Experimental Determination of Elastic and Viscoelastic Material Properties of Fresh Thoracic Tissues in Unconfined Compression for Advanced Finite Element Modeling: An I-PREDICT Investigation

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I. INTRODUCTION

Behind armour blunt trauma (BABT) refers to blunt injuries resulting from back face deformation (BFD) of body armour secondary to projectile impact. Early research demonstrated thoracic and abdominal injuries in live animals resulting from armour BFD following projectile impacts exceeding 240 m/s [1]. However, with improvements in computing power, advanced finite element modeling (FEM) has become the standard method for blunt injury prediction and safety assessments. It can be used to predict injury in different BABT environments and the comparative ability of different countermeasures to protect the individual [2-3]. The quality of the FEM and these predictions is based in large part on accurate and detailed rate-dependent and viscoelastic material models, and validation data. As part of the larger I-PREDICT program, the present study was designed to quantify viscoelastic material properties of thoracic tissues to be incorporated into a statistically based FEM.

II. METHODS

This protocol was approved by all relevant research committees from our Institution. Fresh porcine thoracic tissues were obtained within minutes of death from a local abattoir and transported in a portable incubator (37 deg C). Specimens were treated with warm physiologic saline solution during the entire transportation and preparation. All tests for this protocol were conducted within 5.25 hours of animal death. The following tissues were obtained: cartilage tissues from the distal extent of the ribs; lung tissues from caudal aspect of the right lung; cardiac tissues from the superficial myocardium of the left ventricle; and adipose tissues from the dorsal aspect of the thorax. Test specimens were prepared by hand to dimensions of approximately 25 mm by 25 mm width and 6 mm thickness. Specimen orientations were such that compressive tests would be conducted from the superficial toward the deep region (i.e. compression would occur to the outside surface of the tissues).

A custom indenter with 5 mm diameter spherical tip was machined and attached to a hydraulic piston (MTS Systems Corp, Eden Prairie, MN, USA). Compressive stress relaxation testing consisted of three experimental phases. The testing protocol consisted of placing the indenter in contact with the surface of the specimen and manually controlling piston location to achieve a 0.05-N compressive preload. Dynamic compression was then applied to the specimen using the indenter to achieve a peak compression of 35% strain. The stress relaxation phase then consisted of maintaining that level of compression by holding the indenter in a fixed position for 60 s. Piston displacement was recorded at 10,000 Hz using a linear variable differential transducer (LVDT) and compressive forces were measured using a 111-N interface load cell mounted directly below the specimen.

Stress and strain were computed using the indenter cross-sectional dimensions and initial specimen thickness. The following biomechanical metrics were quantified for the dynamic compression phase of the test for each specimen. Peak strain rate was computed as the steepest slope of the strain versus time plot. Peak stress and strain were computed at peak indenter displacement. Elastic modulus was computed as the slope of the stress versus strain plot. Stress data from the stress relaxation phase were normalised to the peak stress and time was shifted for each test such that time zero occurred at the time of peak stress. To facilitate statistical comparisons, normalised stress was computed at each of the following times during stress relaxation: 0.001 s, 0.01 s, 0.1 s, 0.25 s, 0.5 s, 1.0 s, 2.0 s, 5.0 s, 10.0 s, 30.0 s, 60.0 s. Single factor Analysis of Variance (ANOVA) determined significant differences ($p<0.05$) between tissues in elastic modulus. Repeated measures ANOVA was used to determine differences in normalised stress between tissues during each of the 11 time periods (0.001–60 s). Bonferroni post-hoc analysis was used to identify significantly different pairwise comparisons.

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III. INITIAL FINDINGS

A total of 36 specimens (5 adipose, 12 cardiac, 7 cartilage, 12 lung) were tested under the 35% compressive stress relaxation protocol. Elastic modulus calculated during the initial rise to peak strain was significantly different between tissues ($p<0.0001$). Those differences were largely driven by statistically significantly greater elastic modulus (E) of cartilage tissue (27±7.9 MPa; mean±std error), compared to cardiac (470±60 kPa), adipose (1.9±0.12 MPa) and lung (100±10 kPa) tissues. There were no other significant pairwise comparisons for E.

