The Fundamental Limitations of Clay for Assessing Human Response for Behind Armour Blunt Trauma

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Abstract. Current assessment of both military and civilian body armour uses Roma Plastilina #1 (RP-1), an oil/wax-based modelling clay, as the surrogate for Behind Armour Blunt Trauma (BABT). A depth of 44 mm is the threshold for unacceptable armour backface deformation. In this study, high speed x-ray backface deformation data from hard plate body armour tests in human cadavers and clay are compared to data from simulated rifle BABT indenter tests utilizing porcine models and clay, to evaluate the current clay assessment method. Fifty-two clay indenter impacts were performed with impact energy ranging from 175 J to 508 J, resulting in plastic clay deformations depths from 30.7 mm to 65.3 mm. The indenter velocities during these tests ranged from 31.7 m/s to 55.1 m/s, equivalent to 7.62 x 51 mm rifle round velocities of 651 m/s to 1106 m/s. In contrast to the cadaver and animal models, clay exhibited a strong rebound effect. This effect reduces the final deformation by 5-25% depending on the velocity of the impact, obscuring the actual peak dynamic deformation in the clay by a significant unknown fraction of the residual plastic deformation. When comparing the indenter clay results to experiments with similar indenters on live pigs, the indenter in clay requires over 30% higher energy to achieve deformations similar to those seen in the pig torso, demonstrating that deformation might exacerbated substantially in living tissue. A scaling relationship is developed to relate indenter impact velocity to rifle round velocity based on the body armour as a kinetic energy dissipater. Results imply significant differences between clay and tissue, reiterating that RP-1 is not a suitable surrogate and that the current composition and testing procedures involving RP-1 possess neither the complete plasticity nor a comparative or equal deformation depth to that of living tissue.

1. BACKGROUND

Development of body armour capable of protecting the user from ballistic threats has resulted in the creation and adoption of armour mechanisms that rely on mitigating acute damage through spreading out the impact across a wider area through deformation of armour materials. Body armour has been found to greatly increase survivability of law enforcement officers shot in the torso by reducing the risk of penetrating trauma [1, 2]. However, this distribution of force results in deformation that occurs on the rear surface of the armour plate. Extrusion of armour material due to this deformation is recognized as backface deformation (BFD). As this surface impinges with a high rate upon the physiological body of the wearer, BFD has been shown to cause injuries to the ribcage and internal organs of the thorax, which is recognized as Behind-Armour Blunt Trauma (BABT) [3]. Initially ballistic gelatine was utilized as the tissue surrogate for BABT characterization, but analysis utilizing the gelatine model requires costly high-speed video/camera equipment to capture the maximum deformation, and raised concerns about discerning the correct displacement due to the refractive index of the air-gelatine interface. Examination of the current tissue surrogate utilized to characterize BABT mechanism of injury began in the 1970s [4], with the aim of developing an expedient, low-cost alternative to ballistic gelatine for assessing VIP soft body armours against handgun rounds. The contexts of these earlier studies all address relatively low-velocity impacts from traditional pistol cartridges and thus fail to address characteristics of increasingly relevant high-velocity impacts on armour specifically designed to combat rifle threats.

These early tests performed in the 70s resulted in the adoption of Roma Plastilina #1 (RP-1), an oil/wax-based modelling clay, as the standard tissue surrogate for deformation testing, with a maximum deformation depth of 44 mm being the threshold for unacceptable BFD. In Prather 1977 [4], RP-1 is recognized as a relatively plastic, affordable alternative to ballistic gelatine as it possesses comparable

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maximum deformations. This deformation data is based on a previous BABT test utilizing 45 kg caprine models which were assumed equivalent to an adult human, in which no fatalities were recorded. Recognizing these limitations, the study states the "data is limited and hence no solid conclusions can be drawn as yet regarding the effect of deformation depth". An underlying assumption in these tests is that maximum deformation of the clay is equal to the residual deformation, eliminating the requirement for expensive equipment needed in the gelatine tests. Considering the changes in RP-1 material composition from the 1970s to present day, the limitations of the assumptions made, and the use of low-velocity .38 Special as the sole test metric, the fidelity of RP-1 as a tissue simulant in contemporary BABT testing should be investigated.

