Evaluation of Blunt Cardiac Trauma Volumetric Injury Risk Using Finite Element Models.

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I. INTRODUCTION

Blunt cardiac trauma (BCT) can be difficult to diagnose in emergency settings, as there is no gold standard for diagnosis [1–3]. These injuries can occur from blunt impacts to the chest, including projectiles impacting personal protective equipment at high velocities, such as in cases of non-penetrating blunt impacts (NPBI). BCT includes injuries such as arrhythmias, asystole, contusion, and rupture. Damage to the myocardial tissue can lead to poor cardiac output, where more damage leads to lower cardiac output and higher likelihood of mortality. Previous work has utilised peak organ-level metric values for injury risk, such as maximum principal strain rate, but neglect volumetric effects on injury risk [4]. Therefore, the objective of this study is to develop volumetric curves and thresholds for improved BCT injury risk prediction through the use of finite element models, specifically the finite element ovine thorax model (FE-OTM) [5].

II. METHODS

Ovine Experiments and Injury Classification

A total of 41 ovine subjects were impacted at either 40 or 70 m/s to a depth ranging from 18-60 mm following IACUC protocols [5–6]. Each subject was diagnosed with one or more of three blunt cardiac injuries without large amounts of hemorrhaging: asystole, prolonged arrhythmia, and/or cardiovascular instability. Cardiac arrest can occur due to hemorrhaging elsewhere in the body, which is not the objective of this study, and so hemorrhaging was excluded. Our purpose was to investigate the injuries directly from the impact.

Subject-Specific Finite Element Models

Forty-one total subject-matched simulations were run to extract cardiac organ level metrics using the validated FE-OTM v3, which includes updated heart anatomy representation (Fig. 1) [5]. Each simulation was scaled to match experimental subject's outer dimensions of rib circumference, length, and mass. Metrics included maximum and minimum principal strain, maximum principal strain rate, maximum shear stress, and absement maximum and minimum principal strain for a total of six metrics. The pre-impact volume was determined for each element, along with each metric peak value, for building a normalised cumulative volume graph (Fig. 2). Regions of interest included both atria, both ventricles, and the whole heart for a total of five regions. A volume-response curve was calculated for each subject and region and compiled into one graph for each metric. The area under the curve (AUC) was calculated for each subject, along with the thresholds for 5, 15, 25, 50, and 65% normalised volumes for statistical analyses. Sixty-five percent (65%) volume is the maximum selected, as it is used in cardiac arrest studies due to a 100% mortality rate within 24 hours [7]. The lower volumetric thresholds were selected to obtain a range up to the fatal volume percentage of 65%.

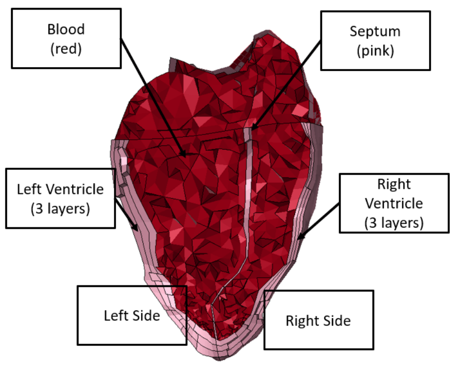

Fig. 1: Detailed heart within the FE-OTM v3.

Statistical Methods

Two sets of statistical analysis were run. The first set focused on determining the best predictive metric for each region and injury type, and the second set compared injury outcomes between the two groups for each region and injury type. For the first set of analyses, logistic regression models were run to determine the best predictor of injury, where the lowest Akaike Information Criterion (AIC) value was considered the best fitting metric. A total

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of 90 models were run for each injury type (n = 3), region (n = 5), and metric of interest (n = 6). The second set of statistical analyses included comparisons between AUC and threshold values between injured and non-injured subjects. AUC comparisons used a Kolmogorov-Smirnov test, whereas threshold value comparisons utilised Mann-Whitney tests (α = 0.05).

