In-Vivo and *In-Situ* Compressive Properties of Porcine Abdominal Soft Tissues

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ABSTRACT. Accurate biomechanical characteristics of tissues are essential for developing realistic virtual reality surgical simulators utilizing haptic feedback. Surgical simulation technology has progressed rapidly but lacks a comprehensive database of soft tissue mechanical properties with which to incorporate. Simulators are often designed purely based on what "feels right;" quantitative empirical data are lacking. A motorized endoscopic grasper was used to test abdominal porcine tissues *in-vivo* and *in-situ* with cyclic and static compressive loadings. An exponential constitutive equation was fit to the resulting stress-strain curves, and the coefficients were compared for various conditions. Stress relaxation for liver and small bowel were also examined. Differences between successive squeezes and between *in-vivo* and *in-situ* conditions were found.

1. Introduction

Accurate knowledge of biomechanical characteristics of tissues is essential for developing realistic computer-based surgical simulators incorporating haptic feedback. As simulation technologies continue to be capable of modeling more complex behavior, an *in-vivo* tissue property database is needed. However, little is currently known quantitatively regarding the force-deformation behavior of the relevant anatomy. Such knowledge would be useful not only to simulation but also for optimizing surgical tool design, creating "smart" instruments capable of assessing pathology or force-limiting novice surgeons, and understanding tissue injury mechanisms and thresholds. It is important to consider the ranges of applied force and deformation measured in surgery for accurate simulation.

2. Background

The biomechanics of soft tissues that are load-bearing during physiological activities have been well studied (muscles, tendons, intervertebral discs, cartilage, blood vessels). The soft abdominal organs do not bear significant loads except in the extreme cases of trauma and surgery. Very little mechanical testing has been done on the abdominal organs relevant to laparoscopic surgery, and most of that work has been done *ex-vivo* on animal specimens or preserved human cadavers.[1-6]

It has only recently become a major thrust of researchers to obtain *in-vivo* measurements of tissue mechanical properties. Brouwer *et al.* developed several methods for measuring porcine tissue response to extension and indentation *in-vivo*.[7] While this was *in-vivo*, it was done invasively. Ottensmeyer developed an instrument for obtaining *in-vivo* uni-axial tissue response to quasi-static and dynamic compressive loading.[8, 9] The device applies small (± 500 µm), low force (<300 mN), high frequency (<100 Hz) compressions. Two more indentation devices have been created by Carter *et al.*[10] One is a large benchtop system for compressing tissues *ex-vivo*. The

other is a hand-held probe capable of producing indentations of about 10 mm travel with 5 N force. This group presents the only known *in-vivo human liver* data to date. Our previous instrument was capable of applying *in-vivo* compressive force via a voice-coil actuated grasper.[11] This instrument was used to test several porcine abdominal tissues *in-vivo* to measure their force-deformation response but was only capable of applying up to approximately 100 kPa compressive stress and did not sense force directly. Other groups have developed devices for testing residual limb and buttock tissues non-invasively using ultrasound indenters.[12-14] Because very little data has been collected on tissues *in-vivo*, even less has been published relating tissue properties *in-vivo* to those postmortem.

It is well known that after several cycles soft tissues typically exhibit a characteristic known as preconditioning,[15] which is a steady-state behavior where the stiffness and the hysteresis in successive cycles is constant. Most researchers precondition their tissue samples to obtain consistent results. However, surgeons do not precondition tissues before operating. First-squeeze behavior of tissues has not been frequently reported. Another unknown is the amount of time required for tissues to recover to their natural state after being compressed.

3. Methods & Tools

The University of Washington Biorobotics Lab has developed a motorized endoscopic grasper (MEG) to examine the compressive properties of porcine abdominal soft tissues (see Figure 1).[16] Detailed mechanism specifications can be found in Brown *et al.*[16] Briefly, the MEG uses a brushed DC motor to drive a Babcock (Karl Storz) grasper. A strain gage sensor estimates the force applied by the grasper jaws to the tissue. The MEG is capable of applying about 70 N (equivalent to a compressive stress of 1.3 MPa) of grasping force at up to 3 Hz. It is hand-held, weighs about 0.7 kg, and can be inserted into the body through standard 10 mm endoscopic ports to perform computer-controlled dynamic uniaxial compressions of soft tissues. Maximum deformation of tissue samples is less than 30 mm. While the MEG is capable of applying up to 70 N, maximum force applied to living tissues was limited to 20 N (354 kPa) to minimize permanent injury to tissues.