As an art modelling clay, the composition of RP-1 is relatively inconsistent and the material has become progressively stiffer over time due to changes in both clay and wax composition [5]. Current testing methodologies developed by the NIJ [6] attempt to address this through substantially varying temperature to ~38^0 C from the original ~20^0 C, partially melting the wax constituents, and utilizing pass/fail calibration drop tests, but this compensatory method is not representative of the original RP-1 composition and potentially changes other material characteristics of the clay. Inhomogeneous working of the clay is an additional limitation of RP-1 as a tissue simulant. Unlike gelatine, it is difficult to visually recognize or otherwise confirm uniformity of the material between tests. Further, maintaining a consistent clay temperature is difficult: the temperature and thus material properties of the clay in one region may be substantially different from another once exposed to an environment of different temperature. While testing in a room-temperature environment, the surface of the clay is often noticeably cooler than the interior and will possess different mechanical properties.

Advances in arms and body armour have also rendered the .38 Special inadequate as a sole metric for the evaluation of all body armour. Rifle cartridges have traditionally defined high-velocity applications, but handgun or pistol cartridges have also been developed since development of the standard that can meet traditionally rifle cartridge velocities. Further, this same standard of 44 mm BFD in RP-1 is utilized for all body armour evaluation with no distinction between hard or soft body armours. While aramid fibres and other soft armour materials defeat the projectile through direct deformation of the material [7], hard plates commonly composed of ceramics such as boron or silicon carbide dissipate energy through fracture [8], and hard Ultra-High Molecular Weight Polyethylene (UHMWPE) plates also dissipate energy through fracture and delamination [9]. This difference in mechanism of action may lead to further inconsistencies when evaluating both with the same standard.

Despite these limitations and change in scope, the RP-1 standards developed for soft aramid body armour in the 70s is still the preeminent technique for body armour assessment. The difference between high-velocity and low-velocity applications has been demonstrated in numerous relatively recent animal model studies, including a study done by Gryth et al., 2007 [10] in which 22 porcine models were used as a tissue surrogate in testing high-velocity impact BABT characteristics with the 7.62 x 51 mm NATO rifle cartridge on hard ceramic armour plates with soft armour backers, with 50% and 25% mortality rates from BABT for 40 mm and 34 mm respective maximum deformation depths. Through scaling, the porcine model is more representative of adult human mass than the original caprine model, further emphasizing questions on the fidelity of RP-1. The current study incorporates data from recent porcine tests with an indenter representative of the deforming backface of armour, serving to compare porcine and clay models [11].

Methods for evaluating the fidelity of RP-1 clay outside of direct comparison to animal or cadaver models have been assessed in past studies through employing measures described in current standards developed by the NIJ. Studies employing such controls evaluate material characteristics by either directly inducing deformation through using a shoot-pack under body armour systems with known characteristics or employing an indenter to simulate the impact of the armour backface against tissue. Utilizing a test box with the same dimensions as described in the standard and creating indenters based on the deformation profiles of armour BFD, Graham and Zhang clarify the dynamic behaviour of RP-1 under impact, observing unrepresentative material characteristics in the results such as clay extrusion post-impact, a rebound causing differences between maximum and residual deformation depth, and impact or penetration characteristics of the indenter [12]. More recently, in 2022 Zhang et al. go on to develop a model of the rebound effect in RP-1 [13].

2. METHODS

2.1 Clay impact tests

In this study, a high-pressure launch tube and indenter were used to provide the impacts to clay representative of armour backface deformation. 3D-printed polycarbonate indenters of masses between

341 g and 350 g with densities and profiles representative of armour deformation profiles found in high-speed x-ray images in rifle-context hard plate (Ultra-High-Molecular-Weight Polyethylene) body armour tests [3, 11] were utilized to evaluate the RP1 clay model under high-velocity impact. Two indenter designs were used utilizing an identical profile head but with different bodies, a cylinder design with straight walls and a wasp-waisted design attempting to remove mantle surface that would impede a rebound effect in the clay.

