基于瞬时弹性成像的粘弹性测量自适应误差补偿

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摘　要　传统方法，基于超声瞬时弹性成像，利用粘弹性逆问题建模分析的方法，可以简单的求解生物软组织的粘弹性系数。但是由于一些因素导致这种测量方法存在测量误差。其中激励源半径和近场效应是导致瞬时弹性成像对剪切波速度高估的主要原因，而衍射效应则是导致对剪切波衰减高估的因素。本文通过对组织进行建模分析，设计出相关自适应误差校正方法来减少剪切波速度和位移衰减的测量误差。实验结果和理论结果相符合，验证了该方法的正确性，为粘弹性精确测量提供一条有效的方法。

关键词　超声成像；瞬时弹性；粘弹性；逆问题建模

A Self-Adapting Bias Correction for Viscoelastic Properties Measured by Transient Elastography

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Abstract　Transient elastography can be used to measure the viscoelastic properties of soft tissues using a simple inverse problem approach. However, there is measuring bias in this method due to several factors, e.g. radius of disk load and near-field effect is the main reason for overestimating the shear velocity, and diffraction effect leads the measurement of shear attenuation to be overestimated. A self-adapting method is proposed to correct both the shear velocity and attenuation biases in our study. Theoretical and experimental results are in good agreement, and this new method is proved to be an effective way to correct the viscoelastic properties bias measured by transient elastography.

Keywords　ultrasound imaging; transient elastography; viscoelastic property; inverse problem

1　Introduction

Many methods[1] have been emerged for depicting variations in tissue elastic properties, such as quasi-static elastography, transient elastography, acoustic radiation force imaging, sonoelasticity[2]. Most of them only concentrated on assessing the tissue stiffness, and ignored its viscosity. Previous papers have shown that traditional elastography could not discriminate between the benign tumors and malignancies, but malignant tumors with high blood vessel concentration exhibit higher viscosity than that of the surrounding tissue[3], this could help to distinguish them.

The transient elastography presents the advantage of potentially rebuilding the medium viscoelastic properties. S.Catheline et al. measured the speed and attenuation of a plane monochromatic shear wave using an ultrafast ultrasonic scanner[4]. Though S.Catheline proposed a Green's function simulation to avoid bias due to

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diffraction, this simple method cannot correct the bias caused by different radius of the disk load because it considers the disk load to be ideally point source. The bias caused by radius of the disk load will be illustrated in our experiments presented in this paper, and a bias correcting method is proposed.

2 A Simple Inverse Problem Approach

Some inverse problem algorithms have been proposed to estimate the viscoelastic property of homogeneous tissue. Voigt model is presented to be the best and the simplest rheological models for Agar-gelatin based phantom. It is composed of a spring linked to the elasticity (μ_1) and a dashpot related to the viscosity (μ_2), and they are placed in parallel (Figure 1).

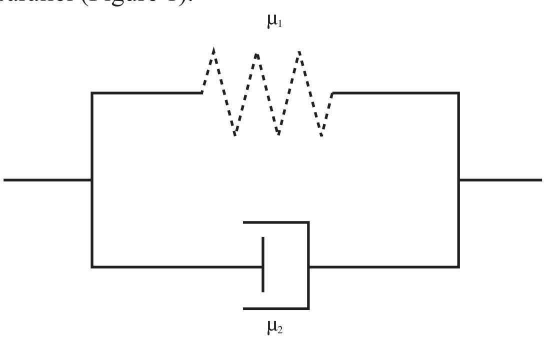


Figure 1. The Voigt's model is composed of a spring linked to the elasticity (μ_1) and a dashpot related to the viscosity (μ_2)

Based on Voigt model and ignoring the derivation procedure, the elasticity (μ_1) and the viscosity (μ_2) of the medium can be expressed as a function of the shear wave velocity (V_s) and attenuation (α_s):

$$\mu_1 = \frac{\rho V_s^2 \left|1 - V_s^2 \alpha_s^2 / \omega^2\right|}{(1 + V_s^2 \alpha_s^2 / \omega^2)^2}$$
$$\mu_2 = \frac{2\rho V_s^3 \alpha_s^2 / \omega^2}{\alpha_s (1 + V_s^2 \alpha_s^2 / \omega^2)^2} \quad (1)$$

Where ρ is the density and w is the frequency of the vibrator [4].

