Injury risk functions for behind armour blunt trauma based on clay backing cavity volume and depth

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Abstract. A review of body armour behind armour blunt trauma (BABT) requirements and test protocols in national and international standards and specifications is presented. Back Face Deformation (BFD) measurement in a clay witness block remains used as a pass-fail tolerance criterion despite its limited medical basis, mainly due to the absence of a better validated and readily implementable testing method for body armour compliance certification. A review and meta-analysis of the extensive historical BABT data were conducted to determine if more relevant information and trends could be extracted. The emphasis was made on comparing the previously developed thoracic BABT Injury Risk Functions (IRF) based on tests with real bullets and armour, and with surrogate projectile replicating the interaction with the armour system, on live animal subjects (LAS) and post-mortem human subjects (PMHS). The test cases of Cooper and Bowen were found to be not fully exploited yet. The different injury scales and metrics used in previous studies have generated apparently diverging IRFs, potentially contributing to adopting widely different BFD tolerance levels in various body armour standards. Published data from reconstructions of BABT survivor field cases on soft armours were used to generate a new IRF called the VD^2 model, where the cavity volume (V) and the square of depth (D^2) in clay backings are combined as a blunt trauma dose parameter for predicting the risk of AIS-2/B injury. The same approach, using VD^2 as the injury predictor, was then applied to the data from reconstruction on clay blocks of the Cooper test cases on non-protected or bare porcine subjects and the Bowen test cases on bare canine subjects with their respective rigid impactors. The correlations obtained between kinetic energy, clay volume, and penetration depth were then used for generating the matched-pair VD^2 data related to the blunt trauma injury severity reported by Cooper and Bowen. The corresponding IRFs obtained for AIS-3 injury (Cooper) and AIS-6 (Bowen) are shown to follow a graded injury trend with the IRFs computed from Rafaels-Bir. The iso-injury-severity curves computed by plotting the data on a deformation-volume map are shown to be parallel with some logical upward offsets. For medium-size cavities (i.e., 125 cm^3), the 44 mm BFD limit can be associated with a 20% AIS-3 injury risk. Adopting a higher BFD limit (e.g., 50 mm) may be considered for clay cavities with smaller volumes but with caution. A lower BFD limit (e.g., 30 mm) would be needed for larger volume cavities to provide a more consistent level of BABT mitigation over the full range of cavity sizes. Until a more physically-based and medically-validated BABT assessment methodology is implemented, clay-based body armour specifications should consider adding the measurement of clay cavity volume, as currently prescribed by the VPAM standard but using laser scanning instead of the water filling method, as a complementary indicator of transmitted energy. However, additional validation of the VD^2 model with more recent and reliable data is needed before considering its potential adoption in body armour performance standards.

1. CURRENT STATUS OF CLAY-BASED BABT TEST METHODS

The role of body armour is to provide ballistic protection against bullet penetrating injuries and to mitigate the Behind Armour Blunt Trauma (BABT) to safe defined levels. BABTs are non-penetrating injuries resulting from the transmitted kinetic energy (KE) and Back Face Deformation (BFD) of the armour when impacted by a bullet. Ballistic resistance testing of a body armour system requires a backing material for replicating the as-worn condition while simulating the human body deformation resistance and acting as a recording medium for quantifying BABT with a measurable parameter. 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, which is a difficult task given all the critical parameters involved (Figure 1a). Due to its relatively low cost, long storage life, re-usability, and ease of implementation and shaping, clay-based BABT assessment has remained the only method specified for certifying body armour despite its limited medical basis and, more specifically, the uncertainty around the correlation between clay-based BFD measurements and BABT injury risks for both soft and hard armours.

Oil-based modelling clay also suffers from other important limitations related to its calibration procedure, temperature sensitivity, and the high variability and low reproducibility of the BFD measurements. Unlike human tissues, clay is naturally non-elastic with some elastic recovery with the residual deformation being slightly smaller than the transient one. The magnitude of the elastic recovery of clay is likely variable and related to the impact conditions. The maximum size of the permanent

