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Viscoelastic Modeling of Brain MRE Data Using FE Method

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***Abstract*—**Dynamic shear test on simulated phantom can be used to validate magnetic resonance elastography (MRE) measurements. Phantom gel has been usually utilized for the cell culture of cartilage and soft tissue and also been used for mechanical property characterization using imaging systems. The viscoelastic property of the phantom would be important for dynamic experiments and analyses. In this study, An axisymmetric FE model is presented for determining the dynamic shear behaviour of brain simulated phantom using ABAQUS. The main objective of this study was to investigate the effect of excitation frequencies and boundary conditions on shear modulus and shear viscosity in viscoelastic media.

***Keywords*—**Viscoelastic, MR Elastography, Finite Element, Brain.

I. Introduction

IT is well known in clinical medicine that the qualitative mechanical properties of tumors are often markedly different from those of surrounding normal tissues. This accounts for the role of elastography as a clinical tool for detecting cancer in the body.

MR elastography (MRE) is a novel MR-based imaging approach that non-invasively measures the viscoelastic properties of tissues to provide additional information for differentiation of benign and malignant lesions (Muthupillai et al., 1995; Kruse et al., 2000; Sinkus et al., 2000; Dresner et al., 2001; Sack et al., 2002; Basford, et al., 2002; Jenkyn et al., 2002; Van Houten et al., 2003). MRE uses a conventional MRI system with an added motion sensitizing gradient (usually in the frequency range of 50–500 Hz) to detect displacements produced by a sinusoidal oscillatory excitation. The shear wavelength is then used to calculate the material stiffness (Manduca et al., 2001) based on the principle that a stiffer material has a longer wavelength because the shear wave travels faster through the material.

It has been shown that brain tissue behaves like a viscoelastic solid (Brands et al., 1999; Darvish & Crandall, 2001; Peters et al., 1997; Prange et al., 2000). MRE studies on human brain show a great variety of shear modulus data [8,20]. The difference between the results may have several reasons such as the dispersion of the shear wave speed at different excitation frequencies, a mismatch between wave propagation and image slice orientation and different boundary conditions[9].

The objective of this study is to identify the proper parameters by finite element modeling of tissue mimicking phantom to yield repeatable and reliable shear modulus measurements.

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II. Materials and Methods

A. Theory

In elastic medium, two types of moduli can be identified based on the type of waves that travel through the medium. compressional wave speed, C_L, is governed by the bulk modulus, λ, and shear wave speed, C_S, is related to the shear modulus, G, also written as μ.

$$C_L = \sqrt{\frac{(\lambda + 2\mu)}{\rho}} \qquad C_S = \sqrt{\frac{\mu}{\rho}}$$

where ρ is the mass density of the medium. Sarvazyan, et al. showed that for different tissue types, the bulk modulus does not vary significantly, whereas the shear modulus varies over seven orders of magnitude [18].

The propagation speed of shear waves can be calculated from the wavelength (l) and the frequency of the externally applied mechanical excitation (f) as : $C_s = f.l$

Human tissue is not perfectly elastic, but has a viscous component. Therefore, tissue has been modeled as a viscoelastic material to account for the deviations from elastic behavior. In a viscoelastic material, the stress and strain change on a time dependent basis. Different mechanical models have been proposed and adopted for the analysis of different tissues such as the Maxwell, Voigt, Zener. The Voigt model has been the most used for analysis of tissue. This model contains a spring and a dashpot in parallel, where the spring represents an elastic component and the dashpot represents a viscous component.

In this model, the bulk and shear moduli are complex to account for losses caused by the viscous components such that $\lambda = \lambda_1 + i\omega\lambda_2$ and $\mu = \mu_1 + i\omega\mu_2$ where λ_1 and λ_2 are the bulk elasticity and viscosity and μ_1 and μ_2 are the shear elasticity and shear viscosity, i is the imaginary number $i = \sqrt{-1}$ and ω is the angular frequency.

