Biokinetics

Skin Penetration Assessment of Less-Lethal Impact Munitions - ARWEN AR40-1 Munition

Report No.:	R24-11
Date:	2024-11-15
Contract No.	P24-93
Status:	Commercial in Confidence
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Preface

This report provides the background and context of a skin penetration assessment methodology for less-lethal kinetic energy impact munitions. The NATO STANREC 4744, Standard AEP-94, is considered to be the preeminent skin penetration test method to evaluate penetrating trauma and is discussed with reference to its basis, safety inferences, and relation to the current state-of-science for injury assessment.

This report is intended to accompany the test methodology and evaluation programs conducted by Biokinetics for less-lethal kinetic energy munitions.

A summary of thoracic skin penetration assessment with the KWESST ARWEN AR40-1 impact munition is provided in the corresponding test report (Biokinetics' Test Report: TR2436 KWESST.pdf, dated Sep. 17, 2024).

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Glossary

Acronym	**Description**
AEP	Allied Engineering Publications
ASTM	American Society for Testing and Materials
NLKE	Non-Lethal Kinetic Energy
NSO	NATO Standardization Office
STANREC	STANdardization RECommendation

1. Overview

This report is intended to provide a basis of the test methodologies used in assessing potential injuries from less-lethal kinetic energy impact munitions. Reference to published information from the standards groups and the scientific literature are provided summarizing the scientific basis for decisions, interpretations, and implementation of the methodologies for less-lethal munitions.

Guidance and context is usually required in the interpretation of injury risk evaluations as not all injury mechanisms, modes, severities, threat types, impact velocities and subject differences (anatomical, age, sex, clothing) have been fully characterized to represent the range of possible outcomes. As such, most current test methods highlight the conditions under which they were derived so that validity can be better assessed. For example, while the STANREC AEP-94 standard for skin penetration assessment has been based on a wide range of threat types and biomechanical test conditions, there have been advances with munition designs that may fall outside the studied test conditions. The scientific experts will, therefore, note these limitations to make the reader aware of these when interpreting their data. This also helps to identify areas of future research that are required to complete our understanding of injury outcomes and to assist in making evidence-based decisions for their selection and use.

The report starts with a brief introduction of impact munitions, their intended function, potential injury risks and external factors that affect their end effectiveness. This is followed by a summary of standard test methods, their methodology and limitations when evaluating injury risks. Finally, a summary of the current test results is presented in the context of the background materials.

2. What are Less-Lethal Impact Munitions

Less-lethal impact munitions are used by law enforcement and corrections agencies to carry out a number of functions including, but not limited to, dispersing/controlling unruly crowds, dissuading individuals from further aggression through incapacitation, and to ensure continued safety of the officers or general public. Less lethal weapons are integral to the use-of-force continuum[1] in the military peacekeeping role and law enforcement community where non-lethal options are desired before the escalation to lethal options. The intended consequences of less lethal weapon use is that any adverse effect or injury sustained by individuals are fully reversible with low risk of permanent injury or loss-of-life [Koene et al., 2008].

A survey of law enforcement agencies confirmed the operational effectiveness of less lethal impact munitions with over 90% of encounters being resolved without the use of lethal force but some injuries resulted ranging from minor to fatal [NIJ 2004]. While the details of the weapon, conditions of use, injury outcome and victim characteristics were documented, additional details of the event and continuing surveillance by agencies is required to better understand the in-field consequences of this type of deterrent. However, a full understanding can only be realized when complimented with the scientific study of munition interactions, injury modes, human tolerances and influencing factors (e.g. age, sex, anthropometry, clothing).

The terms *non-lethal*, *less-lethal*, and *less-than-lethal* have been used interchangeably to describe impact munitions, and while intended to infer that they are not lethal, the terms carry different connotations. Non-lethal weapons are intended to minimize the likelihood of causing a fatality or permanent injury, whereas less-lethal or less-than-lethal weapons acknowledge that while they are designed to be less harmful than conventional weapons, they still carry a risk of serious injury or death. The distinction reflects an understanding of the inherent risks associated with the use-of-force continuum. The military may prefer the term "non-lethal" to emphasize the intent to avoid casualties, while law enforcement agencies might use "less-lethal" to acknowledge the potential for unintended harm, which also reflects the realities of a society where the consequences of weapon use are closely scrutinized. This terminology is important in the context of rules of engagement and the use-of-force, as it guides both the strategy and the ethical considerations of employing such weapons in various situations.

[1] https://nij.ojp.gov/topics/articles/use-force-continuum

Among non-lethal weapons, impact munitions, also known as Non-Lethal Kinetic Energy Weapons (NLKEW), have evolved over the years as law enforcement agencies, military and industry gained experience with their use and effectiveness. A brief summary of impact munition types is presented in the continuum of contemporary less lethal weapons by Bunker (1999) and within the fielded and developmental weapons in the Non-lethal Weapons Reference Book (2011) as well as other public sources[2].

Current commercial impact munitions come in various forms including single or multiple rubber balls, baton rounds, frangible capsules, fin stabilized projectiles, bean bags, and 40 mm diameter rounds, some of which are depicted in Figure 1. Regardless of the technology available, it is important to understand the effect of the munition's impact characteristics on injury risk and the conditions under which they are used.

Examples of munition characteristics used to mitigate injuries are the selection of stiffness and contact area for a given mass and caliber. This has been realized with the 37mm dia. Attenuating Energy Projectiles (AEP) [Smith et al. 2019] having a tuned nose stiffness to deform upon contact with the skull but not in areas of soft tissue such as the abdomen in order to maximize operational effectiveness and reduce the risk of serious injuries. Other examples include a collapsing nose with expanding head to dissipate impact forces such as the 40mm diameter BIP[3].

Figure 1: Sample of impact munitions.

[2] Wikipedia, Non-lethal Weapon, https://en.wikipedia.org/wiki/Non-lethal_weapon.

[3] https://biplesslethal.com/bip-s-1000

The final selection of impact munition is typically made by the governing agency with consideration of numerous factors including: operating environment, perceived threats, deterrent effectiveness, targeting accuracy, acceptable injury risks, training needs, launcher requirements, availability, associated costs of implementation, field experience, and compliance with policy, strategic, social, political, ethical and legal requirements.

