

Definition of a standardized skin penetration surrogate for blunt impacts

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Abstract This paper's goal is to present a surrogate to assess potential skin penetration of blunt impact non-lethal projectiles as a basis for a future NATO standard. The proposed surrogate is made of natural chamois, closed-cell foam and ballistic gelatin. Skin penetration assessment on the surrogate is made on the gelatin. Results from live firings on the surrogate are presented and compared to those from the literature, based on cadavers. A statistical analysis shows that the surrogate results are very comparable to the cadaver ones and reproducible. Some comments are then presented concerning the results and practical considerations concerning the surrogate.

Keywords assessment, criteria, non-lethal, terminal ballistics, standardization

I. INTRODUCTION

Minimizing civilian casualties and unnecessary collateral damage during military or law-enforcement operations has always been a tough challenge. This is the reason why non-lethal weapons have been introduced, allowing a gradual response in case of a continuous escalation in force deployment. Kinetic Energy projectile launchers are the most widespread category of these weapons.

Unfortunately, there are today no universally accepted standards to evaluate the effectiveness and lethality of Kinetic Energy Non-Lethal Weapons (KENLW). Scientists, decision-makers and users emphasize the need for such tools. The need for clear, verifiable standards is urgent, therefore, to be able to define dangerous and safe engagement distances for these weapons and to evaluate possible injuries.

The assessment of non-lethal projectile effects on human targets usually follows two main directions:

- The evaluation of internal damage
- The evaluation of skin penetration

This paper focuses on the second point. The literature gives some energy density values for a 50% skin penetration probability when different parts of the human body are shot at. These values are based on post-mortem human subjects (PMHS) tests conducted in the USA [1]. While it is not proven that the energy density parameter is universal, and that some countries do not allow tests on PMHS, it is much more convenient to use a mechanical surrogate for testing purposes. Therefore, a standard on which different countries can rely is required.

Wayne State University (WSU) proposed in March 2010, as a basis for NATO standardization, a draft proposal of a protocol [2] based on the use of a surrogate. In 2011, a NATO workgroup founded under the auspices of LCG9 re-wrote this protocol in order to make a future standard.

The WSU proposal is based on KENLW live-shooting results [1] summarized in table I. Unlike previous studies such as DiMaio's literature review in 1981 [3], skin penetration has been assessed by shooting real non-lethal plastic projectiles (6.4g 12 gauge - 18.5mm - MK Ballistics RB1-FS) at PMHS. While the biofidelity of PMHS compared to living human beings is always questionable, no evidence or other data seem to be in contradiction with these data.

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After a statistical analysis, values for a 50% risk of penetration have been published for various body regions [1]. The smallest value (which is also the most likely to be exceeded by a given projectile with a limited velocity) has been calculated for a penetration on the anterior rib which is an energy density (ED) of 23,99 J/cm². This value will be the target value of the protocol and surrogate evaluation.

TABLE I
50% RISK OF SKIN PENETRATION FOR VARIOUS REGIONS (STATISTICAL ANALYSIS)

Part	ED50 (J/cm ²)
On Anterior Rib	23.99
Between Anterior Rib	33.30
Liver	39.88
Lateral to Umbilicus	34.34
Proximal Femur	26.13
Distal Femur	28.13

The final protocol aims to give a “go” or a “no go” for a given projectile at a specified distance by shooting numerous times, in the same apparent conditions, on the surrogate. The last protocol proposal states that a “non penetration” will be accepted if there are 28 impacts with no penetration at all.

The actual objective, however, is to compare the measured ED50 (value of the projectile energy-density corresponding with a 50% penetration risk) on the surrogate with the one presented in [1] for the same 12-gauge projectile.

The goal is to build a reproducible mechanical surrogate and define a skin penetration assessment process that gives the same energy density for the same projectile.

II. METHODS

The surrogate

The surrogate is made of a ballistic gelatin block, a closed-cell foam sheet and natural chamois skin. The surrogate can be seen as a black box and does not intend to represent the flesh, subcutaneous and cutaneous parts of the body. The gelatin is called the PAL (Penetration Assessment Layer). There is penetration if a test results in visible damage to the gelatin (cracks or penetration of the projectile with or without perforation of the two other layers).

The foam and chamois together are called LAL (Laceration Assessment Layer). A result will be categorized as “laceration” if one of the LAL items is partially or totally cut, torn or punctured without visible damage to the gelatin. This point is still under investigation since no scientific paper to date statistically links laceration and the surrogate damage.