The strain gage and motor encoder do not directly measure jaw force or jaw angle, respectively. However, by knowing the mechanism's stiffness and taking into account the kinematics of the grasper mechanism, a reasonable estimation of the force and deformation at the jaw tips can be obtained. This has been validated by squeezing linear springs of known stiffness.

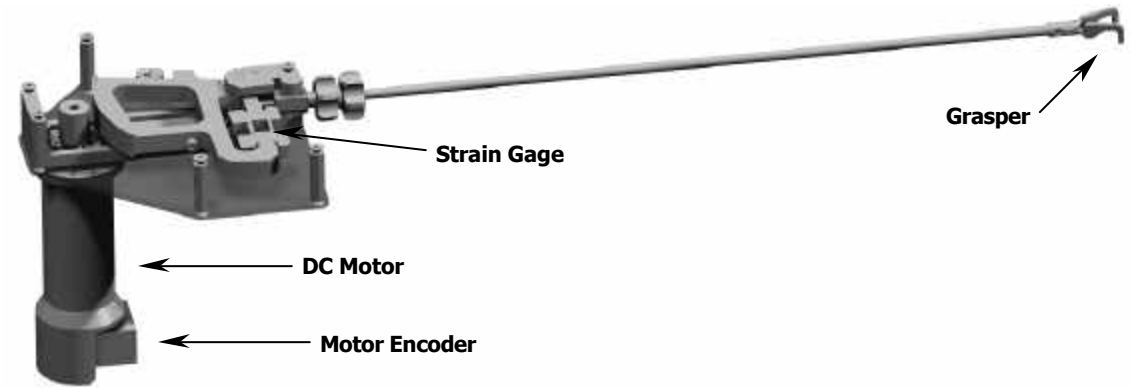

Figure 1. Motorized Endoscopic Grasper (MEG) (rendered CAD drawing; protective top cover not shown)

In order to determine the forces, deformations, and timing of compressive loadings to apply, we examined data collected from previous experiments.[17] We have found that 97.1% of the grasps performed by 5 expert surgeons during three different surgical tasks were held for less than 10 sec (both hands) (Figure 2). The majority of the frequency content in grasping force was below 3 Hz. Maximum grasping force measured (rarely) was about 40 N.

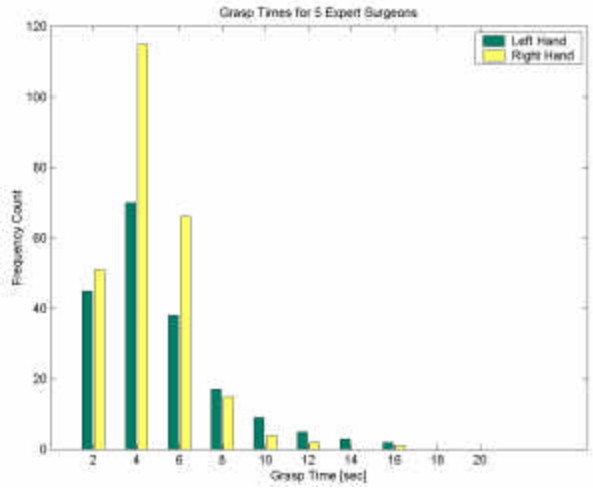

Figure 2. Tissue grasping time for 5 expert surgeons performing 3 different tasks (both hands)

The MEG has been approved by the University of Washington Animal Care Committee for use in animal (pig) experiments in an AALAC-accredited surgical research facility. The device has been used in anesthetized pigs with a standard laparoscopic setup to examine the compressive properties of liver, spleen, gallbladder, small bowel, large bowel, stomach, and urinary bladder. This study presents results from liver (solid organ) and small bowel (hollow organ) only. *In-vivo* liver data has been collected from a total of six different pigs and *in-situ* from four. In addition, an excised cow's liver has also been tested. *In-vivo* small bowel data has been collected from a total of three pigs and *in-situ* from three. Eight different pigs have been tested in all. Two of these pigs have been used to study both *in-vivo* and *in-situ* characteristics of these organs, whereas the remaining animals were tested under *in-vivo* or *in-situ* conditions but not both. Weight of the pigs was around 40 kg and the gender was female.