3 Experiment

A. Experiment Setup

The experiment setup is shown in Figure 2. Ten disk-shape metal of various radius (ranges from 3 mm to 21 mm with increment of 2 mm) were fixed on a mini-shaker[5] (Brüel & Kjær, type 4810, Nærum, Denmark) and placed at the surface of a homogeneous PVA (polyvinyl alcohol) phantom, meanwhile a single element ultrasound transducer (3.5 MHz) was located at the opposite side of the phantom along the center axis of the disk. The transducer has a focal depth of 35 mm. The free surface on which the disk load was placed was defined as z=0 mm.

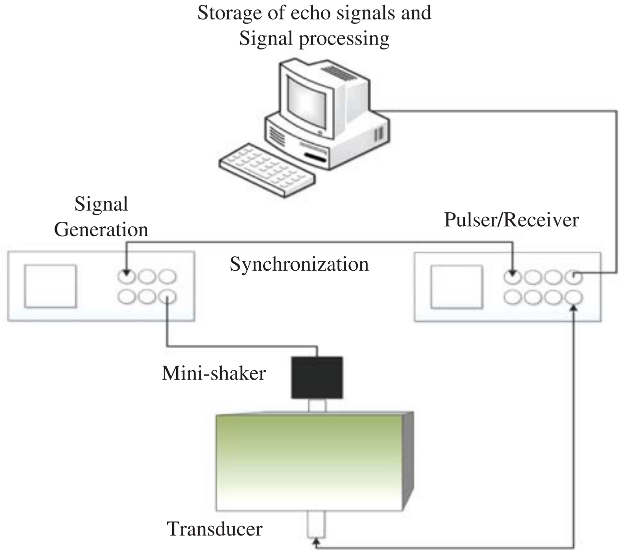


Figure 2. Experiment setup: A low frequency shear wave is generated by a mini-shaker. Meanwhile, the signal in pulse-echo mode with 5 kHz recurrence frequency to track the shear wave

The phantom (7 cm×7 cm×8 cm) used in the experiment was a PVA cryogel. The PVA cryogel solution was a viscous liquid composed 10% of polyvinyl alcohol and 2% of Sigmacell particles (Sigmacell Cellulose, type 20, Sigma Chemical, St. Louis, MO) dissolved in water. One circle of low frequency sinusoid of vibration with 50 Hz frequency was created by the mini-shaker, which was driven by a function generator and caused a shear wave propagating in the phantom. Meanwhile the transducer worked in a pulse-echo mode with 5 kHz pulse repetition frequency to track the displacement induced by shear wave. The radio frequency signals were sampled at 50 MHz and recorded with an acquisition card (Gage, type Compuscope 8500, Lachine, QC, Canada). A cross correlation algorithm was then used to track the displacement of phantom along the axis direction of the ultrasound beam between z=0 and z=50 mm depth with an accuracy of 1 μm[6]. One of the typical results of the displacement is shown in Figure 3. x-axis is time, y-axis is depth, and pseudo-color means displacement of phantom.

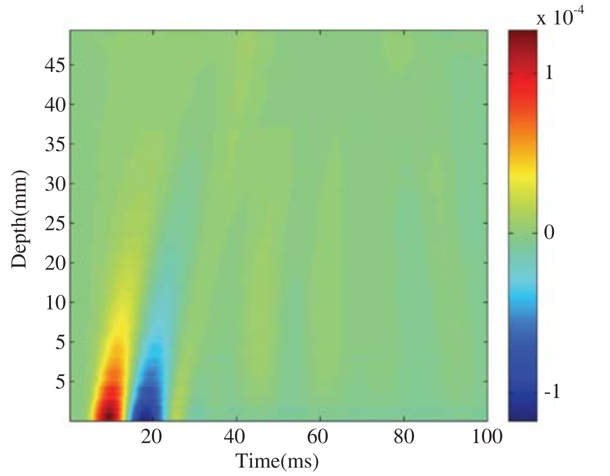


Figure 3. Displacement field obtained in a homogeneous PVA cryogel for a disk load with 5 mm radius, the frequency of the excited pulse is 50 Hz

