Investigation of Freezing and Decay Effects on Material Properties of Porcine Abdominal Organs

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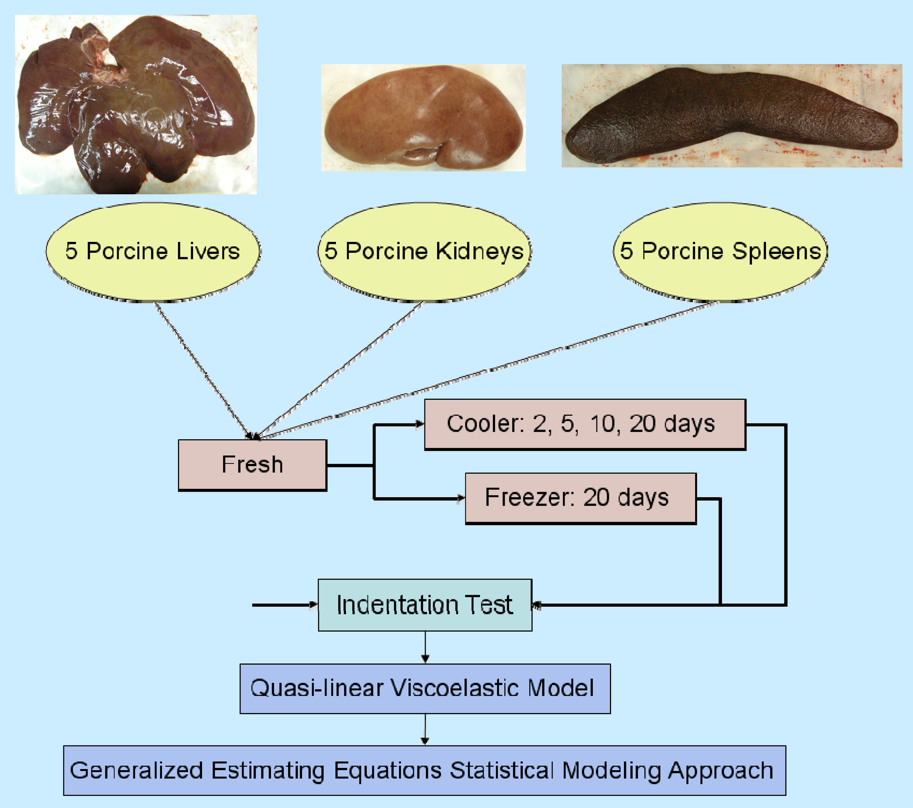
Introduction

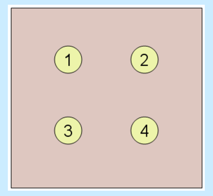
Cadaveric and human numerical models are playing an important role in assessment and optimization of novel restraint systems for reducing the abdominal injuries (about 5% of all traffic injuries). While some concerns were raised regarding the rapid degradation of abdominal organs after death [4], the investigation of possible changes in their material properties is required for better understanding the PMHS vs. human abdominal responses under dynamic loading corresponding to impact environment. To better examine the freezing and decay effects, this study analyzes statistically the data obtained from indentation performed on porcine abdominal organs.