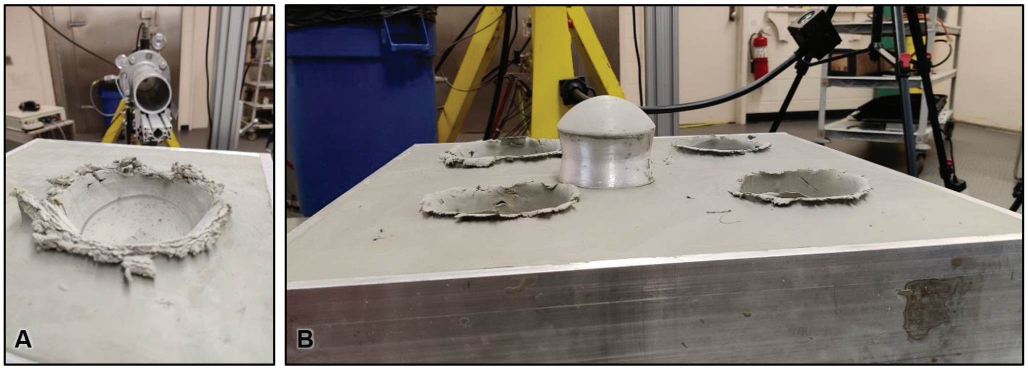

Figure 1. A) High pressure launch tube, B) Wasp-waisted type Indenter on clay box with deformation profiles, note the extrusion of the clay from the indenter impacts and leftover clay residue along the indenter head from the rebound effect of the clay 'grabbing' the indenter.

The impacts were recorded utilizing high-speed video (Phantom v711, Vision Research) perpendicular to the path of the indenter at the muzzle. This high-speed video was then utilized to determine the velocity and rebound of the clay. Post impact, a depth camera (Intel RealSense) and 3D-scanning software (Dot3D, DotProduct) were used to capture the residual deformations in clay to determine volume, area, and profile of the deformations. Residual deformation depth was also measured using a depth micrometer. Clay temperature was measured at 2 cm depth following each impact utilizing a temperature probe.

The clay target 56 cm x 56 cm x 14 cm aluminium box with plywood base followed the NIJ 0101.06 standard for body armour testing. Clay was calibrated with spherical calibrators dropped from a 200 cm height with a resultant acceptable deformation depth of 17 mm to 21 mm. Each clay box sustained 4 indenter impacts during the testing phase before being refilled and planed for reheating, and each reheating phase was held at 40-42 °C for at least an overnight period. Should the box not pass calibration, the box would be planed and reheated or allowed to cool depending on whether calibration deformations were under or over acceptable limits respectively. Heating was performed to soften the clay according to the testing standard such that desired calibration depths were achieved.

After reworking the clay to a uniform flat surface, four equally spaced impact tests were performed in succession. The indenter was propelled utilizing high pressure helium gas. Velocity of the indenter was determined using high speed video. Clay deformation profiles were measured relative to the edge of the box. Once testing was concluded, and the clay was flattened and placed in the oven overnight to achieve equilibrium temperature.

The indenter-clay results were compared with data from simulated rifle BABT indenter tests utilizing porcine models [11] to evaluate the RP1 clay model by comparing clay and living tissue under a high-velocity BABT impact context.

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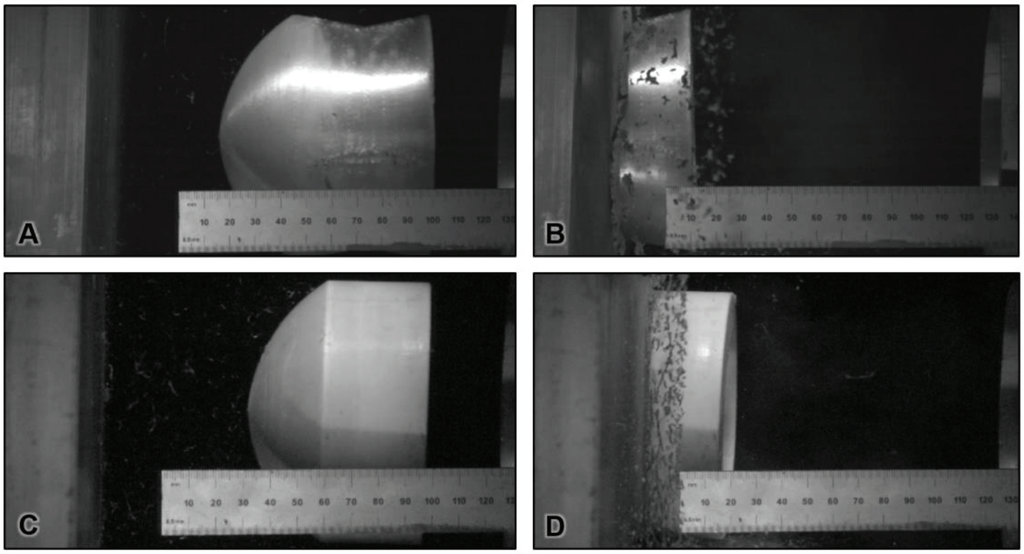

Figure 2. High-Speed Video Frames. A) Wasp-waist type in flight. B) Wasp-waist type impact, note extrusion of material. C) Cylinder type in flight. D) Cylinder type impact.

