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Deformation of the human brain induced by mild angular head acceleration

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Abstract

Deformation of the human brain was measured in tagged magnetic resonance images (MRI) obtained dynamically during angular acceleration of the head. This study was undertaken to provide quantitative experimental data to illuminate the mechanics of traumatic brain injury (TBI). Mild angular acceleration was imparted to the skull of a human volunteer inside an MR scanner, using a custom MR-compatible device to constrain motion. A grid of MR "tag" lines was applied to the MR images via spatial modulation of magnetization (SPAMM) in a fast gradient echo imaging sequence. Images of the moving brain were obtained dynamically by synchronizing the imaging process with the motion of the head. Deformation of the brain was characterized quantitatively via Lagrangian strain. Consistent patterns of radial-circumferential shear strain occur in the brain, similar to those observed in models of a viscoelastic gel cylinder subjected to angular acceleration. Strain fields in the brain, however, are clearly mediated by the effects of heterogeneity, divisions between regions of the brain (such as the central fissure and central sulcus) and the brain's tethering and suspension system, including the dura mater, falx cerebri, and tentorium membranes.

Keywords: Angular acceleration; Brain trauma; Strain; Head injury; Brain deformation; MRI

1. Introduction

Every year there are over 1.5 million new cases of traumatic brain injuries (TBI) in the US. In addition to the devastating human costs, TBI causes over $56.3 billion in economic losses per year (Thurman, 2001). In spite of its importance and its many years of research interest, TBI is not well understood. It is clear that when the skull is accelerated, the brain deforms in response, but the details of the resulting strain fields are not known. It is widely accepted that skull acceleration can lead to brain injury if local strains and strain rates exceed a critical threshold (Gennarelli et al., 1989; Bain and Meaney, 2000), above which the neural fibers (axons) are affected.

Shear strains due to angular acceleration of the skull have been hypothesized to be especially important in TBI. Holbourn (1943) showed that rotation of the human skull could cause large deformations of a gel housed within its cranial cavity. Pudenz and Shelden (1946) supported Holbourn's claims through visualization of the surface of animal brains. They replaced the top half of a monkey skull with transparent plastic, and filmed the deformation of the brain during linear acceleration.

More recently, quantitative studies of brain deformation have been performed using high-speed filming of gel-filled skulls (Meaney et al., 1995; Margulies et al., 1990), high-speed bi-planar X-ray imaging of the cadaveric brain (Hardy et al., 2001), and MR imaging of the brain in human volunteers (Wedeen and Poncelet, 1996; Reese

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et al., 2002; Bayly et al., 2005). In studies done with high-speed filming, quantitative estimates of strain (0.20–0.30) were found in gel-filled pig skulls subjected to angular accelerations similar to those that produced axonal injury in the live animal. Because these studies used gel as a surrogate, they could not capture the effects of heterogeneity, anisotropy, vasculature, meninges, and cerebrospinal fluid on brain deformation. Hardy et al. (2001) performed high-speed (250–1000 frames/s) bi-planar X-ray studies of the displacement of 11 neutrally buoyant radio-opaque markers in cadaver brains during head acceleration. Spatial resolution was limited by the sparseness of the array of physical markers; also tissue properties and brain–skull interactions of the cadaver may differ significantly from those of a live subject. Zou et al. (2007) reported estimates of relative rigid-body rotation and translation of the brain and skull, obtained from the X-ray data of Hardy et al. (2001). Wedeen and Poncelet (1996) demonstrated the use of phase-contrast magnetic resonance images (MRI) to measure strains in the brain parenchyma of human subjects during physiological pulsatile motion and voluntary head shaking. Head accelerations during voluntary motion were not measured. Bayly et al. (2005) studied deformation of the human brain *in vivo,* during controlled linear head acceleration, using tagged MR imaging. This approach provides strain fields with good spatial ($2 \times 2 \times 5$ mm) and temporal (6 ms/frame) resolution. Results of this study suggest that tethering of the brain at the sellar and suprasellar region plays a central role in determining the mechanical response of the brain during linear skull accelerations (Bayly et al., 2005). Head accelerations were primarily posterior–anterior and were limited to values that are safe for the human test subjects (20–30 m/s^2).