Test Procedure

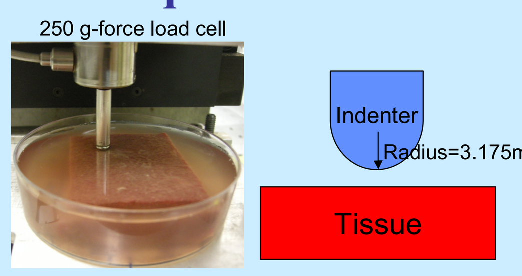


Methods

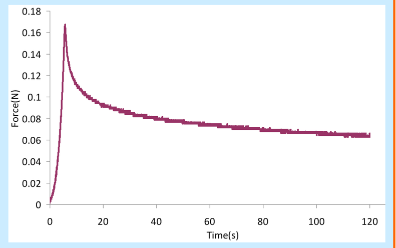
- Specimens (50x50x15 mm^3) were cut with a custom blade assembly from 15 fresh porcine organs, keeping the adipose capsule intact.
- Indentation ramp-hold tests with 2 min hold time and 1 mm displacement peaks were first conducted on fresh specimens at four locations of each sample.
- A uniaxial load cell was mounted between the linear actuator and the shaft of the spherical indenter tip.
- In order to maintain a consistent temperature, all samples were submerged in physiological (0.9%) saline at 75^{0}F.
- Half of the specimens of each organ were then frozen at 10^{0}F ("Freezing Effect") and re-tested after 20 days under the same testing condition, and the other half of the specimens were re-tested at day 2, 5, 10, 20, and were cooling at 40^{0}F between every two sequential tests ("Decay/cooling Effect").



Four points are chosen and tested for each sample.



Representative indentation test on spleen sample #1 point #1



A typical force relaxation curve (Kidney sample #1 point #1)

Data Analysis

- **Hertzian Contact for an Incompressible Material**

$$P = \frac{4\sqrt{R}}{3}\frac{E}{(1-v^2)}h^{3/2} = \frac{8\sqrt{R}}{3}[2G]\cdot h^{3/2}$$

- **Quasi-linear Viscoelastic (QLV) Modeling**

$$G(t,h) = G_r(t)\sigma^e(h)$$

where $G_r(t) = G_0 + G_1e^{-t/\tau_1} + G_2e^{-t/\tau_2} + G_3e^{-t/\tau_3}$ and $\sigma^e(h) = \mu_0 + \mu_1 h^2$

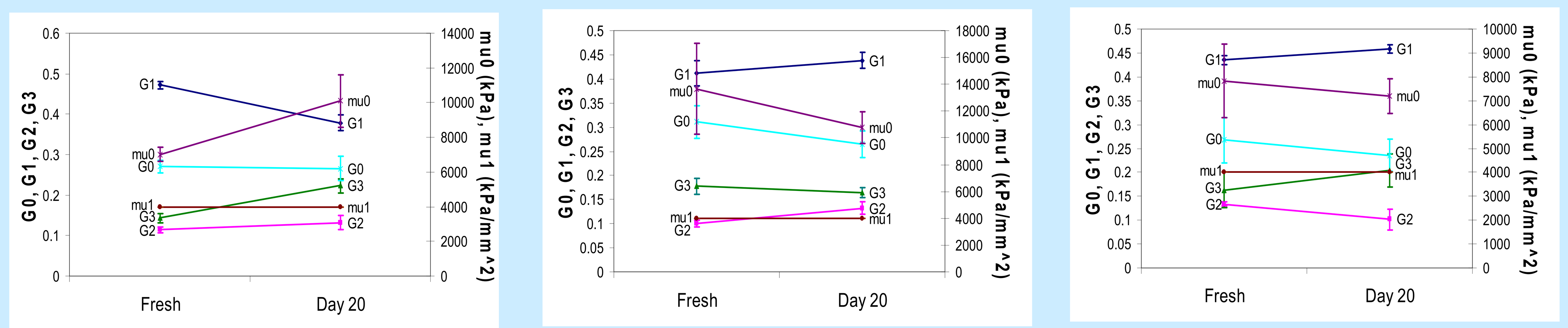
  - G_1 has a time constant of τ_1=1 sec .
  - G_2 has a time constant of τ_2=10 sec.
  - G_3 has a time constant of τ_3=100 sec.
  - μ_0 and μ_1 are the coefficients of the instantaneous response
  - Boltzmann superposition principle was utilized.