2.2 Equivalent Rifle Velocity

The fidelity of the clay indenter model for rifle rounds into hard armour (developed from hard armour x-ray profiles into pigs and human cadavers was evaluated using similar human cadaver [3] and porcine models [11]. An estimate of equivalent rifle round velocity into hard body armour for an indenter impact was determined based on an assumption that the armour dissipates a fraction of the incoming kinetic energy through the fracture or delamination of UHMWPE material. As the body armour material's capacity for energy dissipation is compromised, the remainder of the energy is transferred into the thorax as kinetic energy of the armour backface. The indenter serves to model this residual kinetic energy of the armour and the attacking projectile into the thorax as the thorax deforms. We model this residual energy as an energy fraction (EF) of the incoming energy to match projectile-armour impacts with indenter impacts. With similar displaced volumes and depths in clay between the indenter and projectile-armour models, the equivalent projectile velocity of a 9.5 g 7.62x51 mm NATO (M80 Ball) projectile on UHMWPE can be estimated assuming the indenter kinetic energy is equal to the residual kinetic energy of the armour backface upon impact.

$$\frac{1}{2} m_{indenter}\, v_{indenter}^2 = EF * \frac{1}{2} m_{round}\, v_{round}^2 \quad (1)$$

$$v_{indenter} = \left(EF * \frac{m_{round}}{m_{indenter}}\right)^{1/2} v_{round} \quad (2)$$

To find this energy fraction, regression fits for both the deformation depth in clay and volume of displaced clay were compared between the indenter-clay and projectile-armour-clay and the EF was optimized for closest match between the regression fits.

3. RESULTS

3.1 Clay impact tests

Fifty-two clay indenter impacts were performed with impact energy ranging from 175 J to 508 J, resulting in plastic clay deformations depths from 30.7 mm to 65.3 mm. The indenter velocity upon impact during these tests ranged from 31.7 m/s to 55.1 m/s, equivalent to 7.62 x 51 mm rifle round velocities of 651 m/s to 1106 m/s. In contrast to the cadaver and animal models, clay exhibited a strong rebound effect. This effect reduces the final deformation by 5-25% depending on the velocity of the impact, obscuring the actual peak dynamic deformation in the clay by a significant unknown fraction of the assumed clay residual plastic deformation. The measurements from these impacts can be found in table 1. Blank values

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for the rebound are present for impacts where the indenter fully entered the clay and visual contact was lost.

Table 1. Indenter impact test measurements.