In a viscoelastic medium, the equation for the compressional sound speed does not change because in tissue

$\lambda_2 \approx 0$ and $\lambda >> \mu$, but the shear wave speed in Voigt viscoelastic model changes to [23]:

$$C_S = \sqrt{\frac{2(\mu_1^2 + \omega^2 \mu_2^2)}{\rho(\mu_1 + \sqrt{\mu_1^2 + \omega^2 \mu_2^2})}} \quad (1)$$

where μ_1 is the coefficient of shear elasticity, μ_2 is the coefficient of shear viscosity, ρ is density of medium and ω is the frequency of the mechanical excitation. Validation of Voigt viscoelastic model for brain using simulation and experimental data is of present study objectives. Viscoelastic properties are often determined with steady state oscillation or vibratory tests. The approach is usually referred to as dynamic mechanical analysis (DMA) testing. A sinusoidal oscillatory stress (σ) is applied to the sample, and the resultant strain (γ) and phase lag (δ) are measured. The complex Modulus (G*****) is then obtained as

$$G^* = \frac{\sigma}{\gamma}\cos\delta + i\frac{\sigma}{\gamma}\sin\delta \quad (2)$$

*G****** can be decomposed into real and imaginary parts that is defined as the storage modulus and loss modulus respectively. Storage and loss modulus of brain is acquired from MR Elastography of brain of published literature at different frequency ranges to simulate viscoelastic material properties of tissue-mimicking phantom by ABAQUS.

Furthermore, the propagation pattern of mechanical oscillating waves in viscoelastic media is shown in Fig. 1:

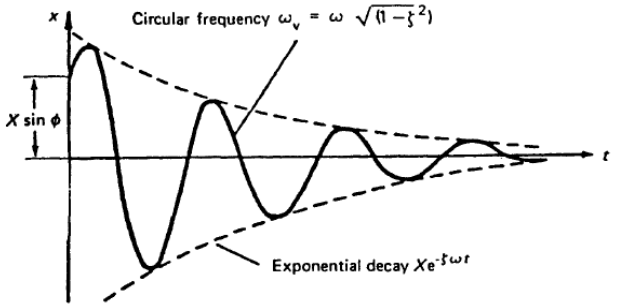

Fig. 1 The response of viscoelastic material to oscillatory excitation when ζ (damping ratio) is less than 1: In this case the portion of two frequent amplitude equal to $e^{\zeta\omega nT}$[2]

The wave propagation pattern of numerical phantom will obtain from FE simulation.

As MR measurements may ultimately be used to validate finite element (FM) models, present study has been validated by comparing shear moduli and shear viscosities of the model with MRE experimental data available in literature to assure its accuracy and effectiveness.

B. Modeling

To make a tissue-mimicking phantom, an axisymmetric rectangular prism model (100mm*20 mm) was generated with ABAQUS 6.6-1 representing a semi-axial cross section of the cylindrical biological gel phantom. The prism was modeled as a homogenous isotropic viscoelastic material with Poisson's ratio 0.495(tissue is assumed incompressible).

Storage modulus and loss modulus (G',G'') of the model were chosen from experimental data available in the literature[22]. Some of these literature results is shown in Fig. 2.

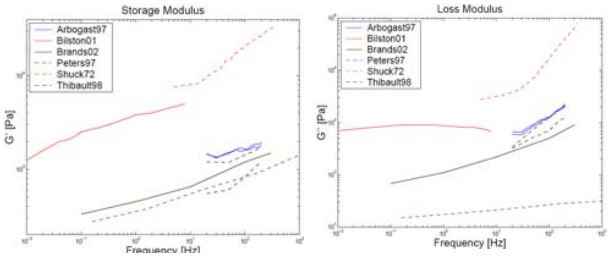

Fig. 2 Dynamic frequency response of brain from some literature

To examine the effects of frequency and boundary conditions, analyses were performed by applying a sinusoidal excitation at 1,10,25,50,80,100,120 Hz and changing the model width, respectively. This exitation is introduced into the model in the y-direction at the top corner of the axisymmetric model. The simply supported boundary condition is simulated by constraining the bottom edge of the model in the y-direction[5].

