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Determining the Relationship between DTI and MR Elastography Metrics in Highly Anisotropic White Matter Structures at 7T

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Synopsis

Keywords: Elastography, Brain

Motivation: Changes in the relationship between MRE and DTI metrics in small white matter structures could indicate alterations in brain microstructure due to white matter damage.

Goal(s): This study aims to determine correlations between metrics measured by MRE and DTI at 7T in the healthy human brain.

Approach: MRE and DTI acquisitions were performed on 14 young, healthy volunteers at 7T, and Shear Stiffness, Damping Raio, FA and RD were calculated for each person.

Results: Significant correlations were found in small, highly anisotropic, brain regions between Shear Stiffness or Damping Raio and FA or RD.

Impact: The high resolutions achieved at 7T for both MRE and DTI allow us to investigate microstructural relationships in small, highly-anisotropic, brain regions. Changes in these metrics or relationships between these metrics could indicate alterations in microstructure integrity, suggesting potential damage.

Introduction

White matter microstructure has been known to change due to inflammation, demyelination, and neurological diseases and disorders. The most common imaging technique for investigating white matter microstructure integrity is diffusion tensor imaging (DTI), which measures restricted diffusion of water in tissue¹. Leveraging ultra-high field 7 Tesla (7T) MRI, with increased signal-to-noise ratio and improved soft tissue contrast allows us to accurately map tissue microstructure. Previous studies at 3T have found correlations between MR Elastography (MRE) and DTI metrics in small white matter structures^{2,3}, but low imaging resolution of the limited specificity small regions due to partial volume effects. In this study, we investigate the relationship between Shear Stiffness or Damping Raio as measured by MRE and Fractional Anisotropy (FA) or Radial Diffusivity (RD) as measured by DTI, both at high resolution at 7T in the human brain.

Methods

Full brain coverage MRE (using a custom SE-2D-EPI-based sequence⁴) was performed on 14 healthy human subjects (Avg. age 27±3 years) at 1.1mm isotropic resolution and 50Hz vibration frequency⁵, using a 32-channel head coil (Nova Medical) on a 7T Siemens Magnetom MRI scanner (TR/slice=140ms, TE=65ms, GRAPPA=3, Partial Fourier 7/8). Raw data were collected for each of these scanning sessions, and images were reconstructed post-hoc using Gadgetron⁶ to reduce the occurrence of phase singularities often found in standard reconstructions of this type. Images were denoised using an MP-PCA algorithm⁷ and unwrapped using Segue 4D unwrapping⁸. The resulting unwrapped displacement data, were used to calculate Shear Stiffness and Damping Ratio using an iterative nonlinear viscoelastic inversion of the time-harmonic Navier's equation⁹.

We also performed a high-angular-resolved (HARDI) diffusion-weighted imaging sequence (dMRI) that allows us to acquire brain images with 1.05 mm isotropic resolution (b=1500 s/mm2, reversed-phase encoding in anteroposterior and posteroanterior directions for paired acquisition in 68 directions) with a total acquisition time of 20 minutes. The dMRI pre-processing was performed using the human connectome project (HCP) pipelines, adjusted to account for significant eddy currents. The pre-processing pipeline included skull-stripping, eddy current correction using FMRIB Software Library (FSL) (www.fmrrib.ox.ac.uk/fsl), correction of gradient non-linearities using the HCP, B0-field inhomogeneity correction, and co-registration to the structural images from the Freesurfer pipeline¹⁰. This allowed estimation of whole brain maps of RD and FA.

Segmentation of individual structures in the white matter, specifically the body, genu, and splenium of the corpus callosum, the anterior, posterior, and superior corona radiata, and the superior longitudinal fasciculus, was performed using the ICBM-DTI-81 white matter atlas and parcellation map¹¹. Registration of the ICBM-152 template to the DTI and MRE image spaces was performed using SPM12¹² and the same transformation was applied to the masks generated by the white matter atlas. Region-wise correlations between Shear Stiffness or Damping Ratio to FA or RD were performed to determine the relationship between MRE metrics and DTI metrics of these highly anisotropic brain regions.

Results

We found a significant positive correlation between FA and Shear Stiffness in the superior longitudinal fasciculus, with trending correlations in the body of the corpus callosum, the full corpus callosum, and the superior corona radiata. We also found significant negative correlations between FA and Damping ratio in the body of the corpus callosum and the full corpus callosum. We found significant negative correlations between RD and Shear Stiffness in the superior corona radiata and the superior longitudinal fasciculus, as well as significant positive correlations between RD and damping ratio in the body of the corpus callosum and the full corpus callosum.