Gelatin blocks are made in 20% concentration ballistics gelatin and are stored at 10° C prior to use. In order to offer a maximum surface for the ballistic test procedure, cubic blocks of edge length of 25cm are recommended. All faces of the cube can be used for the ballistic test.

The foam is bought off the shelf. It is 6mm thick closed-cell foam sold as sheets of 29cm x 21cm. Natural chamois is used and its recommended optimum thickness should be 1,39mm (1,15 to 1,80mm). These three items are placed together and secured with adjustable straps as shown on figure 1.

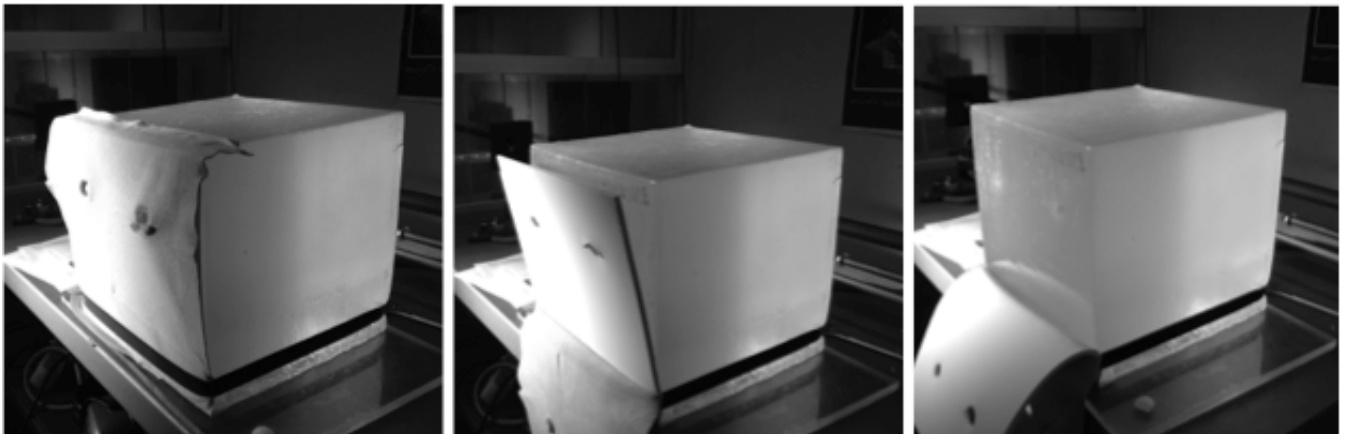


Fig. 1. Surrogate based on chamois, foam and ballistic gelatin secured with adjustable straps

The launcher

In order to measure a v_{50} (value of the projectile velocity corresponding to a 50% penetration risk) and to calculate an ED50 afterwards, shots at different velocities are required. One possibility could be to move the weapon between each shot to change the velocity. This method is obviously not effective. It also makes it difficult to shoot at the prescribed place because of ballistic dispersion. A better solution is to use a specific gun developed to allow firings at different velocities. A homemade pneumatic launcher is used in this study. This launcher, shown in figure 2, is equipped with interchangeable aluminum barrels and can accept an input pressure up to 10 bars. This allows shooting different projectiles up to 40mm in diameter at specific velocities with great precision.



Fig. 2. The homemade non-lethal pneumatic launcher in the non-lethal laboratory

The projectile

The reference projectile is a 6.40g, 12-gauge (18,5mm), fin-stabilized rubber rocket kinetic energy projectile (MK Ballistics RB1-FS). Figure 3 shows one of these RB1-FS projectiles.



Fig. 3. The RB1-FS reference projectile used for the tests

Instrumentation

The velocity of the projectile is measured with a “Drello IR light screen” LS19iN. To ensure an acceptable yaw angle for the projectile (angle of impact $<5^\circ$), we use a high-speed camera “photron Fastcam” SA5, with a frame rate of 50 000im/s. The processing is achieved by a homemade tracking and imaging software [5]. Figure 4 shows the entire setup, including the launcher and the surrogate.