3. Real-world Injuries from Impact Munitions

The study of injuries from impact munitions is problematic due to the limited surveillance mechanisms, limited access to medical details and weapon use, and potentially sensitive nature of the data. While the cause and effect of NLKE injuries is not fully known, insight can be gained from injury studies collected to date. For example, a study conducted by the National Institute of Justice, documented 969 shots with impact munitions that were collected across 106 law enforcement agencies in the US [NIJ 2004]. Out of these, there were 373 incidents of injury reported with eight fatalities. Five of the fatalities were attributed to chest impacts at standoffs of <10 m (30 ft) and typically involved rib fractures with subsequent lung/heart penetrations. The type of impact munition used primarily included bean bags (65%) and plastic batons (28%) with subjects ranging in age from 18-68 years, mostly males. The impact sites in general comprised the abdomen (34%), chest (19%), legs (15%), arms (14%), back (11%), head (2%), and neck or groin (1%). Furthermore, there were 782 injuries documented consisting of bruises (51%), abrasions (31%), serious lacerations (5.5%), fractures (3.5%), and skin penetrations (1.8%).

While the above study is not definitive, it highlights that many body regions are subject to impacts with the majority to the body's core and that more vulnerable impacts to the head or neck were relatively infrequent. With the impact locations depending partly on the weapon's accuracy and biases introduced by training and operational protocols, it can also be noted that these differences may lead to varying severities of injury depending on the specific tolerance of the body region being struck. The scientific literature has noted significant differences in injury modes and tolerances to the skeleton (e.g. ribs, sternum), soft tissue (eg. abdominal), and underlying critical organs (heart, lungs), especially when penetration occurs.

Additional injury case studies involving direct strikes from batons and other less-lethal munitions have started to provide greater insight into the risks and severity of injures from less-lethal munitions. Injury severities from minor to fatal have been documented in the literature for 12-guage beanbag rounds [Olsen et al. 2020, Charles et al. 2002, Grange et al. 2002, Wawro et al. 2002] and for the 37mm diameter AEP [Smith et al. 2019].

Additional less-lethal impact munition injuries were documented during recent US events and include, in part, blindness, TBI and other injuries (Kaske et al. 2021) and primarily involved rubber bullets. Forty percent of the injures were to the head, face and neck areas.

A systematic review of kinetic impact munitions from 1990-2017 was carried out by Haar et al. (2017) which involved rubber bullets, plastic bullets, batons, bean bags, shot pellets and others when used in protests and arrests, among other situations from global events. Within the selected studies, a total of 1984 people suffered injuries comprising 53 fatalities (3%) and 300 (15%) suffering permanent disability. Head and neck strikes were mostly associated with fatalities (49%) and disability (83%) primarily involving vision loss with secondary injuries to the abdomen and limbs. A total of 1931 individuals who survived their injuries (2135 in number) were associated with either multiple bullets or a single bullet causing multiple organ injuries. 71% of these injuries were considered severe and involved the head, neck, eyes, nervous, cardiovascular, pulmonary, thoracic, abdominal and genital systems. Skin injuries were frequent (77%) but of minor severity compared to the musculoskeletal injuries to the limb which were deemed to be severe. Projectiles constructed with metal cores, or all metal, bean bags and plastic impregnated with metal particles were associated with 1219 (57%) of the injuries. Inaccuracy of the rubber/plastic bullets used was cited as a contributing factor to injury risk and disability in addition to the anatomical impact site, short target distance and access to medical care.

Penetrating injuries have also been documented to occur to the thorax, lungs, limbs and head (Thakur et al. 2013, Marrufo et al. 2019, Guenther et al. 2020, Hill et al. 2010, Hubbs et al. 2004, Olsen et al. 2020), with some resulting in fatalities. Skeletal fractures are also associated with kinetic munition impacts with some resulting in fatalities especially when fractured ribs penetrate the heart and/or lungs (Hubbs et al. 2004). In all cases, the impacted body region, engagement distance, and type of round used are often noted as contributing factors to injury.

As a broader knowledge base is gained reflecting the contributions of current impact munitions, subject differences and operational affects, our understanding of injury risks and tolerances will further guide their development and guidelines for use. For now, it is important to be aware of the study limitations to not overgeneralize observations or recommendations. Additional consideration of the standoff distance and impact speed is important to establish safe operating guidelines. This was supported by multiple studies where impacts at close proximity were often associated with bone fractures, penetrations or fatalities. Operationally, controlling standoff distance through rules-of-engagement seem straight forward but the exact critical safe distance will be dependent on the munition's speed, mass, stiffness and shape resulting in unique guidelines for each weapon/munition combination. The subject characteristics, social, political and agency factors will also affect the guidelines and, hence, injury risks, as mentioned previously.

4. Operational Considerations of Less-lethal Munitions

Impact munitions or non-lethal kinetic energy weapons are devices that use physical force to incapacitate or deter a target without causing fatal injuries. Impact munitions can be used by law enforcement agencies to control riots, disperse crowds, or subdue violent suspects. However, they also pose significant risks of injury, trauma, and misuse. Therefore, law enforcement officers receive proper training and guidelines to ensure safe and effective deployment of impact munitions.

The burden of ensuring safety of the impact munitions is shared between the manufacturers to provide safe designs and the users who have a responsibility ethical and safe use. To this end, today's law-enforcement officers are highly trained professionals who follow the best practices for training and deployment of less-lethal weapons.

Training in the use of non-lethal weapons is a crucial aspect of law enforcement and security personnel preparation. Here is a typical outline of what such training involves:

1. **Familiarization**: Officers are introduced to various types of less-lethal weapons, including tasers, pepper spray, batons, rubber bullets, bean bag rounds, and conducted energy devices (CEDs). They learn about the mechanics, capabilities, and limitations of each weapon.
2. **Legal and Policy Considerations**: Training emphasizes the legal and policy frameworks governing the use of less-lethal weapons. This includes understanding when it is appropriate to deploy these weapons, the level of force permitted in different situations, and the potential legal consequences of misuse.
3. **Safety Protocols**: Officers are trained in safety protocols to minimize the risk of injury to themselves, their colleagues, and the public when handling and deploying less-lethal weapons. This includes proper handling techniques, storage procedures, and guidelines for assessing the environment before deploying a weapon.
4. **Effective Deployment**: Officers learn techniques for effectively deploying less-lethal weapons in various scenarios. This involves understanding the range, accuracy, and impact of each weapon, as well as tactics for gaining compliance from subjects.
5. **Decision-Making Skills**: Training focuses on developing officers' decision-making skills to assess threats and determine the appropriate level of force needed in a given situation. This includes evaluating factors such

as the severity of the threat, the presence of bystanders, and the subject's behavior.

