

The Wounding Potential of an Air Gun After Passing Through Clothing

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Abstract— This study presents a comprehensive evaluation of the wounding potential of 4.5 mm air gun projectiles after passing through common civilian clothing. The experiment was conducted in two phases: measurement of velocity loss during textile perforation and measurement of penetration depth in glycerin ballistic soap. Two projectile geometries (pointed and hollow point) and five clothing types were tested. Statistical analysis (Shapiro–Wilk, t-test, ANOVA) confirmed significant effects of clothing type and projectile geometry on velocity loss, penetration depth, and relative wounding potential (RWP). All clothing types allowed penetration depths exceeding 40 mm, and all measured energy densities surpassed the threshold required for human skin perforation. A mathematical model describing projectile–textile interaction was introduced, and measurement uncertainties were quantified using Gauss’s propagation law. The results demonstrate that clothing does not provide meaningful protection against air gun injuries and highlight the substantial wounding potential of low-energy air rifles. The study extends previous experimental work by integrating analytical modeling, statistical evaluation, uncertainty analysis, and comparison with published forensic ballistic literature.

Key words: — air gun ballistics; textile barrier; penetration depth; glycerin ballistic soap; kinetic energy; energy density; relative wounding potential (RWP); forensic biomechanics; terminal ballistics; measurement uncertainty; projectile geometry

I. INTRODUCTION

In contemporary security theory and practice, forensic sciences, and the field of forensic medicine, the issue of air weapons occupies a specific and often controversial position. The traditional view held by the general public, and in some cases also by professionals, has long categorized this type of weapon as a tool intended primarily for sporting activities, basic marksmanship training, or recreational shooting with minimal risk to human life. This historical stereotype, perceiving the air gun as a “toy” or a “youth training tool”, is, however, in direct contradiction with physical reality and empirical data provided by modern wounding ballistics [1].

A significant impetus for reassessing the social dangerousness of these weapons is, for example, technological progress, which has enabled the development of high-performance pneumatic systems (PCP).

Real incidents do not occur under laboratory conditions involving uncovered living tissue; rather, the projectile typically first overcomes a primary barrier formed by clothing. This interaction is not trivial: textile material may function as passive protection, but also as a factor complicating injuries through projectile destabilization or by introducing foreign particles into the wounding. Nevertheless, the scientific literature still lacks systematically quantified assessments of the wounding potential of air weapons specifically in combination with common civilian clothing [2].

In the past, the issue of the wounding potential of air weapons was frequently overlooked within forensic biomechanics in the shadow of lethal high-energy firearms. However, with the advent of modern pneumatic systems (PCP) and in light of legislative changes, this field has become the subject of intensive scientific investigation. Current research can be divided into two main streams: evaluation of penetration capabilities in uncovered tissue (or its simulant) and examination of projectile interaction with barrier materials, typically clothing [1], [3], [4].

Within the Czech Republic, the quantification of the wounding potential of air weapons has been addressed in recent years by several academic qualifications and scientific studies [5], [6].

In his bachelor’s thesis [6], the author focused on the evaluation of 4.5 mm caliber air rifles with muzzle energy approaching the limit of 16 J. Experiments involving firing into 10% ballistic gelatin demonstrated that these commonly available weapons are capable of causing deep penetrating injuries, with measured penetration depths at a firing distance of 1 m reaching up to 26 cm (JSB Exact Heavy ammunition). The calculated energy density (approximately $0.9 \text{ J}\cdot\text{mm}^{-2}$) unequivocally confirmed multiple exceedances of the critical threshold of $0.1 \text{ J}\cdot\text{mm}^{-2}$.

These conclusions were further expanded upon in study [5] which analyzed the influence of firing distance on the wounding potential while also using high-performance PCP-type weapons (5.5 mm caliber, energy approximately 40 J). The author confirmed that modern high-powered air rifles retain sufficient kinetic energy even at a distance of 50 m to penetrate human skin and cause lethal injuries. This work also confirmed the suitability of 10% ballistic gelatin tempered to 4 °C as an optimal simulant for low-energy projectiles.

A foreign study [7], published in 2025, provides current data on the penetration of 4.5 mm caliber projectiles through layers of textiles into ballistic gelatin. The authors confirmed that at energies around 11 J, air weapon projectiles are capable of penetrating the skin even through a clothing barrier, while the depth of the wound channel in the gelatin simulant decreased on average by 15–20 % in the presence of light clothing. Methodologically, this study represents the closest international reference point for the present article.

In the study [8], focused on ballistic skin simulants and investigated skin penetration by projectiles of various energy levels. The authors established that reliable penetration of human skin requires a projectile energy density of at least $0.1 \text{ J} \cdot \text{mm}^{-2}$, while for skin in the torso region this value may be 20–30% higher due to increased dermal thickness. These conclusions are also confirmed by another study [9]. The author's work thus provides empirical justification for the threshold value used in the present study.

The physics of projectile wounding effects on biological tissues at a general level was comprehensively addressed in seminal work [10], which summarizes the mechanisms of projectile energy transfer and parametrizes tissue behavior during the passage of projectiles of various energy classes [10], [11].

The issue of clothing as a primary barrier in relation to air weapons was analyzed in detail in the key international study [2]. The authors' ballistic experiments focused on 5.5 mm caliber pellets fired into gelatin blocks covered with various types of civilian clothing (cotton knitwear, denim, fleece). The authors arrived at several fundamental findings:

- Low-density knitted fabrics (T-shirt fabric) represent only a minimal obstacle for pellets. In contrast, denim forces the projectile to tear fibers apart, leading to substantial energy absorption and a drastic reduction in penetration depth within the simulant [2].
- Tightly fitting denim (positioned directly on the backing material) was more easily perforated, whereas loosely hanging denim acted as a catcher capable of stopping the projectile completely before contact with the tissue [2].
- Even when the projectile penetrates the clothing, it drags textile fiber fragments deep into the wound channel, thereby significantly increasing the risk of post-traumatic infections [2], [12].

