FINITE ELEMENT SIMULATIONS OF ACOUSTIC RADIATION CONTRAST IN MAGNETIC RESONANCE USING OPEN SOURCE SOFTWARE

Anna-Lisa Kofahl[1], Sebastian Theilenberg[1], Deniz Ulucay[1], Judith Wild[1], Saskia Paul[1], Karl Maier[1], and Carsten Urbach[1]
[1]*HISKP, University of Bonn, Bonn, NRW, Germany*

Introduction

Investigating the quasi-static displacement caused by the acoustic radiation force (ARF) via MR phase images offers a new access to the viscoelastic properties of tissue [1,2]. This method (called acoustic radiation contrast in magnetic resonance (ARC-MR)) has been successfully tested on phantoms [3]. For a better understanding and interpretation of the measurements simulations using the finite element method (FEM) have been developed with special regard to the influence of boundary conditions during the measurements using open source software packages.

Method

An ultrasound (US) beam with a resonance frequency of 2.5 MHz, a focal intensity of I=7,15 W/cm² and focal dimensions of 2 cm in transaxial and about 5 cm in axial direction was coupled into a polyvinyl alcohol (PVA) phantom. The cylindrical phantom (6 cm in axial direction, 4 cm diameter) was prepared so that its material properties like Young's modulus were in accordance with values for human tissue [4]. During the measurement it was constricted by different boundary conditions through the fixation in different containers.

The unidirectional ARF caused a displacement Δz in the micrometer range along the beam path inside the phantom. This displacement was measured through the phase shift $\Delta\varphi$ of a displacement sensitive MRI spin-echo sequence with monopolar gradients [5] according to $\Delta\varphi=\gamma G t \Delta z$. The US pulse was irradiated simultaneously to the second gradient.

A model of the phantom previously designed using the commercial FEM software Marc Mentat (MSC Software Corporation, Santa Ana, CA (USA)) was successfully reproduced using the open source packages Gmsh [6] for the mesh generation and FEBio [7] as a non-linear solver. The geometry of the model was consistent with the geometry of the phantom and meshed with 8-nodes hexahedrons. The ARF was implemented as a location dependent body force in z-direction along the central axis with parameters according to the measurements. The material properties were adjusted to simulate human tissue like the phantom [8].

To improve the agreement between the simulations and the measurements the influence of the boundary conditions was investigated.

Results

Figure 1 shows the displacement along the central axis calculated from the finite element simulations with three different sets of boundary conditions (BC1-BC3). Firstly the movement of the nodes on the curved surface area of the cylinder was restricted in radial direction while the nodes on the top were only not allowed to move in z-direction. Gravity was not considered (BC1). BC2 included a body force to simulate gravity which acts in opposite direction to the ARF. BC3 was a model without gravity and the nodes on the curved surface area were also free to move in all directions.

Through BC1 and BC2 the initial measurement configuration was described roughly. There the phantom was placed in a PMMA tube in which the phantom fit snugly and prevented sideway motions. The bottom was closed off with a thin mylar®-foil. Through this foil the US was coupled upwards into the phantom and it constricted the phantom's motion as well. Additionally the phantom was subjected to gravity (C1). To investigate whether the boundary condition had a similar effect on the measurements as they have on the simulation a new phantom container was build (figure 2). In it the phantom was only guided by two PMMA rings at the top and bottom while being placed in a container filled with water to reduce the effects of gravity (C2) thus having similar boundary conditions as in BC3. The US was applied from the bottom upwards. Figure 3 shows the measured displacement curves for the two configurations.

Discussion

Boundary conditions show an immense impact on both the simulation and the measurements of the influence of the ARF in PVA phantoms as it is investigated using ARC-MR. This has to be considered when carrying out more quantitative investigations with the goal to extract the elastic and acoustic values of the phantom. When, however, investigating local lesions inside the US beam path the effect of the boundary conditions are not as disturbing since relative changes caused by lesions can still be detected. The open source FEM software performs to full satisfaction and yields results equal to the commercial software.

Figure 1: FEM simulations

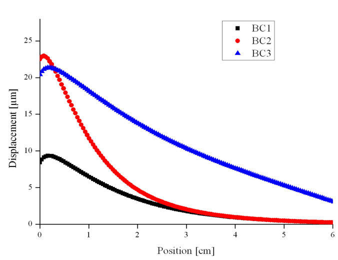


Figure 2: Measurements

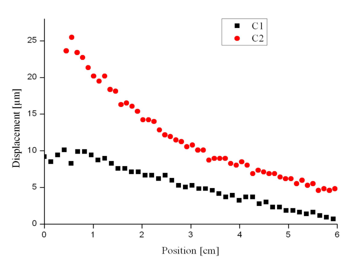
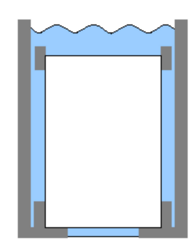


Figure 3: Container C2



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