6. **De-escalation Strategies**: While less-lethal weapons are designed to minimize harm, officers are trained to prioritize de-escalation whenever possible. They learn verbal communication techniques and strategies for defusing tense situations without resorting to force.
7. **Scenario-Based Training**: Officers undergo realistic scenario-based training exercises that simulate potential use-of-force situations. This hands-on training allows officers to practice deploying less-lethal weapons in a controlled environment and receive feedback on their performance.
8. **Aftercare and Reporting**: Following the use of a less-lethal weapon, officers are trained to provide immediate aftercare to any injured parties and to report the incident according to departmental protocols. This includes documenting the circumstances leading up to the use of force and any injuries sustained.
9. **Continuing Education**: Less-lethal weapons training is an ongoing process, with officers receiving regular refresher courses and updates on new techniques, equipment, and legal developments.

By providing comprehensive training in the use of less-lethal weapons, law enforcement and security personnel can effectively mitigate threats while minimizing the risk of serious injury or loss-of-life.

When using less-lethal force, law enforcement and security personnel are trained to target specific areas of the body to minimize the risk of serious injury while still achieving their goal of subduing a subject. These target zones are chosen based on the principle of causing temporary incapacitation or pain without causing lasting harm. Here are some common nonlethal target zones:

1. **Lower Body**: Targeting the legs or feet can help incapacitate a subject by restricting their movement without causing serious injury. Strikes or shots to the legs can disrupt balance and make it difficult for the subject to flee or continue aggressive behavior.
2. **Torso (Non-Vital Areas)**: Strikes or shots to the torso can be effective in causing pain or discomfort without posing a significant risk of serious injury. However, it's crucial to avoid targeting vital organs or areas where the risk of injury is higher.
3. **Upper Arms**: Targeting the upper arms can impair the subject's ability to use weapons or resist arrest without causing significant harm. Strikes or shots to this area can temporarily weaken the subject's ability to move or manipulate objects.

4. **Shoulders**: Striking or targeting the shoulders can disrupt the subject's balance and mobility without causing lasting harm. This can be particularly useful in preventing the subject from using their arms effectively.
5. **Buttocks**: In some cases, targeting the buttocks with less-lethal rounds (such as bean bag rounds) can be effective in causing pain or discomfort without causing serious injury. However, this should be done with caution to avoid causing unnecessary harm.
6. **Muscle Groups**: Targeting large muscle groups, such as the quadriceps or deltoids, can be effective in causing temporary incapacitation without causing significant injury. Strikes or pressure point techniques applied to these areas can help control the subject's movement.
7. **Sensitive Areas (With Caution)**: While targeting sensitive areas such as the groin, eyes, head or throat may be effective in rapidly incapacitating a subject, it should be done with extreme caution due to the increased risk of causing serious injury. These areas are generally considered as a last resort or in situations where there is an imminent threat of serious harm to officers or bystanders.

It's essential for law enforcement and security personnel to receive comprehensive training in less-lethal force techniques, including target selection, to ensure they can effectively subdue subjects while minimizing the risk of causing unnecessary harm. Additionally, officers should always prioritize de-escalation and use less-lethal force only when necessary and proportionate to the threat posed.

Police use-of-force guidelines typically outline the principles, procedures, and limitations governing when and how law enforcement officers are authorized to use force in the performance of their duties. These guidelines are designed to ensure that force is used only when necessary and in a manner that is proportional to the threat encountered. While specific guidelines may vary between jurisdictions and law enforcement agencies, they often include the following components:

1. **Use-of-Force Continuum**: Many agencies employ a use-of-force continuum, which outlines a series of progressively more intense actions that an officer may take in response to escalating levels of resistance or aggression from a subject. This continuum typically begins with officer presence and verbal commands, followed by empty-hand control techniques, intermediate weapons such as batons or tasers, and finally, lethal force as a last resort.
2. **Imminent Threat**: Officers are generally authorized to use force only in situations where there is an imminent threat of harm to themselves, other

individuals, or the public. The level of force used should be reasonable and necessary to neutralize the threat.

3. **Proportionality**: The amount of force used should be proportionate to the level of resistance or threat encountered. Officers are trained to use only the amount of force necessary to achieve their lawful objectives and to discontinue the use of force once the threat has been neutralized.
4. **Objectively Reasonable Standard**: The use of force is evaluated based on an objectively reasonable standard, considering the facts and circumstances known to the officer at the time of the incident. This standard takes into account factors such as the severity of the alleged offense, the level of resistance or aggression exhibited by the subject, and the availability of other options for resolving the situation.
5. **Verbal Warnings and Commands**: Officers are generally required to issue verbal warnings and commands before using force whenever possible. This provides subjects with an opportunity to comply with lawful orders and can help to de-escalate potentially volatile situations.
6. **De-escalation**: Officers are trained to use de-escalation techniques and tactics to reduce the likelihood of force being necessary. This may involve active listening, empathy, and attempts to establish rapport with individuals in crisis.
7. **Reporting and Documentation**: Any use of force by an officer must be promptly and accurately documented in accordance with departmental policies and procedures. This typically includes completing a use of force report detailing the circumstances of the incident, the level of force used, and any injuries sustained by the subject or officers involved.
8. **Training and Supervision**: Officers receive regular training in the use of force and are supervised to ensure compliance with departmental policies and procedures. Supervisors play a critical role in reviewing use of force incidents, providing feedback and guidance to officers, and identifying any training needs or areas for improvement.
9. **Accountability and Review**: Use of force incidents are subject to review by internal affairs departments, oversight boards, or other independent bodies to ensure compliance with policies and procedures. Officers who misuse force may be subject to disciplinary action, including termination or criminal prosecution, depending on the severity of the misconduct.

Overall, police use-of-force guidelines are intended to balance the need for officers to protect themselves and others with the fundamental principles of respect for human rights and the rule of law. By providing clear standards and expectations for officers, these guidelines help to promote accountability, transparency, and public trust in law enforcement agencies.

5. Safety Evaluation of Non-lethal Kinetic Energy Impact Munitions

Less-lethal impact munitions may be used to control threatening crowds or individuals in advance of using lethal force. Evaluation of their safety must be consider their intended performance to immobilize subjects, the operating conditions under which they are used, and the regulatory and procedural requirements stipulated by the organization responsible for their implementation.