B. Shear velocity and attenuation

To obtain the shear wave velocity and attenuation of a certain frequency, Fourier transformation was performed on the displacement signal. Then the phase delay and amplitude of the 50 Hz component were computed at different depths. Linear regression of the variation of the phase delay versus depth gave the speed of the shear wave, and the variation of the amplitude versus depth gave the attenuation of the shear wave.

$$V_d = w/(\frac{d\phi}{dz}) \qquad \alpha_s = \frac{dA}{dz} \tag{2}$$

C. Bias induced by radius of disk load

The influence of disk load radius has been investigated in previous study[7]. For a given angular frequency w, the behavior of the transient elastography system is concerned with the depth z and the radius R of the disk load. The bias of the measured shear wave velocity and attenuation was investigated in the two particular cases: (I) near field and (II) ideal far field. The wavelength of shear wave measured above is about 44 mm, and the depth of one wavelength could be seen as the near field.

In a general situation, in case (I) the shear wave amplitude and velocity can be expressed as:

$$\alpha_d = \frac{dA}{dz} = -\frac{R^2 z}{4V_s^{3/2}\sqrt{R^2+z^2}} \qquad V_d = w/(\frac{d\phi}{dz}) = \frac{3\sqrt{R^2+z^2}}{2z}V_s \tag{3}$$

To sum up, the shear wave velocity measured by spectral method was first overestimated to be an infinity value in the very near filed ($z \ll R$), and then decreased to approach the value of 2.1 V_s as the depth z growing. The attenuation due to diffraction is approximate to be a constant in the very near field, and then gradually changes to a value which was proportional to z^{-1}.

In case (II), the shear wave amplitude and velocity can be expressed as:

$$\alpha_d = \frac{dA}{dz} = -\frac{R^2}{wV_s z^3} \qquad V_d = V_s \tag{4}$$

In the ideal far field, the measured shear wave velocity was equal to the real value, and the attenuation due to diffraction changed as a value proportional to z^{-2}. In experiment, the shear wave can be only tracked in the near field because of attenuation. The shear velocity computed through the spectral analysis was overestimated about 2.1 times of the real value. And the measured attenuation was caused by both diffraction and viscosity. Thus the experiment results should be revised before they were used to calculate viscoelastic properties of phantom.

4 Measurment Bias Correcting

The simulation analysis presented above shows that the radius of disk load R and the selected depth z of the displacement field is two main factors affected the measurement bias. Thus, set these two parameters as the experiment values, then using a self-adaption method to change the parameter of shear velocity V_s until the shear

