# **Development and validation of simulations and phantoms mimicking the viscoelastic properties of human liver**

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##### BRIEF DESCRIPTION OF THE PROJECT:

FEBio [[2](#_ENREF_2)] models corresponding to three CIRS materials (E2297-AX, E2297-BX and E2297-CX) have been generated. Quasi-linear viscoelastic material properties and an acoustic pushing beam based on a published paper from Dr. Palmeri’s work [[1](#_ENREF_1)] have been assigned to each numerical model. Those models were used to investigate estimation of shear wave (SW) phase velocity and SW dispersion. Those FEBio models contain 1.0 – 1.5 million tetrahedral elements and take approximately 6 hours to solve for a high end multi-core workstation (12 cores, 64 GB memory, Ubutu 12.04). **Subsequently, simulated SW data were analyzed to obtain phase velocity values and their frequency dependence.**

**Approach:**

**Task 1**: Simulate Acoustic pushing pulse

The following conditions were simulated, consistent to the early publication by Dr. Palmeri [[1](#_ENREF_1)]:

* + Acoustic pressure pulses of a typical curvilinear transducer (Siemens 4C1)
  + F#2 and center frequency of 2.3 MHz
  + One focal depth at 30 mm
  + Measured Pressure pulses by hydrophones (by Duke) were applied
  + One cycle of the sinusoidal pulse was applied

**Task 2**: Fit material properties using a Quasi-linear Viscoelastic (QLV) model available in FEBio [[2](#_ENREF_2)]

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| **Figure 1.** An illustration of Three-element Standard Linear Solid (SLS) model. A spring () and a dashpot (η) are first connected in series (Maxwell body). Then the Maxwell body is connected with a spring () in parallel. |

Viscoelasticity of soft tissues was taken into consideration by a quasi-linear viscoelastic (QLV) material model[[3](#_ENREF_3)] implemented in FEBio[[2](#_ENREF_2)]. In the quasi-linear viscoelastic model, a relaxation function G(t) was used[[4](#_ENREF_4)] to simulate time dependent behaviors as follows,

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| --- | --- |
|  | (1) |

where represents one of relaxation time values in the Prony series, and is the viscoelastic coefficient in the Prony series. In this study, N was set to be 1 and Eqn. (1) became a three-element Standard Linear Solid (SLS) model (see Fig. 1). Parameters of three CIRS materials (E2297-AX, E2297-BX and E2297-CX) suggested by Dr. Mark Palmeri have been fitted into the above-mentioned relaxation function (see Eqn. (1)).

The elastic contributions to the quasi-linear viscoelastic material model [[3](#_ENREF_3)] are being simulated using the well-known Neo-Hookean model [[3](#_ENREF_3)] to match respective for each model. The parameters are listed in Table 1 below.

**Table 1**. Viscoelastic coefficients and relaxation times used in the FEA simulations. 1 gram/cm^3 was used as mass density for all three materials.

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| --- | --- | --- | --- | --- |
| **Component** | **Viscoelastic coefficient**  **()** | **Relaxation time () Unit: second** | **(kPa)** | **Poisson’s Ratio** |
| E2297-AX | 4 | 0.278 | 2 | 0.495 |
| E2297-BX | 2.75 | 0.167 | 4 | 0.495 |
| E2297-CX | 4 | 0.083 | 4 | 0.495 |
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**Task 3**: Perform FEA simulations and data analysis

FEA simulations were performed for 6 different frequencies (50, 100, 150, 200, 250 and 300 Hz) for each phantom. Time step sizes were scaled according to respective excitation frequencies (approximately 1/100f where f is the excitation frequency). All shear wave (phase) velocities were estimated by a lateral TTP algorithm [[1](#_ENREF_1)]. All 18 numerical models are attached as a part of the deliverables.

**Results:**

The estimated SW phase velocities are displayed in Figs. 1a-c below. More quantitative numbers are provided in Table 2 below for the sake of completeness. All phase velocities were estimated from 5 depths (3, 3.25, 3.5, 3.75 and 4cm) between the 3-4 cm depth. Recall that the focal depth was set to be at 3 cm in all FEA simulations. This region appeared to be most stable and therefore was selected for estimations of SW phase velocities.

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| **Figure 1.** Plots of phase velocity vs. excitation frequency for three different materials: (a) E2297-AX, (b) E2297-BX and (c) E2297-CX. Error bars denote one standard deviation. All slopes were fitted using data points between 100 – 200 Hz. |

**Table 2** Tabulated results of estimated phase velocities for three different materials from 50 to 300 Hz. The estimated phase velocity is displayed as mean ± one standard deviation.

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| --- | --- | --- | --- | --- | --- | --- |
|  | 50 Hz | 100 Hz | 150 Hz | 200 Hz | 250 Hz | 300 Hz |
| E2297-AX | 1.73 ± 0.08 | 1.93 ± 0.09 | 2.19 ± 0.05 | 2.25 ± 0.05 | 2.24 ± 0.08 | 2.26 ± 0.12 |
| E2297-BX | 2.21 ± 0.13 | 2.30 ± 0.15 | 2.56 ± 0.16 | 2.68 ± 0.09 | 2.74 ± 0.07 | 2.76 ± 0.11 |
| E2297-CX | 2.65 ± 0.04 | 2.60 ± 0.10 | 2.81 ± 0.15 | 3.07 ± 0.15 | 3.14 ± 0.09 | 3.15 ± 0.08 |

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**Summary**

The preliminary results show that FEBio can be used to perform simulations of shear wave propagation in viscoelastic media. From the 100 to 200 Hz range, the frequency dependence of SW phase velocities is clearly visible. Overall., the simulated results are in a good agreement with the experimental results from the 100 to 200 Hz range. However, more investigations are needed in order to fully understand the use of FEBio for shear wave simulations.

**References**

[1] M. L. Palmeri, M. H. Wang, J. J. Dahl, K. D. Frinkley, and K. R. Nightingale, "Quantifying hepatic shear modulus in vivo using acoustic radiation force," *Ultrasound Med Biol,* vol. 34, pp. 546-58, Apr 2008.

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[3] Y. C. Fung, *Biomechanics : mechanical properties of living tissues*, 2nd ed. New York: Springer-Verlag, 1993.

[4] A. Gerig, J. Zagzebski, and T. Varghese, "Statistics of ultrasonic scatterer size estimation with a reference phantom," *Journal of the Acoustical Society of America,* vol. 113, pp. 3430-3437, 2003.