Velocity (m/s)	Plastic Deformation (mm)	Rebound (mm)	Momentum (Kg*m/s)	Energy (J)	Area (cm^2)	Volume (cc)
42.9	54.3	3.4	15.0	321.0	98.8	272.4
42.9	53.0	3.5	15.0	321.0	95.3	269.6
44.8	56.1	4.7	15.6	350.0	97.9	312.6
51.5	65.3	7.3	18.0	463.0	104.8	407.7
35.1	41.0	7.4	12.2	215.0	91.8	187.1
39.2	45.8	6.0	13.7	268.0	99.9	232.0
33.2	40.0	8.5	11.6	192.0	98.2	192.4
33.6	39.3	6.4	11.7	197.0	90.3	175.9
31.7	30.7	6.0	11.1	175.0	100.3	119.7
40.1	43.4	8.6	14.0	281.0	93.2	215.3
38.4	37.6	6.5	13.4	257.0	95.7	171.4
40.6	40.1	9.5	14.2	288.0	98.6	197.1
40.6	45.0	5.6	14.0	285.0	94.4	238.1
44.8	44.0	9.9	15.5	348.0	96.6	303.0
43.0	37.0	10.3	14.9	320.0	99.7	280.3
41.2	45.0	9.9	14.3	294.0	93.7	244.9
41.9	48.6	7.3	14.5	303.0	104.4	273.4
46.9	51.9	7.7	16.2	381.0	105.4	316.8
40.1	43.4	7.6	13.9	279.0	102.5	239.9
41.0	47.0	9.5	14.2	291.0	98.4	263.0
42.4	47.0	7.7	14.7	312.0	100.1	289.0
43.2	48.2	9.9	14.9	323.0	93.8	263.2
38.5	41.8	6.0	13.3	256.0	126.9	190.0
44.4	45.9	7.3	15.4	342.0	105.9	242.3
44.8	51.2	7.3	15.5	348.0	112.7	272.9
45.4	55.2	8.1	15.7	357.0	107.2	316.7
46.6	53.3	9.4	16.1	375.0	104.3	288.8
48.0	57.0	9.4	16.6	399.0	113.4	342.5
53.5	51.5	9.6	18.5	496.0	115.6	301.0
38.3	43.5	6.0	13.4	257.0	91.4	214.8
38.6	42.7	8.7	13.5	260.0	90.4	214.0
40.5	44.6	6.9	14.2	287.0	87.0	225.0
42.1	45.7	9.8	14.7	310.0	97.8	256.7
51.4	62.8		17.7	455.0	115.4	386.4
45.6	51.3		15.7	359.0	128.9	296.2
43.0	47.9	6.9	14.8	318.0	115.9	260.8
39.0	40.9	8.0	13.4	262.0	102.8	211.5
40.3	44.4	7.3	13.9	280.0	118.7	228.4
43.9	48.3		15.2	333.0	100.0	261.1
46.6	53.0		16.1	375.0	106.3	302.8
49.0	55.7		16.9	413.0	116.2	347.3
41.0	46.4	8.1	14.1	289.0	103.1	234.1
39.9	43.6	8.5	13.8	275.0	122.9	222.4
49.8	56.4		17.2	428.0	101.2	327.3
49.7	60.2		17.2	427.0	130.1	385.6
52.7	60.4	10.3	17.5	462.0	111.2	399.2
52.6	57.3	5.1	17.5	460.0	106.1	354.2
52.9	59.0	11.1	17.6	466.0	109.3	404.6
54.2	61.4	11.1	18.1	491.0	109.1	422.8
54.0	61.1	7.3	18.0	487.0	111.5	420.4
55.1	64.7	12.1	18.4	508.0	117.3	483.2
48.8	57.4	9.6	17.2	419.0	109.2	353.3

When comparing the effect of the wasp-waisted design with the cylindrical body, both body designs had equivalent results that could not be separated. For further analysis the results are grouped together with consistent results.

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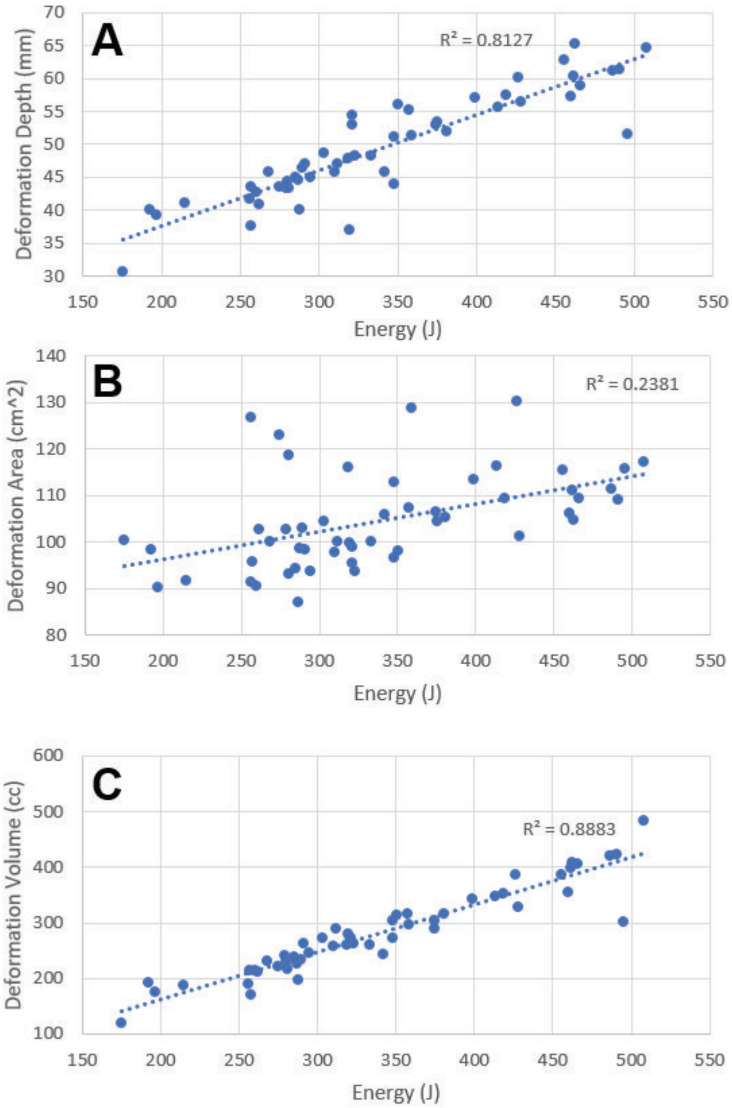


