Analysis of Anisotropic Propagation Utilizing Wave-Guide Constrained Magnetic Resonance Elastography

A. J. Romano[1], P. B. Abraham[1], S. I. Ringleb[2], P. J. Rossman[3], J. A. Bucaro[1], R. L. Ehman[3]

[1]Physical Acoustics, Naval Research Laboratory, Washington, DC, United States, [2]Biomechanics, Mayo Clinic and Foundation, Rochester, MN, United States,
[3]Radiology, Mayo Clinic and Foundation, Rochester, MN, United States

Introduction: The determination of the elastic properties of biological materials such as muscle is of great interest. These materials, however, are comprised of a complicated structure of fibers which often vary in both their orientation as well as their thickness. Because of these inherent structural complications, standard methods for the determination of the elastic moduli from displacement data often yield inconsistent results due to the rotations, degree of elastic anisotropy, and boundary conditions. In this paper, we implement a previously introduced measurement and analysis approach called Wave-Guide Constrained Magnetic Resonance Elastography[1] which is appropriate for tracking waves in guided structures such as muscle. We analyze the waves propagating along a particular fiber direction utilizing space-wavenumber analysis which permits the tracking and characterization of wave types, velocities, and coupling along arbitrarily oriented fibers for media characterization. The approach will be demonstrated using a 3-D MRE in-vivo measurement of a human calf muscle excited acoustically at 100 Hz.

Theoretical and Experimental Development: Analysis was performed on the right calf of a healthy 24 year old female volunteer in 10% dorsiflex and all data were taken at the Mayo Clinic on a 1.5-T GE Signa. In Fig. (1) we show the midplane of a clinical MRI scan of 40 axial slices (of thickness 0.005m) showing the location of the acoustic actuation and wave path location. 3-D MRE was performed with a field of view of 0.2 X 0.2 m, and 16 saggital slices of 0.0015m thickness. The calf was excited at 100 Hz and four time offsets were taken for each of three sensitizations (x, y, z). Temporal Fourier transforms were performed on the displacement data to extract the first harmonic. Additionally, a Helmholtz decomposition was performed on the data separating the x, y, and z displacement components into their longitudinal and shear terms, which we show in Fig.(2). As a demonstration, a spectral filter was implemented which provided only those wave components which were propagating parallel to the x-axis through the Tibialis anterior muscle. A sliding window spatial Fourier transform was then performed on this filtered data with a window width of 0.15 m providing space-wavenumber images for the forwardly propagating waves.

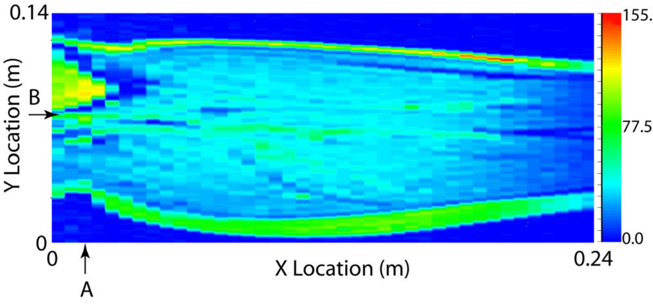

Figure (1) Clinical MRI scan of calf showing a)location of actuator and b) wave path location.

Analysis of Results: With regards to Fig. (3), we see the wave types that remain after our filtering, and which are propagating down the Tibialis anterior. There is a very fast compressional wave observed in the longitudinal term of the x-displacement component, as well as a coupled shear-longitudinal wave around k_τ = 152 (radians/m) for all three components shown, which corresponds to a velocity of 4.128 m/s. There are three additional velocities as well, which can be observed in Fig. (3a) at k_τ = 14 (radians/m) (with a velocity of around 45 m/s), in Fig. (3b) at k_τ = 48 to 41 (radians/m) over the length (with a velocity varying from 13 m/s to 15 m/s), and in Fig. (3c) at k_τ = 21 to 35 (radians/m) (with a velocity varying from 30 m/s to 18 m/s). Therefore, in this simple analysis, we can observe five distinct and/or coupled wave speeds. Since any infinite anisotropic medium can only support three wave speeds for any direction [2], there is more going on here - in particular the effects of boundary conditions. Whatever the specific physical causes, this method provides a way of analyzing such data.

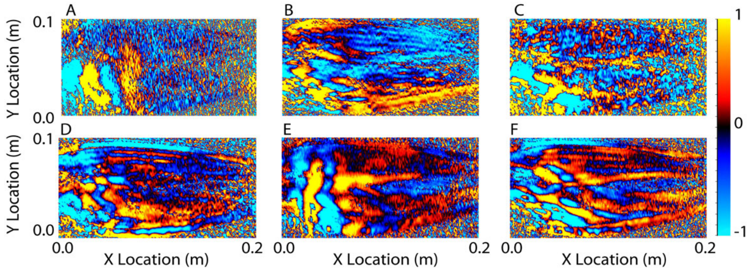

Figure (2) Helmholtz decomposition of the displacements within the central plane of data: a), b), c), longitudinal x, y, and z components; d), e), f), transverse x, y, and z components.

Conclusions: It has been demonstrated that the combination of clinical MRI with MRE enables the tracking of waves along arbitrarily oriented fibers, establishing a method for waveguide constrained MRE. Future work will investigate the propagation of waves along particular fiber paths.

Acknowledgements: This work was supported in part by the Office of Naval Research and the National Institute of Health Grants EB001981 and EB00812.

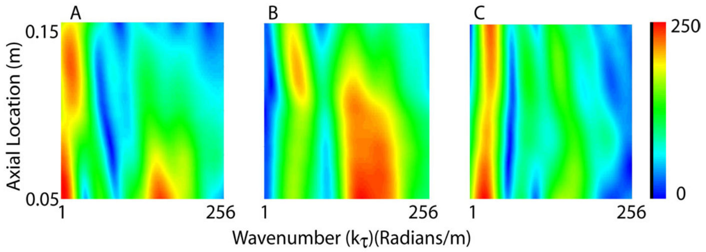

Figure (3) Space-wavenumber profiles of a) longitudinal x, b) transverse y, and c) transverse z components.

References

[1] A. J. Romano, P. J. Rossman, J. A. Bucaro, and R. L. Ehman, "On the Development of Wave-Guide Constrained Magnetic Resonance Elastography", Proceedings of the Thirteenth Scientific Meeting, Kyoto, Japan, May 2004.

[2] B. A. Auld, "Acoustic Fields and Waves in Solids", 2nd ed., John Wiley and Sons, 1990.