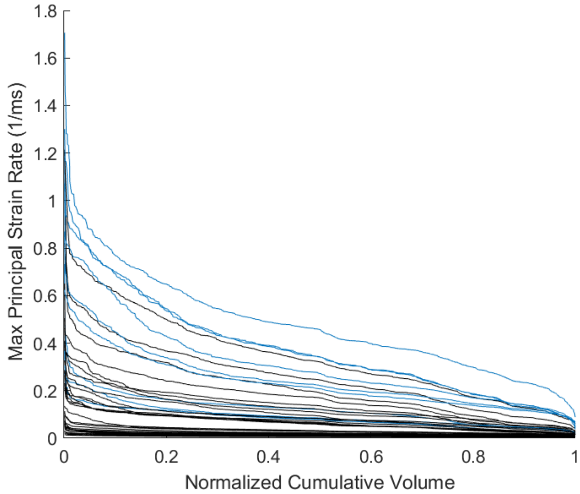

Fig. 2: Exemplar volumetric curve graph, depicting the peak maximum principal strain rate over the volume of the right atria. Injured subjects are plotted in blue; uninjured subjects are plotted in black.

III. INITIAL FINDINGS

Of the 41 animals, 9 had asystole, 15 had prolonged arrhythmia, and 16 had cardiovascular instability. Fourteen of those subjects had two or more injuries of interest, and 17 subjects had no blunt cardiac trauma. All the simulations terminated normally, and cardiac organ mechanics data was successfully extracted from each model. For asystole, maximum principal strain rate was considered the best fitting metric for the right atrium, whereas for the left atrium and the whole heart, the minimum principal strain was the best. A specific example of a threshold for asystole injury would be for the right atrium, where if 65% of the volume experiences at least 157 strains/second, the subject is likely injured (Table 1). As for both ventricles, maximum shear stress was considered the best predicting metric. As for prolonged arrhythmia, maximum principal strain rate was best for both ventricles and the whole heart. No metrics were significant for the atria for prolonged arrhythmia nor for any region for cardiovascular instability.

TABLE 1: RESULTING THRESHOLD VALUES BY REGION AND INJURY TYPE FOR SIGNIFICANT BEST-FITTING PREDICTORS. REGIONS: RA = RIGHT ATRIUM, LA = LEFT ATRIUM, RV = RIGHT VENTRICLE, LV = LEFT VENTRICLE, AND WH = WHOLE HEART. METRICS: T = MAXIMUM SHEAR STRESS, E_1/S = MAXIMUM PRINCIPAL STRAIN RATE, AND E_3 = MINIMUM PRINCIPAL STRAIN.

Injury	Region	Best Fit Metric	65% Threshold
Asystole	RA	ε_1/s (1/s)	157
	LA	ε_3	-0.128
	RV	τ (kPa)	11.21
	LV	τ (kPa)	11.31
	WH	ε_3	-0.208
Prolonged Arrhythmia	RV	ε_1/s (1/s)	79
	LV	ε_1/s (1/s)	84
	WH	ε_1/s (1/s)	55

IV. DISCUSSION

A variety of potential mechanisms are evident in the resulting metrics from this study for each injury type. For asystole, both crush and rate-dependent mechanisms are evident, and may be due to coup-contrecoup mechanisms based on the region of interest. As for prolonged arrhythmia impacts, both ventricles and the whole heart showed rate dependency, likely due to disruptions in the electrophysiology of the heart that is responsible for coordinating heartbeat. While electrophysiology is not part of the model, it is something to consider in future studies. This study does have limitations, including limited information regarding impact timing with respect to the cardiac cycle and that simulations did not include subject-specific anatomy – only subject specific dimensions. As for the simulated anatomy, all subjects, including the subject used to develop the model, were from the same breeder, resulting in low inter-subject variability. This study successfully calculated volumetric curves for specific metrics to predict two types of blunt cardiac injury, including specific metrics by location. This data may be used to inform future products and safety of personal protective equipment.

V. REFERENCES

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