Viscoelastic Effects in Sonoelastography: Impact on Tumor Detectability

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Abstract

The sonoelastographic theory of tumor detection predicts enhanced image contrast as vibration frequency increases. However, the opposite effect is observed when imaging liver lesions at frequencies (200-400 Hz) where strong viscoelastic effects dominate. Mechanical testing was performed and confirmed the viscoelasticity of liver tissue. The time dependence of the stress relaxation suggests a viscoelastic model with a complex modulus which increases monotonically with frequency. It is shown how this model explains the anomalous frequency effect.

I. INTRODUCTION

Sonoelastography has been proposed as a method of imaging the relative elastic (shear and Young's) moduli of soft tissues [1]. We have previously demonstrated the detectability of hard lesions of various sizes in phantom materials [2, 3]. Hard lesions in Zerdine phantoms show increased contrast when the applied vibration frequency is increased. When lesions are induced in liver tissue by either the injection of formaldehyde or RF ablation it was found that vibration above 300 Hz did not enhance lesion contrast. The viscoelasticity of bovine liver is investigated in order to explain these divergent outcomes. Unconfined uniaxial compression tests were performed to study both the stress relaxation of liver tissue and Zerdine phantom material.

II. COMPARISON OF PHANTOM AND TISSUE IMAGES

While developing a theory of tumor detectability for sonoelastography Parker et al. [4] showed that lesion contrast increases when vibration is increased. Figure 1 shows two sonoelastograms of a 1.3 cm spherical hard lesion in a Zerdine phantom. The top image was taken using forced vibration of 5 tones [133 160 187 213 240] Hz with a low frequency content. Low grayscale values indicate low vibration which indicates an elevated Young's modulus. The bottom image was captured using 4 tones [200 267 333 400] Hz and illustrates how contrast increases with higher frequency forced vibration. Multiple tones are used to reduce the effect of vibration artifacts caused by reflections.

In contrast figure 2 shows a lesion induced in a bovine liver using radio frequency (RF) ablation. On the left a low frequency set of tones were used for image acquisition revealing a region of decreased vibration marked by two arrows. On the right is an image of the same lesion using a high frequency set of tones. Clearly the higher frequency vibration decreased tumor detectability.

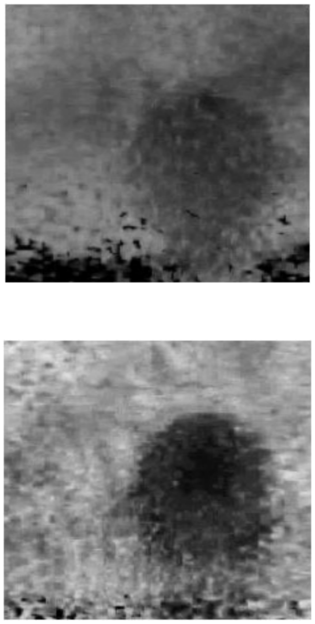

Figure 1: Hard Inclusion in Zerdine Phantom low vs. high frequency.

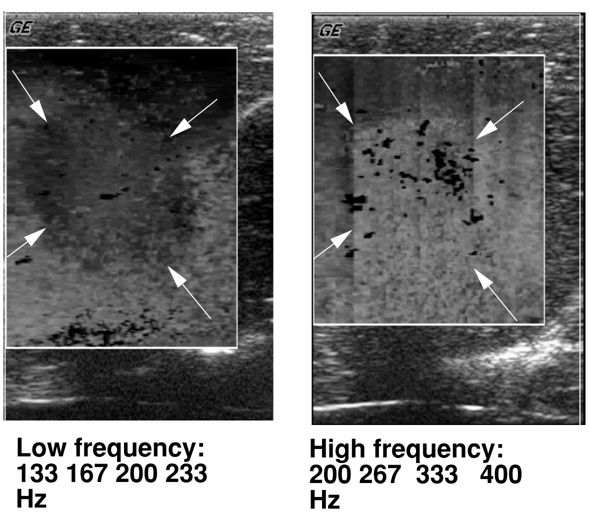

Figure 2: Lesion in liver low vs. high frequency.

III. MECHANICAL TESTING: THEORY

Samples of bovine liver and Zerdine phantom material were tested using uniaxial unconfined compression and stress relaxation was used to characterize the material's viscoelasticity. When an elastic material is compressed the stress (force) required to maintain a constant strain (displacement) remains constant in time. In a viscoelastic material relaxation occurs and the stress decreases with time. The frequency domain response can be obtained from the time domain and will have a (complex) single valued Young's modulus at any frequency. In sonoelastography, lesion contrast of a viscoelastic material is the ratio of the lesion's modulus to that of the background tissue.

III. MECHANICAL TESTING: METHOD

Fresh whole bovine liver was obtained from a local butcher, refrigerated and stored in blood overnight as necessary. The samples were typically rectangular solids measuring 22 mm by 22 mm in cross sectional area and 13 mm in height. An MTS QT/5 with a 50 N load cell was used for testing. The samples were compressed between two metal platens lined with Teflon to ≈ 15 % strain while the applied stress required to maintain that strain was recorded over time. Tests lasted about 900 seconds where an equilibrium condition was reached. Stress relaxation was acquired for 10 distinct liver samples.

One cylindrical Zerdine sample measuring 2.5 cm thick and 5 cm in diameter was acquired from the manufacturer, Computerized Imaging Reference Systems (Norfolk, VA) and tested using uniaxial unconfined compression. The samples were compressed between two metal platens coated with olive oil to ≈ 10 % strain while the applied stress required to maintain that strain was recorded over time.

