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● *Original Contribution*

DEVELOPMENT OF OIL-IN-GELATIN PHANTOMS FOR VISCOELASTICITY MEASUREMENT IN ULTRASOUND SHEAR WAVE ELASTOGRAPHY

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Study Motivations and Objectives

<u>Work was carried out in 2012 with Dr. Man Nguyen (summer intern)</u>

- Develop and fabricate viscous tissue mimicking phantoms for ultrasound shear wave elastography
- Develop and evaluate processing and reconstruction algorithms that construct elasticity and viscosity

- Clinical applications of liver tissue viscosity measurement
  - This study was mainly motivated by Barry et al. “Shear wave dispersion measures liver steatosis”, Ultrasound Med Biol 2012;38(2):175-182
  - Some clinical studies reported higher liver stiffness and correlated increased shear viscosity in patients with fibrotic liver diseases

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Methods

Phantoms Fabrication

Viscous tissue-mimicking phantoms

- 3-7% Gelatin (elasticity)
- 0-40% Castor oil (elasticity & viscosity)
- 2% graphite (backscattering)
- 7% propanol (Speed of Sound)

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Methods: Material Concentrations of Viscous Phantoms

Table 1. Material concentrations by weight for oil-in-gelatin phantoms.

Material Components	Phantoms 1-4	5-6	7-8	9-12	13- 14
Gelatin (%)	3	4	5	6	7
Graphite (%)	2	2	2	2	2
N-propanol (%)	7	7	7	7	7
Castor oil (%)	0, 10, 20, 40	0, 20	0, 20	0, 10, 20, 40	0, 20

Example: material weight for 4% and 7% gelatin phantoms

Phantom	Gelatin	Castor Oil	DI water	(2-propanol)	Graphite	Total weight
4% phantoms	4% (40g)	0% (0g)	87% (870g)	7% (70g)	2% (20g)	100% (1000g)
	4% (40g)	20% (200g)	67% (670g)	7% (70g)	2% (20g)	100% (1000g)
7% phantoms	7% (70g)	0% (0g)	84% (840g)	7% (70g)	2% (20g)	100% (1000g)
	7% (70g)	20% (200g)	64% (640g)	7% (70g)	2% (20g)	100% (1000g)

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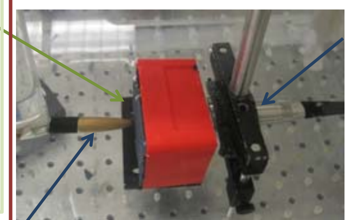
Methods

Phantoms Fabrication → **Acoustic Properties Measurement** →

Viscous tissue-mimicking phantoms
- 3-7% Gelatin (elasticity)
- 0-40% Castor oil (elasticity & viscosity)
- 2% graphite (backscattering)
- 7% propanol (Speed of Sound)



Single element transducer
(Panametrics 3.5MHz)

Hydrophone (Onda)
- Data acquisition with GageScope/Matlab

Measurements:

Attenuation measurement (dB):

$10\log(ISPPA_{phantom}/ISPPA_{no\text{-}phantom})$

Speed of sound in phantoms

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Methods

Phantoms Fabrication → Acoustic Properties Measurement → **Visco-elastic Property Measurement**

Viscous tissue-mimicking phantoms
- 3-7% Gelatin (elasticity)
- 0-40% Castor oil (elasticity & viscosity)
- 2% graphite (backscattering)
- 7% propanol (Speed of Sound)

Philips Shear Wave Elastography Prototype on iU22
↓
Capture raw RF data
↓ **Offline**
Motion tracking & Voigt's model fitting
↓
Shear modulus | Shear viscosity

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Methods: Viscoelasticity Measurements

