Behind Armor Blunt Trauma Injuries Assessment with Clay Backing: A Meta-Analysis of Injury Risk Functions and a Proposed Cavity Volume-Depth Model

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I. INTRODUCTION

When defeating a projectile, body armor deforms and transfers energy to the body, which may lead to behind armor blunt trauma (BABT). Multiple studies on BABT have been conducted over the last 45 years to understand BABT injury mechanisms better and develop proper assessment methods and relevant tolerance limits. Due to its relatively low cost and ease of implementation, clay-based BABT assessment will likely remain the method of choice for certifying body armor in the near future, despite uncertainty around the correlation between clay-based BFD measurements and BABT injury risks. Even though clay was never intended to be a biofidelic tissue simulant but rather a simple witness material, its response to armor back face deformation (BFD) matches male and female thorax deformation corridors more closely than ballistic gelatin [1-2]. Unlike human tissues, clay is non-elastic and does not recover after deformation, thus allowing the direct measurement of armor BFS. NIJ-101.06 [3a], the most widely used body armor standard, specifies a maximum BFD depth of 44 mm (80% upper tolerance limit and 95% confidence) as a pass/fail criteria. The UK Home Office [4] adopted a more conservative BFD limit of 30 mm for hard armor. To address soldier overload, lighter ballistic plates exploiting the latest material technologies and reducing torso coverage ratio are being procured and deployed for low-intensity threat environments [5]. For those plates, a BFD requirement of 58 mm was also adopted based on epidemiological data indicating a relatively high BABT safety margin against the threats encountered in recent military conflicts. ASTM has reviewed the clay BFD methodology [6] to improve reproducibility and repeatability in supporting the NIJ-101.07 standard [3b]. The ongoing development of a temperature-insensitive clay material [7] should also make clay BFD testing more efficient and reliable. With the measurement of clay indent with laser scanners, improved injury criteria accounting for clay cavity volume (**Vol**), external surface area, and base cavity area can now be explored. Reconstructions of BABT survivor field cases [8-9] have shown that cavity volume, although related to transmitted kinetic energy, is not a better injury predictor than cavity depth alone. The clay cavity normalized surface area/volume metric proposed by Rafaels [9b] provided a better correlation. A meta-analysis of clay-based IRFs formulated over the years was conducted and is presented in this paper. An alternate BABT metric, based on clay cavity volume and depth referred to as the VD2 model, is proposed.

II. INITIAL FINDINGS AND DISCUSSION

Figure 1 illustrates impactors [10-12] designed or used to replicate BFD interactions and simplify testing with animals and post mortem human subjects. BABT injuries have been found to be similar to those caused by the direct impact of non-lethal kinetic energy projectiles. For example, based on the IRF proposed by Arborelius [12], an impact velocity of 82 m/s or 195 J would cause a 50% risk of rib fracture. In addition, based on the IRF proposed by Shedd [13], scaled for the Arborelius impactor, there is a 65% probability of a skin and open wound injury at the same energy level, which is coherent with BABT pathologies reported in previous studies.

Many BABT IRFs have been developed [8a, 9a, 12, 14] based on clay BFD measurement and chest wall displacement, as shown in Figure 2. Some IRFs were generated for soft armor [10] while others for hard armor [14]. Different injury scales and injury levels were also used, partly explaining the variability observed. The proposed VD2 model (Figures 2-3) is based on the same premises as Rafaels' model [9b], with increased volume and deformation causing more severe BABT injuries. However, it uses instead **Vol** times $\mathbf{BFD^n}$ as the injury predictor following a similar form to the Gadd severity index for head injury. Logistic regressions of BABT reconstructions were conducted with a Logit link function where the weighting factor "**n**" was varied from 1 to 3. An "**n**" value of 2 provided a degree of correlation similar to Rafaels' model [9b] while being easier to implement.

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The cavity volume and depth data were taken from the papers by Bir [8a] and Rafaels [9a, b]. The **BFD²** term aligns with the Livermore cone depression factor [15]. Back face velocity (BFV) being inversely proportional to the base area of cone-shaped clay cavities [9b], the viscous injury criterion (VC) can then be expressed as a function of **BFD²** like the VD2 model. The VD2 model is, however, not valid for clay cavities with extremely low **Vol·BFD²** since it gives a non-zero injury risk. Logistic regression with non-symmetric link functions (e.g., Weibull, log-logistics) will be explored to address this issue and potentially increase the correlation obtained.