Figure 3. Residual deformation depth (A), area (B), and volume (C) of displaced clay for all indenter tests as a function of indenter kinetic energy. Volume of displaced clay correlates best with impact energy.

When comparing the residual depth, area and volume of the deformation in the clay in Figure 3, both the depth and volume show a good correlation with the impact energy, with the volume slightly outperforming the depth. Deformation area is more variable and reflective of the limited surface area of the indenter, but still correlates with impact energy.

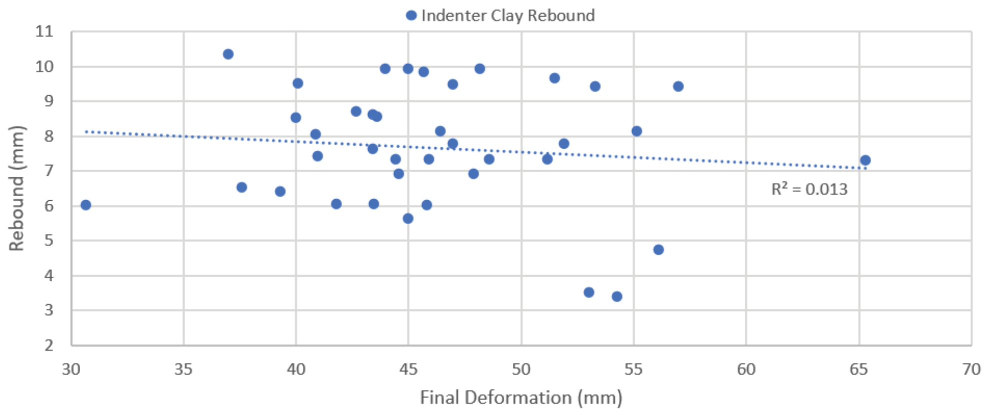


Figure 4. A strong rebound effect showed no correlation to the total residual deformation depth.

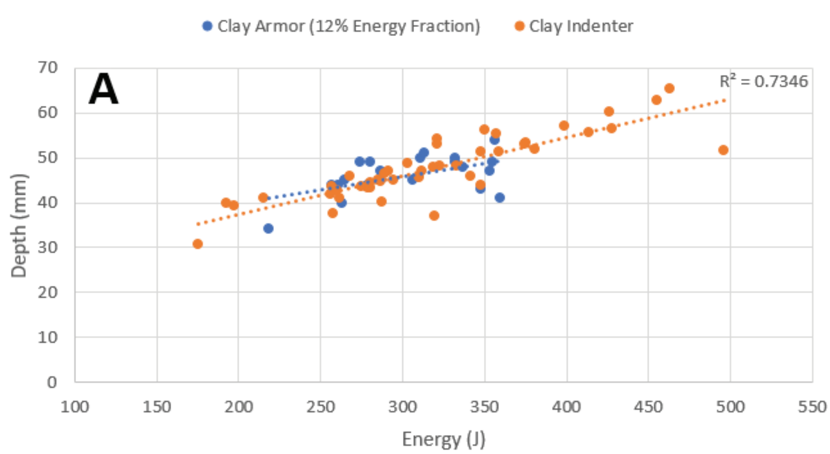
A strong rebound effect was observed for all impacts, resulting the in the final deformation differing substantially from the maximum achieved dynamic deformation during impact. These rebounds can be seen in Figure 4. The rebound distance was quite variable between impacts and showed no correlation to impact energy or to residual deformation. As a percentage of the final deformation, the rebound comprised anywhere from 5% to 25% of the total deformation depth. This shows that clay is a dynamic material with transient material properties.