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residual cavity can then be captured, allowing the direct measurement of the maximum indentation/cavity depth. The maximum permanent BFD is the pass/fail criterion specified in current test standards.
To have the right consistency and pass calibration, clay must also be heated around 35 °C limiting the usage time (e.g., 45 min) at room temperature. Before ballistic testing, the consistency of clay is calibrated with a drop test which cannot be done at the same location on the clay box as the area where the armour sample will be positioned, which is another drawback of the method. The recent development of a temperature-insensitive clay ballistic grade [1], referred to as ARTIC, should make BFD measurements more repeatable and reliable without needing pre-heating and re-conditioning the clay block so that its calibration remains stable. The clay BFD methodology has been reviewed recently by the ASTM Subcommittee E54.04 [2-4] to improve its reproducibility and repeatability in supporting the NIJ-101.07 standard. For the more accurate measurement of maximum cavity depth for curved hard ballistic plates, the depth gauge and bridge caliper method, suitable for planar armour systems, has been replaced by laser surface profilometry in US DoD military standards [5] with a pre-scan of the curved clay reference plane and a post-scan of the clay cavity. Comparisons of the 3D solid models generated from the pre-scan of the original undisturbed clay surface and the post-impact surface are then made semi-automatically nowadays [6-8] with suitable point-cloud analysis software (e.g., *Geomagic*) to obtain the maximum cavity depth relative to the line of fire. Additional cavity shape parameters such as volume, cavity base and external surface areas (Figure 1b) can also be easily obtained. The complete 3D cavity profiles can be archived and used later in match-pair studies correlating blunt trauma severity. Clay being non-transparent, only post-impact static measurements can be made, which is another important limitation. For characterising the dynamic deflection-time response, an instrumented clay box with ultrasonic and pressure sensors [9] was developed to record the deformation, velocity and acceleration time history, which may be better related to the injury mechanisms but not captured with static BFD measurements where only magnitude and spatial distribution are recorded. Alternative test methods continue to be explored to replace clay-based testing, but despite promising progress, none is sufficiently mature and validated yet for implementation in a national standard.

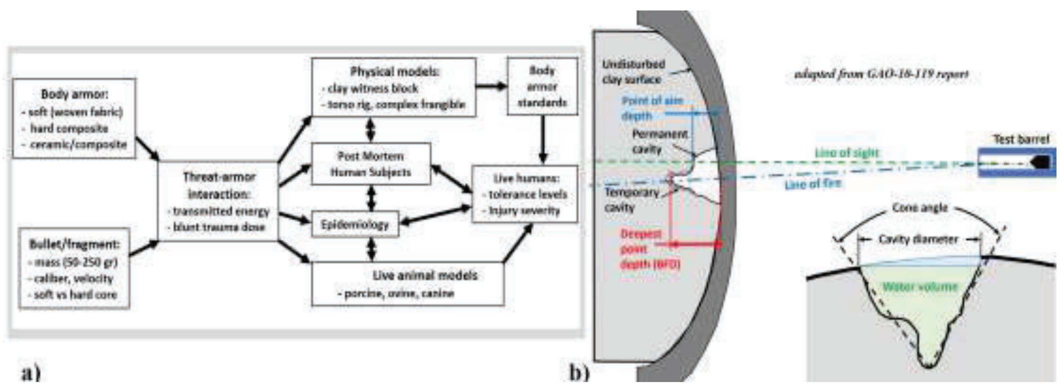

Figure 33: a) BABT key factors involved, b) cavity depth and volume measurement for curved surfaces

Table 1 compares the clay-based BFD test methods and requirements for commonly used law enforcement and military standards. NIJ-101.06 [10], the most widely used body armour standard, specifies a maximum BFD depth of 44 mm (80% upper tolerance limit and 95% confidence) as a pass/fail criterion. In the German VPAM BSW-APR standard [11], the BFD limit is adjusted as a function of the measured clay consistency, with a value of 44 mm for softer clay and 40 mm for harder clay. VPAM is the first standard to introduce the maximum cavity volume as an additional requirement. The UK Home Office [12] adopted a more conservative BFD limit of 30 mm for hard armour. 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 [13]. For those plates, a BFD requirement of 58 mm was also adopted based on epidemiological data indicating no occurrence of severe thoracic BABT injury in recent military conflicts.

Furthermore, no soldier battlefield fatalities are known from the perforation of hard ballistic plates by projectiles they were designed for [14]. The 58 mm BFD limit is estimated not to affect soldiers' survivability significantly. In the Russian GOST standard [15], no BFD limit is specified for rifle projectiles, while for handguns, BFD is limited to 17 mm. Such a lower limit may indicate the desire to minimise blunt trauma and probably more incapacitation, ensuring that the wearer would remain functional during shooting incidents. The significant differences in the BFD tolerances levels between the national standards raise the question of which one should be used and if they really are incompatible and diverging that much.

Adopting a too-low and very conservative BFD limit is not necessarily better since it would impose a weight penalty hindering soldiers' mobility. A higher BFD limit may put soldiers at risk of severe BABT injuries. Establishing an optimal trade-off between armour weight, soldier mobility, and protection remains a non-trivial challenge. Scalable body armour systems are being developed, which allow the protection level to be adjusted to the perceived ballistic threat and take into account the acceptable level of injury severity from potential BABT overmatch ballistic threats. Improvement in ballistic materials often leads to lighter and more flexible armour systems having the same threat-stopping capability, but where the weight reduction may not be fully exploitable because BFD could become the design driver.

