Qualitative Comparison of Harmonic and Transient Excitations in a Finite Element Brain Model for Magnetic Resonance Elastography

Mehmet N. YILDIRIM[1], Samuel Evans[2], Daneil Gallichan[1]
[1] CUBRIC / School of Engineering, Cardiff University, Cardiff, UK
[2] School of Engineering, Cardiff University, Cardiff, UK
Email: YildirimMN@cardiff.ac.uk

Introduction: Magnetic Resonance Elastography (MRE) noninvasively quantifies tissue mechanical properties by analysing induced wave propagation, crucial for diagnosing neurological disorders [1]. MRE combines mechanical excitation, motion-sensitive phase-contrast imaging, and data inversion to estimate tissue stiffness. During acquisition, acoustic vibrations are applied using a passive driver, which transmit the vibrations created by active driver located outside of the scanner room. Depending on the excitation type, the wave field is sampled differently: harmonic MRE relies on repeated cycles with varying phase offsets to capture steady-state wave motion, whereas transient MRE captures wave propagation following a brief excitation [2]. Understanding how these excitation methods influence wave propagation is important, as it directly affects the spatial distribution and the accuracy of reconstructed stiffness maps. This study directly compares harmonic and transient excitations to reveal how each method uniquely governs wave propagation characteristics and consequently shapes the spatial distribution and interpretability of mechanical properties in brain MRE. Computational models such as finite element (FE) simulations can be utilized in MRE studies to simulate wave propagation and systematically investigate how anatomy and material properties influence tissue mechanics. In this study, we used the open-source FEBio [3] software to simulate wave propagation in a 3D simplified FE model of the brain.

Methods: A 3D brain geometry was exported in STL format from a previously published finite element (FE) model [4]. This geometry was imported into MATLAB using the GIBBON toolbox [5] to generate an input file for FEBio simulations. The mesh was created with TetGen using tetrahedral (tet4) elements, consisting of 587,811 elements for the brain and 450,645 elements for the cerebrospinal fluid (CSF). Material properties used in FE simulation shown in **Table.1** were selected from published literature. Since real CSF behaves as a fluid and cannot resist shear (shear modulus G = 0), it is challenging to model it directly in standard FE simulations without advanced solvers. To avoid numerical issues and maintain a clear mechanical contrast with brain tissue, the CSF was modelled as a very soft solid.

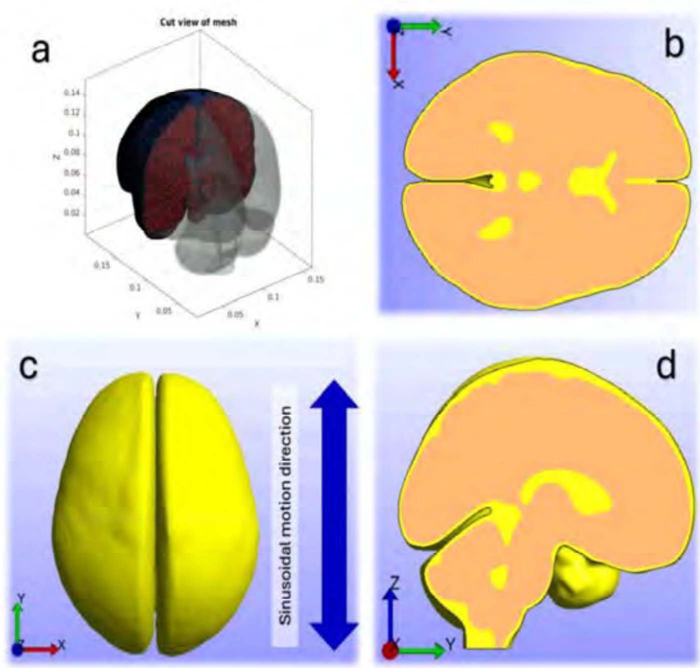

Fig. 1. Visualization of the 3D brain finite element (FE) model and anatomical structures. (a) Cut view of the meshed brain model showing tetrahedral elements representing brain tissue (red) and cerebrospinal fluid (CSF) (blue). (b) Axial cross-section of the brain model highlighting internal structures. (c) Lateral view of the brain model surface with the indicated direction of applied sinusoidal motion (Y-axis), simulating MRE excitation. (d) Midsagittal view of the brain illustrating the anatomical regions. Coordinate axes (X, Y, Z) are shown according to MR scanner coordinate system for reference in each panel.