The literature review clearly indicates that although the wounding potential of air rifles without clothing barriers

[5], [6] and the behavior of textiles under ballistic impact [2] have been relatively well documented, there remains room for follow-up research. Scientific interest in this area has increased significantly in recent years in the context of forensic biomechanics, forensic medicine, and legislative assessment. Wightman's foreign study worked with specific British 5.5 mm caliber weapons; therefore, considering the recent liberalization of the market in the Czech Republic and the high popularity of the 4.5 mm caliber, it is necessary to apply these findings to local conditions [2], [5], [6].

Significant findings regarding the terminal ballistic behavior of pellets penetrating simulants were presented in the study [13], which systematically investigated the behavior of air gun pellets in ballistic gelatin of various concentrations in 2010. Among other aspects, the authors tested firing through porcine bone inserted into the gelatin block and evaluated wound channel depth using CT imaging. The Authors demonstrated that pointed pellets penetrated the gelatin up to 50% deeper than spherical pellets at comparable impact energy. Furthermore, the Bloom value of the gelatin used was shown not to be a reliable indicator for predicting the behavior of a specific projectile. This study is particularly relevant as a comparative basis for evaluating the behavior of pointed versus expanding pellets used in the present study [10], [13].

The most recent available study directly comparable to the present experiment is study [7], focused on the penetration of 4.5 mm caliber pellets into porcine tissue and ballistic gelatin at energies ranging from 3.28 to 15.71 J. The authors found that weapons with muzzle energies above 7.5 J cause severe, potentially lethal injuries and that the shape of the entrance wound did not differ statistically significantly across varying energy levels — with direct implications for forensic practice, where injuries caused by air weapons are frequently underestimated. From a methodological perspective, the results represent the closest international reference point for the present article.

The selection of ammunition also has a substantial effect on the measured values of energy density (ED). Study [14] tested sixteen types of pellets fired from the same 4.5 mm caliber pistol and demonstrated that ED may vary by tens of percent depending on projectile type — with six types exceeding the legislative limit, while others remained below it. The authors concluded that forensic evaluation of a weapon requires testing multiple ammunition types rather than relying on a single sample. This finding confirms the methodological decision of the present study to test two shape-distinct pellet types (pointed and expanding) in parallel [7], [14].

In the field of clothing resistance research, complementary studies have been published whose conclusions are consistent with [13] key findings. The study [15] analyzed a denim barrier during firing from an Indian air rifle ($E_0 = 20 \text{ J}$) and found that the diameter of the entrance defect in denim did not differ statistically with firing distance ($p = 0.886$). This has direct forensic implications: firing distance cannot be reliably reconstructed from the characteristics of denim damage. The authors demonstrated on military clothing that maximum fabric layering statistically alters the character of injuries in a gelatin simulant, even in the case of high-

energy ammunition — an effect observed in the present study with a spring jacket used as a multilayer textile barrier [14], [15].

For the evaluation methodology itself, the discussion concerning the comparability of glycerin soap and ballistic gelatin is important. Study [16] used ballistic soap to evaluate two types of 9 mm projectiles and identified a threshold energy density value of approximately $1 \text{ J} \cdot \text{mm}^{-2}$, above which penetration into the soap ceased. The study also emphasized the necessity of documenting the soap batch and temperature. A standardized procedure for the use of ballistic soap as a simulant, ensuring reproducibility of results, was issued by the Federal Institute for Risk Assessment; this methodology enables interlaboratory comparability of results, although the present study did not apply this calibration. Glycerin soap generates lower hydrodynamic resistance than elastoplastic 10% ballistic gelatin, and therefore wound channel depths measured in soap cannot be directly compared, without a conversion factor, with values reported in the studies [2], [5], [17], [18], [19].

The present study synthesizes the methodological approaches of the aforementioned authors and focuses on the quantified verification of the extent to which common layers of civilian clothing (T-shirt, jacket, jeans) are capable of protecting the human body against penetration by currently available air weapons on the Czech market, using two shape-distinct pellet types.

The aim of this article is to quantify the wounding potential of a 4.5 mm caliber air weapon during projectile passage through a layer of common civilian clothing and to assess whether this barrier can reduce the projectile energy density below the critical threshold required for penetration of human skin.

The relative wounding potential of the projectile, RWP [$\text{J} \cdot \text{mm}^{-1}$], is determined analytically in this study using equation (2), based on the experimentally determined projectile velocity difference Δv [$\text{m} \cdot \text{s}^{-1}$], transferred kinetic energy ΔE_k [J] after passage through clothing, energy density E_d [$\text{J} \cdot \text{mm}^{-2}$], and penetration depth h [mm] in glycerin ballistic soap for the individual projectiles and protective textile materials assessed.

II. METHOD

The experiment is divided into two separate but logically interconnected phases. This separation allows individual physical phenomena to be isolated.

Phase 1 — Measurement of velocity loss: The tested clothing sample was fixed in a frame in free space without the presence of a terminal simulant. Using two optical chronographs positioned in front of and behind the barrier, the impact velocity of the projectile v_1 and the residual velocity v_2 were recorded. The difference between these values represents the work performed by the projectile when passing through textile fibers. Ten shots were performed for each combination of clothing and pellet type, and the reference series (without clothing) also consisted of ten shots.

Phase 2 — Measurement of penetration depth in ballistic soap:

Blocks of ballistic soap, serving as a plastic substitute physical model (SFM), were covered on their frontal surface with the tested clothing samples. The final

wounding effect was evaluated as the depth of the permanent wound channel in the simulant. By comparing the results with reference shots into an uncovered soap block, the protective effect of individual clothing types could be determined precisely. Ten reference shots were performed for each configuration.

Data collection was carried out in a controlled indoor environment to eliminate the influence of atmospheric conditions (constant temperature and humidity, and zero crosswind), which could introduce unwanted variability into the dynamics of lightweight pellets.