3.2 Equivalent Rifle Velocity

After scaling the energy fraction of the rifle round impacts on clay performed in a previous study [3], energy fractions were obtained for both a residual depth regression and a residual volume regression. The energy fraction of the simulated UHMWPE armour is best fit as 12% on a depth basis and 8.7% on a volume basis, and the regression fits for these can be seen in Figure 5. Using the obtained energy fractions we can then apply them to Equation (1) and (2) to obtain scaling relationships:

$$v_{indenter} = 0.049 * v_{round} \text{ (Volume basis)} \quad (3)$$
$$v_{indenter} = 0.058 * v_{round} \text{ (Depth basis)} \quad (4)$$

This model was verified with data from high velocity rifle round impacts on armour plate equipped human cadavers [3] and live indenter impact porcine test fracture data [11], comparing the 50% risk of fracture round velocity (700 m/s) in cadaver relative to the 50% risk of fracture indenter velocity in porcine (32.75 m/s) and its equivalent round velocity (668 m/s) on a volume basis. This suggests hard body armour functions as a dissipater of 88-91.3% of the kinetic energy of the incoming round.



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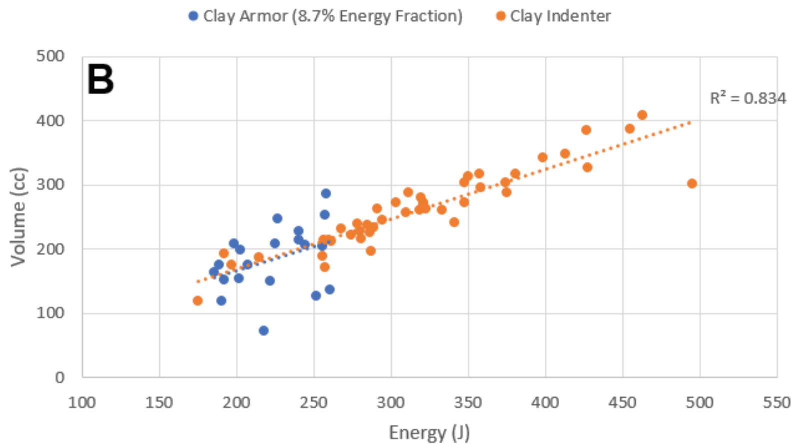

Figure 5. Regression fits of kinetic energy of the indenter and scaled rifle round with respect to A) residual clay depth, and B) residual clay volume. Rifle round kinetic energy was scaled down to 12% (A) and 8.7% (B).

3.2 Comparison to live porcine impacts

When comparing the deformation depth of the impacts to those seen live porcine impacts in a previous study [11], the indenter in clay requires over 30% higher energy to achieve deformations of similar magnitude to those seen in the pig torso. These results can be seen in Figure 6. Impacts that resulted in clay deformation depths below 44 mm resulted in significant injuries in the animals that would require immediate medical attention in the field.

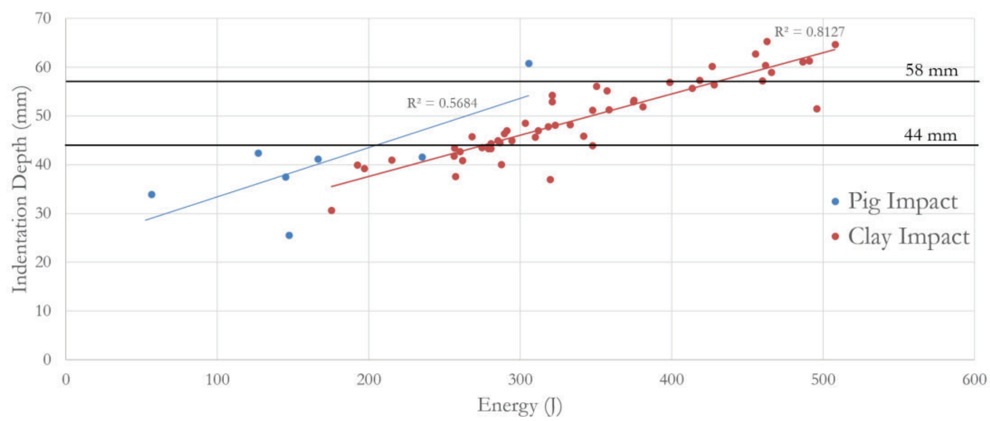

Figure 6. The relationship between the Porcine and Clay models using indenter impacts. This highlights the difference between clay and live tissue, with clay being stiffer and requiring more kinetic energy to achieve a similar deformation depth as the porcine impacts.

