MEASUREMENT OF STRAIN BY MRI TAGGING IN PHYSICAL MODELS OF BRAIN INJURY

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ABSTRACT

Two-dimensional (2-D) tensor-valued strain fields were estimated non-invasively in simple experimental models of closed-head brain injury. In the first model, shear deformation of a gel was induced by angular acceleration of its spherical container. In the second model, the brain of a euthanized, 8-day old, rat pup was deformed by a mechanical impacter. Tagged MR images were acquired stroboscopically during repetition of the motion. Strain was estimated by harmonic phase (HARP) analysis [1]. The strain analysis method was validated on simulated images. Strain fields from experimental data provide insight into levels of deformation in current injury models.

INTRODUCTION

High strains and strain rates in brain tissue may lead to diffuse axonal injury (DAI) [2-3] e.g.. Physical models using accelerated gel-filled skulls have shown large shear strains [2-3]. In milder injuries, neuronal changes are less obvious, but may be responsible for long-term cognitive deficits [4]. The strain required to caus subtle cognitive changes is not known. Finite element models of head injury have been developed [5], but credible validation remains lacking.

MRI tagging methods have been developed in the last decade to measure cardiac strain non-invasively [1,6-8]. Recently Osman et al. [1] developed an efficient method (HARP analysis) to estimate strain from the “harmonic phase” of tagged MR images.

In this paper we describe application of MRI tagging principles and HARP analysis to estimate strain fields typical of mild traumatic closed-head injury.

METHODS

Simulation

Artificial tagged images were created by plotting sets of curves representing an orthogonal grid subjected to specified deformations. The deformations corresponded to simple shear or radial-circumferential shear.

Gel phantom

A gel “phantom” was created by filling a spherical flask with gelatin (Jello). The phantom was held in a custom fixture inside the bore of an MR scanner (Siemens Sonata 1.5T, Fig. 1) and subjected to angular oscillations of $\pm\pi/12$ radians at roughly 5 Hz.

Animal model

An eight-day old Wistar rat pup was euthanized by overdose of chloral hydrate. The animal was placed in a molded head base integrated into an MR-compatible impact mechanism. The assembly was placed in a Varian 4.7Tscanner. A controlled force of 0.9 N was applied repeatedly through a 6 mm diameter impactor on top of the head about 4 mm rostral to the interaural line. The duration of force was ~100 ms with ~250 ms cycle. Tagged images were acquired in the coronal plane 4 mm rostral to the interaural line. Data acquisition was synchronized using a TTL-compatible trigger pulse on each cycle before contact. A SPAMM1331 sequence was applied after the trigger pulse (before indentation) in 2 perpendicular directions. Tag spacing was 0.4 mm. Imaging parameters were: TR/TE: 16.7/3 ms; field-of-view: 1.2 cm x 1.2 cm; matrix size 128x128; slice thickness 1 mm. 15 frames were acquired with 16.7 ms temporal resolution.

Analysis

Images were analyzed by implementing the HARP approach [1]. Contours of constant phase provided “synthetic tag lines.” Apparent 2-D strain fields were estimated from the gradients of phase as described by Osman et al. in reference [1]. All components of the 2-D strain tensor were estimated. The strain was described in either a Cartesian frame or in a radial-circumferential system.

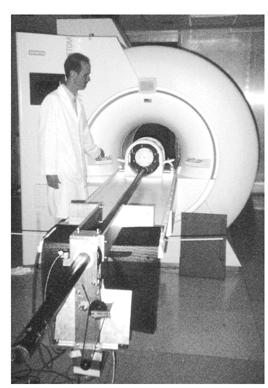

Figure 1. Photo of rotating gel phantom in the 1.5T scanner.

RESULTS

Simulated images are shown in Figs. 2a-2b. A tagged MR image of the gel phantom is shown in Fig. 2c. In Fig. 3, strain fields estimated from images in Fig. 2 are shown. Figures 4a-c show tagged MR images of the undeformed and deformed rat brain. Figures 5a-c show the strain field estimated for the deformed brain in Fig. 4b.

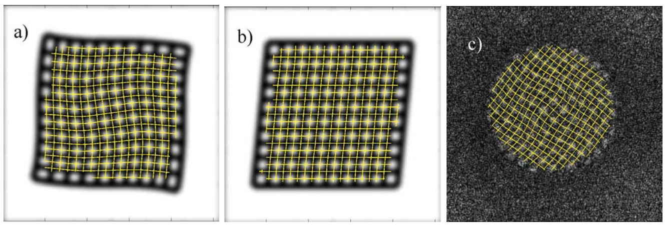

Figure 2: (a-b) Simulated images. (c) Tagged MR image of gel phantom.