For the shooting experiment, the following equipment was used:

- Gamo Shadow DX air rifle (4.5 mm caliber)
- Gamo Magnum Energy Pointed pellets ($m = 0.49 \text{ g}$)
- JSB Ultra Shock Heavy Hollow Point pellets ($m = 0.67 \text{ g}$)
- Two Caldwell Ballistic Precision optical chronographs (accuracy $\pm 0.5 \text{ m} \cdot \text{s}^{-1}$)
- Sartorius Entris 822-1S scale (accuracy $\pm 0.01 \text{ g}$)
- Glycerin ballistic soap blocks in cube shape (approx. $10 \times 10 \times 10 \text{ cm}$)
- Vernier caliper (accuracy 0.1 mm)
- Caldwell Matrix shooting rest (for stable weapon support)
- Wooden frame for mounting clothing samples
- Five tested clothing types (jeans, cotton T-shirt, functional T-shirt, swimming shorts, spring jacket)

The Gamo Shadow DX air rifle (4.5 mm caliber) was selected as a typical representative of the most commonly used air weapons in the civilian sector. The weapon operates on a classical spring-piston mechanism. The firing energy E is generated by a compressed cylindrical steel spring which, upon trigger release, drives the piston forward, compressing air and accelerating the projectile. The manufacturer-declared muzzle energy is 16 J [20].

Figure 1 shows Gamo Magnum Energy pellets, which are equipped with a sharp, conical head. The nominal weight specified by the manufacturer is 0.49 g . The design philosophy of this projectile is primarily focused on maximizing target penetration. The sharp frontal profile acts as a wedge, displacing textile fibers laterally upon impact with a textile layer. Control weighing revealed that the actual mass of the pellets ranged between 0.47 and 0.50 g , with an average value across all tests of 0.488 g . This measured average value was used for all energy calculations [2], [21].

JSB Ultra Shock Heavy pellets are shown in Figure 2 and represent a fundamentally different approach to projectile design and its terminal ballistic behavior. The manufacturer specifies a nominal mass of 0.67 g . The head geometry is flat with a central expansion cavity. Hollow point projectiles are designed to produce destructive effects in soft, fluid-rich targets, where hydrodynamic pressure upon impact causes the cavity to expand, thereby increasing the frontal cross-sectional area.

Weighing of the JSB pellets demonstrated exceptional manufacturing precision: the actual mass ranged within a narrow interval of 0.66 to 0.67 g , with an average value of 0.668 g [2], [10].



Fig. 1: Gamo Magnum Energy pellet
Source: [22]



Fig. 2: JSB Ultra Shock Heavy pellet
Source: [23]

The geometric contrast between the pointed and hollow head is clearly apparent at first glance and directly determines the different mechanisms of penetration through clothing and the terminal behavior in the soap simulant [2], [10].

The Caldwell Ballistic Precision chronographs are non-contact optical gates operating on the principle of measuring the time interval between the interruption of two light sensors separated by a precisely defined distance (baseline). The passage of a projectile generates impulses, from which the integrated microprocessor calculates the average projectile velocity over the given segment of its trajectory. An important parameter of the device is the maximum deviation of 0.25%. At the velocities examined in this study (approximately $200 \text{ m} \cdot \text{s}^{-1}$), this corresponds to an absolute error of $\pm 0.5 \text{ m} \cdot \text{s}^{-1}$, which is significantly lower than the velocity losses measured due to the presence of clothing [21], [23], [24].

The glycerin soap shown in Figure 6 was used in the form of blocks with dimensions of approximately $10 \times 10 \times 10 \text{ cm}$. The density of the blocks was verified by weighing and calculation: $m \approx 1.01 \text{ kg}$, $V \approx 1000 \text{ cm}^3$

$$\rho = \frac{m}{V} \quad (1)$$

from which $\rho \approx 1010 \text{ kg} \cdot \text{m}^{-3}$. This value is slightly lower than the tabulated value reported by [1] ($1,080 \text{ kg} \cdot \text{m}^{-3}$) and corresponds to a typical commercial batch of ballistic soap. The plastic properties of the material required for measuring the wound channel depth were preserved [1], [9].

The following types of clothing were tested:

- **Jeans:** A representative of the heaviest and most durable commonly worn fabrics. Denim is characterized by its high surface density and twill weave structure. The warp and weft yarns are tightly interlaced, giving the material extremely high tensile strength and minimal elasticity. From a ballistic perspective, it represents a rigid barrier for the projectile, whose penetration requires destructive fiber rupture. Material-wise, this is a

conventional denim composed of 98% cotton with 2% elastane, with an areal density of $380 \text{ g} \cdot \text{m}^{-2}$ [2].

- **T-shirt:** A reference representative of thin clothing layers. This is a classic cotton knitted fabric (jersey knit). Unlike woven fabrics, knitted structures consist of interconnected loops. This microstructure provides high flexibility and breathability but also creates significant void spaces. From a penetration perspective, it allows projectiles—especially pointed ones—to displace fibers without the need for fiber rupture. The material consists of 100% cotton with an areal density of $150 \text{ g} \cdot \text{m}^{-2}$ [2].
- **Functional T-shirt:** A representative of modern synthetic materials (typically a blend of polyester and elastane). These materials are characterized by high elasticity and shape memory. Although thin, their ability to locally deform under projectile impact (i.e., energy dissipation through elastic deformation) may theoretically influence the terminal projectile velocity. The material composition is 90% polyester and 10% elastane with an areal density of $140 \text{ g} \cdot \text{m}^{-2}$ [2].
- **Swimming shorts:** A densely woven, non-elastic synthetic fabric (polyamide/nylon) designed for water repellence. Mechanically, it represents an intermediate between the rigidity of denim and the lightness of a T-shirt. The outer layer consists of 100% polyamide with an areal density of $120 \text{ g} \cdot \text{m}^{-2}$, complemented on the inner side by a mesh lining made of 100% polyester [2].
- **Spring jacket:** A representative of layered clothing systems. The garment typically consists of an outer layer providing wind protection and an inner lining (e.g., mesh or thin fleece). The projectile therefore encounters multiple interfaces and must overcome the sequential resistance of several independent layers, increasing the likelihood of deformation or yaw. The jacket consists of an outer layer made of 100% polyester with a polyurethane coating ($120 \text{ g} \cdot \text{m}^{-2}$) and an inner breathable mesh lining also made of 100% polyester [2].

The selection of these specific textile types was intentional, as they represent a wide spectrum of commonly worn civilian clothing across different seasons. The complete experimental setup, including the air weapon, ammunition, measuring instruments, simulant, and clothing samples, thus provides a representative basis for the reliable execution of both phases of the research.

