A Finite Element Model of Shear Wave Propagation Induced By an Acoustic Radiation Force Impulse

R. De Luca[1], J. Fromageau[2], H.W. Chan[2], F. Marinozzi[3], J. Bamber[2]

[1]Institute of Cancer Research and Royal Marsden Hospital, Sutton, England, UK. Sapienza University of Rome, Dept. of Mechanical and Aerospace Engineering, Rome, Italy
[2]Institute of Cancer Research and Royal Marsden Hospital, Sutton, England, UK
[3]Sapienza University of Rome, Dept. of Mechanical and Aerospace Engineering, Rome, Italy

Abstract

Shear wave elastography is an innovative technique that employs one conventional focused ultrasound beam to induce shear waves and another to detect them. The final quantitative elasticity image is presented as a colour map overlaying the B-mode image. This new technique is used in combination with traditional ultrasound imaging in order to improve the specificity of distinguishing malignant and benign tumours and with potential to improve the ability to monitor the response of cancer to treatment.[1]

A two-dimensional finite element model (FEM) was developed in COMSOL Multiphysics® to simulate the propagation of shear waves induced by an acoustic radiation force impulse (ARFI) in various media. Since this project aims to record the shear deformation under the action of ARFI and therefore to estimate shear wave speed, we employed the Structural Mechanics Module. Initially, for FEM validation purposes, uniform tissue-mimicking phantoms were analysed with different shear modulus in the range 1-200 kPa. Following this, phantoms with uniform background and an embedded stiffer inclusion were studied. The medium was assumed to be isotropic, homogeneous, linear elastic and quasi-incompressible (the Poisson's ratio is 0.49). The surface of the phantom opposing the ARFI-generating transducer was fully constrained while the surface in contact with the transducer was constrained only in the lateral direction[2]. ARFI was applied as a time-varying force-boundary condition to generate the shear waves. A mapped mesh with rectangular elements and the technique of the mesh biasing were employed. Smaller elements in the area of the focused ARFI beam, and gradually bigger elements when moving towards zones where the stress gradient was smaller, were used. A time-dependent analysis was performed and the time step was selected according to the Courant-Friedrichs-Levy restriction. Example of time-varying transversal displacements recorded in the region of interest, which were subsequently processed using MATLAB® with COMSOL Multiphysics® in order to obtain the shear wave speed and therefore the shear modulus, are shown in Figure 1 for a homogeneous medium without an embedded inclusion. In general the results confirmed a number of expectations: displacement amplitude decreases with increasing shear modulus and the maximum amplitude of shear wave displacement is proportional to the duration of the push [3]. The wave amplitude also decreases with the increasing radial distance from the pushing focus. This is due only to the wave divergence because viscosity is not considered in this study[3]. The

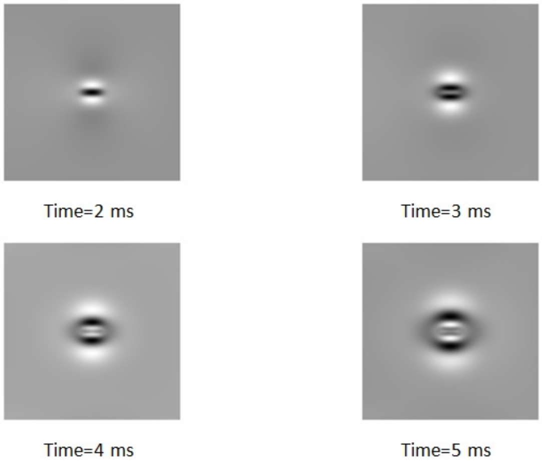
shear wave speed, calculated using the time-to-peak method, was found to be in good agreement with theory.
The results show that the FEM analysis provided a reliable model of shear wave generation and propagation. COMSOL Multiphysics® could be a useful tool for the evaluation of inversion algorithms for shear wave elastography and for the investigation of artefacts associated with this imaging technique such as scattering, reflection or refraction of both the shear wave and the pushing beam.

Keywords: ultrasound imaging, shear wave elastography, ARFI, COMSOL Multiphysics®

Reference

1. Jeffrey Bamber et al., EFSUMB Guidelines and Recommendations on the Clinical Use of Ultrasound Elastography. Part 1: Basic Principles and Technology, Ultraschall Med, Vol.34(2),169-184,(2013)
2. Mark L. Palmeri et al., A Finite-Element Method Model of Soft Tissue Response to Impulsive Acoustic Radiation Force, IEEE Trans Ultrason Ferroelectr Freq Control., Vol.52(10), 1699 - 1712 (2005)
3. Samuel Callé et al., Temporal analysis of tissue displacement induced by a transient ultrasound radiation force, J. Acoust. Soc. Am., Vol.118(5), 2829-2840 (2005)

Figures used in the abstract



Time=2 ms

Time=3 ms

Time=4 ms

Time=5 ms

Figure 1: Example of shear wave propagation (E=100kPa, ν=0.49) at different times after the start of the acoustic radiation force impulse. The ARFI source is located on the left. The brightness of the greyscale indicates the instantaneous shear wave displacement, with bright indicating displacement in the direction of the force, dark indicating the opposite direction and mid-grey indicating zero displacement. In each image the displacement amplitude is normalized to the maximum reached after cessation of the push.