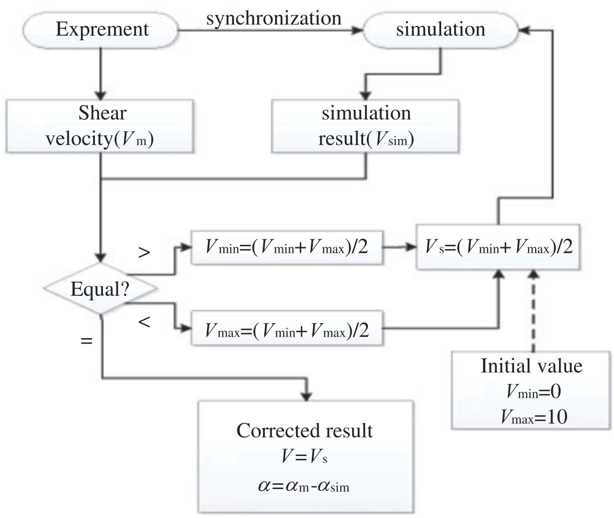


Figure 4. Flow char: bias correcting method correcting results

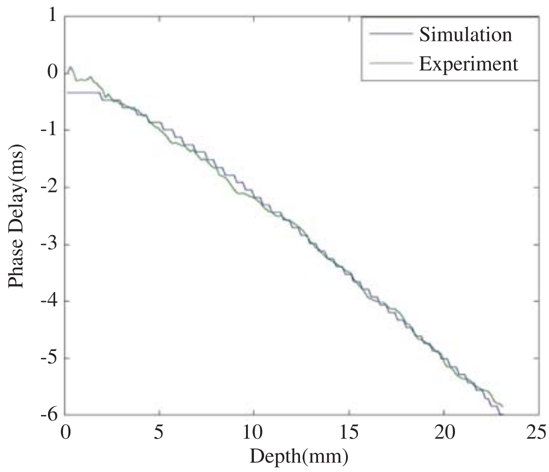
velocity calculated from simulation V_d is equal to the measured result of experiment V_m. The final shear velocity V_s value is corrected velocity we can use to calculate the viscoelastic properties. As the simulation result V_d monotonically increased as V_s increasing, a bisection method was used to find the corrected value quickly. The range V_s was set to be between 0 m/s and 10 m/s initially. The correction process doesn't end until the difference between experimental result V_m and simulation result V_d is less than one percent of the V_m. The flow chart of this bias correcting method is shown in Figure 4.

Shear wave diffraction is regarded as the only factor to lead the attenuation in the amplitude in simulation. But in experiment, not only the diffraction caused attenuation, but also the viscosity of the medium. We hypothesized that the shear attenuation measured by transient elastography α_m could be decomposed into a viscosity component α_v adding on a diffraction component α_d :

$$\alpha_m = \alpha_v + \alpha_d \tag{5}$$

Thus, the simulation result α_d can be used to correct the bias of attenuation.

Figure 5 shows the comparison between experiment and simulation results of the phase delay and amplitude curves versus depth. The shear velocity V_m computed from experiment data is 3.793 m/s and the attenuation αm is 93.98 dB/m. In contrast, the simulation result V_d was 3.793 m/s, z α_d was 85.05 dB/m. And the corrected shear velocity V_s was 2.2 m/s and the viscosity attenuation α_v was 8.93 dB/m.



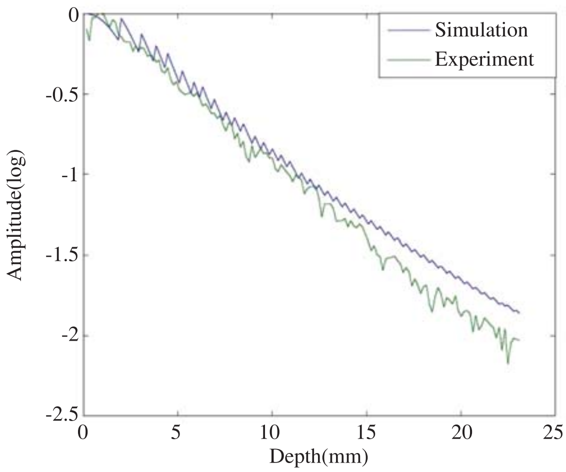
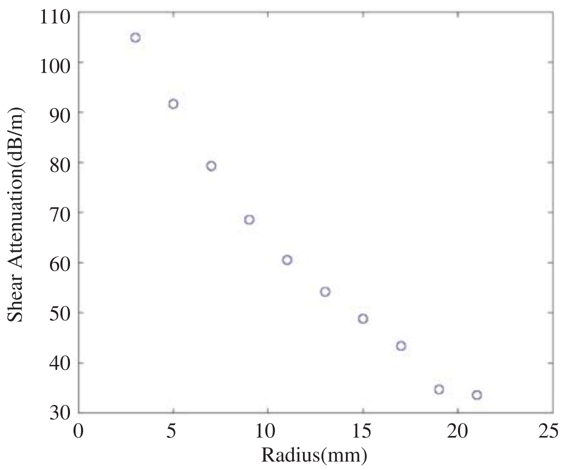


Figure 5. Comparison between experiment and simulation results of the phase delay and amplitude curves versus depth

To test and verify the accuracy of this method, ten different radiuses of disk loads (ranging from 3 mm to 21 mm with the increment of 2 mm) were used to calculate the shear wave velocity and the shear wave attenuation using the correcting method. Figure 6 shows the comparison between experimental results and simulation results of the shear velocity and attenuation for the ten different radiuses circular vibrators.