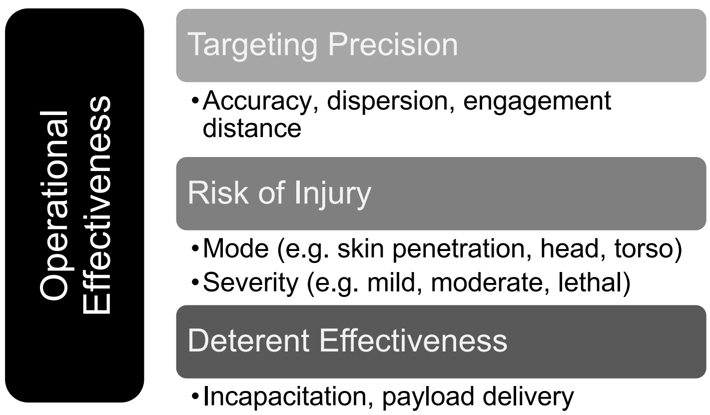

Figure 2: Factors in determining operational effectiveness of less-lethal munitions.

For non-lethal kinetic energy (NLKE) impact munitions, their operational effectiveness is dependent on several factors including those in

The outcome of any one of the factors is dependent on the distance of engagement with the targeted person having associated minimum and maximum distances for optimal performance. However, the optimal distances vary for each factor and a balance is typically required to establish the recommended operational range as shown in the illustration below.

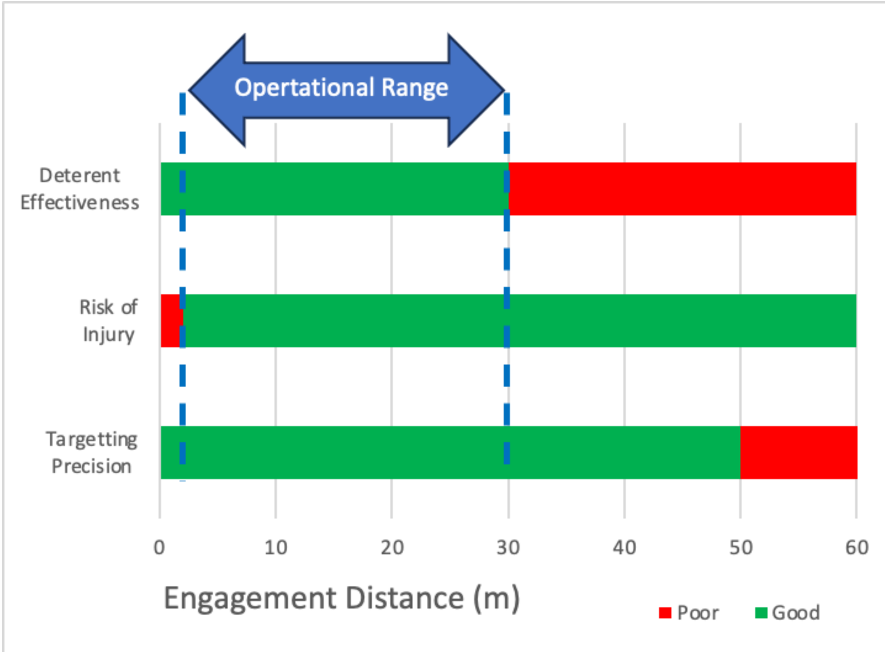

Figure 3: Illustration of operational range for effective engagement.

Each performance factor must be evaluated to quantify the range of engagement using scientific methods where possible to provide confidence and traceability of the results. As such, standards organizations and scientific agencies have developed test methods and performance metrics for NLKE impact munitions over the past decades to provide the needed confidence and traceability as well as a consistent means to assess performance, whether it be targeting precision or injury risk. This need has been realized with the publication of the NATO Standardization Office (NSO) list of recommended test methods to assess the risks of using NLKE impact munitions across the full spectrum of operational requirements, mission areas and operating environments. The test procedures are grouped under the "STANdardization RECommendation STANREC 4744 - Risk Assessment of Non-lethal Kinetic Energy Projectiles" and includes the following four Allied Engineering Publications (AEP) [NATO 2021a, NATO 2021b, NATO 2021c, NATO 2021d], Figure 4

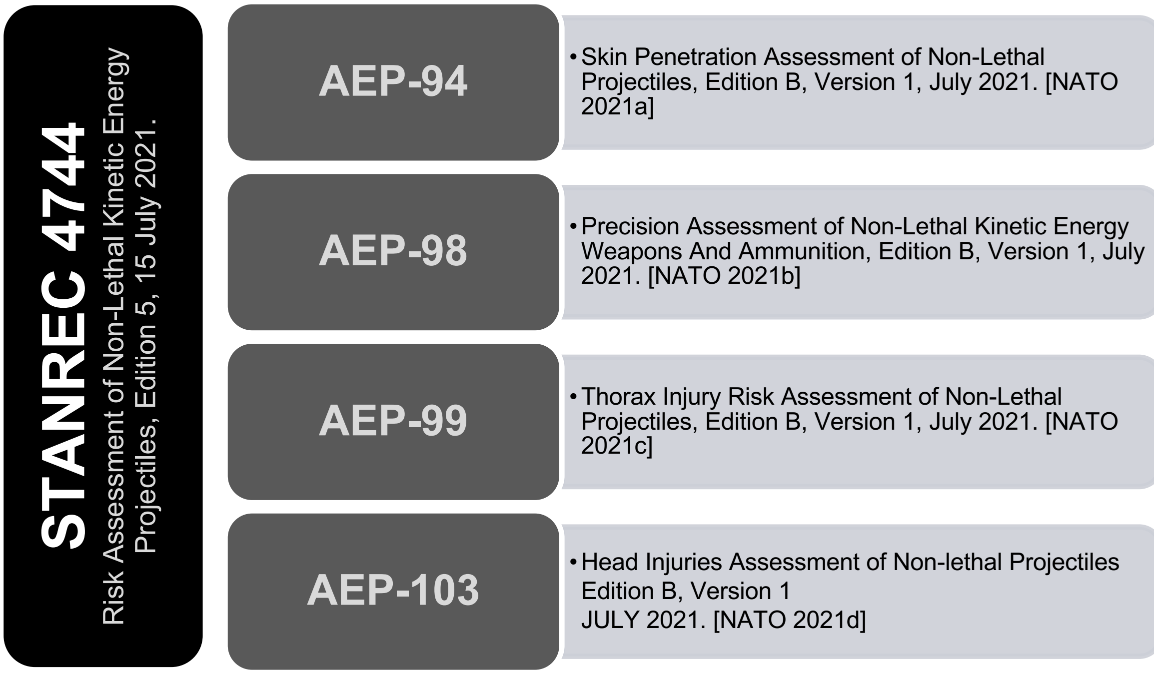

Figure 4: Test and evaluation methods provided under NATO STANREC 4744.

