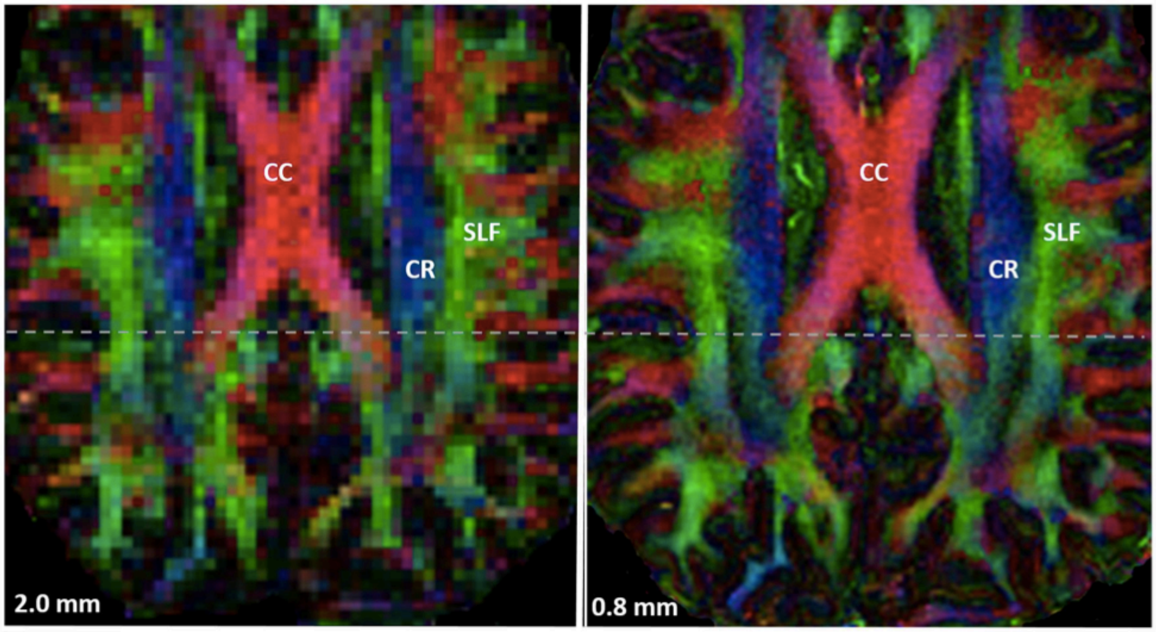

Figure 1: High-resolution DTI better delineates fiber structures in the brain.