Table 15. Summary of back face deformation requirements in body armour standards

Body Armour Standard	Backing Type	Backing Material Consistency	Pass-Fail Criteria Measurement method
NIJ 101.06 USA, 2008	Roma Plastilina #1	1 kg sphere 2 m drop 19 ±3 mm range 19 ±2 mm average	All BFD ≤ 44 mm or All BFD ≤ 50 mm if 95 % confidence that 80 % of all BFD≤ 44 mm (one-sided CI)
NIJ draft 101.07 USA, 2018 ASTM E3004 ASTM E3068 ASTM E3086	Roma Plastilina #1 from Sculpture House Inc	1 kg sphere 2 m drop 19 ±2 mm all drops 1 kg cylinder 2 m drop 6.15 - 6.27 m/s velocity 25 ±3 mm	Same as NIJ 101.06 BFD measurement with Ø6.35mm probe tip depth gage
CAST-2017 UK, 2017	Roma Plastilina #1	1 kg sphere 2 m drop 19 ±3 mm range 19 ±2 mm average	Soft armour: BFD ≤ 44 mm Hard armour: - single shot BFD ≤ 30 mm - max mean BFD≤ 25 mm
VPAM BSW-APR 2006 Germany, 2009	Weible Plastilina	1 kg sphere 2 m drop 20.0 ± 2.0 mm Plasticity (P): 18-22 mm	BFD ≤ P + 22 mm Volume ≤ (0.134 x P-1.13) x 70 J Measured with water filling
ESAPI Rev. J US DoD, 2018	Not specified	1 kg cylinder 44.5 mm diameter hemispherical tip 2 m drop 25 ±3 mm	BFD ≤ 44 mm, laser scanning 1st shot: 90% UTL - 90% Confidence 2nd shot: 80% UTL - 90% Confidence
SPS Light Torso Plate PEO Soldier, 2020	Roma Plastilina #1	Same as ESAPI	BFD ≤ 58 mm Measured with laser scanning

2. REVIEW OF BABT INJURY RISK FUNCTIONS AND SCALES

The correlation between BFD and BABT severity is still limited and is still based on the ballistic tests conducted 45 years ago by Prather [16] with soft armour on goats from which lethality curves were drawn (Figure 2, left). Therefore, the 44 mm BFD limit was selected as the proposed threshold for soft armour corresponding to a 6% lethality risk. To address the limited medical basis issue, a number of complementary Injury Risk Functions or IRF have been developed with tests on PMHS and LAS. The main BABT IRFs developed based on clay BFD measurement and chest wall displacement [17-24] are shown in Figure 2, with some generated for soft armour and others for hard armour.

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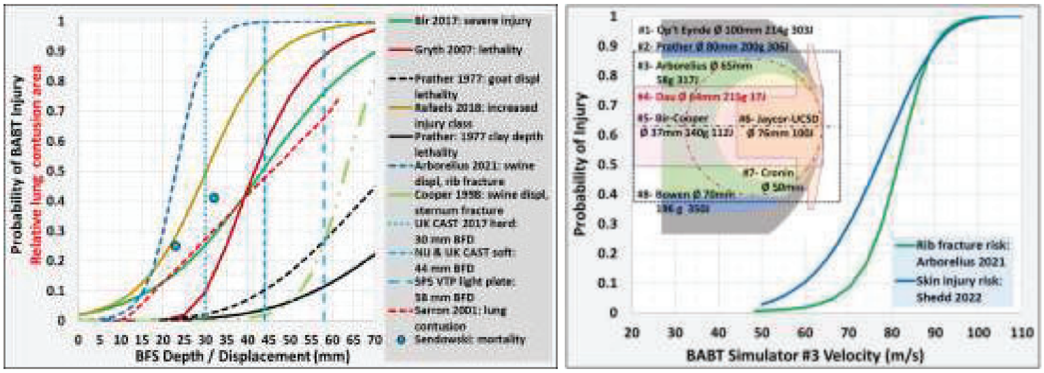

Figure 2: BABT injury risk functions/data: vs depth/displacement (left), vs velocity (right)

Several injury scales have been defined to provide a common basis for evaluating BABT injuries when conducting epidemiology studies and LAS/PMHS tests, which have led to the formulation of several IRFs which, at first, look diverging for the allowable safe BFD level. For the analysis of recreated field cases of law enforcement soft body armour, Bir and Rafaels have refined the AIS scale, which classifies the severity of individual injuries from grade 1 to 6 in terms of threat-to-life, by adding two classes, A and B (Table 2). This refinement was done to provide increased discrimination between minor and clinically insignificant injuries with no medical attention needed (class AIS-1A, green box) and those clinically significant since requiring wound care (class B: AIS-2/6, red boxes).