Wave propagation finite-element analyses in the model were conducted in the present study by ABAQUS 6.6-1 capability. ABAQUS employs the ''modal dynamic'' approach to solve the nonlinear problems. In this approach, natural frequency is extracted from the static perturbation response of the load that is applied (Lonczos solver is selected method to eigenvalue extraction in this study), then modal dynamic is used to characterize the propagation of wave.

The model consist of an 8-node biquadratic plain strain reduced integration element named CAX8R in ABAQUS 6.6-1 commercial software. This element may be used for Stress/displacement without twist applications of a shell model. The element theory is in ABAQUS documentation. In order to get convergence in the results, the size of elements was selected $1mm \times 1mm$ throughout the model.

III. Results

One illustration of the shear wave propagation in the model at frequency of 25Hz is shown in Fig. 3. The blue regions indicate peaks and the red regions indicate valleys.

The shear waveform along the top edge in both models is illustrated in Fig. 4. The shear wavelength was computed from distance between two successive peak or valley.

In order to ensure the accuracy of simulation results, damping factor η(tan δ) of the shear waveform has been calculated and compared to damping factor of used data[22] at the first step of modeling. Then simulation results have been verified with corresponding experimental data available in literature.

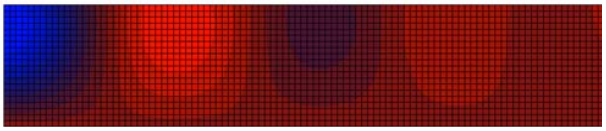

Fig. 3 An example of the shear wave propagation in undeformed shape of tissue mimicking phantom

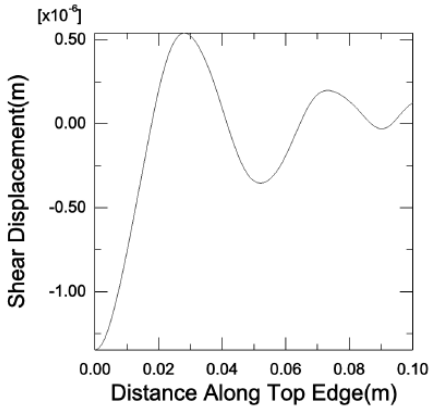

Fig. 4 Shear waveform along top edge of the model

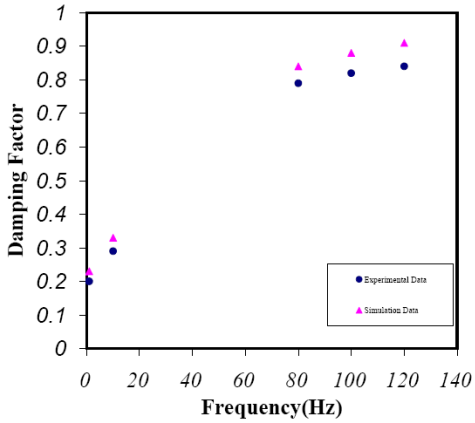

Fig. 5 Comparison between simulation by ABAQUS and experimental data by Vappou(2007)[22]

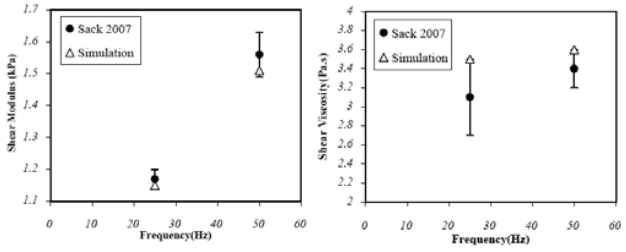

Fig. 6 Comparison of viscoelastic parameter of human brain by simulation and experimental data (Sack; 2007 [17])

Base on the dynamic equilibrium equation of viscoelastic motion for a single degree of freedom and refer to Fig. 1, The damping factor η(tan δ) is equal to the ratio of the imaginary part of the complex modulus to the real part of the modulus as described in (2). The results in Fig. 5 illustrate the damping factor calculated from both pre(from experimental data) and post of the simulation.