$$P(t) = \frac{8\sqrt{R}}{3}\int_0^t G(t-\tau)\left[\frac{d}{d\tau}\left(\mu_0 h^{3/2} + \mu_1 h^{7/2}\right)\right]d\tau$$

where t: time and h: indentation depth

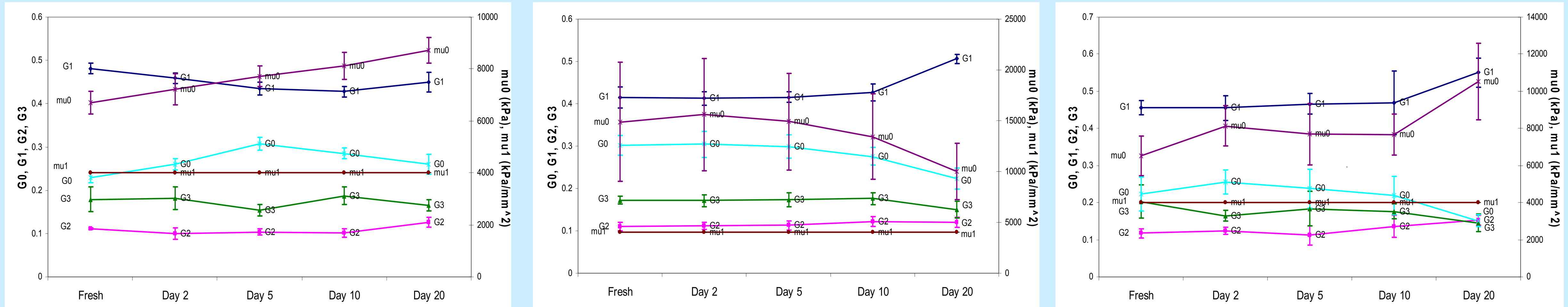
- The QLV model coefficients were obtained by minimizing the sum of squared errors (SSE) between the model and experimental force.
- **Generalized Estimating Equations (GEE) Statistical Approach**
  - Statistical Model: $Y = \alpha + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_1 x_2$
    where Y: Coefficients (G_0, G_1, G_2, G_3, μ_0, μ_1)
    X_1: Specimen # (1-5) or cooling/frozen effects
    X_2: Time (Fresh, Day 2th, 5th, 10th, 20th)
  - GEE is a robust method of inference on regression coefficients against model specification, to study population-average pattern or trend over time for longitudinal data.

Results



(a) Kidney (b) Spleen (c) Liver

Figure 1. Mean and 95% C.I. for each of QLV coefficients (G_0, G_1, G_2, G_3, μ_0, μ_1) in freezing effect tests (fresh vs. tissues preserved by freezing 20 days).



(a) Kidney (b) Spleen (c) Liver

Figure 2. Mean and 95% C.I. for each of QLV coefficients (G_0, G_1, G_2, G_3, μ_0, μ_1) in decay effect tests (comparing fresh, cooling after 2, 5, 10, and 20 days).

- Overall, the average value of the G_1 coefficients have highest contribution to the total relaxation response (≈45%), while G_2 coefficients have least contribution (<15%).
- The freezing effect changes the relaxation properties of kidney, but changes the instantaneous elastic responses of all three organs.
- The decay effect impacts instantaneous elastic response of all three organs but changes relaxation response for spleen and liver only.

Effects	Kidney			Spleen			Liver		
	G_1	G_0	μ_0	G_1	G_0	μ_0	G_1	G_0	μ_0
Freezing	**	**	**			**			**
Decay		*	**	**	**	**		**	**

*P<0.05, **P<0.01

Statistical results of time dependency for coefficients G_1, G_0, and μ_0 on three abdominal tissues - The freezing effect compares tissues at fresh status and at Day 20, while the cooling effect compares times at fresh status, Day 2, 5, 10, and 20.

- For all the three types of tissue, mean level of relaxation coefficient G_1 after 20 days of cooling is significantly higher (7%-8%) than G_1 after 20 days of freezing. Accordingly, in kidney and liver, cooling significantly lowers G_3 level by 7%-8% compared to freezing, while in spleen the cooling just marginally (p=0.09) decreases G_3 level by 2%.