While anesthetized, organs were grasped with the MEG in various locations and various loading profiles, using a new site for each test regime to ensure the natural (unconditioned) state of the tissue was measured. To emphasize, *no preconditioning was performed on these tissues*. When tests were conducted *in-vivo* and then repeated *in-situ*, different locations were used for both conditions. Four different loading profiles were tested: haversinusoidal, constant velocity, constant step strains, and periodic step strains. The first two tests, both continuous cyclical loadings, were varied in frequency, from 0.25 Hz to 3 Hz, in different tests. Jaw closing velocity during a 0.25 Hz constant velocity squeeze was approximately 8.2 mm/s, 1 Hz was 32.2 mm/s, and 2 Hz was 65.3 mm/s (strain rates of up to 0.5, 2, and 4 sec^{-1}, respectively). The constant step strain was held for 60 sec at 3 different strains. The periodic step strains were always held for 10 sec, with the time between squeezes varying from 2.5 to 30 sec (duty cycles of 80%, 66.7%, 50%, 33.3%, and 25% were used). These tests were also done at 3 different strain levels. After *in-vivo* testing was complete, the animal was euthanized and time of death recorded, and the protocol was repeated to obtain *in-situ* data. All *in-situ* data were typically collected within 3 hrs postmortem.

Calculated stress-strain data were fit to the exponential function

$$s = b\left(e^{ae} - 1\right) \quad (1)$$

where a and ß are fit coefficients, s is compressive stress (force per unit reference area), and e is the compressive strain (deformation per reference length), using a nonlinear least squares minimzation approach. This equation is derived from the typical elastic response of soft tissues, as described by Fung.[11, 15]

4. Results and Discussion

Representative stress-strain plots for liver and small bowel are shown in Figure 3 through Figure 8. These curves are all the response to 1 Hz constant velocity compressions. Figure 3 shows a typical response for liver to 10 successive constant velocity compression cycles of liver tissue *in-vivo*. The exponential curve fits are also plotted. Figure 4 shows the stress-strain results for the same liver tested *in-vivo* and *in-situ*. First-squeeze stress-strain curves for livers from all animals, including an

excised (and previously frozen) cow's liver and a gelatin artifical liver model (Simulab Corp.), are shown in Figure 5. Similar plots are shown for small bowel in Figure 6 to Figure 8.

The coefficients (a and ß, from Equation 1) for the exponential curve fits for the cyclic loading tests were plotted. These calculated curve-fit parameters were analyzed for all the organs tested. Figure 9 shows these results. Averaged exponential coefficients (a and ß) are plotted for all livers and small bowels tested. Coefficients are shown averaged across squeezes and animals.

Stress relaxation behavior due to constant and periodic step strains appears in Figure 10 to Figure 12. Tissues tested tended to exhibit the well-known decaying exponential stress over time with a constant strain. The amount of decay did seem to vary between *in-vivo* and *in-situ* conditions (Figure 11 and Figure 12). The amount of recovery between step strains depended on the resting time and the condition. In Figure 11, very little recovery occurred in the 2.5 sec rest periods between squeezes. Figure 12 shows more recovery between the longer rest periods, with more recovery being seen *in-vivo* than *in-situ*. It is also interesting to note that the first-squeeze relaxation behavior appears quite exponential, while subsequent squeezes tend to be almost linear.

Some points of interest:

- There is a large amount of variability in the response of tissues tested that may mask effects from other variables, such as *in-vivo* vs. *in-situ*, or frequency-dependence.
- Tissues exhibited some strain history-dependence, especially the hollow organs, like small bowel. This is most likely due to compression of movable material within the hollow structure, such as feces or gas or fluid. Tissues generally stiffened with each successive squeeze. Given the large variability, tissues did not generally tend to reach a state of preconditioning within 10 cycles.
- Tissues did not show much rate-dependence in the narrow frequency range tested.
- Curve fits were not exact. As seen in Figure 4, there is some change in stiffness at high stresses, particularly for liver. This feature may be due to a mechanical problem with the device (slipping or pushrod buckling), motion artifacts, or plastic deformation (injury) within the tissue. Eliminating this potential artifact would likely result in better fits. However, hollow organs, such as small bowel, tend to show a much sharper "elbow" than liver that may not be fit well by a purely exponential function. This again is likely due to the early compression of the contents of the organ and then the actual tissue itself.
- Recovery between subsequent periodic step strains appears to be greater for longer rest periods and for in-vivo conditions. This is likely due to the higher perfusion of pressurized fluids within the in-vivo tissue.