It can be observed that simulation results and experimental data are in good agreement; although there are some minor values discrepancies, probably due to estimation of damping factor by voigt viscoelastic model[2]. It was thus concluded that the simulation of the dynamic mechanical analysis with the ABAQUS was accurate because its results were in accordance with an experimental data.

Sack et al. (2007) performed a series of experiments on living human brain at different frequncies using MRE (see experimental data in Table I).

TABLE I
INTERINDIVIDUAL MEAN(±SD) OF THE SHEAR MODULI AND SHEAR VISCOSITIES OF THE HUMAN BRAIN AT 25HZ AND 50HZ MECHANICAL EXCITATION FREQUENCIES

	μ_1		μ_2	
	25Hz	50Hz	25Hz	50Hz
Average	1.17±0.03	1.56±0.07	3.1±0.4	3.4±0.2

IV. DISCUSSION AND CONCLUSION

In this study a FE model was created to analytically examine of excitation frequencies and boundary conditions on shear modulus and shear viscosity estimation in homogenous viscoelastic phantoms, via shear waveform.

The effects of boundary conditions are an important consideration FE modeling or MRE measurements. The vertical dimension in the model (20 mm), is choosen small to removing the longitudinal wave effects on the shear waveform.

Manduca[12] has concluded that the spatial wavelength and shear stiffness decrease and increase respectively as the mechanical frequency increases, and attenuation increases. Our results indicates that the shear modulus and shear viscosity increase with excitation frequency(Fig. 6). Klatt et al. (2007) have reported MRE results on viscoelastic properties of the human brain. The reported value for shear viscosity base on Zener viscoelastic model is equal to 6.7 ± 1.3 Pa.s. This value is calculated between 3.5-3.6 Pa.s in our study and 3.1-3.4 Pa.s in Sack(2007) research. This diviation not only because of the model type (Voigt or Zener), but also because of different experiment conditions such as the slice thickness , kind of brain and in-vivo or ex-vivo execution.

The difference between shear modulus data for 25 Hz and 50 Hz vibration frequency (of the order of 0.4 kPa) is presumably the result of the inadequacy of Voigt's model for predicting the behavior of viscoelastic brain tissue(Fig. 6). A separate view on storage modulus yields a smaller error than when storage modulus and loss modulus are combined, as required by more elaborate viscoelastic models[16]. Nevertheless, values of shear moduli are in the same order of magnitude as in several rheological studies performed on ex-vivo mammalian brains [4,15,22] as shown in Fig. 2.

However, the observed modulus dispersion indicates a limited applicability of Voigt's model to explain viscoelastic behavior of brain parenchyma, the FE model show good agreement between experiment and prediction at the frequency range. Obtained results of this method can be help to understanding the dominant conditions on wave propagation phenomena.

REFERENCES

[1] Basford, J.R., Jenkyn, T.R., An, K.N., Ehman, R.L., Heers, G., Kaufman, K.R., 2002. Evaluation of healthy and diseased muscle with magnetic resonance elastography. Archives of Physical Medicine and Rehabilitation 83, 1530–1536.

[2] Beards C.E. Structural Vibration: Analysis and Damping. Butterworth-Heinemann, 1996.

[3] Bishop J, Poole G, Leitch M, Plewes DB. Magnetic resonance imaging of shear wave propagation in excised tissue. J Magn Reson Imaging 1998; 8:1257– 65.

[4] Brands DWA, Bovendeerd PHM, Peters GWM, Paas M, van Bree J,Wismans JSHM (1999) Comparison of the dynamic behaviour of brain tissue and two model materials. Stapp Car Crash Conference Journal, 1999, Paper no. 99sc21, 5764

[5] Chen Q., Ringleb S.I., Manduca A., Ehman R.L., An K.N. A finite element model for analyzing shear wave propagation observed in magnetic resonance elastography, Journal of Biomechanics: 2198–2203, 2005.

[6] Darvish, K.K. and Crandall, J.R., (2001). 'Nonlinear viscoelastic effects in oscillatory shear deformation of brain tissue.' Medical engineering and Physics, 23(9), 633–645.

