MR imaging of brain deformation during mild angular acceleration, referenced to brain anatomy and microstructure

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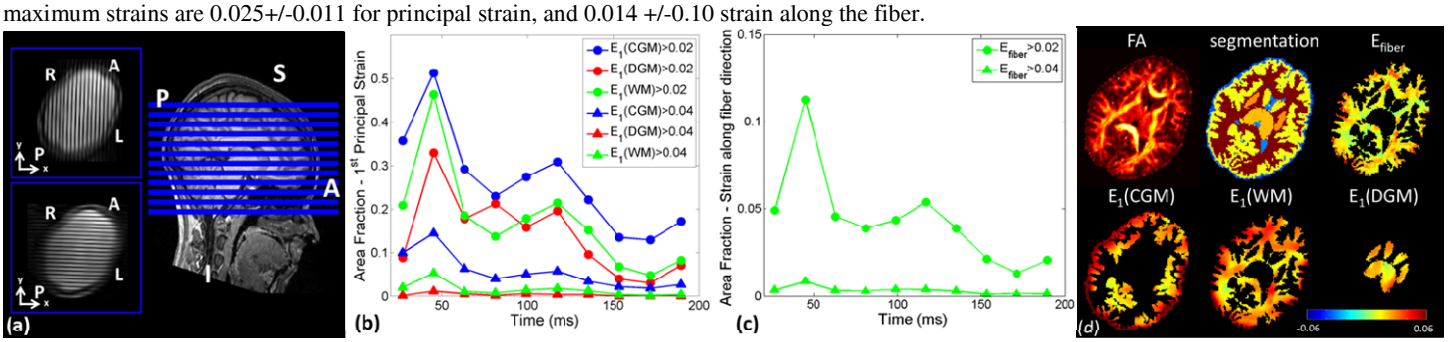
Target audience: Clinicians and researchers interested in understanding the interaction between mechanical deformation in the brain and the underlying structure identified using MRI.

Purpose: To provide the first ever experimental measures of brain deformation in the live human brain along principal fiber directions and in different brain regions in response to mild angular acceleration.

Methods: Four subjects were imaged on a Siemens 3.0T mMR Biograph scanner. The protocol was approved by the IRB at the NIH. Using a 16-channel head coil, a 3D T2-weighted image (TE/TR=409ms/3200ms, 0.5x0.5x1.0mm^3), 3D MPRAGE (TE/TR=3.0ms/2530ms, TI=1100ms, 1mm isotropic), a series of diffusion-weighted images (2D multislice EPI acquisition, TE/TR=96ms/17000ms, 2mm isotropic, 30 directions at b=1000, 5 directions at b=300, 5 images at b=0, 1 image at b=0 with reversed phase encode direction) were acquired. EPI distortion correction was applied using the approach by Holland et al.[1] Eddy current correction, motion correction, and tensor estimation were performed using TORTOISE (https://science.nichd.nih.gov/confluence/display/nihpd/TORTOISE). The MPRAGE was segmented into cortical gray matter, deep gray matter (including thalamus, caudate, and putamen), and white matter using TOADS (http://www.nitrc.org/projects/toads-cruise/).

The subject was removed from the scanner and placed in an MRI-compatible device that constrained head motion to rotate about the inferior/superior axis[2]. To initiate the motion, the subject released a latch, allowing for a free rotation of 32° towards the left shoulder before coming to an abrupt stop. The resulting motion was a mild angular acceleration, with peak values around 200rad/s^2. To track brain deformation, a series of 10-12 axial tagged MR images[3] covering the entire brain (Figure (a)) were acquired using a four-channel flex coil (2D cine gradient echo acquisition, TE/TR=1.7ms/3.1ms, FOV=240x240, slice thickness=8mm, ROxPE=160x24, tag spacing=8mm, segments=6, tag directions along x and y axes, repetitions per slice=4). To reduce variability between repetitions, tag lines were applied when the subjects initiated the motion, and image acquisition began after the subjects rotated through 29° (prior to the stop). A set of tagged images with no motion and a 3D MPRAGE image (TE/TR=2.7ms/2530ms, TI=1100ms, 2mm isotropic) were acquired for registration purposes. Motion tracking was performed using harmonic phase analysis[4]. Strain, being independent of rigid-body translation and rotation, was used to characterize deformation. Lagrangian strains were computed using finite differences in Cartesian coordinates, and principal strains were calculated. The image segmentation and processed diffusion data were mapped into tagged image space using 3D rigid registration. First, the 1mm isotropic MPRAGE and T2-weighted images were registered to the 2mm isotropic MPRAGE. Then the "no-motion" tagged images were registered to the first frame of the "motion" tagged images. The computed transformations were combined and applied in a single step to map FA, the diffusion tensor, and segmentation to each voxel in the tagged image space. For strain along the fiber direction, only voxels with principal eigenvectors within 30° of the image plane and with FA>0.3 were considered. Vectors were projected into the image plane, normalized, and the cross product with a vector along the z-axis was computed to form a basis within the imaging plane. The strain tensor was then transformed from the global Cartesian coordinate system to the local system.

Results: The area fraction of strain represents the fraction of voxels with strain above a threshold value. Figure (b) shows the area fraction of the first principal strain (E_1) greater than 2% and 4% in cortical gray matter (CGM), deep gray matter (DGM), and white matter (WM). Figure (c) shows the area fraction of strain along the principal fiber direction (E_{fiber}). Both plots were computed across all four subjects and all acquired slices. Part (d) of the figure shows the maximum strain value over the time series at each voxel for a single image slice of one subject. In the white matter, the maximum strains are 0.025+/-0.011 for principal strain, and 0.014 +/-0.10 strain along the fiber.



Discussion: Obtaining strain measurements in the live human brain, even at low accelerations, is important to provide reference data for computational models of traumatic brain injury. Quantifying the amount of deformation along the principal fiber direction and in different anatomical regions provides an understanding of how brain structure influences the response to applied forces. For studied motion, the largest principal strains were observed in the cortical gray matter, generally furthest from the center of rotation. Strain along the fiber direction is considerably lower than the principal strains within the white matter.

Conclusion: Here we present the first ever set of brain deformations mapped to anatomical structures and along principal fiber orientations obtained in live human subjects. Future studies will extend this work to measure 3D deformations and examine linear head accelerations.

References:

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