475.

Development and Validation of an Open-Source Pulseq-Based MRE Sequence Using Experimental and Finite Element Phantom Data

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Introduction Magnetic Resonance Elastography (MRE) is a noninvasive imaging technique used to assess the mechanical properties of soft tissues by visualizing the propagation of externally induced shear waves through the tissue [1]. MRE enables the estimation of viscoelastic parameters such as stiffness, which are valuable for diagnosing and monitoring a variety of pathological conditions, including liver fibrosis[2], tumors[3], and neurodegenerative diseases [4]. The reliability of MRE depends heavily on the accuracy of both the pulse sequence used to acquire motion-sensitive images and the inversion algorithms that convert the wave image into Stiffness maps [5]. To support the development and validation of novel MRE pulse sequences and inversion techniques, phantom studies offer a controlled environment with well-characterized mechanical properties. In this work, we developed an open-source MRE pulse sequence based on the Pulseq framework. The sequence was tested experimentally on a homogeneous MRE phantom over a frequency range of 50–120 Hz using a 3 T MRI scanner. In parallel, a finite element (FE) model of the phantom was created in FEBio[6] to simulate the wave propagation under identical boundary conditions and excitation frequencies. This dual experimental and simulation approach enabled a comprehensive comparison of the measured and simulated displacement fields, providing a robust framework for validating the custom Pulseq-based sequence.

Methods A homogeneous cylindrical phantom (diameter 150 mm, height 130 mm; CIRS Inc., VA, USA) was imaged on a 3 T MRI scanner using a custom MRE sequence developed with the Pulseq within MATLAB. The sequence employed a gradient-echo echo-planar imaging (GE-EPI) readout and incorporated motion-encoding gradients (MEGs) synchronized with externally applied mechanical vibrations. MEGs were applied in the through-plane (Z) direction with an amplitude of 10 mT/m. Mechanical excitation was delivered using a pneumatic active driver system (Resoundant Inc., USA) connected to a passive driver placed on the phantom's top surface (Fig. 1). The phantom was positioned within a 32-channel head coil, and sinusoidal shear waves at 50, 60, 70, and 120 Hz were induced and synchronized with the MRE acquisition. For all frequencies, the driver amplitude was fixed at 30%. Image acquisition was performed using a single coronal slice positioned at the isocenter of the phantom. Displacement fields were encoded over a single vibration cycle to capture transient shear wave propagation, and motion-induced phase shifts were reconstructed into phase-difference maps. For finite element (FE) simulation, the phantom geometry was meshed using the GIBBON toolbox within MATLAB and imported into FEBio (Fig. 2). The phantom was modeled with a Young's modulus of 9 kPa, Poisson's ratio of 0.49, and density of 1000 kg/m^3. To match the experimental boundary conditions, nodes on the lateral cylindrical surface were constrained in the X and Y directions, while a single-cycle sinusoidal displacement (amplitude 150 μm) was applied in the Z direction at the same four frequencies. Transient time-domain simulations were conducted.

Results Phase images from the experimental and simulated datasets were compared (Fig. 3) at selected time points for each frequency (50, 60, 70, and 120 Hz). Overall, there was good qualitative agreement in wavefront shape and propagation direction. At 50–70 Hz, both datasets showed coherent wave patterns with similar wavelengths. At 120 Hz, increased attenuation and shorter wavelengths were observed, with the experimental data showing more noise and edge artifacts. These results indicate reasonable alignment, though some differences were evident, particularly at higher frequencies.

Discussion The agreement between experimental and simulated phase images indicates that the Pulseq-based MRE sequence and FE simulation can capture key features of shear wave propagation in the phantom. Similar wave behavior was observed across all frequencies; however, discrepancies in amplitude and edge effects, especially at higher frequencies, suggest limitations in the current setup. These may result from unmodeled factors such as imperfect driver-phantom coupling, material property mismatches, or oversimplified boundary conditions. Overall, the results are promising but highlight the need for further refinement of both the sequence and simulation for improved accuracy.

Conclusion This study demonstrates the feasibility of using an open-source Pulseq-based MRE sequence in combination with finite element simulations for phantom validation. While qualitative agreement in shear wave propagation was observed across frequencies, discrepancies in wave amplitude and boundary effects indicate that further refinement of both the sequence and simulation setup is needed. This framework provides a solid starting point, but additional work is required to improve accuracy and robustness for broader application.

Acknowledgments Mehmet Nebi YILDIRIM's PhD study was funded by the Republic of Türkiye Ministry of National Education under the Study Abroad Scholarship Program.

Data and Code Availability The data are available upon request.

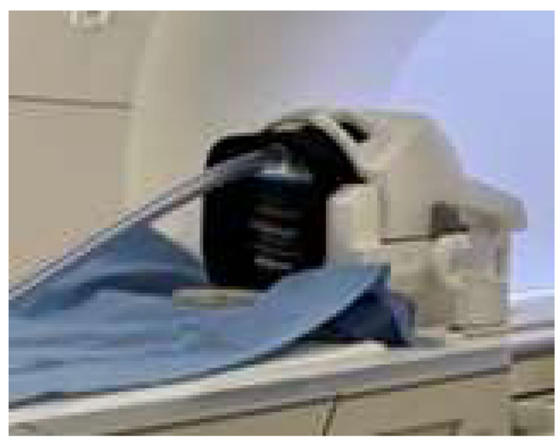

Figure 1 Experimental setup of MR Elastography with MRE phantom in 3T MR scanner.