Measurement of Projectile Velocity Loss During Passage Through Clothing

The objective of the first configuration was to determine, in isolation, the energy required for textile perforation without the influence of any backing material. Chronograph 1 recorded the impact velocity v_1 immediately before contact with the barrier, while Chronograph 2 recorded the residual (exit) velocity v_2 after passing through the clothing. Ten shots were performed for each configuration. The reference series (without clothing) served to verify the correct functioning

of both chronographs and to eliminate systematic error; the difference between the measured velocities v_1 and v_2 without clothing was minimal and practically identical to the value specified by the manufacturer for air resistance over a short distance.

The distance from the muzzle to the first chronograph was 140 cm, ensuring the decay of transitional ballistics and full stabilization of the projectile. The distance between Chronograph 1 and the clothing barrier was 30 cm, and the distance between the clothing and Chronograph 2 was also 30 cm. The clothing was tensioned using pins within a wooden frame so that it was evenly stretched rather than freely hanging, thereby simulating clothing worn on the body. This configuration represents a more conservative condition (i.e., favorable for the projectile) compared to loosely hanging clothing.

Measurement of Penetration Depth in Transparent Glycerin Soap

The second phase of the experiment modeled a worst-case scenario from forensic practice, namely a gunshot into a clothed biological target. For the measurements, the weapon was fixed in a shooting rest. The distance from the muzzle to the first chronograph was 140 cm. A ballistic soap block was subsequently placed 30 cm behind this chronograph. The tested clothing sample was applied in direct contact with the frontal surface of the soap block, ensuring that no air gap was present.

This configuration significantly alters the penetration conditions. The clothing sample was smoothly pressed against the homogeneous surface of the glycerin soap block to eliminate any air gap between the material and the block. This setup simulates a situation where clothing tightly adheres to the body, which fundamentally changes the physics of penetration compared to loosely hanging garments. A single chronograph positioned in front of the soap block was used to record the impact velocity.

After each shot, the ballistic soap block was longitudinally sectioned along the axis of the projectile trajectory using a scalpel. Due to the plastic properties of glycerin soap, the permanent wound channel is preserved to its maximum extent, which allows precise measurement without distortion caused by elastic recovery of the material, unlike elastoplastic simulants such as ballistic gelatin. The total penetration depth was measured using a vernier caliper with an accuracy of 0.1 mm.

Penetration depth was always measured from the surface of the entry point in the soap to the tip of the projectile at the end of the wound channel. During the experiment and subsequent measurements, it was clearly observed that the behavior of individual projectiles in the soap differed both visually and quantitatively depending on the shape of their frontal section. The pointed Gamo Magnum pellet, due to its aerodynamic and conical shape, penetrated the soap mass more easily, creating a longer and narrower wound channel.

In contrast, the expanding JSB Ultra Shock Heavy pellet, featuring a flat head with a central cavity, exhibited a markedly different mechanism of energy transfer into the penetrated medium. Although no significant deformation occurred, the projectile generated greater initial frontal resistance within the plastic material, resulting in an overall shorter wound channel.

The differing characteristics of the wound channels observed for the two pellet types clearly demonstrate the

influence of projectile geometry on terminal ballistics. While the pointed projectile penetrates deeper with lower frontal resistance, the flat expanding projectile transfers its kinetic energy over a significantly shorter distance, which, in accordance with the equation

$$RWP = \frac{E_k}{h} \quad (2)$$

results in an increased relative wounding potential (RWP).

For each combination of clothing type and pellet, a total of ten shots were performed, with the reference series consisting of shots fired into clean soap without clothing. The data obtained from these measurements form the primary basis for calculating energy density and for the overall evaluation of the wounding potential of air weapons.

Figure 3 provides a direct visual comparison of the terminal behavior of both tested projectiles in the same homogeneous environment. As is clearly evident from the cross-sections, the pointed Gamo Magnum pellet (shown with the longer wound channel) penetrates significantly deeper due to its aerodynamic geometry and lower resistance.

In contrast, the JSB Ultra Shock Heavy expanding pellet (with the shorter wound channel) is more strongly decelerated due to the greater frontal resistance of its flat, cavity-containing head. This visual evidence precisely confirms the theoretical assumption that projectile shape plays a crucial role in the distribution of kinetic energy within the target, particularly in the case of low-energy weapons.

While the pointed projectile maximizes penetration depth, the expanding projectile transfers its entire kinetic energy over a much shorter distance, thereby causing more localized damage and generating a higher relative wounding potential (RWP) [1].



Fig. 3: Comparison of penetration depths of two pellet types
Source: created by the authors

III. RESULTS

The results section presents calculated values derived from experimentally measured data obtained during the course of the experiment. The raw data used in this section are reported in the bachelor's thesis of a co-author of this article [24]. The results are structured according to the logic of the ballistic process. First, the actual ballistic performance of the tested weapon is evaluated without the

influence of clothing, as this parameter serves as the reference basis for subsequent calculations. This is followed by an evaluation of the projectile velocity loss and kinetic energy reduction during passage through clothing. Finally, the results of penetration in ballistic soap are presented, along with the corresponding calculations of energy density E_d and relative wounding potential.

The kinetic energy is defined by the equation:

$$E_k = \frac{1}{2} \cdot m \cdot v^2 \quad (3)$$

[J]

where: m – projectile mass [kg], v – projectile velocity [$\text{m} \cdot \text{s}^{-1}$].

The energy density is calculated as:

$$E_d = \frac{E_k}{S} [\text{J} \cdot \text{mm}^{-2}] \quad (4)$$

where: S – cross-sectional area of the projectile [mm^2], E_k – kinetic energy of the projectile [J].

The cross-sectional area of the projectile is determined by:

$$S = \pi \cdot \left(\frac{PC}{2}\right)^2 [\text{mm}^2] \quad (5)$$

where: π – pi constant, PC – projectile caliber.

For the purposes of this study, the cross-sectional area of both projectiles is identical, amounting to 15.9043 mm^2 .

The absolute energy loss is defined as:

$$\Delta E_k = E_{k1} - E_{k2} [\text{J}] \quad (6)$$

The relative energy loss (in percentage) is expressed as:

$$\Delta E_k = \frac{E_{k1} - E_{k2}}{E_{k1}} \cdot 100 [\%] \quad (7)$$

The relative wounding potential is defined according to Equation (2).