Table 2. AIS injury scale with Bir-Rafaels BABT complementary classes (A &B)

Abbreviated Injury Scale (AIS-2015) AIS code/severity & *typical injuries* *Probability of death [44]*		A: Clinically insignificant No wound care	B: Clinically significant Wound care needed
1	**Minor:** ***1-2 rib fractures, skin/muscle contusion hematoma, Probability of death: 0.2%***		
2	**Moderate:** ***3+ adjacent rib fractures, fractured sternum, 50% liver contusion*** ***Probability of death: 1%***		
3	**Serious: not life-threatening:** ***4+ rib fractures, heart contusion*** ***Probability of death: 2%***		
4	**Severe: threat to life but survivable:** ***displaced sternum, major contusions*** ***Probability of death: 9%***		
5	**Critical: survival uncertain:** ***Bilateral flail chest, ruptured liver*** ***Probability of death: 25%***		
6	**Fatal:** ***Probability of death: 100%***		

Since BABT injuries have been found to have similar characteristics to those caused by the direct impact (i.e., target without armour) of non-penetrating projectiles used for Less Lethal Weapons (LLW), such projectiles and BABT rigid simulators (Figure 2, right) [25-31], specially designed to reproduce the backface deformation profile or force history, have been used in BABT studies to avoid using actual armours and bullets and provide better control of the variables involved when testing with PMHS and LAS. The IRF proposed recently by Arborelius [21] is shown in Figure 2 (right), where for an impact velocity of 82 m/s or 195 J, the risk of rib fracture would be 50%. Based on the IRF proposed by Shedd [32], scaled for the Arborelius BABT impactor using the Blunt Criterion, the probability of a skin and open wound injury at the same energy level would be 65%, which is coherent with BABT pathologies reported in previous studies.

3. DEVELOPMENT OF THE VD^2 IRF FROM THE DATA OF RECREATED FIELD CASES

Reconstructions of BABT survivor field cases have shown that clay cavity volume, although related to transmitted kinetic energy, is not a better injury predictor than cavity depth alone. Rafaels [19] developed an IRF based on the normalised cavity surface area/volume ratio to account for the empirical evidence that post-impact cavities with increased volume and BFD depth resulted in greater BABT, as illustrated in Figure 3, where cavity shape and volume can vary greatly depending on the armour type (soft/flexible vs stiff/hard) and projectile characteristics (velocity and core hardness) for the same BFD depth [33]. Projectile impacts on soft/flexible armour vests tend to produce more conical cavities than those on stiffer hard armour plates.

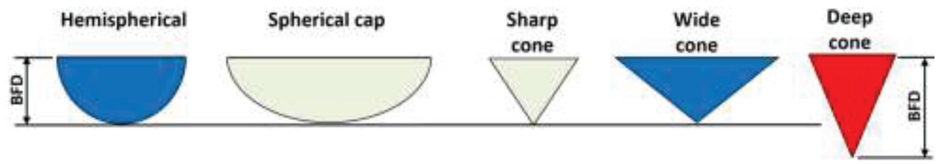

Figure 3: Comparison of backface cavity shapes

An analysis of the Bir-Rafaels data was conducted using a similar approach but only considering cavity depth and volume and not shape where the blunt trauma dose injury predictor selected is clay cavity Volume times Depth raised to exponent $\boldsymbol{n}$, i.e., $\boldsymbol{Vol\cdot BFD^2}$. This formulation is similar to the Gadd severity index [34] for head injuries, where the injury metric is based on acceleration and time with more weight on acceleration from the exponent 2.5, i.e., $\boldsymbol{a^{2.5}\cdot T}$. The proposed $\boldsymbol{Vol\cdot BFD^2}$ injury predictor does not, however, take time into account, which is one of its differences with the Livermore Conical Depression Factor (CDF) [35] where: $\boldsymbol{CDF = 3\cdot Vol\cdot BFD/T}$, where $\boldsymbol{T}$ is the time at which the cone/projectile velocity has slowed to 5% of its initial velocity and almost reached its maximum depth. Back face velocity $\boldsymbol{V}$ is known to be inversely proportional to the cone base surface area $\boldsymbol{Ab}$ of cone-shaped clay cavities [20], where $\boldsymbol{Ab}$ can be expressed as **3·Vol/BFD**, so $\boldsymbol{V \approx BFD/3\cdot Vol}$. The viscous injury criterion ($\boldsymbol{VC}$) can then be expressed as $\boldsymbol{VC \approx BFD2/Vol}$**,** which is a different formulation where less weight would be given to cavity volume, which is somewhat counter-intuitive.

Logistic regressions of the BABT recreated test data were conducted with a Logit link function where the weighting factor "$\boldsymbol{n}$" was varied from 1 to 3. An "$\boldsymbol{n}$" value of 2 provided a degree of correlation similar to Rafaels' model [19], and the proposed model is referred to as $\boldsymbol{VD^2}$. Since the initial Logit function [36] gave a non-zero injury risk at an extremely low $\boldsymbol{Vol\cdot BFD^2}$ values, the data were re-analysed statistically by performing non-linear regressions with several sigmoidal functions. The best fit obtained with Equation 1a is shown graphically in Figure 4 (green curve), with the dotted lines representing the 95% confidence intervals. For example, a BABT dose of 715 cm^5 corresponds to a risk of a BABT injury of AIS-2/B of 50% (Equation 1b).

