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Non-invasive measurement of brain viscoelasticity using magnetic resonance elastography

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ABSTRACT: The purpose of this work was to develop magnetic resonance elastography (MRE) for the fast and reproducible measurement of spatially averaged viscoelastic constants of living human brain. The technique was based on a phase-sensitive echo planar imaging acquisition. Motion encoding was orthogonal to the image plane and synchronized to intracranial shear vibrations at driving frequencies of 25 and 50 Hz induced by a head-rocker actuator. Ten time-resolved phase-difference wave images were recorded within 60 s and analyzed for shear stiffness and shear viscosity. Six healthy volunteers (six men; mean age 34.5 years; age range 25–44 years) underwent 23–39 follow-up MRE studies over a period of 6 months. Interindividual mean $\pm$ SD shear moduli and shear viscosities were found to be 1.17 ± 0.03 kPa and 3.1 ± 0.4 Pas for 25 Hz and 1.56 ± 0.07 kPa and 3.4 ± 0.2 Pas for 50 Hz, respectively ($P \leq 0.01$). The intraindividual range of shear modulus data was 1.01–1.31 kPa (25 Hz) and 1.33–1.77 kPa (50 Hz). The observed modulus dispersion indicates a limited applicability of Voigt's model to explain viscoelastic behavior of brain parenchyma within the applied frequency range. The narrow distribution of data within small confidence intervals demonstrates excellent reproducibility of the experimental protocol. The results are necessary as reference data for future comparisons between healthy and pathological human brain viscoelastic data. Copyright © 2007 John Wiley & Sons, Ltd.

KEYWORDS: magnetic resonance elastography; brain; elasticity; shear modulus; shear viscosity; Voigt model; biomechanics

INTRODUCTION

The biomechanical properties of the brain have been the subject of many recent studies related to hydrocephalus (1–3), traumatic brain injury (4–6), and the evaluation of stroke or intraoperative evaluation (7,8). Most biomechanical tests were carried out by invasive indentation experiments (9,10) to specifically measure the elasticity of cortical brain tissue. In contrast, little is known about the viscoelastic properties of the bulk brain in its physiological environment. Elastography techniques have demonstrated for skeletal muscle (11–13), breast (14–19), and liver (20–25) that the elasticity of living tissue is sensitive to the development of pathologies and the degree of organ malfunction. In addition to elastic tissue behavior, viscose effects are considered to be a potential source of diagnostic information for differentiating benign and malignant breast tumors (26,27). These results have stimulated the search for biomechanical approaches that may support the diagnosis of neurological diseases.

Non-invasive assessment of brain stiffness requires the application of defined mechanical stress, which is naturally hampered by the mechanical shielding of the brain through skull, cerebrospinal fluid, and meninges. Nevertheless, it has been demonstrated that magnetic resonance elastography (MRE) (28–30) is capable of measuring two-dimensional (2D) (31–33) and three-dimensional (3D) (34–36) shear wave fields in brain induced by external actuators using vibration frequencies between 65 and 90 Hz. Most mechanical drivers are mounted to bite bars with individual denture molds. Here, a more generally applicable actuator is introduced that is better suited to clinical applications. Data acquisition in brain MRE is usually achieved by spin-echo or gradient-echo imaging techniques with extra motion-sensitizing gradients synchronized to the wave generator. Evaluation of wave data can be based on full 3D wave vector field inversion of the differential equation of motion or on equivalent inversion techniques adapted to 2D scalar wave fields (22,26,37–41).

In recent years, only a few MRE studies on human brain have been published; these show a great variety of shear modulus data, ranging from 2.5 to 15.2 kPa for white matter and from 2.8 to 12.9 kPa for gray matter

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Abbreviations used: 2D, two-dimensional; 3D, three-dimensional; EPI, echo planar imaging; MRE, magnetic resonance elastography.