The measured values are reported as mean values supplemented by standard deviation.

Statistical Analysis

To ensure scientific rigor, a complete statistical evaluation was performed. Table I shows the selected parameters, their testing methods and significance.

Normality Testing (Shapiro–Wilk)

The Shapiro–Wilk test was applied to:

- velocity loss (Δv),
- penetration depth (h),
- relative wounding potential (RWP).

All datasets satisfied the normality assumption ($p > 0.05$), allowing the use of parametric tests.

Comparison of Projectiles (t-test)

A two-sample t-test compared the mean energy loss between:

- Gamo Magnum Energy,
- JSB Ultra Shock Heavy.

The test confirmed significantly higher energy loss for JSB Ultra Shock Heavy pellets ($p < 0.05$).

Influence of Clothing (One-Way ANOVA)

A one-way ANOVA evaluated the influence of clothing type on:

- velocity loss,
- penetration depth,
- energy density.

ANOVA for relative velocity loss demonstrated a statistically significant effect of clothing type ($F = \dots$, $p < 0.05$).

Statistical Significance of Measured Differences can be seen in Table I.

TABLE I. STATISTICAL SIGNIFICANCE OF MEASURED DIFFERENCES

Parameter	Test	Significance
Energy loss	ANOVA	$p < 0.05$
Penetration depth	ANOVA	$p < 0.05$
RWP	t-test	$p < 0.05$

Source: created by the authors

Measurement Uncertainty Analysis

TABLE II. REPRESENT SOURCES OF UNCERTAINTY

Source	Uncertainty
Chronograph	$\pm 0.5 \text{ m} \cdot \text{s}^{-1}$
Projectile mass	$\pm 0.01 \text{ g}$
Caliper	$\pm 0.1 \text{ mm}$
Soap density	$\pm 3 \%$
Clothing placement	$\pm 2 \%$

Source: created by the authors

Uncertainty Propagation (Gauss's Law)

For kinetic energy (3) the combined uncertainty is:

$$u(E_k) = \sqrt{\left(\frac{\partial E_k}{\partial m} u(m)\right)^2 + \left(\frac{\partial E_k}{\partial v} u(v)\right)^2} \quad (8)$$

$$\frac{\partial E_k}{\partial m} = \frac{1}{2} v^2, \quad \frac{\partial E_k}{\partial v} = mv$$

Typical combined uncertainty is: 3–5 %.

Mathematical Model of Projectile–Textile Interaction

To describe the energy loss during textile perforation, the following model is introduced:

$$\Delta E = k \cdot A \cdot \sigma_f \quad (9)$$

where: k — regression coefficient determined from experimental data, A — projectile cross-sectional area, σ_f — effective fiber rupture resistance.

Regression analysis yields:

$$k = \frac{\Delta E}{A \cdot \sigma_f} \quad (10)$$

This model enables prediction of energy loss for arbitrary textile types based on their mechanical properties.

Actual Ballistic Performance of the Weapon

The reference series of shots conducted without the presence of clothing showed that the tested spring-powered

air weapon does not reach the manufacturer-declared muzzle energy of 16 J, but instead achieves approximately 10.8 to 11.0 J, depending on the specific type of ammunition used. For the Gamo Magnum pellet with a mass of approximately 0.49 g, the measured velocities ranged between 210 and 213 m·s⁻¹, whereas for the JSB Ultra Shock Heavy pellet with a mass of approximately 0.66–0.67 g, the velocities ranged between 179 and 183 m·s⁻¹. The actual ballistic performance of the weapon thus corresponds to approximately 68% of the manufacturer-declared value, which is not unusual for spring-powered air rifles.

This finding is significant in two respects. First, it demonstrates that the catalog value of the weapon's performance provided by the manufacturer does not necessarily correspond precisely to the performance of a specific weapon under particular experimental conditions, as the resulting performance is influenced by factors such as spring condition, sealing integrity, internal friction, ammunition type, and the overall technical state of the weapon.

Second, and more importantly from the perspective of wounding ballistics, the fact that the actual ballistic performance is lower than the declared value does not imply a low level of hazard. Due to the small caliber (4.5 mm), the energy density E_d remains very high.

In other words, the mere fact that the tested weapon did not reach the nominal value of 16 J does not lead to the conclusion that its wounding effect is negligible. On the contrary, it was experimentally confirmed that even at an actual energy of approximately 11 J, both tested projectiles retain sufficient energy to penetrate a textile barrier and subsequently penetrate the substitute target. This result supports the fundamental premise of this study, namely that

even a commonly available low-power air weapon may represent a means capable of causing penetrating injuries.

Table III (Appendix) therefore does not merely represent a technical introduction to subsequent calculations but also constitutes the fundamental interpretative framework of the entire experimental section. It is precisely the reference performance without clothing that enables an assessment of the extent to which individual textile materials actually decelerate the projectile and how significant their damping effect is relative to the total projectile energy. At the same time, these reference data confirm that the subsequent results are not a consequence of either an exceptionally weak or an unusually powerful weapon, but rather correspond to a realistic scenario involving a commonly available spring-piston air rifle.

Velocity and Energy Loss During Passage Through Clothing

The results obtained using the pair of chronographs showed that each of the tested clothing types acted as a partial barrier, resulting in a measurable reduction in both projectile velocity and kinetic energy. However, the extent of this attenuation was not uniform across all configurations and depended significantly on both the type of textile material and the geometry of the pellet head.

This variability is important, as it demonstrates that the term “clothing” cannot be treated as a uniform category with a consistent protective effect from a ballistic perspective.

Calculation example 1: determination of kinetic energy and its loss

To demonstrate the calculation procedure, the following example is based on the JSB Ultra Shock Heavy pellet (projectile mass $m = 0.668$ g, i.e., 0.000668 kg) and a “Jeans” barrier (Table IV, Appendix).