The AEP publications are intended to standardize the evaluation methodology for each performance aspect with thresholds suggested or referenced. However, it is the responsibility of the agency utilizing the publication to establish suitable performance criteria meeting their specific operational objectives. Furthermore, the publications are not meant to be prescriptive with regard to the technical operating procedures used, but instead, they are meant to identify suitable performance metrics and the typical means by which these can be obtained with consideration to applicability and reproducibility in order to inform decision makers and risk management processes. It may also be noted that while NATO STANREC 4744 outlines criteria and thresholds for each assessment, they also acknowledge that there are inherent uncertainties and limitations in the data and models used, and that the results should be interpreted with caution and expert judgment.

Other organizations, such as the ASTM E54 Committee on Homeland Security Applications are also developing voluntary consensus-based standards for the testing and evaluation of non-lethal kinetic energy projectiles (https://www.astm.org/). The standards are initiated and formalized through working groups attended by stakeholders, and upon completion, are published as a formal test methods for reference by regulating agencies. The scope of evaluation is currently limited to targeting precision and energy measurement with the publication of the following standard:

- **ASTM E3276/E3276M-21**[4], Standard Test Method for Assessing Impact Energy and Precision of Direct-fire, Single-projectile Less Lethal Impact Rounds Used by Public Safety Officers

Additional efforts are underway to further define test methods for penetration risk and thoracic blunt trauma assessment but are at the initial stages of development. Development of these standards are the responsibility of working groups attended by law enforcement user representatives, regulators, scientists, practitioners and standard's bodies. The following working group is responsible for the less-lethal impact munitions effort:

- **ASTM WK70043**[5], New Specification for the Safety of Targeted Individuals During Deployment of Less Lethal Impact Devices used by Law Enforcement

In the absence of timely standardized and prescriptive test procedures, research agencies, test laboratories and industry may resort to internal technical operating procedures to ensure consistency, traceability and confidence in the test results. One such procedure, Biokinetics' Document Biokinetics and Associates Ltd.-NLKEA-01 "Non-Lethal Kinetic Energy Ammunition -Performance Test Protocols", was developed by incorporating the technical requirements of STANREC 4744 AEP-94[6] but with additional consideration of internal test procedures encompassing equipment setup, validations, sample preparation and testing, along with quality management and reporting practices.

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[4] https://www.astm.org/e3276_e3276m-21.html

[5] https://www.astm.org/workitem-wk70043

[6] Biokinetics and Associates Ltd., "Standard Operating Procedure for NATO Standard AEP-99 - Thorax Injury Risk Assessment of Non-lethal Projectiles", Document: BAL AEP-99 SOP, Edition B, Ver. 1, 2024.

6. Skin Penetration Assessment of NLKE Impact Munitions

NLKE weapons can cause a range of injury severities with the more serious ones including open skin lacerations and penetrations such as to the head and thorax when beanbags are used [Olsen et al. 2020, Hubbs et al. 2004]. The mode and severity of the injuries are partially related to the engagement distance which influences the impact speed, and to the projectile characteristics with primary factors including the projected contact area, mass, velocity, stiffness and shape of the impact face.

Assessing the risk of skin perforation requires that the target, or surrogate, possesses human-like (*i.e.* biofidelic) properties in terms of penetration resistance of the skin and compliance of the underlying tissues [Keone et al. 2008]. The degree of any laceration/penetration of the skin and/or underlying tissue disruption can then be related to a severity of injury in a qualitative sense. i.e. penetration or no-penetration.

Alternatively, a surrogate that is able to measure the kinematics related to the insult from impact (*e.g.* force, compression) and correlate this to skin penetration may also be used to quantify the risk of penetration. This approach requires the surrogate to be biofidelic to ensure dynamic equivalence and to be robust enough for repeated use without sensor damage. Unfortunately, no such surrogate has been developed to date limiting the ability to assess skin penetrating risk.

6.1 AEP-94 - Skin Penetration Assessment Test Method

The scope of the AEP-94 test method is to quantify the risk of skin penetration of non-lethal projectiles based on impacts to a surrogate with associated penetration criterion from non-lethal projectile impacts on post mortem human subjects (PMHS) [NATO AEP-94 2021a, Robbe et al. 2023]. The surrogate is intended to be realistic in terms of skin and penetrating characteristics and has been validated with a 12 gauge fin-stabilized rubber less-lethal projectile (6.4g, MK Ballistic Systems RB1-FS) fired on PMHS [Bir 2005, Bir 2012, Papy 2012]. The degree of tissue penetration of the NLKE is inferred through observation of gelatine damage with or without skin penetration. Marks on the gelatine with cracks is defined as a penetration regardless of the damage to the skin or underlying layer. A typical experimental test setup is shown in Figure 5.

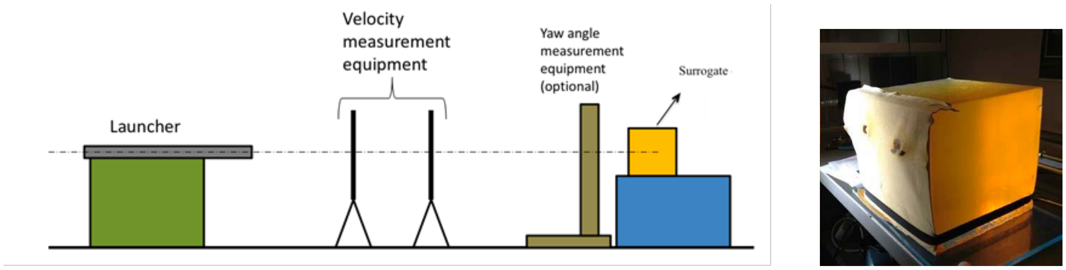


Figure 5: Experimental setup for skin penetration assessment with chamois-foam-gelatine surrogate [reproduced from AEP-94].