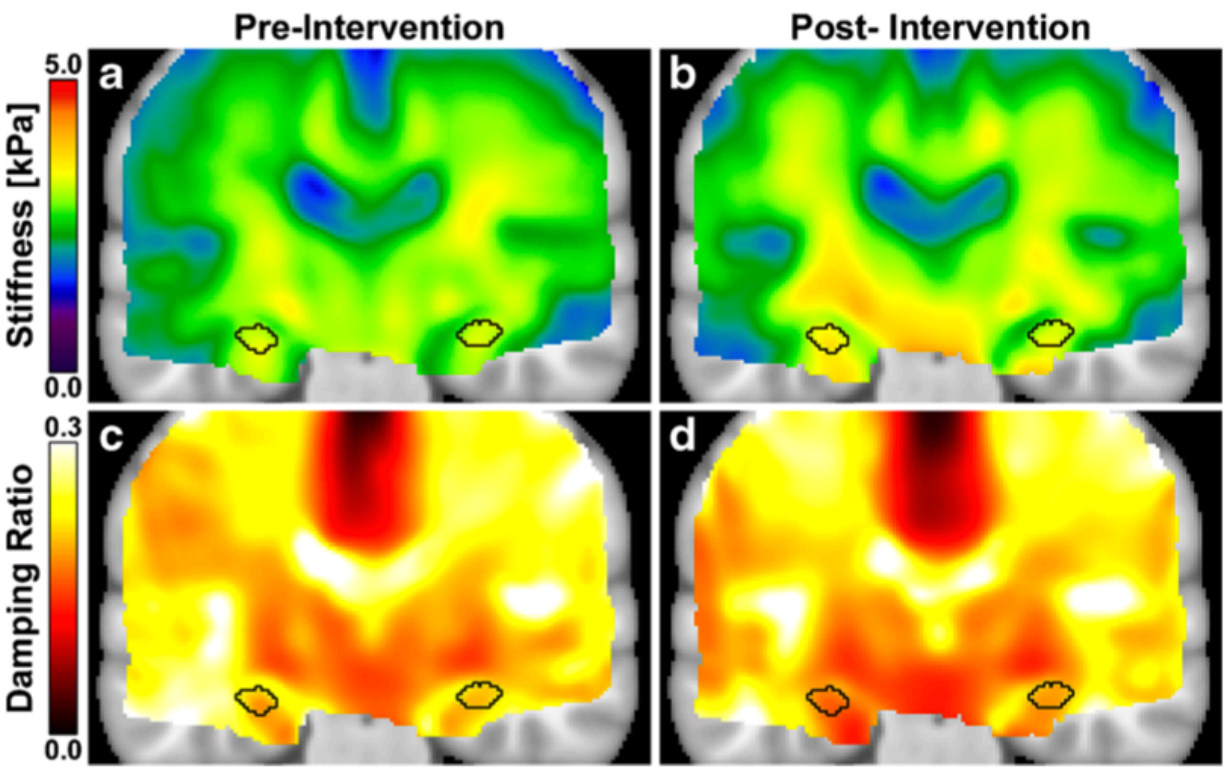

Figure 2: Hippocampal viscoelasticity is correlated with memory performance in young adults. This measure of hippocampal tissue health, unique to high-resolution MRE, provides a novel method to evaluate the brain, as illustrated by its improved sensitivity over hippocampal volume, a classical brain health measure.

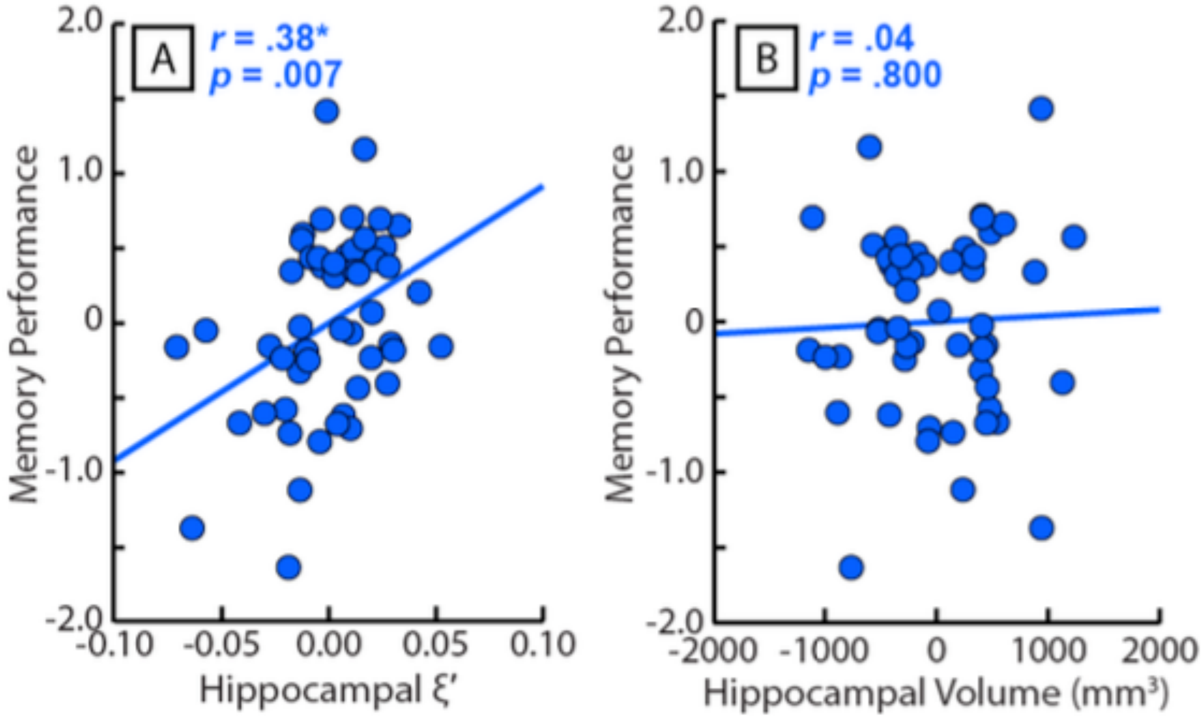

Figure 3: Hippocampal viscoelasticity is improved by exercise training in persons with multiple sclerosis. Exercise therapy improves brain health and cognition, and the MRE measure is used to evaluate the recovery of hippocampal integrity following intervention, and can be used to better design and deliver rehabilitative treatments in the future.