Time	Adipose	Cardiac	Cartilage	Lung
0.001 s	0.999±0.002	0.997±0.002	1.0±0.001	0.988±0.007
0.01 s	0.980±0.011	0.972±0.013	0.991±0.005	0.920±0.041
0.1 s	0.831±0.023	0.798±0.041	0.881±0.073	0.668±0.098
0.25 s	0.734±0.025	0.689±0.049	0.830±0.096	0.578±0.092
0.5 s	0.683±0.024	0.617±0.056	0.796±0.106	0.516±0.085
1.0 s	0.631±0.024	0.543±0.061	0.755±0.109	0.462±0.080
2.0 s	0.576±0.025	0.467±0.064	0.709±0.108	0.417±0.074
5.0 s	0.489±0.027	0.365±0.063	0.637±0.097	0.367±0.066
10 s	0.415±0.029	0.290±0.058	0.570±0.083	0.318±0.074
30 s	0.302±0.033	0.190±0.048	0.449±0.052	0.266±0.061
60 s	0.242±0.033	0.143±0.041	0.371±0.043	0.231±0.067

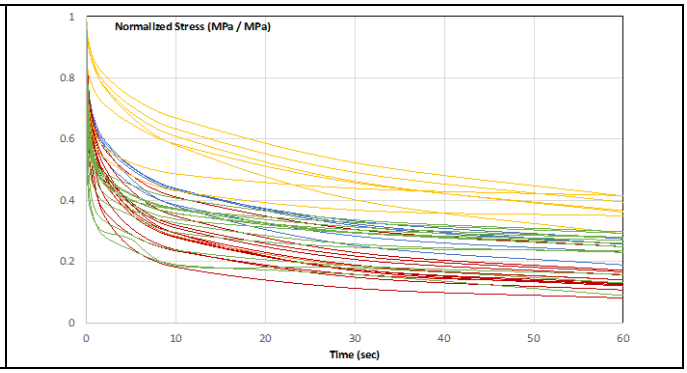

Fig. 1. *Left*: normalized stress values (mean±stdev) for tissues at different time steps during the stress relaxation test. *Right*: normalized stress vs time demonstrating stress relaxation of different thoracic tissues. Different tissues are represented by different colours: cartilage (yellow), adipose (blue), lung (green) and cardiac (red).

Repeated measures ANOVA demonstrated significant differences ($p<0.05$) by timestep and tissue type. Relative magnitudes of normalised stress relaxation varied with time. Post-hoc analysis revealed that lung tissue demonstrated significantly higher magnitudes of stress relaxation during time steps less than 1.0 s, followed by a relatively consistent and more shallow change in normalised stress relaxation beyond that time. Although cardiac tissue had a less dramatic change in stress relaxation initially, average magnitudes of stress relaxation for cardiac tissue were greater than all other tissues beyond 10 s ($p<0.05$ beyond 30 s). Cartilage demonstrated the least stress relaxation, with significantly less stress relaxation ($p<0.05$) than all other tissues beyond 10 s.

IV. DISCUSSION

This study has provided a unique set of elastic and viscoelastic material properties for fresh porcine thoracic tissues tested within 5.25 hours of death. Results demonstrated significant differences in elastic and viscoelastic properties by tissue type and highlighted time-dependent stress relaxation responses. Absolute differences and time-dependent nature of the relative (i.e. between-tissue) stress relaxation responses necessitate the quantification of these properties for all tissues that are to be used in advanced FE models. Prior studies demonstrating significant changes in mechanical response of biological tissues with frozen storage [4] necessitate the use of fresh tissue, with minimisation of the transportation and storage time after death. Within-tissue variations in properties might stem from the somewhat limited sample sizes. As compression and velocity (Cmax, Vmax, and VCmax) are traditionally correlated to soft tissue and organ injuries under high-speed loading from animal studies, and for military applications, as data are needed for tissues such as those used in this study, the current results can be used as a first step in exercising FEMs. The authors of this study are using these properties for the I-PREDICT program to exercise probability-based FEMs of varying complexity

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VI. REFERENCES

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