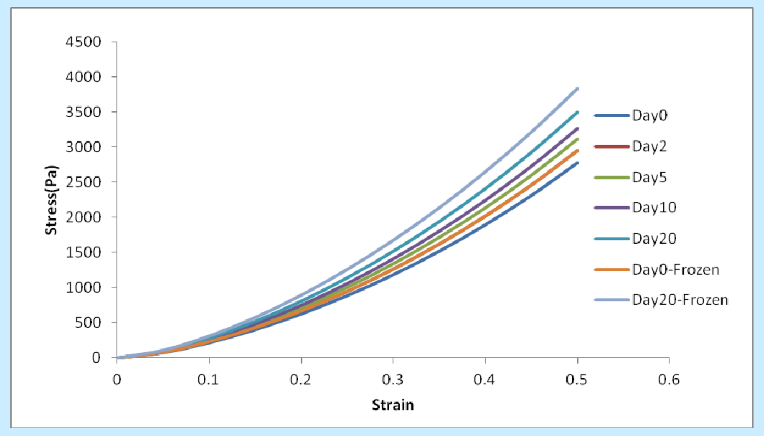


Figure 3. Average Instantaneous Elastic Response for Kidney. When time increases, both cooling and freezing storage make the kidney stiffer. Freezing storage method makes the kidney stiffer than the cooling method.

- As for the instantaneous elastic coefficients, in kidney, u_0 after 20 days of cooling is marginally (p=0.06) lower by 1245 compared to day 20 u_0 after freezing. In liver, however, u_0 after 20 days of cooling is significantly higher by 4386 compared to that obtained by freezing.

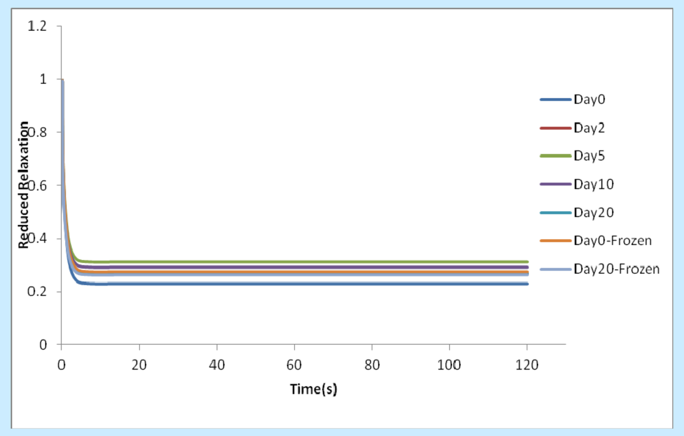


Figure 4. Average Reduced Relaxation Response for Kidney. The changes between cooling and freezing methods may not have significant difference as shown in the figure; in fact, statistical analysis shows that the relaxation behavior of kidney are not quite sensitive when comparing the cooling and freezing effects.

Discussion

- The primary hypothesis that the material properties of the porcine abdominal organs are all time dependent in frozen and decay effects is supported by the results of this study. Significant differences between freezing and cooling effects are also found in this study.
- Statistical analysis found that the viscoelastic relaxation were time dependent for the kidney with freezing effect and for the spleen and liver with cooling effect.
- The instantaneous elastic coefficients, μ_0 and μ_1, were found to be strongly time dependent relative to the relaxation coefficients in all three organs.
- It is believed that the results of this study may help in better understanding of the impact of the cooling and freezing effects on abdominal organs. The generalized estimating equations approach is suggested for further use in the biomechanical longitudinal data (e.g. time dependency) analysis.

Future Work

- Future investigations on studying the anisotropic material properties of the abdominal tissues by indenting different directions on the tissues are highly suggested.
- The abdominal organ perfusion state may change the material property, so a more robust method would be suggested to test the organs while the blood vessels are perfused with fluid.
- The abdominal tissues usually consist of the outer capsule and the inner parenchyma structures. While this study test them together, testing these structures individually will be desirable and the results can be more accurate to model the abdominal organ mechanical behavior.
- While we only investigated the mechanical response of the tissues, we may add the investigation of freezing/cooling effect on the injury tolerance as well.
- Principle analysis which efficiently combines all information of relaxation coefficients would be suggested to examine a full scope of experimental data.

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