The test surrogate is made of 20% ballistics gelatine representing the subcutaneous tissues (hypodermis). The stiffness of the gelatine is controlled by temperature, normally specified to be 10˚C in AEP-94. Biokinetics has sourced an alternative 20% gelatine block[7] that is stabilized with additives allowing the block to be used at room temperature while still complying with calibration requirements, defined by shooting a 4.5 mm copper plated lead ball at a prescribed velocity and meeting the penetration depth targets. Restrictions on the available testing time period due to warming of the gelatine blocks is therefore removed and ensures greater consistency between shots.

The gelatine block is typically covered by a chamois and foam layer representing the epidermis and dermis layers, respectively. After confirming gelatine block consistency prior to testing, the NLKE munition test is then performed to the manufacturer's specifications for speed and obliquity.

The use of chamois in AEP-94 has been recognized as a suitable replica of human skin for injury assessment but it has also been identified as a major source of variability by the NATO STANREC 4744 group [Robbe et al. 2023] responsible for AEP-94. The current AEP-94 methodology for assessing the occurrence of skin penetration requires a large number of tests (28) to obtain statistical confidence according to the Clopper-Pearson binomial theory. As a result, any variability in the test round or surrogate will require a greater safety margin to ensure compliance, achieved by lowering the impact velocity for a specific round. Improved confidence in test outcome of the surrogate was obtained in an investigation conducted for Defence Research and Development Centre (DRDC) by Biokinetics [Anctil 2013] with the replacement of chamois with a synthetic skin (polyurethane film Tuftane™, 400 μm thickness) which was shown to assess the velocity at which there is a 50% probability of penetration (i.e. V50) equivalent to chamois, but with much greater consistency. While this approach is not yet adopted in the current version of AEP-94, it was recognized by DRDC (a NATO

[7] Ballistic Dummy Lab: https://ballisticdummylab.com.

STANREC 4474 member) and has therefore been proposed for use within the current evaluation until such time validated alternatives are available.

As mentioned previously, the required sample size is dictated by the degree of desired confidence in expected round performance, i.e. no penetration. According to binomial theory, where a sample size of 28 is associated with a 90/90 reliability specification (*i.e.*, reliability of non-penetration 90% of the time with a confidence better than 90%). In comparison, a 10 shot test series with sequential non-penetrating results is associated with a 90/74 reliability specification. The 10 shot series has been used for the current test series to provide initial assessment of skin penetration occurrence. A passing grade for the less-lethal impact munition is achieved when all 10 sequential shots do not exhibit any penetration.

Biokinetics experimental equipment is similar to that specified with details provided in Table 1. The NLKE munition launcher is replaced with a smooth bored barrel mounted to an air cannon capable of launching the projectile body (without cartridge) at equivalent speed and yaw conditions seen with a typical launcher. Projectile targeting is well controlled (<3 mm) as is yaw (<5˚) due to the short distance between the barrel and surrogate (387 mm). The shot targeting and yaw are confirmed independently prior to the beginning of a test series.

Table 1: Experimental equipment used to measure projectile parameters.

Description	Device
Projectile Speed	Biokinetics dual beam light gate located at the muzzle. Beam spacing 50.8 mm, sampling rate 10 kHz.
Projectile Yaw	High-speed video, 1000 frames/sec
Projectile Obliquity and Targeting	Dictated by alignment of the air cannon barrel and target, 90 degrees obliquity, +/-3 mm placement repeatability.

All tests are conducted at ambient temperature with the stabilized gelatine block. A total of two or more shots are conducted on each face of the gelatine block with assurance that there is no interaction with previous shots or influence from edge conditions. Upon completion of a test, the block is rotated to a new face and testing resumed with the skin and foam impacted at a new location. The best practices set out in BAL-NLKEA-01 test methodology were used to guide testing [Biokinetics 2014].

7. Skin Penetration Research

7.1 Skin Penetration Risk Studies

Skin penetration research in the context of less-lethal impact munitions is primarily focused on the risk to penetrating injuries to the hypodermis layer, the layer of tissue beneath the epidermis (skin) and underlying dermis. This deeper layer is associated with a higher risk of severe injuries due to the closer proximity of underlying vessels, organs and skeletal structure. The evaluation of penetrating injury risk, however, must involve the physical response of all three layers (epidermis, dermis, hypodermis) in order to provide realistic and representative interactions with the impact munitions including the resistance to penetration and local failure modes (laceration, rupture, evulsion) of the tissues. This approach has been used in the study of human skin penetration and in the development of injury assessment surrogates. The AEP-94 standard recognizes the surrogate developed by Bir et al. (2012) utilizing chamois, foam and 20% ballistic gelatine. Its injury assessment capabilities are based on the prior work of Bir et al. (2005) with cadavers and 12 gauge impact munition. Due to the desire for improving the repeatability of the surrogate and reflecting the latest research, the NLKE ToE are investigating recent research in this area including, in part, the work of Shedd et al. (2022) and Foley et al. (2023). Brief summarizes and findings of these studies are summarized below as these may impact future tests methods adopted in AEP—94.

7.1.1 Threat Assessment Metrics

Prior to the summaries, it will be important to note that the various studies have used different metrics to represent either the severity of the threat. The prominent metrics are reviewed to assist in their reporting:

SD (Sectional Density): It has long been established that the mass of a bullet and its presented area are indicative of penetrating potential. The ratio of this mass to area has been referred to as the Sectional Density (SD) and is often quoted to indicate the potential severity of a ballistic threat for penetrating wounds. This concept has since been adopted in the study of less-lethal impact munitions and it is important to note, however, that the penetrating mechanisms and resulting injury modes may differ from that of bullets.

The equation for SD is as follows:

$$SD = M / A$$

where:
M = mass of the projectile (g)
$A = \pi D^2/4$ (cm^2), the presented area of a projectile with diameter D (cm)

V (Velocity): A first approximation of an impact projectiles threat severity can be represented by its Velocity (V) as this relates to the momentum and energy transfer if the threat's mass is accounted for. But, without the inclusion of mass, the sole use of velocity is typically limited to a specific threat or category with similar characteristics.

ED (Energy Density): Not unexpectedly, Energy Density (ED) has been favoured for representing the injury causing potential of a threat. Energy is a measure that represents the capacity of the projectile to deform tissue and cause injury, and, when normalized by the presented area, it is applicable to a wider range of projectiles having different mass, velocity and presented areas. It is of the form:

$$ED = \frac{1}{2} M V^2 / A$$

where:
M = mass of the projectile (kg)
V = velocity of the projectile (m/s)
$A = \pi D^2/4$ (cm^2), the presented area of a projectile with diameter D (cm)

7.1.2 Skin Penetration Assessment Studies

The following are brief summaries of skin penetration injury studies that are either incorporated in the AEP-94 test method or are being considered by the NATO ToE for NLKE munitions.