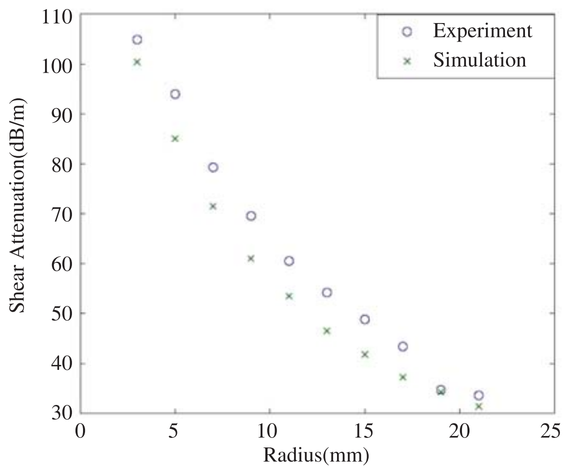


Figure 6. Comparison between experiment measurement and simulation result of the attenuation for the ten different circular vibrators. The theoretical results and experiment data obtained with transient elastography are in very good agreement

Table I. Comparison Between Experiment Measurement and Simulation Result of the Attenuation for the Ten Different Circular Vibrators

R(mm)	V_m(m/s)	V_s(m/s)	Bias	α_m	α_v	α_d
3	3.665	3.568	2.65%	104.9	100.4	4.5
5	3.793	3.793	0.00%	93.97	85.05	8.92
7	4.061	4.087	–0.64%	79.35	71.54	7.81
9	4.406	4.391	0.34%	69.58	61.06	8.52
11	4.762	4.742	0.42%	60.59	53.47	7.12
13	5.057	5.072	–0.30%	54.28	46.57	7.71
15	5.371	5.427	–1.04%	746.8	41.85	705
17	5.768	5.759	0.16%	43.42	37.29	6.13
19	6.201	6.127	1.19%	34.74	34.31	0.43
21	6.847	6.452	5.77%	33.63	31.4	2.23

Experimental results are in keeping with the simulation results for overwhelming majority, see Table 1. The bias between simulation result V_s and experiment measurement V_m is defined by the expression as:

$$bias = \frac{|V_m - V_S|}{V_m} \tag{6}$$

The results show that when the radius of vibrators used in the range of 5 mm to 13 mm, the bias between simulation result and experiment results is less than 1%, and the corrected attenuations are hovering around 8 dB/m, which prove our hypothesis that the attenuation is composed of the viscosity component and the diffraction component. Although the bias of velocity is large than 5% as the radius increase to 21 mm because of the bad contact between the vibrator and the surface of phantom, in general, the theoretical results are in accordance with the experiment measurements. It was proved to be an efficient method to correct the viscoelastic bias measured by transient elastography.

5 Conclusion

The results presented in this paper show that there is bias in measuring vicoelastic properties using a simple inverse problem method based on transient elastography. Radius of circular vibrator and near-field effect are two main factors leading the measurement bias of shear velocity. A self-adapting bias correcting method is presented to correct the measurement bias of transient elastography. By decomposing the shear wave attenuation into a viscosity part and a diffraction part, the bias correcting method described in the paper can be used to correct both the shear wave velocity and shear wave attenuation. Comparisons have shown that simulation and experimental results were in good agreement. We believe that, this bias correction method can improve the accuracy of the measurement results of transient elastography and make it a more powerful tool in clinical practice.

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