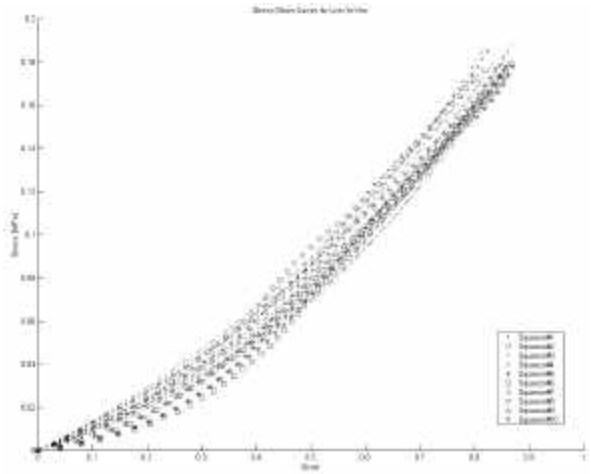

Figure 3. Liver stress-strain curves (*in-vivo*), 10 cycles, 1 animal (dashed lines are curve fits)

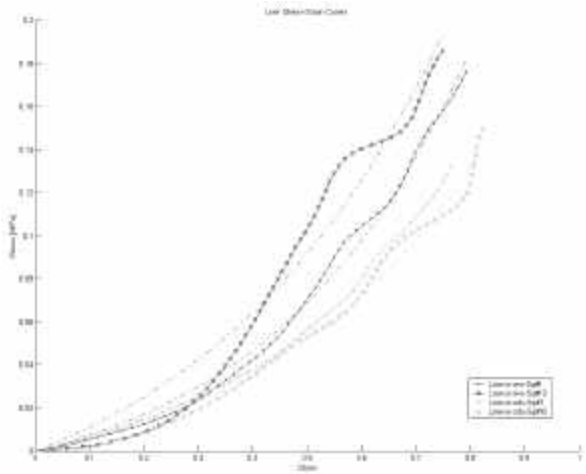

Figure 4. Liver stress-strain curves (*in-vivo* and *in-situ*), 1st and 10th squeezes, 1 animal (dashed lines are curve fits)

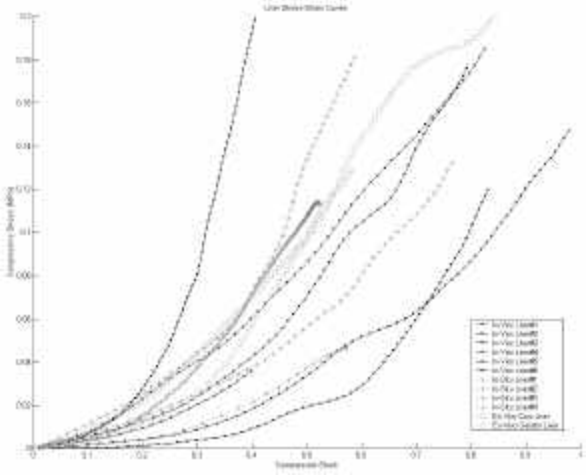

Figure 5. Liver stress-strain curves (*in-vivo* and *in-situ*), 1st squeeze only, all animals

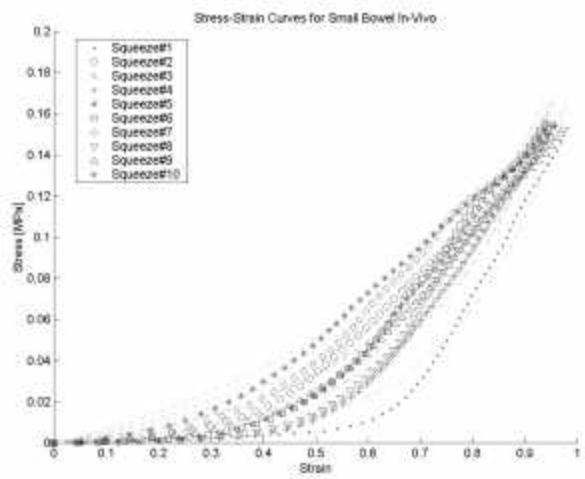

Figure 6. Small bowel (*in-vivo*), 10 cycles, 1 animal (dashed lines are curve fits)