Bir (2005) Skin Penetration Assessment of Less Lethal Kinetic Energy Munitions

The skin penetration tolerance of fresh cadaver subjects (4 male, 4 female, 58-80 yr, 52-84 kg, 155-174 cm) was evaluated for the front and back portions of the torso, abdomen, lower back and femur with 12 gauge rubber fin stabilized impact munitions (MK Ballistic Systems model RB-1-FS) having a SD=2.5 g/cm^2 [Bir 2005]. The lowest tolerance to penetration involving subcutaneous tissue damage was found to occur on the anterior rib with a 50% risk of penetration corresponding to an energy density of 24 J/cm^2. With regard to impacts to the to the abdominal area, as recommended by current operational protocols, the lowest tolerance was found to be 34 J/cm^2. A complete list of results is provided in Table 2. It was noted that the use of elderly cadavers likely provides a conservative estimate of penetration risk due to the degradation of the skin's physical properties with age. The AEP-94 suggested limit for 50% risk of penetration is based on the Bir (2205) study with an impact munition have an ED=24 J/cm^2.

Shedd 2022 The Risk of Skin Injury Caused by High-Rate Blunt Impacts to the Human Thorax

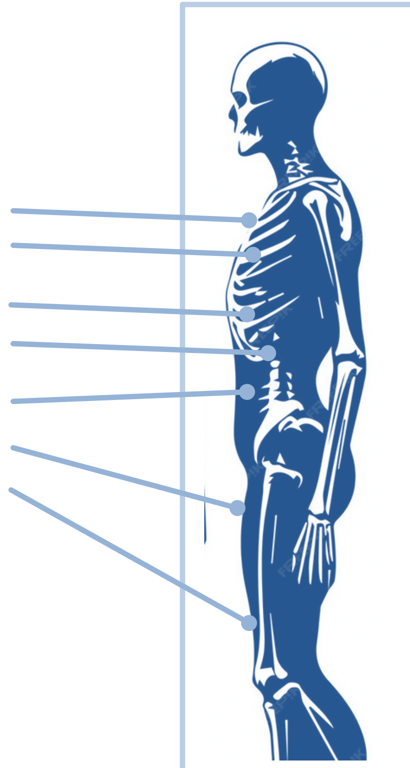
Recent studies have obtained greater insight into injury tolerance for a wider range of impact conditions from less-lethal ammunition. The risk of penetrating injuries has been assessed for impacts to the thorax for conditions of equal sectional density to help identify contributing factors [Shedd et al. 2021, Shedd et al. 2022]. The use of a fixed sectional density, i.e. the projectile mass normalized by the projected area, of 2.3 g/cm^2 was chosen to control the regime of less-lethal threats and is similar to that used in Bir (2005). Shedd et al. focused on projectiles of smaller caliber (13-25 mm dia), different impact face curvatures (flat cylindrical, spherical), various projectile masses (2.9-11.6 g) and impact speeds (60-167 m/s) [Shedd et al. 2022]. The injury risk functions that were developed showed sensitivity to projectile impact speed, impact location (due to skin thickness differences), projectile diameter, and contact face shape. Logistic regressions of the data were provided as a function of impactor speed. The estimates for 50% skin penetration risk were not tabulated in Shedd and further analysis is required to provide these estimates. Additionally, the risk of skin penetration expressed as a function of ED would be of interest for comparison with the data of Bir et al. (2005) and Foley et al. (2023) so that the effects of calibre and contact face shape can be ascertained.

Foley 2023 Evaluation of Skin Penetration from Less Lethal Impact Munitions and Their Associated Risk Predictors

Another recent, but preliminary study by Foley et al. (2023), assessed skin penetration risk under impacts with rubber ball projectiles of 16 mm and 25 mm diameters. Both impact speed and energy density were identified as predictors of skin penetration for most regions of the torso with the exception of the abdomen which was also dependent on body mass index. Interestingly, it was not possible to predict injuries to the sternum nor for the anterior thorax over a rib with statistical certainty, likely due to the small sample size. The complete results are provided in Table 2

Table 2: The risk of 50% skin penetration for various body regions based on ED.

	ED_{50} (J/cm^2)	
Impact Location	Bir (2005) RB-1-FS (SD=2.52)	Foley (2023) 5/8"Ø (SD=1.42) 1"Ø (SD=2.54) Rubber Balls
Sternum	33	20
On anterior rib	**24**	16
Between anterior rib	33	**22**
Liver	40	
Abdomen	34	**19**
Proximal femur	**26**	**13**
Distal femur	**28**	**13**
Scapula	**51**	**33**
On posterior rib	**53**	**34**
Lower back	**38**	**29**
(Note: **bolded** ED values indicates that statistical significance was reached.)		



While the above studies provide valuable insight into injury risks for common impact munitions, the applicability of the injury tolerances for different calibers, contact face shapes, compliances and SDs remains to be demonstrated and to obtain the consensus of the less-lethal scientific, technical and regulatory communities. Some of the limitations of the study are presented in the following sections.

7.1.3 Geometric Effects

Early studies of skin penetration risk have suggested that the sectional densities and energy densities of ballistic projectiles were predictive of skin penetration risk and had similar results across a range of pellets and bullets. More recent studies have suggested that differences exist based on projectile masses and velocities. The original work of Bir (2005) was based on a single impact munition, the MK Ballistic Systems' Model RB-1-FS, having a SD=2.5 g/cm^2 and quantified the penetration risk for several body regions. In subsequent studies by Folley et al. (2023) and Shedd et al. (2022), projectiles with the similar SD were used but different penetration risk levels were achieved. Shedd indicated that projectile caliber and shape (flat, spherical) can affect the injury risk[8], for the projectiles

[8] Shedd presented data based on velocity and not ED.

studied. The risk of penetration was greater for larger calibers and for spherical impact faces. This suggests that some of the differences between Bir et al. (2005) and Foley et al. (2023) could be attributed to these factors. If this were to be definitive, then penetration risk levels would be required for each impact munition, or alternatively, a different normalized metric could be used that would be applicable to a wider range of impact munition types. For example, an injury risk function developed by Shedd et al. (2021), utilized the caliber, shape and subject's skin thickness as predictive parameters as these were found to have the greatest predictive power for the projectiles studied. Anecdotally, it may be noted that field data with 40 mm impact munitions have shown a reduced occurrence of skin penetration risk compared to smaller caliber rounds [Robbe et al. 2023, Kapeles et al. 2019] but keeping in mind that there are also mass affects that need to be recognized.