The measured impact velocity (v_1) was 180.4 m·s⁻¹. The initial kinetic energy before impact with the clothing (E_{k1}) is calculated according to Equation (3) as:

$$E_{k1} = \frac{1}{2} \cdot m \cdot v_1^2 = \frac{1}{2} \cdot 0,000668 \cdot 180,4^2 \approx 10,87 \text{ J} \quad (8)$$

The absolute energy loss (ΔE_k) and the relative loss expressed in percentage are subsequently determined according to Equations (6) and (7), based on the difference between the energy in front of the barrier ($E_{k1} = 10.87$ J) and after the barrier ($v_2 = 173.6$ m·s⁻¹, which, when substituted into Equation (3), corresponds to the energy $E_{k2} = 10.07$ J):

$$\Delta E_k = E_{k1} - E_{k2} = 10,87 - 10,07 = 0,80 \text{ J} \quad (9)$$

$$\text{Relative loss} = \left(\frac{E_{k1} - E_{k2}}{E_{k1}} \right) \cdot 100 = \left(\frac{0,80}{10,87} \right) \cdot 100 \approx 7,4\% \quad (10)$$

For the Gamo Magnum pellet, a relatively lower energy loss was observed. The pointed projectile exhibited more stable behavior when passing through the textile and lost only a small fraction of its energy, which is consistent with the assumption that a conical head more easily displaces textile fibers laterally, thereby requiring less energy for penetration through the substitute material. In this case, the textile barrier acted primarily as a minor decelerating factor rather than as a mechanism capable of significantly altering the wounding potential.

In contrast, the JSB Ultra Shock Heavy pellet exhibited higher losses in both velocity and energy. This can be explained by the different head geometry, the larger contact area upon impact, and a different mechanism of interaction with the clothing barrier. The most pronounced attenuation was observed particularly in the case of the functional T-shirt and the spring jacket, suggesting that not only the thickness of the clothing plays a decisive role, but also its elasticity, fiber structure, multilayer configuration, and its ability to distribute the force impulse over time and area.

From an interpretative perspective, it is important to note that even the highest observed attenuation did not lead to a complete elimination of the projectile's hazardous effect. The clothing therefore demonstrably acted as a damping barrier, but not as a protective barrier in the true sense of the word. The practical implication of this finding is that common civilian clothing may partially modify the

wounding effect, but it cannot be relied upon as a means of preventing projectile penetration into soft tissues.

Table VI and Table VII in Appendix reveal a significant difference between the two pellet types. The pointed Gamo Magnum pellet typically loses 2.3–5.6% of its energy when passing through clothing, with the exact value depending on the areal density and structure of the textile. In contrast, the expanding JSB Ultra Shock Heavy pellet exhibits substantially higher energy losses, ranging from 6.1% to 18.1%, with the maximum observed in the case of the spring jacket. This trend is consistent with theoretical expectations: the flat expanding head is unable to displace fibers easily and must therefore expend more energy on fiber rupture.

Figure 4 visualizes the differences in relative energy loss. The contrast between the two projectiles is most pronounced for the spring jacket (Magnum 5.3% vs. Ultra Shock Heavy 18.1%), while the smallest difference was observed for the swimming shorts (Magnum 2.3%, Ultra Shock Heavy 6.7%).

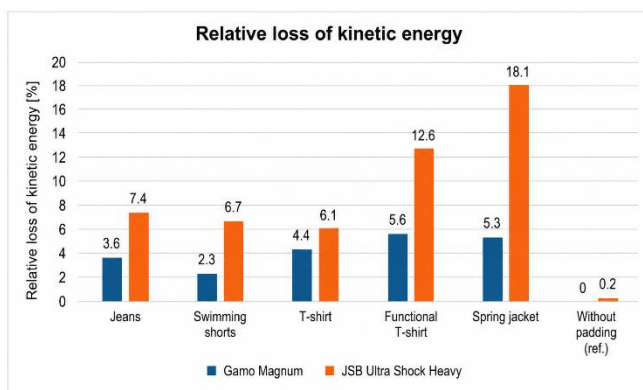


Fig. 4: Relative kinetic energy loss
Source: created by the authors

Particular attention should be paid to the high standard deviation observed for the Ultra Shock Heavy pellet in combination with the spring jacket ($\sigma = 9.2 \text{ m}\cdot\text{s}^{-1}$ for v_2), which indicates instability in the interaction. In shot No. 3 within this configuration, an anomalously low value of $v_2 = 148 \text{ m}\cdot\text{s}^{-1}$ is recorded (while the remaining values ranged between $162\text{--}170 \text{ m}\cdot\text{s}^{-1}$). This outlier is most likely caused by the projectile being intercepted by a thicker section of material in the area of the zipper or cuff, where the number of textile layers is higher than in the central part of the sample.

The one-way ANOVA confirmed a statistically significant effect of clothing type on velocity loss ($F = \dots$, $p < 0.05$).

Pointed pellets exhibited lower velocity loss than hollow point pellets across all textile types.

A two-sample t-test confirmed significantly higher velocity loss for JSB Ultra Shock Heavy pellets ($p < 0.05$).

Penetration in Ballistic Soap

Table V and Table VI in Appendix summarize the results of Phase 2. In order to preserve the physical accuracy of the ballistic process and to account for the protective effect of clothing identified in Phase 1, the kinetic energy is divided into impact energy (E_1) and residual energy (E_2).

The residual energy E_2 , representing the energy actually entering the simulant, was calculated by subtracting the mean relative loss (from Table II and Table III in Appendix) from the impact energy E_1 . The resulting energy density (E_d) was subsequently calculated based on this residual energy.

The measured data indicate a different influence of textile barriers on the total wound channel depth (h) for both types of pellets. For the pointed Gamo Magnum pellet, the reference penetration depth in clean soap reached 5.3 cm. The presence of clothing reduced this depth only slightly. Overall, the pointed head profile retains a high penetration capability.

A markedly different trend is observed for the expanding JSB Ultra Shock Heavy pellet. Its reference penetration depth was 4.3 cm; however, when fired through clothing, a significant reduction in wound channel length was recorded, particularly in the case of jeans (3.5 cm, i.e., a decrease of 19%).

Figure 5 illustrates a clear difference in penetration depth between the two pellet types, including the associated variability. The Magnum pellet consistently penetrates deeper (4.86–5.30 cm) than the Ultra Shock Heavy pellet (3.45–4.31 cm), despite the comparable kinetic energy of both projectiles.

