Fragment penetration into the heart: initial findings

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I. INTRODUCTION

Explosive devices have been a significant cause of injury in terrorist attacks and in conflict. The main mechanism of the resulting injury is due to fragments energised by the blast wave; these fragments have been found across different regions of the human body [1]. Injuries with high severity to the torso have been recorded in suicide bombings against civilians [2-3], whereas this body region is largely protected in military personnel.

Predicting the probability of severe penetrating injuries is essential for improving emergency response, medical services, and the design of large infrastructure in order to minimise the number of casualties and improve their treatment alike. One way of predicting the penetrating injuries is to use human tissue surrogates. Currently, tissue surrogates such as ballistic gelatine at 10% and 20% concentration are widely used to replicate penetrating injuries to soft tissues. These have been shown to replicate penetrating injuries in porcine muscle [4]. There are no tissue surrogates, however, which have been shown to allow for quantifying the probability of penetrating injuries to the vital organs of the torso. This study aims to quantify the risk of severe injury to cardiac tissue and determine a biofidelic tissue surrogate for it.

II. METHODS

Materials

A cadaveric animal model was developed in order to study penetrating injury to the heart. Lamb hearts under 12 months old were chosen because their dimensions and material properties are closer to those of the human heart compared to other available animals [5-6]. Cadaveric lamb hearts were obtained from a local abattoir; five lamb hearts were frozen within 24 hours of slaughter and thawed at room temperature on the day of testing. Handling and disposal of animal cadaveric tissue followed well established institutional regulations.

Each sample was held in a thin plastic bag which was clamped onto the mounting apparatus as shown in Fig. 1. Preliminary experiments with the plastic bag holding water of the same mass as the sample showed negligible reduction in the velocity of energised fragments, suggesting a negligible effect of the plastic bag on the interaction between the fragments and the sample.

Ballistic gelatine (grade A, 300 bloom) was produced at 5%, 10% and 20% concentration using previously published techniques [4]. The dimensions of each gelatine block were approximately 250 × 145 × 50 mm. They were kept at 10 °C before and after each test.

Experiment

A 32-mm bore gas-gun system was used to propel a 5-mm sphere towards the test sample [7]. The 5-mm sphere was prolific in the Boston marathon bombing [8] and is recommended in the NATO standardisation agreement on ballistic protection [9]. As the left and right ventricular walls of the heart have slightly different thicknesses, each specimen underwent one impact on the left and one on the right ventricular wall with impact velocities ranging from 20 m/s to 60 m/s. Approximately 10 shots against each gelatine block were fired at impact velocities ranging from 20 m/s to 150 m/s. The impact velocity of the projectile was calculated from the recording of a high-speed camera (Phantom VEO 710, Vision Research, USA) mounted at the target end of the gas gun.

After each shot, each heart specimen was scanned on the top, side and front face using radiographic imaging (Fluoroscan InSight^{TM}-FD, Hologic Inc., USA). The depth of penetration (DOP) was calculated using the distances between the impact face and the furthest end of the retained projectile obtained from the three scanning images. The DOP in the gelatine blocks was measured with a ruler after the block was cut along the cavity caused by the projectile.

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The impact velocities of the projectile at 50% probability (V_{50}) of penetration into the lamb heart, 5%, and 10% gelatine were also estimated. An impact resulting in penetration was defined when the projectile was retained inside the sample, regardless of the DOP, or perforated through it. V_{50} values were calculated from the arithmetic mean of the three lowest velocities of penetration and the three highest velocities of non-penetration.

III. INITIAL FINDINGS

Fig. 2 shows the DOP against the striking velocity for the lamb heart and the gelatine of different concentrations. The experimental data of the gelatine were fitted with linear regression and 95% confidence intervals are shown. The calculated V_{50} values (presented as mean ± SD) were 21 ± 2 m/s for the 5% gelatine, 45 ± 11 m/s for the 10% gelatine, 33 ± 13 m/s for the left ventricle, and 35 ± 13 m/s for the right ventricle.

Fig. 1. Mounting apparatus of polycarbonate for the lamb heart.

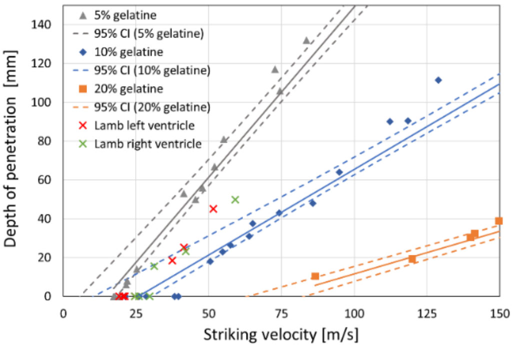

Fig. 2. Striking velocity against depth of penetration estimated using linear regression. 95% confidence intervals (CI) are shown with dotted lines.

IV. DISCUSSION

Initial tests were carried out using fresh-frozen lamb hearts, 5%, 10% and 20% gelatine blocks to measure the DOP and make a preliminary assessment as to which concentration of gelatine replicates the penetrating behaviour of a 5-mm sphere into the heart. In order to evaluate the penetration threshold in a low-velocity region, the V_{50} values for penetration into the 5% and 10% gelatine, and the left and right ventricle of the lamb heart were also obtained. The initial results show that, out of the three concentrations of gelatine assessed here, the 10% gelatine has the best correlation with cardiac penetrating injuries. The results also suggest that resistance to penetration into left and right ventricular walls were similar; this is despite their significant difference in thickness, which suggests that thickness in itself is not contributing to the penetration resistance of cardiac tissue. The V_{50} values of penetration into the heart were almost 3 times lower those of the least resistant thoracic tissues [10], so even a low-velocity fragment is capable of causing severe cardiac injuries after perforating the thoracic tissues.

Fresh-frozen lamb hearts were chosen in these initial tests. A freeze-thaw cycle almost halves the failure strain of bovine liver [11]; therefore, it is likely that lamb heart tissue is also affected by this cycle. Albeit fresh-frozen tissue allowed for the experimental protocol to be established, the next set of experiments will be conducted using fresh tissue; the results will be used to develop injury probability curves and identify the most suitable concentration of gelatine for evaluating cardiac penetrating injuries in a laboratory setting.

V. REFERENCES

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