a) $$P(AIS2/B) = 1 - e^{\left[-\left[Vol\cdot BFD^2/870.7\right]^{1.86}\right]}$$ **b)** $$Vol\cdot BFD^2 = 715 \quad (1)$$

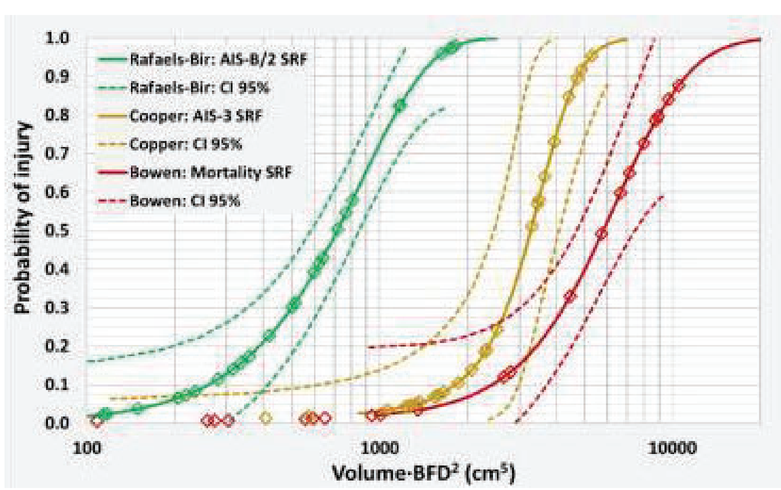

Figure 4: VD2 IRFs for Rafaels-Bir data, Cooper data, and Bowen data

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4. CHARACTERISATION OF RP1 CLAY WITH RIGID BABT SURROGATE IMPACTORS

From the review of BABT historical data, the study of Cooper [29] with porcine subjects and the study from Bowen [30], with canine subjects were identified as a valuable source of test results with conditions resulting in higher BABT injury severities worth being analysed with the VD^2 model, but this required conducting reconstruction match-pair conditions with clay blocks and the same rigid impactors and velocities. The impact of rigid/blunt projectiles onto clay blocks, even though shown to reproduce chest wall velocity and injury severity when impacting unarmored animal bodies when adequately designed [21], has some limitations since the interaction mechanisms with clay are likely not entirely similar.

A series of tests were then conducted with the DRDC gas gun launcher, which included the 140-gram-37mm diameter cylinder of Cooper, also used by Bir later on, the 196-gram-70 mm diameter cylinder of Bowen as well as the BABT impactor of Arborelius [21], and a rigid version of the Lacrosse ball of Dau [26] (Figure 5a). Once impacted, the clay blocks were levelled and drawn off with a flat blade sliding on the reference side edges to remove the clay cavity lip.
The cavity depth was measured with a calibrated digital caliper, and the volume was measured as per the VPAM standard [11] with water using graduated syringes (Figure 5c) which work well with flat clay block but would not be adequate for curved armour as illustrated in Figure 1b). The plaster of Paris and silicone moulding methods could also be used for cavity volume measurement of flat armour samples but are much more laborious and less applicable for routine testing. The plaster or silicone cavity moulds (Figure 5b) help visualise and compare cavity shapes. Projectile velocity and orientation were measured using a *Photron* SA-Z high-speed camera. For the Bir impactor (140-gram, 40 m/s), the video data was analysed with the *Xcitex ProAnalyst* software to obtain the deformation time history of the projectile by tracking a reference line. The results obtained are presented in the four graphs of Figure 6. Based on the Bir-Wilhelm torso biofidelity corridors [25, 26] (Figure 6a), even though clay is not a tissue simulant, it does provide a similar match to ballistic gelatin, with both materials fitting within the male corridors initially and moving to the female corridors afterwards. The measurements of the permanent final depth were only 4% lower than the maximum transient deformation, which is less than the 30% recovery reported by Kinsler [36]. A linear fit (Figure 6b) provided a good correlation of cavity volume vs KE.

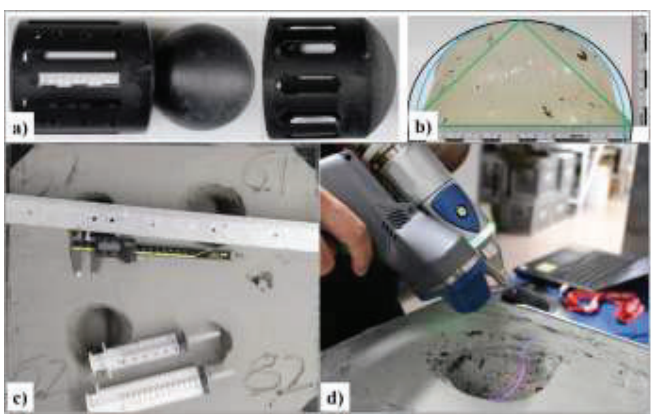

Figure 5: Dau and Arborelius rigid impactors (a), silicone cavity mould (b)
Cavity volume measurement with water (c) and laser scanning (d)