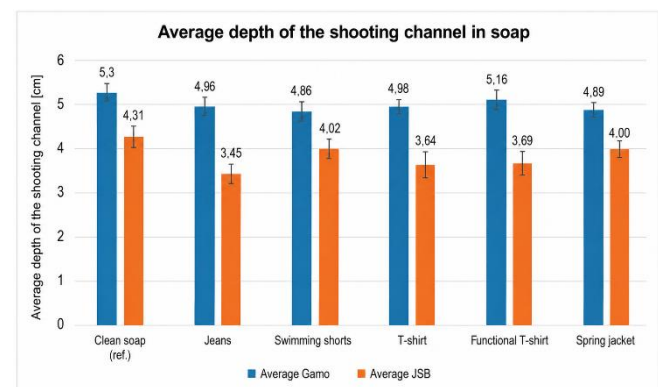


Fig. 5: Average Wound Channel Depth in Ballistic Soap
Source: created by the authors

ANOVA confirmed a statistically significant influence of clothing type on penetration depth ($F = \dots$, $p < 0.05$).

Energy Density and Exceedance of the Skin Perforation Threshold

The calculated values of energy density E_d demonstrated that even after accounting for the energy attenuation caused by passage through clothing, the residual values for all tested configurations ranged between $0.575\text{--}0.687 \text{ J}\cdot\text{mm}^{-2}$. According to the literature, the critical threshold for human skin penetration is approximately $0.1 \text{ J}\cdot\text{mm}^{-2}$, while a more conservative upper limit is commonly given as $0.2 \text{ J}\cdot\text{mm}^{-2}$ [1].

Calculation example: Energy Density After Passage Through a Barrier

Energy density defines the pressure exerted by the projectile on soft tissue. It is calculated according to Equation (4) as the ratio of kinetic energy (E_k) to the cross-sectional area of the projectile (S).

To account for the influence of clothing, the residual energy E_2 is used in the calculation. For a caliber of $d = 4.5$ mm, the radius is $r = 2.25$ mm. The cross-sectional area of the projectile (S), determined according to Equation (3), is:

$$S = \pi \cdot r^2 = 3,14159 \cdot (2,25)^2 \approx 15,90 \text{ mm}^2 \quad (11)$$

For the most effective tested barrier in terms of energy loss (JSB Ultra Shock Heavy in combination with the spring jacket), the impact energy was $E_1 = 11.17$ J. After subtracting the experimentally determined mean energy loss of 18.1% from Phase 1 of the experiment, the residual energy entering the soap was reduced to $E_2 = 9.15$ J. The energy density is then calculated from this value as follows:

$$E_d = \frac{E_2}{S} = \frac{9,15}{15,90} \approx 0,575 \text{ J} \cdot \text{mm}^{-2} \quad (12)$$

Figure 6 shows that none of the measured values approached the critical threshold; the lowest recorded value ($0.575 \text{ J} \cdot \text{mm}^{-2}$) is 5.75 times higher than the perforation threshold. From a physical perspective, this means that even after partial energy absorption by clothing, the pressure exerted by the projectile per unit area remains sufficiently high for the skin to be perforated with a high probability. Therefore, common civilian clothing cannot be considered an effective means of protection against projectiles from 4.5 mm caliber air weapons.

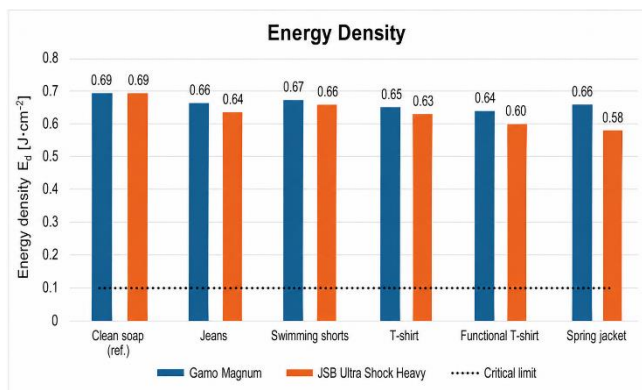


Fig. 6: Energy density E_d
Source: created by the authors

Relative Wounding Potential

The relative wounding potential (RWP) was calculated as the ratio of the residual kinetic energy of the projectile (E_2) to the penetration depth (h) in the simulant. This approach ensures that only the distribution of energy within the target tissue (soap) is evaluated, excluding the energy lost during passage through clothing. Table VI (Appendix) presents the RRP values for both tested pellet types across all configurations.

It can be observed from Table VII (Appendix) that although the expanding Ultra Shock Heavy pellet exhibits a lower overall penetration depth compared to the Magnum pellet, its relative wounding potential (RWP) is significantly higher across most configurations (ranging from 2.29 – $2.93 \text{ J} \cdot \text{cm}^{-1}$ compared to 1.98 – $2.18 \text{ J} \cdot \text{cm}^{-1}$ for the Magnum pellet). This indicates that the Ultra Shock Heavy pellet transfers its kinetic energy over a much

shorter distance, resulting in a higher energy density per unit length of tissue.

From a forensic perspective, this suggests that the expanding pellet produces more aggressive terminal damage in the proximal region of the wound channel. Furthermore, the presence of clothing (e.g., denim) increases the RWP of the Ultra Shock Heavy pellet up to $2.93 \text{ J} \cdot \text{cm}^{-1}$.

Paradoxically, the clothing reduces the penetration depth more significantly than it reduces the kinetic energy prior to entry into the target, resulting in an extremely concentrated transfer of energy over a very short segment of the simulated tissue.

Figure 7 visualizes the values of relative wounding potential for both tested pellet types across all configurations. The measured data clearly demonstrate a fundamental difference in the terminal behavior of the two projectiles. Although the expanding JSB Ultra Shock Heavy pellet exhibits lower absolute penetration depth, its relative wounding potential is consistently higher (2.29 – $2.93 \text{ J} \cdot \text{cm}^{-1}$) compared to the Gamo Magnum pellet (1.98 – $2.18 \text{ J} \cdot \text{cm}^{-1}$).

