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An Analytical Model of Magnetomotive Ultrasound Signal Generation

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Background, Motivation and Objective

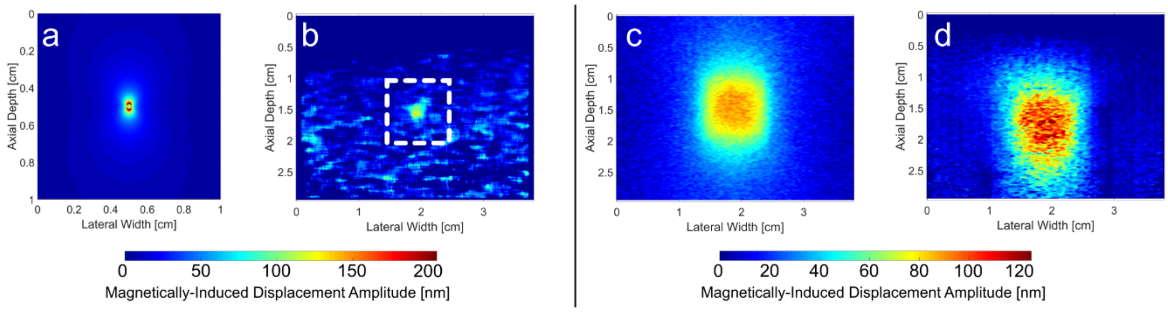
Magnetomotive Ultrasound (MMUS) is a targeted imaging modality in which magnetic nanoparticles (MNPs) driven by a modulated magnetic force serve as contrast agents through the use of a motion-based detection algorithm. In our work with phantoms, properties of MNP-labeled regions such as volume and elastic modulus, as well as scan parameters such as magnet placement and modulation frequency have been shown to affect the MMUS signal. Thus, MMUS shows promise for volume- and elastic modulus-sensing applications such as diagnosis and treatment monitoring of thrombosis, where such indicators are clinically relevant. Using these parameters as inputs, we have developed an analytical model of MMUS signal generation which lays the groundwork for reconstruction of medium properties from MMUS images.

Statement of Contribution/Methods

MMUS signal is quantified by the magnetically-induced vibration amplitude of labeled regions in the imaging area. An analytical model of this signal was first developed for a single MNP in an infinite medium. The particle was modeled as a sphere subject to a sinusoidal magnetic force, and the medium was modeled as elastic and isotropic. A forward model was then used to simulate the signal of a cubical MNP-labeled inclusion. The simulated displacement fields due to a single MNP and an inclusion are shown in Fig. 1. Gelatin tissue-mimicking phantoms with embedded magnetic beads were used as models for validation of the single particle model, while phantoms with cubical gelatin inclusions labeled with iron oxide nanoparticles served to validate the forward model.

Results/Discussion

In the single MNP case, MMUS signals from both simulated and phantom data varied inversely with the medium Young's modulus, and MMUS signal magnitudes corresponded favorably. Magnet modulation frequency had an insignificant effect on simulated and validation MMUS signals, and signals varied spatially according to the amplitude of the inhomogeneous magnetic force. Similar results were observed for the cubical inclusions. Using the model, elastic moduli and inclusion areas extracted from experimental data were consistent with the ground truth, demonstrating the ability to measure medium properties of simple gelatin phantoms using MMUS – an important step toward volume- and elastic modulus-sensing of arbitrary magnetically-labeled structures.



Simulated (a), and phantom (b) magnetomotive ultrasound displacement amplitude maps (in nm) for a single 0.5 mm diameter magnetic bead. Simulated (c), and phantom (d) displacement maps of cubical inclusions labeled by iron oxide nanoparticles. Phantoms are constructed from 5 kPa Young's Modulus gelatin embedded with graphite nanopowder for scattering, while simulations model an infinite, elastic, and isotropic piece of gelatin with a 5 kPa Young's Modulus. Simulated and experimental magnetic force amplitudes were held constant for each pair of images. The area displayed in (a) is enlarged relative to (b) in order to show detail, and the corresponding area in (b) is shown dashed.