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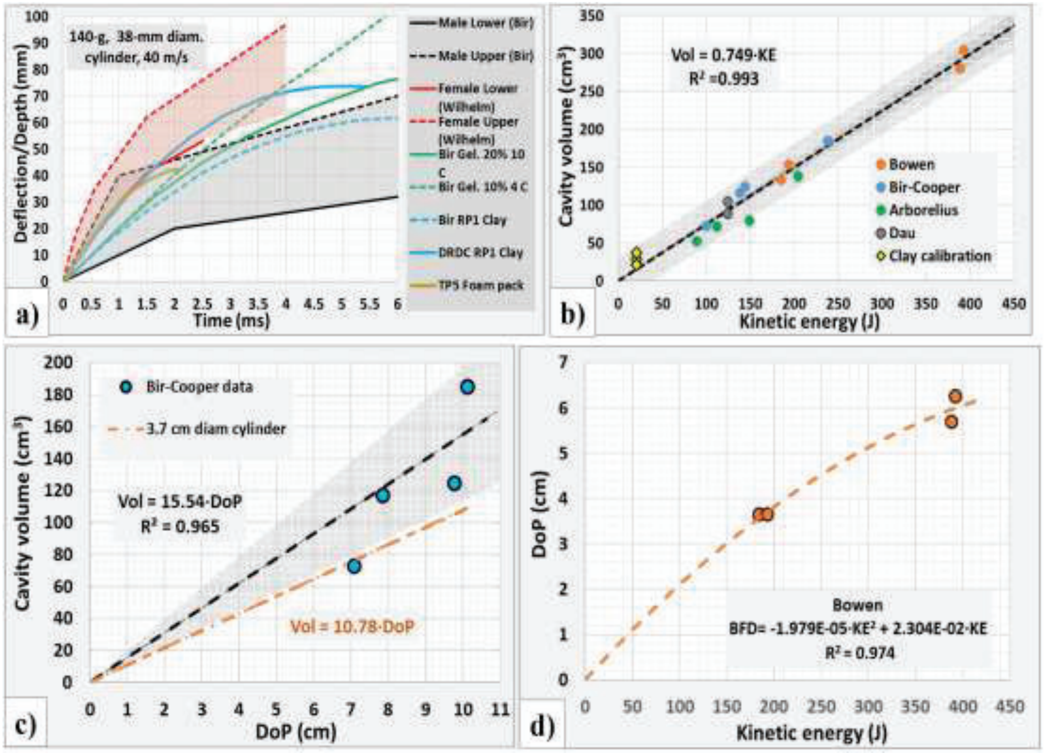

Figure 6: a) Bir-Wilhelm torso biofidelity corridors and RP1 cavity depth vs time for Bir impactor b) volume vs KE for 4 impactors, (c) volume vs DoP for Bir, (d) DoP vs KE for Bowen

5. APPLICATION OF THE VD^2 MODEL TO THE DATA OF COOPER

Cooper [29] conducted extensive live-fire tests on live anesthetised porcine specimens instrumented with pressure sensors where high-speed photography was used to measure chest wall displacement. The animals were impacted at the anterior mid-sternum with rigid projectiles with a diameter of 37 mm and masses of 140 and 380 grams striking at velocities between 20 and 72 m/sec. The 37mm-140-gram impactor from Cooper was used ulteriorly by Bir and Wilhelm [26, 27] for their studies with male and female PMHS. Wilhelm demonstrated that the impacts of this projectile onto bare 20% gelatin blocks provided a good match of the deflection time profile of actual soft armours on the same gelatin blocks. As shown in Figure 6a), the deflection-time response of RP1 clay and 20% gelatin are relatively close in the range of interest (i.e., up to 60 mm) for the 37mm-140 mm impactor. Comparative studies of soft armour on clay blocks and BABT torso rigs with membranes [38, 39] also show the same trend, i.e., that ***DoP*** in RP1 clay can be assumed to be close enough to the maximum chest wall displacement. For injury assessment, Cooper used a five (5) grades injury scale for rating cardiac injuries, while sternal injuries were rated as either no fracture or fracture with or without displacement. The injury scores obtained were plotted as a function of the chest wall displacement (P) ratio to the anteroposterior diameter (***AP***), i.e., ***P/AP***. A value of 24 cm was assumed for ***AP***, enabling the calculation of the chest wall displacement ***P*** for the data points included in Cooper's graph. The ***DoP*** for the match-pair tests were assumed to correspond to the chest displacement (***P***) values using the previously discussed assumptions. The injury grades from Cooper were translated to equivalent AIS numbers (Table 2), making possible comparisons with IRFs which are often based on the AIS scale. The volumes of the cavities for the match-pair tests in clay blocks with the same impactor were calculated using the equation given in Figure 6c), then allowing the blunt trauma doses ($Vol \cdot DoP^2$) computation for the 37 mm diameter impactor cases recreated experimentally with calibrated clay blocks. A logistic regression analysis with a Logit link function for the cases leading to AIS-3 and greater injuries gave Equation 2a, shown graphically in Figure 4 (light brown curve), with the dotted lines representing the 95% confidence intervals. Contrary to recreated soft armour field cases, the Logit fit did not display a non-zero injury for low blunt trauma doses, which is often a limitation when using logistic regressions for generating IRFs [40]. A BABT dose of 3280 cm^5 corresponds to a risk of a BABT injury of AIS-3 of 50%, as given by Equation 2b.