Two types of mechanical loading were simulated: (1) Harmonic excitation at 60.1 Hz, using a continuous sinusoidal motion; and (2) Transient excitation, using a single sinusoidal impulse. To attempt to replicate experimental MRE conditions (where an inflatable pillow driver is used underneath the head), a Y-direction displacement of 150 µm was applied to all nodes on the outer CSF surface. These nodes were also fixed in the X and Z directions to simulate the skull's restriction. Simulations ran for 200 ms with a time step of 2 ms, ensuring consistent time resolution for both loading types. Post-processing was carried out in MATLAB to extract Y-direction displacement data and compare the harmonic and transient responses using 2D image slices.

	Material Model	Parameters	Value	Unit
CSF	neo-Hookean	Young's Modulus	100	Pa
		Poisson's ratio	0.495	-
		Density	1005	kg/m^3
Brain	neo-Hookean	Young's Modulus	3000	Pa
		Poisson's ratio	0.49	-
		Density	1040	kg/m^3

Table 1. Material properties of CSF and Brain used in FE

Results: Simulations were performed using both harmonic and transient excitations to investigate differences in wave propagation within the brain model. Sagittal slices at different time-points in the simulation revealed distinct wave patterns under harmonic and transient excitations (**Fig. 2**). Harmonic excitation produced smooth, periodic wavefronts with consistent propagation across the brain, reflecting steady-state behaviour. In contrast, transient excitation generated complex but coherent wave patterns with broader spatial variation and faster attenuation. Despite the shorter excitation duration, transient loading still produced measurable wave propagation suitable for analysis.

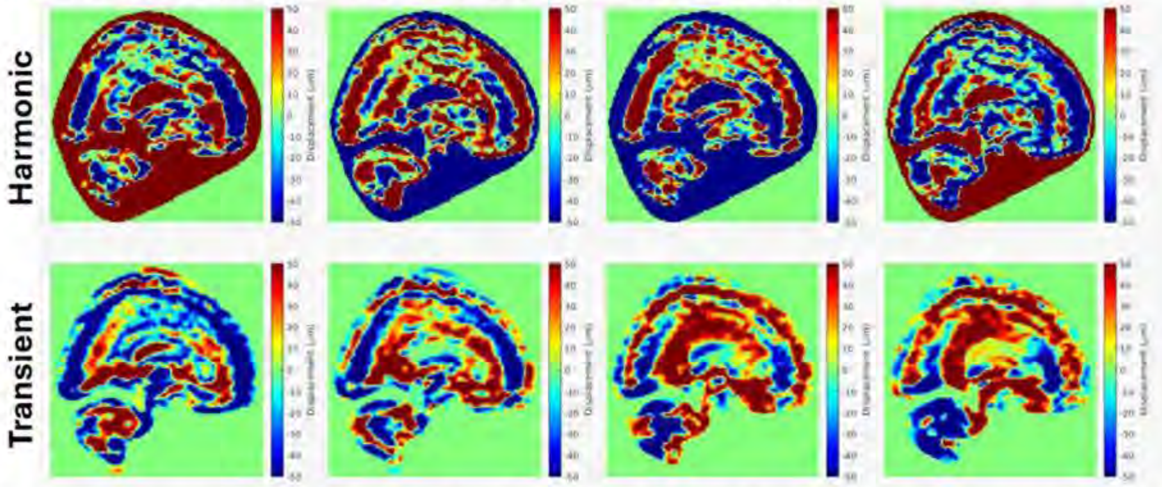

Fig.2 Shows displacement fields in the Y-direction for harmonic (top row) and transient (bottom row) excitations at different time-points in the simulation within a sagittal slice of the brain model.

Discussion: This study shows that both harmonic and transient excitations can generate usable wave patterns in the brain model. While harmonic loading produced smooth, periodic waves, transient excitation resulted in more complex but analysable waveforms. Although a simplified model was used, consisting only of homogeneous, elastic brain and CSF, the results demonstrate how excitation type affects wave behaviour.

Conclusions: This study used a simplified finite element brain model to qualitatively examine the effects of harmonic and transient excitations on wave behaviour. The simulation results revealed distinct spatiotemporal wave characteristics associated with each excitation type. The model effectively captured these differences, demonstrating its suitability for exploring excitation-dependent dynamics in MRE. Future work will focus on incorporating viscoelastic and anatomically detailed properties to enhance physiological accuracy and broaden clinical relevance.

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