An important purpose for measurement of brain deformation is to generate quantitative data to validate computer models. Computer models of the brain (Ruan et al., 1991; Kleiven, 2006; Takhounts et al., 2003; Zhang et al., 2004) offer great potential for studying brain biomechanics, if they are shown to be accurate. For example, simulations could be used to provide estimates of brain deformation for accelerations that would be unsafe for human subjects (as in, for example, Kleiven and von Holst, 2002), or for studies that would be costly, difficult, or inconclusive with cadavers or animals. However, accurate computer simulations require accurate information about the brain's material properties, boundary conditions, and tissue connectivity. It is critically important for computer simulations to be verified by comparison to observations.

The current experimental study was performed to illuminate the mechanical response of the brain to mild *angular* acceleration. The brain was imaged using dynamic tagged, gated MRI during angular motion of the head in the transverse plane (rotation about the long axis of the neck). Deformation was quantified by computing the two-dimensional (2-D) Lagrangian strain tensor in four parallel axial planes.

2. Methods

2.1. Overview

Three adult male subjects of average height and weight (age 25–42 yrs; 70–80 kg; 1.7–1.8 m tall), performed controlled head rotation using a custom, MR-compatible device (Fig. 1) that imparted a repeatable mild angular acceleration of ~250–300 rad/s^2. These accelerations are about 10% of those experienced during heading of a soccer ball (Naunheim et al., 2003). The protocol was reviewed and approved by the Washington University Human Research Protection Office. Tagged MR images were acquired in three to four axial planes in each subject. Images of different planes in the same subject were acquired on different days.

2.2. Head rotation

A custom MR-compatible head rotator (built in the Washington University Instrument Shop) was used to impart mild angular accelerations to the head of a test subject (Fig. 1). The head cylinder, which cradles the subject's head, was designed to fit inside the head coil of a Siemens Sonata MRI (Siemens, Munich, Germany) and rotate freely about a plastic bearing at the back of the device. Rotation was initiated by releasing a latch, which allowed the plastic counterweight to apply torque to the head cylinder Release of the latch also tripped a fiber optic switch that activated a TTL pulse to the MRI, initiating the scanning sequence. After approximately 200 ms, the weight impacted a stop pin, imparting an impulse to the rotating assembly (Fig. 1).

The associated angular deceleration produced measurable deformation in the subject's brain.

The magnitudes of angular acceleration experienced by each subject were found by recording the linear tangent acceleration at a site on the head cylinder 10 cm from the axis of rotation. A representative time series of angular acceleration from subject S2 is shown in Fig. 2. The duration of the peak acceleration pulse was approximately 40 ms. The magnitude of angular acceleration for subject S1 was 299 ± 29 rad/s^2; for subject S2, it was 244 ± 7 rad/s^2; and for subject S3, 370 ± 21 rad/s^2 (mean $\pm$ S.D.). These values are roughly 10–15% of those experienced by soccer players during voluntary impact between the head and soccer ball (Naunheim et al., 2003).

2.3. Imaging protocol

The FLASH2D MR cine sequence was used to collect tagged images of the deformed brain. The sequence had a frame rate of 6 ms and an echo time TE = 2.9 ms. For each nominally identical repetition of the head rotation, a single line of k-space data (192 samples) was collected 90 times; each acquisition separated by 6 ms. The phase encoding-gradient was incremented after each repetition of motion. In total, 144 rotations of the head were required, leading to a 192×144 data matrix (image) for each of the 90 time points.

To superimpose tag lines on the image, immediately after the latch was released, radio-frequency (RF) pulses were applied in combination with magnetic gradients. This sequence causes longitudinal magnetization of spins to vary spatially in a sinusoidal fashion (Axel and Dougherty, 1989), resulting in an image superimposed with an array of light and dark lines. These "tag lines" move with the tissue, and their intersections may be tracked to characterize motion.

Images were collected in axial planes at several levels (Fig. 3). The reference plane (0 cm height) passed through the genu and splenium of the corpus callosum. Images were also acquired from parallel planes 2 and 4 cm superior to the reference plane, denoted as +2 and +4 cm, and 1 cm inferior (−1 cm).

2.4. Strain estimation procedures

The analysis of deformation is illustrated in Fig. 4. Tag-line intersections were identified and tracked using contours of "harmonic