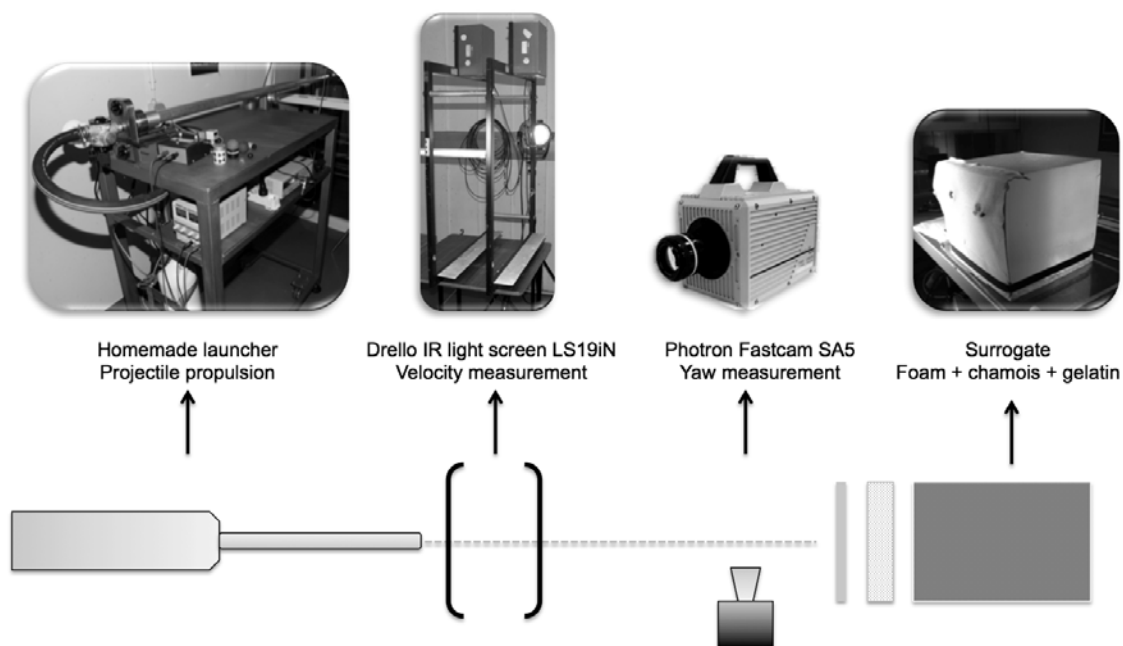


Fig. 4. Vertical view of the whole test setup

Methodology

Gelatin is conditioned to 10°C for 24 hours prior to the test sequence. All testing has to be completed within 45 minutes after removal of the sample from the test facility. Copper plated 0.177 calibre BB projectiles traveling at a velocity of 179 m/s (± 4.5 m/s) are used for calibration. A penetration depth of 3.81 to 7.62cm is considered as an acceptable range [2].

Projectiles are then fired at the prescribed velocities. The surrogate shot pattern is chosen to avoid side and shot-to-shot effects. Figure 5 shows the proposed pattern for 25cm blocks. If damage extends beyond these limits, the shot pattern is then revised.

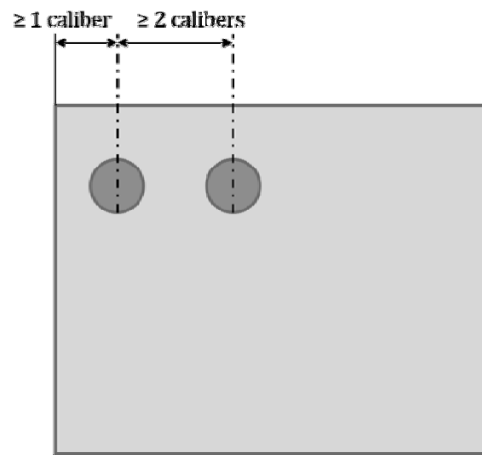


Fig. 5. The surrogate shot pattern

After each shot, the gelatin block (PAL) is examined for damage. As noted earlier, if there is a crack or a shred, we consider there is damage and consequently that the projectile did penetrate. Penetration or no penetration is assessed whatever the state of the foam and/or chamois. After checking that the shot is a fair hit (acceptable impact position and yaw angle), the couple velocity/penetration is recorded in a 0/1 form (no penetration/penetration).

Figure 6 shows examples of penetration and no penetration. This evaluation is sometimes quite difficult but is a key parameter for the assessment method.