IV. RESULTS

Stress relaxation % for each test was calculated by subtracting the stress at equilibrium, where nearly complete relaxation occurred, from the peak initial stress then dividing by the peak initial stress. Bovine liver proved to be very viscous relaxing 84% ± 4% ($n = 10$) samples while the Zerdine phantom material proved to be more nearly elastic relaxing only 9% ± 2% in ($n = 10$) tests on single sample.

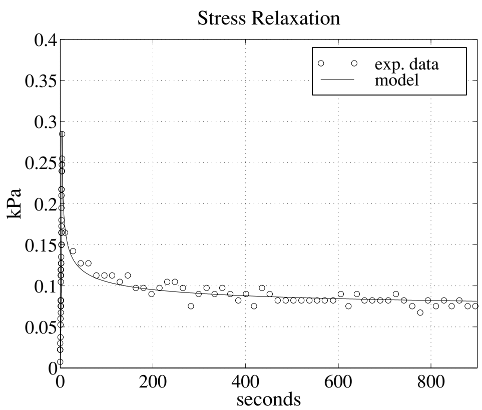

Figure 3: Stress Relaxation of liver sample

Figure 3 shows a typical stress relaxation curve for a liver sample. The open black circles are the data points; the solid black line is a curve with time dependence $t^{-\alpha}$, where $\alpha = 0.36$ and t is time. Data is noisy because the load (stress) levels measured were well below the full scale value of the load cell.

V. DISCUSSION

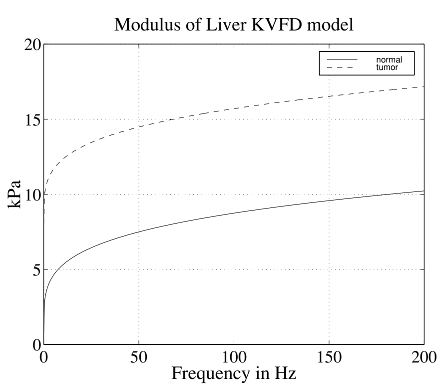

Figure 4: Frequency Dependence of the KVFD model

In the results section we have calculated the % relaxation to establish that liver is much more viscoelastic than the Zerdine phantom material. The concept is sound but the functional dependence of the relaxation function in time is what characterizes the viscoelasticity of a material completely. Koeller [5] has shown that the stress relaxation function for the Kelvin-Voight Fractional Derivative (KVFD) model has a time dependence $t^{-\alpha}$ where t is time. Caputo [6] introduced the fractional calculus into the field of viscoelasticity in 1967 while studying materials of geological interest. The KVFD model proposed by Caputo consists of a spring in parallel with a dashpot where the the stress in the dashpot is equal to the fractional derivative of order α of the strain.

A formal definition of fractional differentiation can be found in Caputo's paper. Of more interest to this work is the Fourier Transform (FT) of the fractional derivative of order α which is

$$FT(D^{\alpha}f(t)) = (j\omega)^{\alpha}F(\omega) \tag{1}$$

where $j = \sqrt{-1}$ and ω is radian frequency. We derive the frequency dependence of this model by starting with the constitutive equation

$$\sigma(t) = E_0\varepsilon(t) + \eta D^{\alpha}\varepsilon(t) \tag{2}$$

where σ is stress, ε is strain, E_0 is the elastic element, η is the dashpot parameter and D^{α} is the fractional derivative operator of order α. Taking the Fourier Transform of this equation yields

$$\sigma(\omega) = E_0\varepsilon(\omega) + \eta(j\omega)^{\alpha}\varepsilon(\omega) \tag{3}$$

where ω is radian frequency and $j = \sqrt{-1}$. Recalling that a modulus is a ratio of stress to strain $E^*(\omega) = \sigma(\omega)/\varepsilon(\omega)$ we can write

$$E^*(\omega) = E_0 + \eta cos\left(\frac{\pi\alpha}{2}\right)\omega^{\alpha} + j\eta sin\left(\frac{\pi\alpha}{2}\right)\omega^{\alpha} \tag{4}$$

where $E^*(\omega)$ is the complex Young's modulus and $\omega \geq 0$ is assumed. Equation 4 tells us that the complex Young's modulus has a frequency dependence equal to monotonically increasing with radian frequency.

Figure 4 shows frequency domain curves of the Young's modulus (absolute value) for equation 4. The parameters are hypothetical but illustrate the principle behind the observed loss of contrast. A large viscous parameter is assumed, which is consistent with the large % relaxation measured for liver. The dashed line is a curve for a lesion which is 10 times stiffer at zero frequency than the solid line which is for the normal background tissue, as would be observed during lesion palpation. At zero frequency the lesion has a modulus of 8 kPa while the background tissue has a modulus of 0.8 kPa. At 200 Hz the lesion has a modulus of 17 kPa while the background tissue has a modulus of just over 10 kPa. The lesion/background ratio is less than two. Clearly lesion contrast decreases as frequency increases.

V. SUMMARY AND CONCLUSIONS

Mechanical tests show that liver tissue is much more viscoelastic than Zerdine phantom material. The time dependent response of the stress relaxation agreed well with a Kelvin-Voight Fractional Derivative model. This model has a Young's modulus which is monotonically increasing with vibration frequency. At low frequency, as in digital palpation, the elastic element dominates but at higher frequencies the viscous element dominates. We conclude that lesion contrast will decrease with increasing frequency for any tissue which follows this model if the lesion process does not increase the viscous element.

References

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