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a) $P(AIS3) = 1/(1 + e^{(4.9192 - 0.0015)})$ b) $Vol \cdot BFD^2 = 3280$ (2)

6. APPLICATION OF THE VD² MODEL TO THE DATA OF BOWEN

The same approach used for the analysis of the data from Cooper was applied to the data from Bowen [31], which conducted experiments on live anesthetised canine specimens impacted onto the right lateral chest wall near the mid thorax by flat rigid cylinders with diameters of 70 mm and masses varying from 60 to 380 grams at velocities ranging from 20 to 90 m/s. Bowen rated the sustained blunt trauma injuries simply as a function of the number of rib fractures and time to death. The animals that survived were all sacrificed after 30 to 40 minutes. The canine specimens' weight ranged from 14.5 to 23.1 kg with no scaling applied to the data, which was a necessary simplification. The match-pair tests onto clay blocks were only performed with the 196-gram cylinders with a slightly smaller diameter (i.e., 68 mm instead of 70 mm) to fit the gas gun barrel readily available at the DRDC impact laboratory. The equation of Figure 6b was used to compute the cavities volume for the impact kinetic energies and velocities for the test conditions reported by Bowen. The resulting ***DoP*** in the clay blocks were calculated using the equation of Figure 6d. Assuming as previously that ***DoP*** can be used as a proxy for BFD, the corresponding blunt trauma doses ($Vol \cdot DoP^2$) were then calculated by performing non-linear regression analysis of the cases resulting in mortality (AIS-6) with a wide range of sigmoidal functions. The best fit was obtained with Equation 3a, shown in Figure 4 (red curve), with the dotted lines representing the 95% confidence intervals. A BABT dose of 5800 cm^5 corresponds to a 50% risk of AIS-6 injuries (Equation 3b), which is likely conservative since the data was not scaled to a 70 kg man.

a) $P = 1/\left[1 + e^{\left[-0.000356 \cdot (29638 + Vol \cdot BFD^2\right]^{208387}}\right]$ b) $Vol \cdot BFD^2 = 5800$ (3)

7. BABT SEVERITY MAP WITH POTENTIAL PASS-FAIL CRITERION

The three IRFs developed in sections 3, 5 and 6, using the VD² model for the Rafaels-Bir AIS-2B injuries from recreated field cases, the Cooper AIS-3 and Bowen AIS-6 BABT injuries are illustrated graphically in the injury map of Figure 7. They are shown to follow the same trends and be logically spaced with a larger upward offset between the 50% AIS-2/B and the 50% AIS-3 curves than between the 50% AIS-3 and the 50% AIS-6 curves. The solid black line represents the 50% risk of AIS-2B, the solid blue line the 50% risk of AIS-3 injuries, and the solid red line the 50% risk of AIS-6 injuries. The dotted lines, as indicated in the legend of Figure 7, were generated for the probabilities of injuries of 10%, 20%, and 70%. It can be seen that the iso-BABT severity curves generated follow the same trends where for the 50% injury risk, the allowable BFD is inversely proportional to the square of the cavity volume. This trend is coherent with the initial premise that for a given BFD, clay cavities with larger volume will lead to increased BABT severity and reversely that for a given cavity volume, impacts producing deeper cavities in clay will cause more severe BABT injuries.