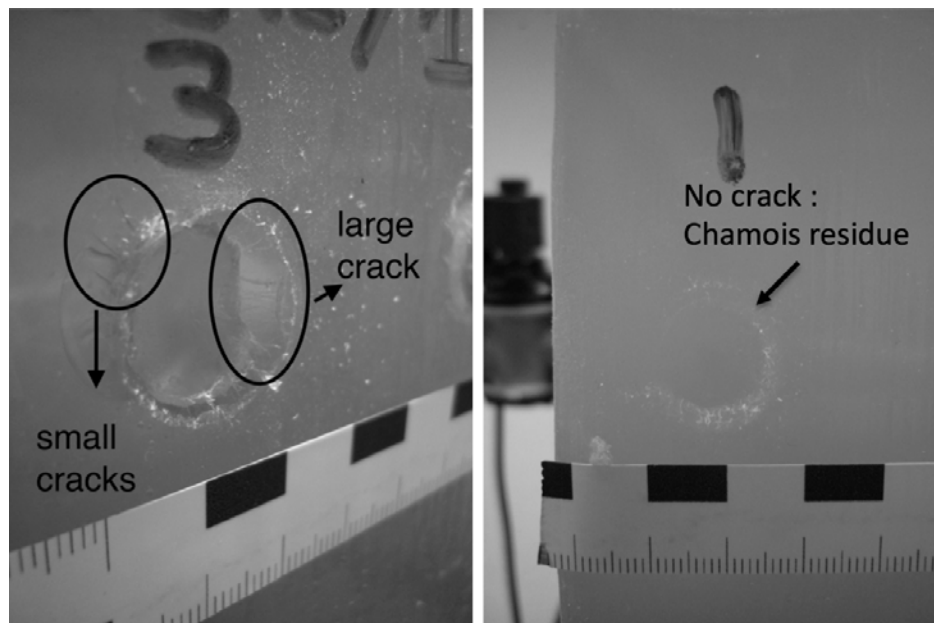


Fig. 6. Crack (penetration) and no crack (no penetration) in the PAL

Since our goal is surrogate validation, we must verify that the ED50 from PMHS tests can be achieved by using our surrogate by comparing it with the one calculated from the surrogate results [1].

In order to have a valid ED50 calculation, a series of data is needed containing a velocity zone where no penetration occurs, a zone where there is always penetration and, more importantly, a mixed zone. In this last zone, we expect results where there are both penetration and no penetration for the same velocity range.

To get the ED50, the Probit method [4,6] is applied. We first calculate a v_{50} and an Sv_{50} (standard deviation of the v_{50}). Knowing the projectile mass and diameter, we then calculate ED50. Equation (1) relates ED to v ,

where m is the projectile mass (kg), v is the projectile impact velocity (m/s) and S is the projectile frontal area (m²).

$$ED = \frac{0,5.m.v^2}{S} \quad (1)$$

The calculation of the frontal area S is misleading. It seems initially quite obvious but can give different results. First, the diameter can be chosen between the real projectile diameter and a reference one. For our 12-gauge projectile, it could evolve between 17,91mm (measured) and 18,5mm (12-gauge reference). Afterwards, it could even be smaller because of the partial penetration of the projectile in the Gelatin. For this reason, we suggest using a reference diameter. Also, it makes easier the extrapolation of the calculation to deforming projectiles (for which the diameter is variable during impact).

III. RESULTS

Several tests were conducted with the prescribed RB1-FS projectile and the results were calculated. An example of v_{50} curve is presented in figure 7. The 13 black dots represent the individual results: penetration (1) or no penetration (0). These data are then processed to obtain the curve. The 50%-probability value is 137,7m/s with a sv_{50} of 2,1m/s. The calculated ED50 (diameter of 18,5mm) is 23,63 J/cm², which is quite close to the expected 23,99 J/cm².

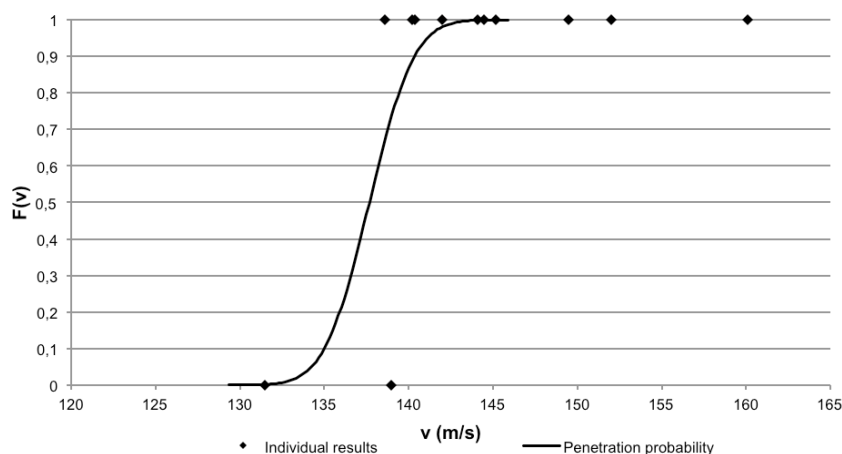


Fig. 7. Probability of penetration in function of impact velocity for the RB1-FS projectile (2nd test in table II)

Table II gives a summary of the four tests we conducted in the same nominal conditions. We can clearly see that the ED50 is always around the expected value and that its dispersion remains limited.