- Shear wave elastography research prototype on Philips iU22 & C5-1 curvilinear transducer
- Push and tracking pulse specs
  - Push pulses with pulse repetition frequency of 70 Hz → shear waves with fundamental at 70 Hz and harmonics at 140, 210, 280 Hz
  - Tracking PRF 2KHz at multiple tracking locations
- Data processing steps
  - Motion tracking to estimate shear wave induced displacement
  - Bandpass filter to remove background motion
  - Shear wave phase velocity measurement ([70, 280 Hz])
  - Voigt model fitting

$$c_s(\omega_s) = \sqrt{\frac{2(\mu_1^2 + \omega_s^2 \mu_2^2)}{\rho(\mu_1 + \sqrt{\mu_1^2 + \omega_s^2 \mu_2^2})}}$$

c_s: shear wave speed
u_1: shear modulus
u_2: shear viscosity
ρ: medium density

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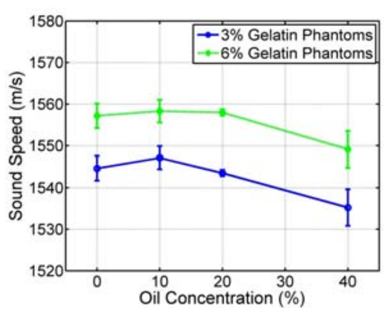
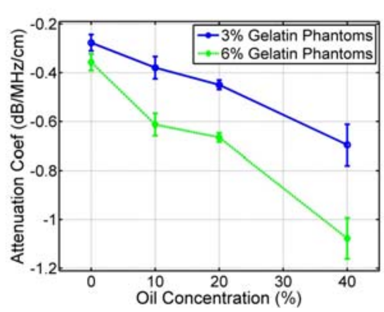
Acoustic Properties of Phantoms as a Function of Oil Concentration

Speed of Sound



Attenuation Coefficient



- Fabricated phantoms have comparable sound speeds and attenuation coefficients to those of soft tissues

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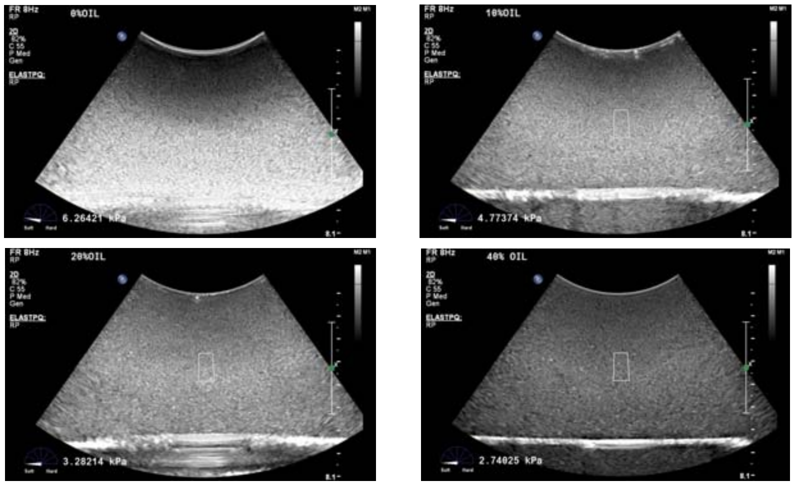
B-mode Images of 3% Gelatin Phantoms with Different Oil Levels



- Higher attenuation for compressional wave in phantoms with higher oil concentration

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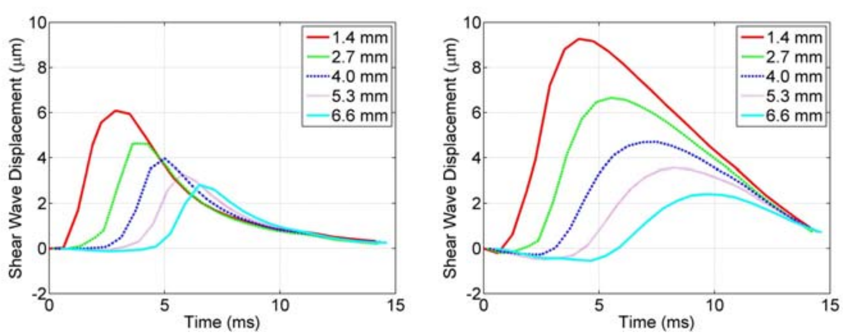
Shear Wave Displacement Profiles

One data acquisition at measurement depth 40mm

3% gelatin + 0% oil   3% gelatin + 20% oil



- Shear wave has higher frequency content and lower attenuation along the propagation path in 0% oil phantom than 20% oil phantom