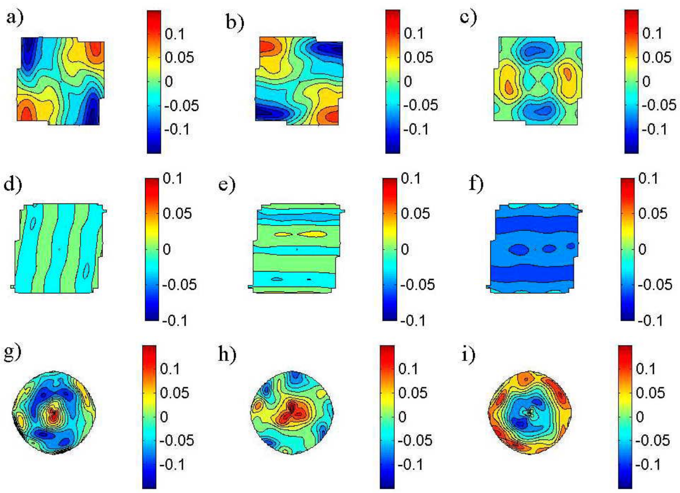

Figure 3: (a-c) Strain field for Fig. 2a: (a) ε_{xx} (b) ε_{yy} (c) ε_{xy}. (d-f) Strain field for Fig. 2b: (d) ε_{xx} (e) ε_{yy} (f) ε_{xy}. (g-i) Strain field for Fig. 2c (radial-circumferential): (g) ε_{rr} (h) $\varepsilon_{\theta\theta}$ (i) $\varepsilon_{r\theta}$

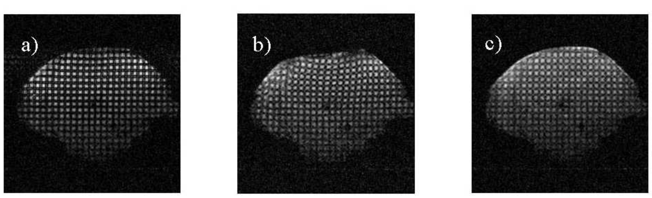

Figure 4: (a) Tagged MR image of undeformed rat brain before impact. (b) Deformed brain during impact. (c) Undeformed brain after impact.

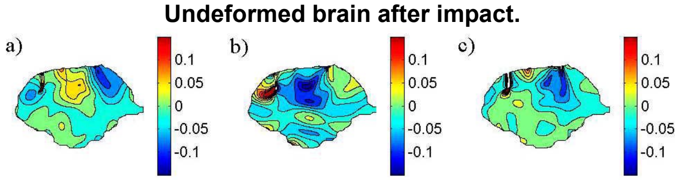

Figure 5: (a-c) Strain field for deformed rat brain (Fig 4b): (a) ε_{xx} (b) ε_{yy} (c) ε_{xy}.

DISCUSSION AND CONCLUSIONS

The harmonic phase (HARP) method was used to estimate strain fields in simulated and experimental data. The components of the strain tensor estimated from simulated images are accurate to within about ±0.02 strain. This accuracy is adequate for characterizing the moderately large deformation seen in the experimental data. Error in strain can be traced to numerical issues in estimation of gradients and filtering of image data. Averaging of strain fields may be able to reduce the spatially oscillatory strain artifacts seen in Figs 3d-f.

Strain fields were also estimated from tagged MR images of a gel phantom subjected to angular acceleration. The strain fields were described in terms of radial-circumferential directions, and are consistent with the apparent deformation. This technique appears promising for estimation of strain in cadaver or animal models of large enough size.

Finally, strain fields were estimated in a rodent model of closed-head injury; the method was demonstrated in a dead animal. Shear strain concentrations are evident beneath the corners of the indenter; shear strains are positive on the left, indicating clockwise shearing of material, and negative on the right, indicating counterclockwise shearing. The horizontal strain is highest directly beneath the indenter. The peak vertical compressive strain occurs a small distance beneath the center of the indenter, with a corresponding horizontal stretch as required by the incompressibility of brain tissue. The force levels used are known to cause extensive excitotoxic and apoptotic cell death in live rat pups [9]. The imaging procedures are readily applicable to live anesthetized animals. Using this approach, strain can be measured and compared to neuronal degeneration in quantitative studies of brain injury.

These results suggest that MR tagging provides a viable method for non-invasive estimation of strain fields characteristic of mild closed-head injury.

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