[7] Dresner, A.M., Rose, G.H., Rossman, P.J., Muthupillai, R.,Manduca, A., Ehman, R.L., 2001. Magnetic resonance elastography of skeletal muscle. Journal of Magnetic Resonance Imaging 13,269–276.

[8] Green M, Sinkus R, Cheng S, Bilston L. 3D MR-elastography of the brain at 3 tesla. Proceedings of the International Society of Magnetic Resonanc Medicine 13. 2005; 2176.

[9] Hamhaber U, Sack I, Papazoglou S, Rump J, Klatt D, Braun J. Three-dimensional analysis of shear wave propagation observed by in vivo magnetic resonance elastography of the brain. Acta Biomater. 2007; 3(1): 127–137.

[10] Klatt D., Hamhaber U., Asbach P., Braun J., Sack I. 2007 .Noninvasive assessment of the rheological behavior of human organs using multifrequency MR elastography: a study of brain and liver viscoelasticity. *Phys. Med. Biol.* 52 7281-7294

[11] Kruse, S.A., Smith, J.A., Lawrence, A.J., Dresner, M.A., Manduca, A., Greenleaf, J.F., Ehman, R.L., 2000. Tissue characterization using magnetic resonance elastography: preliminary results. Physics in Medicine and Biology 45, 1579–1590.

[12] Manduca A., Oliphant T.E., Dresner M.A., Mahowald J.L., Kruse S.A., Amromin E., Felmlee J.P., Greenleaf J.F., Ehman R.L. Magnetic resonance elastography: non-invasive mapping of tissue elasticity. Medical Image Analysis 5, 237–254. 2001.

[13] Muthupillai R, Lomas DJ, Rossman PJ, Greenleaf JF, Manduca A, Ehman RL. Magnetic resonance elastography by direct visualization of propagating acoustic strain waves. Science 1995;269:1854 –7.

[14] Prange, M.T., Meaney, D.F. and Margulies, S.S., (2000). 'Defining Brain Mechanical Properties: Effects of Region, Direction and Species.' StappCar Crash Journal, 44, 205–214.

[15] Peters, G., Meulman, H. and Sauren, A., (1997). 'Application of the Time Temperature Superposition Theory on Brain Tissue.' Biorheology, 34, 127–138.

[16] Sack I, Beierbach B, Hamhaber U, Klatt D and, Braun U. Non-invasive measurement of brain viscoelasticity using magnetic resonance elastography. NMR In Biomedicine, 2007, In press.

[17] Sack, I., Bernarding, J., Braun, J., 2002. Analysis of wave patterns in MR elastography of skeletal muscle using coupled harmonic oscillator simulations. Magnetic Resonance Imaging 20, 95–104.

[18] Sarvazyan AP, Rudenko OV, Swanson SD, Fowlkes JB, Emelianov SY. Shear wave elasticity imaging: a new ultrasonic technology of medical diagnostics. Ultrasound Med Biol 24 (9):1419-1435, 1998.

[19] Sinkus R., Tanter M., Xydeas T., Catheline S., Bercoff J., Fink M. Viscoelastic shear properties of in vivo breast lesions measured by MR elastography. Magnetic Resonance Imaging 23: 159–165, 2005.

[20] Uffmann K, Maderwald S, de Greiff A, Ladd M. Determination of gray and white matter elasticity with MR elastography. Proceedings of the International Society of Magnetic Resonanc Medicine 12. 2004; 1768.

[21] Van Houten E.E.W., Weaver J.B., Miga M.I., Kennedy F.E., Paulsen K.D. Elasticity reconstruction from experimental MR displacement data: initial experience with an overlapping subzone finite element inversion process. Medical Physics 27, 101–107,2000.

[22] Vappou J., Breton E., Choquet P., Goetz C., Willinger R., Constantinesco A. Magnetic resonance elastography compared with rotational rheometry for in vitro brain tissue viscoelasticity measurement. Magn Reson Mater Phy (2007) 20:273–278

[23] Yamakoshi Y, Sato J, Sato T. Ultrasonic imaging of internal vibration of soft tissue under forced vibration. IEEE Trans Ultrason Ferroelectr Freq Control 37 (2):45-53, 1990.