The BABT injury map obtained by plotting the VD2 model against volume and BFD is shown in Figure 4, along with the BABT survivor data and relevant points from previous studies [16-18]. Such mapping also discriminates between cavity shape-related BABT such as ballistic punch and pencilling injuries. The shaded area illustrates a potential body armor BFS acceptance criteria using 58 mm as the upper BFD limit for cavity volume lower than 85 cm^3, then decreasing to a BFD of 38 mm following the VD2 model matching the AIS-3 IRF derived from Cooper's data. The development of improved and validated BABT methods should be further pursued to support the optimization of body armor relying on better defined BABT protection requirements.

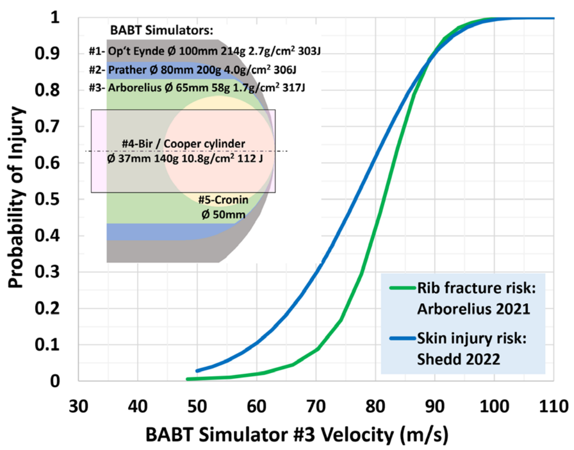

Fig. 1. Injury risk functions vs velocity

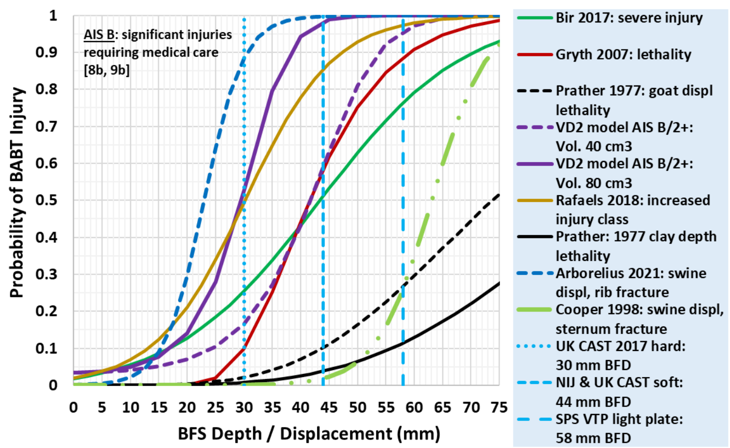

Fig. 2. IRFs vs BFS depth and displacement

$$P = 1/\left[1 + e^{(3.3463-0.0048 \cdot Vol \cdot BFD^2)}\right]$$

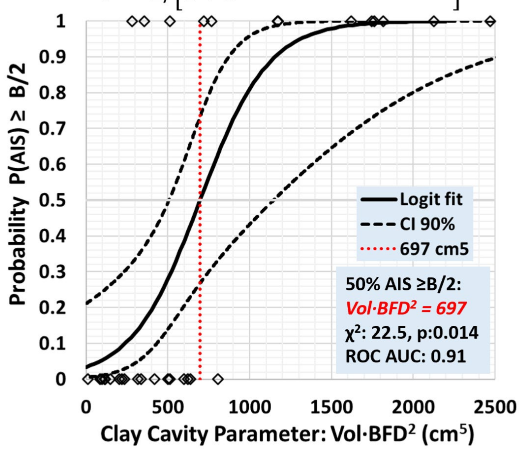

Fig. 3. Logistic regression of Vol·BFD² data

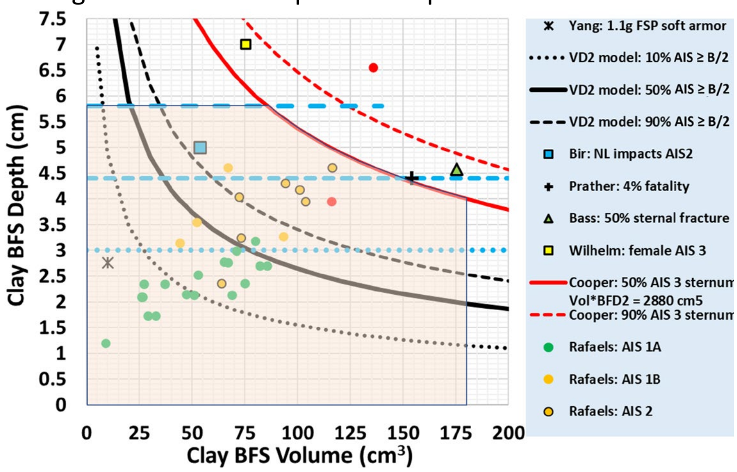

Fig. 4. VD2 model IRF vs BFS depth and volume

III. References

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