Discussion

Our correlation between FA and MRE metrics implies greater stiffness and lower energy dissipation across the volume in small regions where the uniform directionality of the white matter fibers is high. This indicates the need for anisotropic viscoelastic inversion specifically in these areas of the brain. Alterations in the correlation between metrics in these areas may be indicative of damage to the white matter microstructure. While it is possible that the correlation between RD and MRE metrics are related to axon density, this remains under investigation.

Conclusion

While correlations between the DTI metrics of FA and RD, and MRE metrics of Shear Stiffness and Damping Ratio are not apparent in larger structures, the high resolution achieved at 7T for both MRE and DTI allows us to investigate these relationships in small, highly anisotropic, brain regions. Changes in these metrics or the relationships between these metrics could signal changes in microstructure indicative of damage to white matter microstructure.

Acknowledgements

The authors would like to acknowledge Dr. Jelle Veraart for supplying the MP-PCA denoising algorithm. The authors would also like to acknowledge the support from NSF CMMI 1953323 and NIH funding R21AG071179.

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Figures

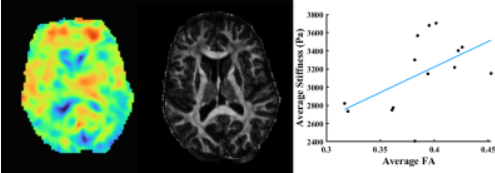


Figure 1: Overview Figure showing (from left to right) MR Elastography Shear Stiffness and Fractional Anisotropy in the same subject, and the Significant (p<0.05) correlation between Average Shear Stiffness and FA in the Superior Longitudinal Fasciculus.

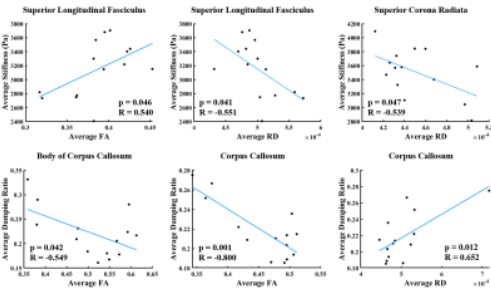


Figure 2: Selected Significant Correlations (p<0.05) Between Average Stiffness and FA or RD (top row) and Average Damping Ratio and FA or RD (bottom row).

Brain Region	FA & Shear Stiffness		RD & Shear Stiffness	
	R	p-value	R	p-value
Gray Matter	0.028	0.925	-0.214	0.462
White Matter	0.304	0.290	-0.357	0.210
Corpus Callosum (Body)	0.489	0.076	-0.526	0.053
Corpus Callosum (Genu)	0.322	0.262	-0.327	0.254
Corpus Callosum (Splenium)	0.167	0.568	-0.348	0.223
Corpus Callosum	0.482	0.081	-0.527	0.053
Corona Radiata (Anterior)	-0.035	0.905	0.100	0.734
Corona Radiata (Posterior)	0.019	0.949	-0.014	0.963
Corona Radiata (Superior)	0.497	0.071	-0.539	0.047
Corona Radiata	-0.185	0.526	0.149	0.612
Superior Longitudinal Fasciculus	0.540	0.046	-0.551	0.041

Table 1: Correlation Coefficients and p-values of FA, MD, or RD and Shear Stiffness for Each Brain Region. There is a significant positive correlation (p<0.05, bolded) between FA and Shear Stiffness in the superior longitudinal fasciculus, with trending correlations in the body of the corpus callosum, the full corpus callosum, and the superior corona radiata. There are also significant negative correlations (p<0.05, bolded) between RD and Shear Stiffness in the superior corona radiata and the superior longitudinal fasciculus.

Brain Region	FA & Damping Ratio		RD & Damping Ratio	
	R	p-value	R	p-value
Gray Matter	-0.193	0.508	0.351	0.218
White Matter	-0.275	0.341	0.332	0.247
Corpus Callosum (Body)	-0.549	0.042	0.652	0.012
Corpus Callosum (Genu)	-0.398	0.159	0.062	0.833
Corpus Callosum (Splenium)	0.035	0.904	0.096	0.745
Corpus Callosum	-0.800	0.001	0.677	0.008
Corona Radiata (Anterior)	-0.239	0.411	0.210	0.472
Corona Radiata (Posterior)	-0.020	0.947	0.139	0.637
Corona Radiata (Superior)	-0.365	0.199	0.393	0.164
Corona Radiata	-0.157	0.593	0.229	0.431
Superior Longitudinal Fasciculus	-0.163	0.578	0.211	0.468

Table 2: Correlation Coefficients and p-values of FA or RD and Damping Ratio for Each Brain Region. There are significant negative correlations (p<0.05, bolded) between FA and Damping ratio in the body of the corpus callosum and the full corpus callosum. There is also a significant positive correlation (p<0.05, bolded) between RD and damping ratio in the body of the corpus callosum and the full corpus callosum.