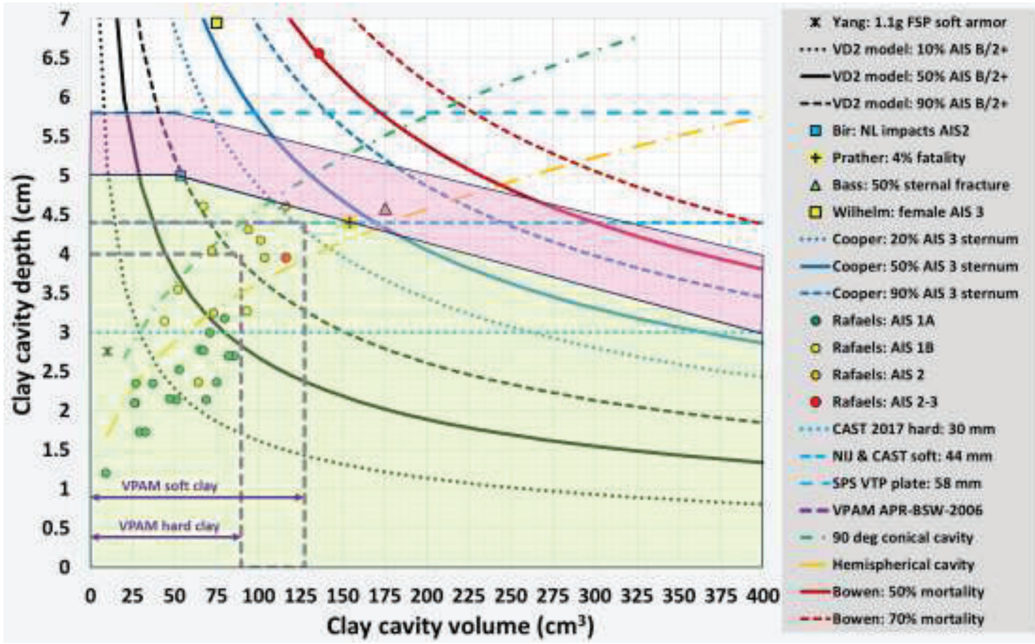

Figure 7: Cavity depth vs volume graph with iso-BABT severity curves derived from VD^2 IRFs

The BABT survivor data used for generating the AIS-2B IRF is also plotted in the injury map and is shown to be well distributed on both sides of the 50% injury risk curve. Relevant data points from other BABT studies [41, 42] not included for generating the three new IRFs are also shown to be in general concordance with the iso-BABT severity curves. The body armour BFD tolerance levels of Table 1 are also plotted in Figure 7, where it can be seen that the range of volumes and maximum BFD allowed by the VPAM standard (purple rectangular box) fits in the map centre between the 50% AIS-2/B and AIS-3 curves, and between the lines for hemispherical and 90° conical cavities.

The UK CAST, 30 mm limit, is shown to be highly conservative for small clay cavity volumes and more applicable to larger volume cavities. For cavity volumes greater than 75 cm^3, the 58 mm BFD limit is predicted to allow for severe to serious and potentially critical injuries. A good assessment of the likely direct fire threat to be encountered during the mission will be needed such that the body armour degree of ballistic perforation resistance and BABT injury mitigation adequately match the anticipated threat severity. A potential acceptance criterion is illustrated in Figure 7 as the green shaded area, where for cavity volumes below 50 cm^3, a maximum BFD of 50 mm would be allowed and then declining linearly to a maximum BFD of 30 mm at a cavity volume of 400 cm^3 following the Cooper 20% AIS-3 injury risk curve. The pink area in Figure 7 illustrates another trade-off option relying more on increased mobility from the lighter armour systems than BABT injury protection for soldier survivability, where the BFD limit was increased to 58 mm for low cavity volumes and 40 mm for high cavity volumes.

The impact velocities specified in body armour standards correspond to engagements at point blank, with standard barrel lengths and impacts occurring at zero obliquities, a worst-case situation rarely arising in operational theatres. The employment ranges of the heavier calibre weapons (e.g., 7.62x54mm sub-machine guns and marksman rifles) are also typically longer than those used with assault rifles such as the 5.45x39mm calibre (AK-74) more often used nowadays by Russia [43] or the 7.62x39mm AK47 rifles which are less of a concern for BABT overmatch due to the lower projectile mass (AK47 and AK 74) and velocity (AK47). When updating body armour standards, it may be worth adding BABT overmatch threat classes covering larger calibre sniper rifles (e.g., 338 Lapua) where the BFD assessment would be done at the typical engagement range (e.g., 500 m). For such threats, more prevalent in theatre nowadays, using anti-trauma plates worn in conjunction with plate inserts may be a worthwhile option

8. SUMMARY AND CONCLUSIONS

Based on the data from reconstructed soft armour field cases, the VD^2 model provided a good prediction of the BABT injury risks. Given the assumptions made, similar trends and levels of correlation were also obtained for the IRFs computed for the rigid impactors of Cooper and Bowen, where the original impact

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conditions were recreated onto calibrated clay blocks. A linear correlation was obtained between cavity volume and transmitted kinetic energy indicating that ***Vol·BFD***^{2} could be considered as a weighted energy-based BABT criterion. The injury map produced was shown to be helpful in defining body armour acceptance criteria considering both cavity maximum depth and volume. It was shown that the current 44 mm BFD limit could be increased up to 50 mm, but only for impacts with cavities volumes smaller than 75 cm^3. A BFD limit of 58 mm should be used cautiously for impacts resulting in larger cavity volumes where the more stringent BFD limit of the UK CAST standard (30 mm) would procure BABT injury mitigation at a safer level. More experimental data with PMHS and LAS resulting in higher severity injuries are needed to quantify better the BABT dose effect and the development of better-suited medically-based IRFs. Improved laboratory assessment methodologies should continue to be developed in parallel and implemented in body armour standards when fully validated. Measuring clay cavity shape and volume using laser scanning should be recommended in body armour specifications to complement BFD measurement, as this would help discriminate between the BABT mitigation potential of two armour systems having the same maximum BFD.

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