Previous ballistic penetrations studies reported on by Ouellet et al. (2020) showed that the failure mode of the skin changes with stretching (tensile) failures at low SD and punch through failures (shear) with projectiles of higher SD. Furthermore, in a study of the skin's mechanical properties, it was generally noted that the measured stiffness of the skin when indented is reduced with increasing size of the indenter suggesting an influence of projectile caliber [Joodaki et al. 2018]. The same study highlighted that variations in the skin's physical properties will have a large effect on the mechanical response whether it is a difference in the thickness, stiffness, or elasticity. It is, therefore, important to note the cadaver's characteristics, body regions impacted and skin condition for the various studies presented previously and the implications when the findings are applied to the general population at risk.

7.1.4 Additional Confounding Factors

The presence of clothing has been noted to affect the operational effectiveness of NLKE impact munitions due to its added resistance [Robbe et al. 2023, Smith et al. 2019]. Similarly, Hubbs et al. (2004) noted that clothing likely affected injury risk but was not able to establish statistical significance due to the small sample size.

We will also note that the use of gyroscopic stabilization for improving targeting accuracy of some impact munitions has not been studied in the literature for potential to aggravate skin penetration. An independent study of ballistic projectile penetrations has shown that some rotational energy is transmitted to the body during ballistic penetration with increasing potential for tissue damage [Brass Fetcher Ballistic Testing[9]]. The implications to less-lethal impact munitions

[9] https://brassfetcher.com/Wounding%20Theories/Bullet%20SpinZZZ.html

remains to be shown but is likely to be affected by its available rotational energy (when gyroscopic stabilization is employed), nose shape, caliber and compliance.

7.1.5 Injury Assessments

While the risk of injury assessed in AEP-94 is consistent with field data, it likely overestimates the occurrence of skin penetration for average healthy and clothed adults, i.e. it is conservative due to the skin penetration assessment surrogate being based on the elderly population and with impacts onto bare skin [Robbe et al. 2023].

It can also be noted that the AEP-94 test method assesses skin penetration risk with a threshold test only where the performance of the round is qualified as a PASS if all impacts result in a non-penetration. The threshold at which failure occurs is dependent on the characteristics of the test surrogate, which for the AEP-94, is based on a penetration threshold of 50% {Robbe et al. 2023, Bir et al. 2012]. The requisite use of binomial sampling theory in AEP-94 dictates a need for 28 shots to ensure that the expected non-penetrating outcome of the impact tests are consistently below the threshold of 50% penetration with a high degree of confidence. The AEP-94 does not currently allow the actual percentage risk of penetration to be established on a graded scale.

7.1.6 Surrogate Development

Research is ongoing for surrogates to overcome some of the current operational and measurement limitations. This includes replacement of the ballistic gelatine due to the high fabrication time required and the short time available to conduct the tests prior to warming of the gelatine and subsequent change of results [Robbe et al. 2023]. Different gelatine formulations, synthetic variants and foam backings are being investigated and have not necessarily undergone rigorous validations for biofidelity, repeatability or inter-lab reproducibility. Biokinetics' current approach to address some limitations includes the use a stabilized 20% ballistic gelatine allowing for room-temperature testing and long shelf life while still complying with the calibration requirements and maintaining the injury assessing modes of ballistic gelatine.

Additionally, the AEP-94 test methodology maintains the use of a skin-foam-gelatine epidermis and dermis layers of the surrogate despite the repeated concern for test variability due to material inconsistencies. Efforts are under way to investigate the use or development of alternative materials that are more realistic and repeatable including polymer synthetics and bio-synthetics but require validation and acceptance. The concern for chamois variability has been partly addressed with Biokinetics' recommended use of a synthetic skin (Tuftane™) in place of the natural chamois which was shown to have similar performance to the Bir et al. (2005) study but with much lower variability [Anctil 2013]. Its applicability to different less-lethal impact munitions remains to be assessed, as with other candidates.

8. Test Results

The details of the AEP-94 skin penetration tests results are presented in Biokinetics' Report No. TR2436 KWESST with the salient data items summarized below.

8.1 Surrogate Calibration

The gelatine test surrogates were validated according to AEP-94. All blocks of gelatine complied with the requirements of AEP-94, see Table 3.

Table 3: Gelatine block validation results according to AEP-94.

Block ID	Shot	Velocity (m/s)	Penetration (cm)	AEP-94 Compliant
1	1	186	5.8	YES
1	2	191	6.1	YES
1	3	201	6.9	YES
2	1	211	7.9	YES
2	2	217	8.1	YES
2	3	208	7.8	YES
3	1	179	5.5	YES
3	2	185	5.7	YES
3	3	207	7.5	YES

8.2 Skin Penetration Assessment

The KWESST ARWEN AR40-1 impact munition was evaluated for skin penetration according to the methodology described above in Section 6. The results are provided in Table 4. The occurrence of skin penetration was seen for all tests.

Table 4: Skin penetration assessment results for the ARWEN AR40-1.

Serial No.	Fair Shot	Velocity (m/s)	Penetration	Notes	Location	Gel Block
1	Y	70.6	Y	gelatine cracked	1	1
2	Y	71.2	Y	gelatine scuffed, with some pitting	2	1
3	Y	71.5	Y	gelatine cracked	2	1
4	Y	71.1	Y	gelatine cracked	1	1
5	Y	69.0	Y	gelatine cracked	1	2
6	Y	70.4	Y	gelatine cracked	2	2
7	Y	71.2	Y	gelatine cracked	2	2
8	Y	69.9	Y	gelatine cracked	1	2
9	Y	71.5	Y	gelatine cracked	1	3
10	Y	70.9	Y	gelatine cracked	2	3

9. Test Summary

The ARWEN AR40-1 impact munition was evaluated for skin penetration per the requirements of AEP-94 employing the recommended alternative skin simulant and gelatine base to reduce test variability. All fair shots resulted in penetration as determined by the definitions in AEP-94 which state that any visible damage to the gelatine such as cracks or projectile penetration into the gelatine, with or without perforation of the external skin or foam layers, are considered penetrations [AEP-94, Robbe et al. 2023].

The ARWEN AR40-1 impact munition impacted nominally at 70 m/s (230 ft/s) presented a risk of skin penetration.

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