# shots	ED50 (J/cm ²)	σ -ED50 (J/cm ²)
14	24,23	1,34
13	23,63	0,72
10	23,46	1,50
14	23,46	0,98

Figure 8 shows ED50 for the conducted tests and the uncertainty around 3σ . The average ED50 is $23,70 \text{ J/cm}^2$ and quite consistent with the expected $23,99 \text{ J/cm}^2$.

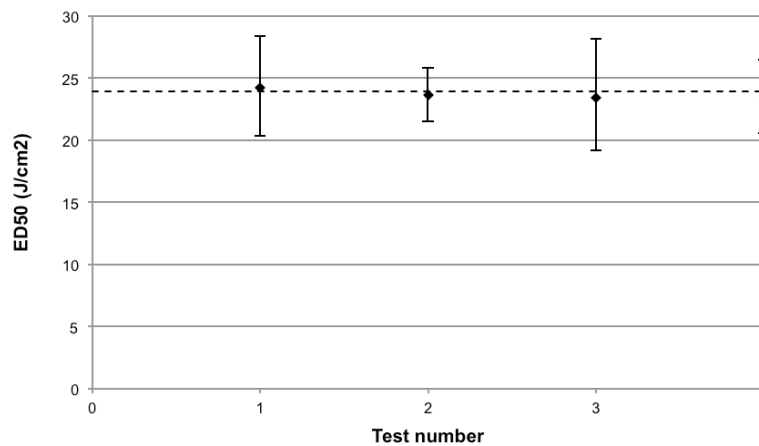


Fig. 8. Individual ED50 results (with 3σ uncertainties) and $23,99 \text{ J/cm}^2$ target value

IV. DISCUSSION

The presented results show a pretty good agreement between the proposed protocol and the previous PMHS tests summarized in table I. The average ED50 calculated from the surrogate test results is 1,2 % below the target value. Moreover, there are no values or data in [1] concerning the uncertainty linked to the measurements. The study's first goal – having a surrogate and a protocol that allows the skin penetration assessment of blunt projectiles – was achieved.

Furthermore, the statistical analysis of the ED50 calculation showed that the uncertainties are well limited, although more tests need to be conducted to ensure that the test-to-test reproducibility remains acceptable as the first four results seem to show.

The weakest point of this protocol is certainly linked to the availability of its components. There is no problem with the PAL - 20% ballistic gelatin block. It is widely used in various NATO countries for assessing the effects of lethal projectiles. Basic materials are available and preparation protocols are known.

The story is quite different for LAL. The outer layer is natural chamois. A product collected from a natural source cannot ensure perfect reproducibility. Furthermore, its thickness needs to be measured and compared to the proposed 1,39mm. The first problem is to find a suitable method to measure accurately the thickness of a soft material whose thickness changes when compressed (most thickness-measuring systems are based on plates pushing on the material). The second one is that every chamois material we used was below 1,39mm (and probably around 1mm). The thickness value of 1,39mm must be validated since the results seem acceptable.

The closed-cell foam used in the LAL is also problematic. It was originally designed for manufacturing toys. If toy manufacturing evolves, the future availability of the foam in its current form and any changes in its fabrication process that could affect its response behavior in our research is uncertain.

Future work needs to address the uncertainties of the surrogate adaptation. Replacing the natural chamois by a synthetic, controllable element and the current commercially available foam by a “generic” foam characterized by some calibration test are required.

The last point is related to damage assessment. The test results rely on the definition of what penetration means on the PAL. Figure 6 shows the difference between a crack and no crack on the gelatin. The difference

may seem obvious but practically it is sometimes not the case (for example, some chamois residue can be erroneously seen as micro-cracks). A clear definition of what penetration means should be added to the protocol to avoid “false-positives”.

V. CONCLUSION

This paper is scientific evidence that a cheap surrogate can accurately be used for the skin-penetration assessment of blunt impacts. The surrogate is made of natural chamois, closed-cell foam and ballistic gelatin. Firing non-lethal RB1-FS rounds on it showed a good correspondence with PMHS results based on the same projectile. A statistical analysis supports the results and addresses the uncertainties linked to the measurements.

Some issues still need to be addressed such as availability and controllability of the surrogate basic components. These points will be further investigated and reconciled and the surrogate will be adapted accordingly.

VI. ACKNOWLEDGEMENT

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