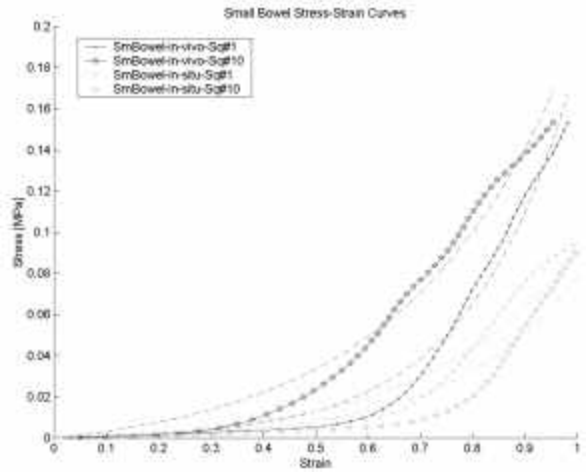

Figure 7. Small bowel stress-strain (*in-vivo* and *in-situ*), 1st and 10th squeezes, 1 animal (dashed lines are curve fits)

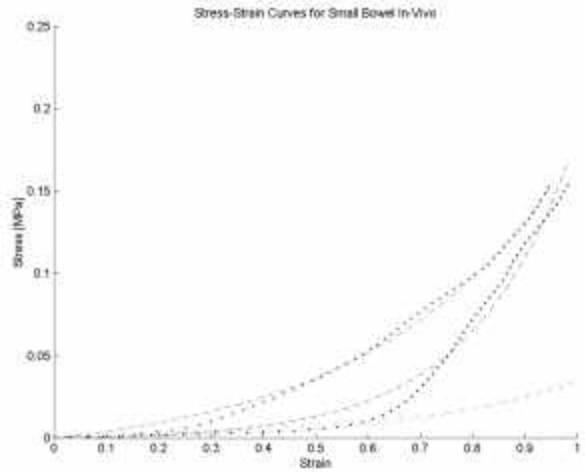

Figure 8. Small bowel stress-strain response (*in-vivo*), 1st squeeze only, 3 animals (dashed lines are curve fits)

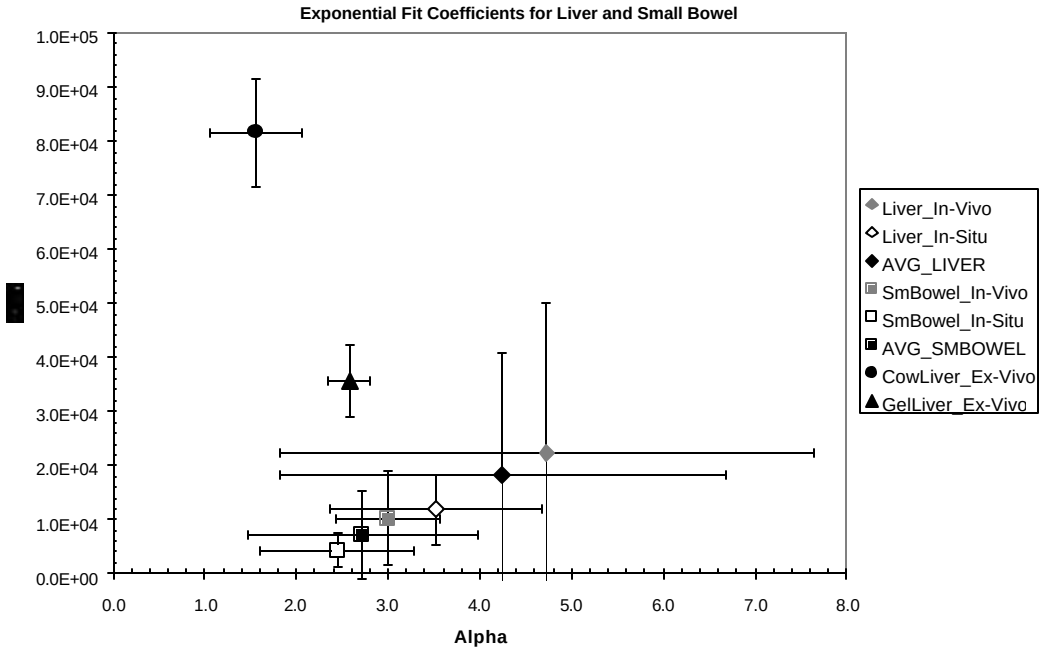

Figure 9. Exponential fit coefficients for liver and small bowel (*in-vivo* and *in-situ*), all animals, 10 cycles