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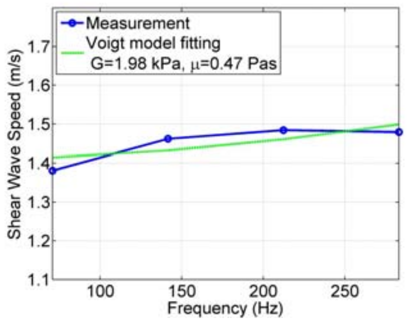
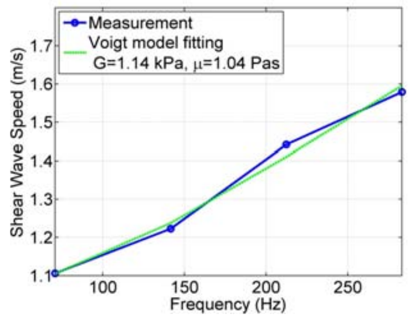
Shear Wave Phase Velocity as Function of Frequency and Voigt Model Fitting

One data acquisition at measurement depth 40mm

3% gelatin + 0% oil



3% gelatin + 20% oil



- Shear wave speed increases more as a function of frequency (higher slope) in 20% oil phantom than 0% oil phantom

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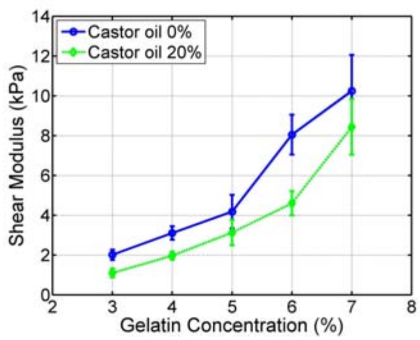
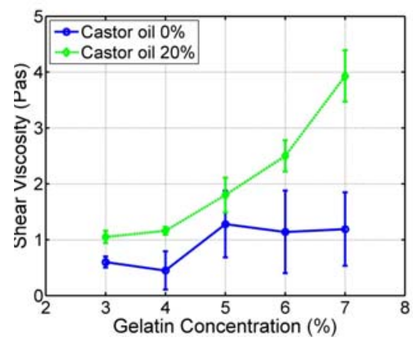
Visco-elasticity Measurement for 3-7% Gelatin Concentration and 0 & 20% Oil

Shear modulus



Shear viscosity



- Shear modulus increases with gelatin percentage but decreases with castor oil percentage
- Shear viscosity increases with castor oil percentage

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Shear Wave Dispersion Measured by Shear Wave Speed Slope

Slope is measured by linear fitting shear wave phase velocity in the frequency range [70, 280]Hz

- 3% gelatin phantoms

Table 2. Shear modulus, shear viscosity and shear wave dispersion slope for 3% gelatin phantoms with four castor oil levels

	Castor oil level			
	0%	10%	20%	40%
Shear modulus (kPa)	2.01	1.68	1.10	0.88
Shear viscosity (Pa·s)	0.60	0.89	1.05	1.06
Dispersion slope (m/s/100 Hz)	0.06	0.15	0.27	0.32

- 6% gelatin phantoms

Table 3. Shear modulus, shear viscosity and shear wave dispersion slope for 6% gelatin phantoms with four castor oil levels

	Castor oil level			
	0%	10%	20%	40%
Shear modulus (kPa)	8.05	8.66	4.60	2.98
Shear viscosity (Pa·s)	1.14	2.25	2.50	1.97
Dispersion slope (m/s/100 Hz)	0.03	0.10	0.25	0.28

- Dispersion slope monotonically increases as a function of oil level
- 6% gelatin phantoms have dispersion slopes in a similar range as 3% gelatin phantom; but much higher absolute viscosity in 6% phantoms than in 3% phantoms
- Hypothesis: dispersion slope is a more independent measure of shear wave dispersion than shear viscosity derived from Voigt model fitting

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Conclusions and Discussions

- Tissue-mimicking viscous phantom were constructed using a gelatin base with additives including castor oil, alcohol (N-propanol), graphite powder and water
- Measured sound speeds and attenuation coefficients of fabricated phantoms were similar to those of soft tissues
- Reconstructed results show that gelatin concentration increases shear modulus, castor oil decreases shear modulus but increases shear wave dispersion and acoustic attenuation
- Study limitations
  - Phantom durability remains an issue (manufacturers such as CIRS may provide viscous phantoms of longer shelf life)
  - Shear wave frequency range characterized in this study is relatively narrow

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