4. DISCUSSION

This study elucidates several parameters that are used to evaluate the fidelity of the RP-1 clay model of BABT. First, elastic volumetric rebound of the clay varies by incoming velocity and invalidates the assumption that the clay responds fully plastically under dynamic deformation. Indeed, the elastic rebound for this indenter is 5-25% of the total depth, implying that direct clay measurements under predict actual clay deformation by a variable amount sufficient to substantially increase injury risk (cf. [5]). This increase in risk is presumably dependent on area characteristics of the backface and cannot be assessed using clay response alone.

Second, this study finds different residual clay depths in this study compared with previous porcine and human cadaver depth measurements in indenter and armour tests at similar impact energies. This finding invalidates the second assumption of clay testing, the concordance between human deformation depths and clay deformation depths under similar conditions. Using energy as a metric accounts for the variable indenter mass between the different tests and provides a dynamically appropriate comparison between porcine and clay models. For live pig indenter tests under similar conditions [11], the indenter was found to cause a greater peak deformation in living tissue when compared to the residual plastic deformation of the clay model. This is especially concerning as it demonstrates that the extent of deformation in clay may be exacerbated in living tissue. Other contexts find indentation in clay may be reduced compared with porcine models [11]. This also highlights the need for a more accurate assessment method for high-velocity high-energy contexts such as those for hard armour.

Third, assessing the relationship between the impact energy of the 7.62 x 51 mm NATO M80 Ball round used in the armour-clay tests and the indenter-clay test performed in this study demonstrates the applicability of the indenter model for the evaluation of RP-1. A series of energy fractions were examined with respect to residual deformation depth and the UHMWPE armour utilized in the armour tests was found to permit 8.7-12% of the M80 Ball projectile's kinetic energy to be transferred to the wearer to create the back face deformation depth, or residual deformation depth in clay.

Fourth, the use of the two different indenter body profiles to examine the rebound effect of RP-1 was also investigated. During testing, it was noted that the plastic clay extrudes outwards to 'grab' the indenter upon impact, and no corresponding difference was seen in the percentage of indenter rebound between the wasp-waisted and cylindrical indenters at the same kinetic energies. No difference is noted between residual deformation volumes between the two indenter types; it can therefore be assumed that indenter behaviour is relatively independent of indenter mantle shape. This study also shows that increasing energy generates larger deformation volumes and depths, but deformation area is loosely correlated with impact energy. This may be a limitation of the indenter model given the constant cross-sectional area and frontal profile.

5. CONCLUSION

In conclusion, this study demonstrates the strong limitations of the fidelity of RP-1 as a tissue surrogate in the context of BABT. By following the universal test procedures utilized in evaluating body armour, this study elucidates differences in BABT from high-velocity and low-velocity impacts on the RP-1 clay model under these standards. Results from the clay and porcine tests imply significant differences between the two models, reiterating that RP-1 is not a suitable tissue surrogate especially in the context of high-velocity impact and that the current composition and testing procedures involving RP-1 possess neither the complete plasticity nor a comparative or equal deformation depth to that of living tissue. Major points of difference include the different mechanical structure between clay and physiological ribs or internal organs, response at different impact energies with respect to deformation depth, volume, and area.

These implications may also be applied to current and future body armour development noting that the current 44 mm deformation depth in RP-1 standard may not prevent BABT injury, the current use of RP-1 as a tissue surrogate being based on low-velocity impact is inadequate for evaluating high-velocity impact rated hard armour plating, and that RP-1 possesses characteristics not reflective of living tissue such as the lack of rib response, more centred deformation, and greater extrusion of material. Further, this study contributes new methodologies to the field of injury biomechanics, including a new methodology in comparing BABT tissue surrogates to other BABT models through utilization of 3D-printed indenters based on cadaver deformation profiles for rapid expedient characterization of a BABT tissue surrogate.

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