Feasibility of Evaluating the Spinal Cord with MR Elastography

S. A. Kruse[1], A. Kolipaka[1], A. Manduca[1], and R. L. Ehman[1]
[1]Radiology, Mayo Clinic, Rochester, MN, United States

Introduction

Magnetic Resonance Elastography (MRE) is a noninvasive technique for quantitatively assessing the mechanical properties of soft tissues. It provides new parameters for characterizing tissues, including the intrinsic stiffness [1-2] and the effects of tension [3]. The goals of this work were to investigate the feasiblily of applying MRE to evaluate the spinal cord by: 1) determining whether it is possible to generate and image acoustic shear waves in the cord *in vivo*, and 2) testing prospective inversion algorithms to calculate the stiffness from this wave information.

Materials and Methods

The methods for imaging propagating mechanical waves in tissue were implemented on a 1.5T whole-body imager and have been previously described in detail [1-2]. Seven volunteer studies were conducted with IRB approval and informed consent. A head coil (N=2), 5-inch surface coil (N=1), and 8-channel spine coil (N=4) were used to examine several regions of the spine: cervical, thoracic, and lumbar. An active driver source driven at 60-120 Hz provided motion to a passive acoustic driver placed under the spine (Figure 1). The gradient echo (GRE) MRE scanning parameters included the following: a pulse repetition time (TR) of 50 ms, an echo time (TE) of 21.8 ms, a flip angle of 30^o, an acquisition matrix of 256 x 96, a slice thickness of 4-5 mm, a field of view (FOV) of 36-40 cm, one pair of interleaved, toggling, motion-encoding gradients acquired for each phase encoding view, and 4-6 phase offsets. The acquisition was repeated three times to collect data in 3 orthogonal sensitization directions.

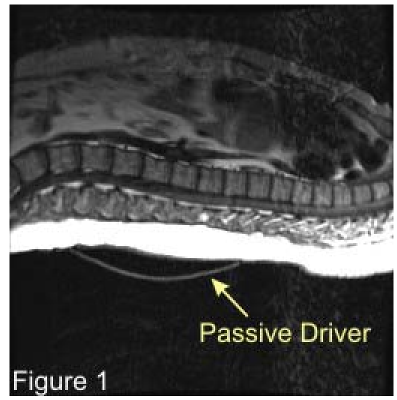


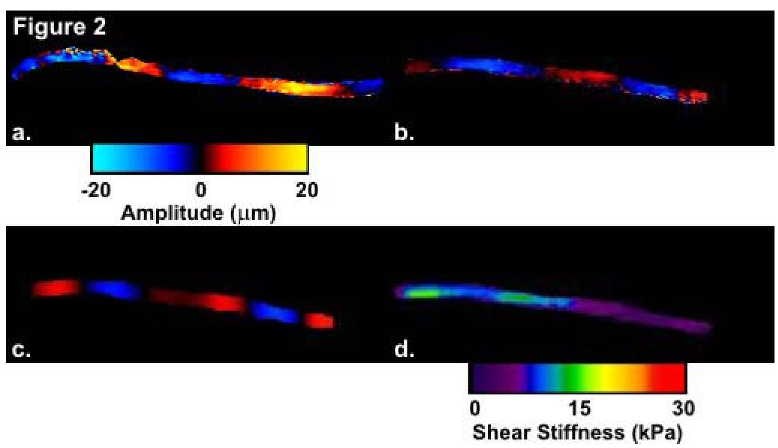
Figure 1

Conventional inversion algorithms for MRE are not suitable for evaluating isolated structures with spatial dimensions comparable to the shear wavelength. In this situation, structural dimensions and dynamic behavior need to be incorporated into the algorithm. We used a model of flexural vibration in beams as a basis to develop an inversion algorithm for processing the wave data in the spinal cord. The basic hypothesis (e.g. Bernoulli-Euler theory of beams) involved in deriving the equations of motion in this case is that cross-sectional planes, initially perpendicular to the axis of the beam, remain planar and perpendicular to the neutral axis during bending [4]. Analysis in 1D of a small differential element experiencing these flexural vibrations and requiring the forces and moments to balance on either side of the differential element gives rise to Eq.1 [4], where I=moment of inertia, E=Young's modulus of the material, w=displacements along the transverse direction, S=cross-sectional area of beam, ρ=density of the material (assumed to be 1000 kg/m^3) and ω=rotational frequency. MRE encodes the transverse component of displacement (w), which is input to Eq.1. The obtained E is converted to shear modulus μ using the relationship E/2(1+ν), where ν= Poisson's ratio (0.5). Savitzky-Golay (SG) filters [5] were used to provide estimates of the high-order spatial derivatives.

$$EI\left(\frac{\partial^4 w}{\partial x^4}\right) = \rho S \omega^2 w \quad (1)$$

Results

Figure 2a demonstrates waves at 80 Hz propagating in the spinal cord of a volunteer. From the data, the 1st harmonic is extracted (Figure 2b). Figure 2c shows the 4th order derivative estimated with SG filters. The shear stiffness of the superior portion of the spinal cord (Figure 2d) is estimated to be 12.1 ± 2.4 kPa, while that of the cauda equina, in aggregate (expected to be less stiff) is estimated at 2.7 ± 0.8 kPa.



Discussion

This study provided initial evidence for the feasibility of applying MRE to evaluate the spinal cord. The results of the inversions need to be validated and we expect that there is considerable scope for improving the shear wave illumination of the cord. If successful, this work would provide new parameters for characterizing the spinal cord in health and disease, including the potential to measure the degree of tension in the cord and the cauda equina.

References

[1] Muthupillai R, et al. *Science*. 1995. 269(5232):1854-7. [2] Muthupillai R, et al. *MRM*. 1996. 36(2):266-74. [3] Jenkyn TR, et al. *J Biomech*. 2003. 36(12):1917-21. [4] Junger MC, et al. *Sound, Structures and Their Interaction*. 1972. 195. [5] Press WH, et al. *Numerical Recipes in C*.1992. 650-655.