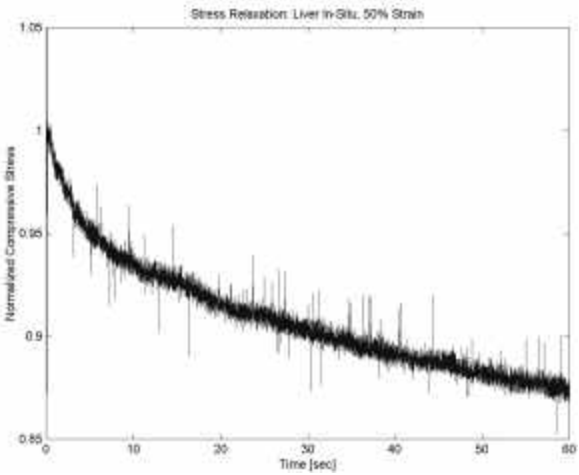

Figure 10. Relaxation of liver (*in-situ*), subjected to 60 sec step strain of about 50%

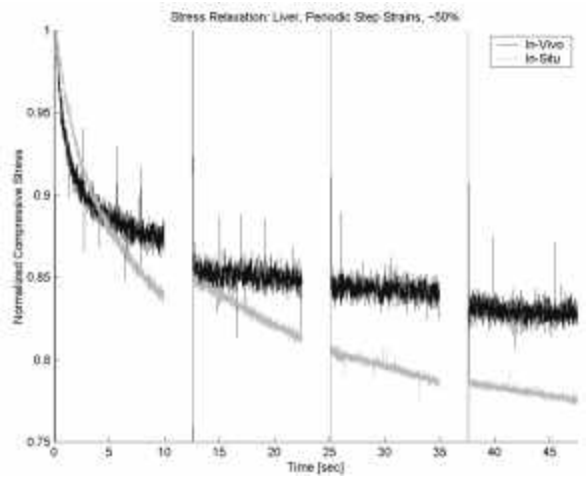

Figure 11. Relaxation of liver (*in-vivo* and *in-situ*), subjected to periodic step strain with 80% duty cycle, same animal

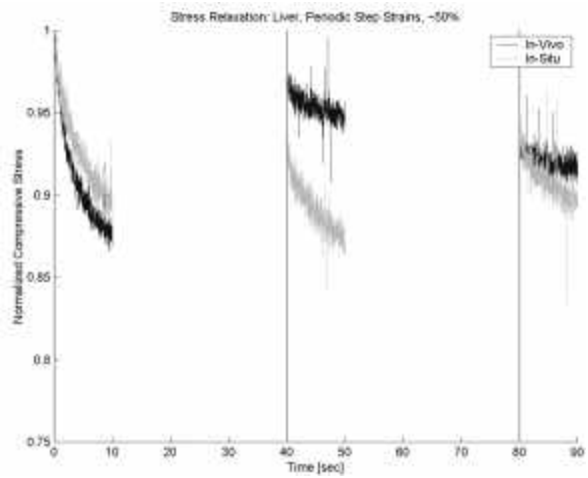

Figure 12. Relaxation of liver (*in-vivo* and *in-situ*), subjected to periodic step strain with 25% duty cycle, same animal

5. Conclusions

Simulators should be based on accurate representations of the forces and deformations observed during actual surgery. Surgically relevant levels of force and deformation can be applied with the MEG to abdominal tissues while measuring the resulting force-deformation characteristics. Because tissues are not preconditioned during surgery, first-squeeze behavior is important to know and model, as well as how the behavior changes with subsequent squeezes. Observing the viscous nature of the tissues – within the range of loading rates applied during surgery – is also of interest.

We recorded both *in-vivo* and *in-situ* data in animal experiments using the MEG. Results show nonlinear stress-strain behavior for liver and small bowel. Tests included cylic loadings of varying frequency to observe elastic response, as well as constant and periodic step strains to observe stress relaxation. Exponential curves were fit to the elastic data and the resulting coefficients were plotted. Equation 1 did not always result in high quality curve fits; the stress-strain data does not appear to exactly follow this constitutive relation. Nevertheless, the curves fit still shed light on interesting differences in behavior between subsequent squeezes and between *in-vivo* and *in-situ* conditions. In future studies, fitting different constitutive laws to the data will be examined, as well as fitting decaying exponential curves to the stress relaxation data to quantitatively examine the change in time constant(s) as a function of squeeze cycle and rest time between squeezes.

It appears from this preliminary study that tissue behavior did not change significantly within three 3 hrs postmortem, at least in regard to elastic response. Some difference was seen in the stress relaxation behavior. We plan future work to further examine how tissue properties change with time postmortem by testing them over a 24-hr period postmortem. The results of MEG tests

will also be compared to similar tests done on removed organs using a MTS universal testing machine to further validate the MEG as an accurate and effective mechanical testing device.

6. References

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