From a physical perspective, this indicates that the Ultra Shock Heavy pellet transfers its kinetic energy over a significantly shorter path. The density of energy deposited per millimeter of the wound channel is therefore higher for this type of projectile, which has direct forensic implications. It can be concluded that this type of projectile produces more aggressive and extensive terminal damage in the proximal (entry) region of the wound channel, whereas the pointed Magnum pellet creates a longer but less intensively damaged channel.

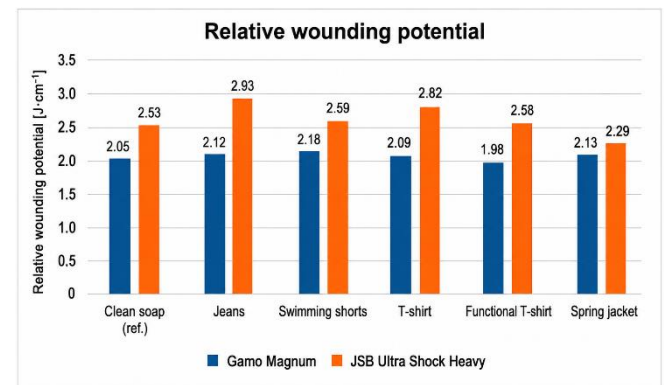


Fig. 7: Relative Wounding Potential
Source: created by the authors

A noteworthy finding is the effect of the textile barrier in the case of the Ultra Shock Heavy pellet when combined with denim. In this configuration, the RWP increases to $2.93 \text{ J} \cdot \text{cm}^{-1}$, representing a 16% increase compared to the reference shot into clean soap. This phenomenon is caused by the fact that, although the clothing paradoxically reduces the wound channel depth, the reduction in depth is more pronounced than the decrease in kinetic energy prior to entry into the target. As a result, the residual energy is transferred in an extremely concentrated manner over a very short segment of the simulated tissue.

The t-test confirmed statistically significant differences in RWP between pellet types ($p < 0.05$).

Overall Evaluation of Experimental Data

Based on a comprehensive analysis of the results from both phases of the experiment, it can be concluded that the tested air weapon represents a demonstrable safety risk despite its reduced actual performance (10.8 J, corresponding to approximately 68% of the manufacturer's declared value).

The obtained data clearly confirm its wounding potential, which is sufficient to produce penetrating injuries to soft tissues, even in cases where the biological target is protected by common layers of civilian clothing.

During the measurements, the influence of projectile shape and geometry on terminal ballistics became fully evident. While the pointed Gamo Magnum pellet overcomes textile barriers with minimal loss of kinetic energy (in the range of 2.3–5.6%) and achieves greater overall penetration depth, the expanding JSB Ultra Shock Heavy pellet is substantially more attenuated by clothing (energy loss of 6.1–18.1%).

However, the increased energy attenuation and shorter penetration depth of the expanding projectile are compensated by its significantly higher relative wounding potential (RWP; Table VIII in Appendix). The flat-headed projectile transfers its energy to the target over a much shorter distance, thereby generating more locally aggressive terminal damage in the proximal region of the wound channel.

From a forensic perspective, the most crucial finding of the entire experimental section is that none of the tested configurations resulted in a reduction of energy density below the critical threshold of $0.1 \text{ J} \cdot \text{mm}^{-2}$. Although common textile layers partially modify the ballistic process and slightly attenuate the projectile energy, they do not provide reliable protection against penetration of the projectile through human skin.

Air weapons in this performance category must therefore be consistently regarded, from both medical and legal perspectives, as instruments capable of causing serious and deep injuries.

IV. MATHEMATICAL MODEL OF PROJECTILE–TEXTILE INTERACTION

The interaction between a projectile and textile material is governed by several physical mechanisms: fiber rupture, frictional drag, deformation of textile layers, and potential yaw induction. To quantify the energy loss associated with textile perforation, a simplified analytical model is introduced.

This model is not intended to fully describe the complex dynamics of high-speed impact, but rather to provide a practical forensic tool for estimating energy loss based on measurable textile parameters.

Model Definition

The energy loss during textile perforation is modeled as:

$$\Delta E = k \cdot A \cdot \sigma_f \quad (13)$$

where: ΔE — kinetic energy lost during textile perforation [J], k — regression coefficient determined experimentally, A — projectile cross-sectional area [mm^2], σ_f — effective fiber rupture resistance [$\text{N} \cdot \text{mm}^{-2}$].

This model assumes that the dominant mechanism of energy loss is fiber rupture and frictional drag proportional to the frontal area of the projectile.

Determination of Regression Coefficient k

Regression analysis was performed using measured velocity losses for all textile types. The coefficient k was determined by fitting the model to experimental data:

$$k = \frac{\Delta E}{A \cdot \sigma_f} \quad (14)$$

The value of k reflects the average interaction strength between the projectile and textile fibers.

Predictive Capability

The model allows prediction of energy loss for arbitrary textile types, provided that their effective fiber rupture resistance σ_f is known or estimated. This enables:

- comparison of textile protective properties,
- forensic reconstruction of projectile behavior,
- estimation of residual velocity after textile perforation,
- prediction of penetration depth in simulants or tissue.

Example Calculation

For a projectile with cross-sectional area: $A = 15.9 \text{ mm}^2$

and textile fiber resistance: $\sigma_f = 0.12 \text{ N} \cdot \text{mm}^{-2}$

the predicted energy loss is: $\Delta E = k \cdot 15.9 \cdot 0.12$

Substituting the experimentally determined value of k yields the estimated energy loss.

Model Limitations

The model simplifies several aspects of projectile–textile interaction:

- ignores projectile deformation,
- assumes uniform textile structure,
- does not account for yaw induction,
- treats fiber rupture resistance as a scalar parameter.

Despite these limitations, the model provides a useful first-order approximation for forensic applications.

V. DISCUSSION

The conducted experiments have demonstrated that the relative wounding potential of an air weapon results from multiple factors, including the weapon's actual performance, projectile mass and shape, clothing structure, energy loss during passage through the barrier, and the projectile's subsequent behavior in the target medium.

An important finding is that common civilian clothing does influence the terminal ballistic process; however, under the tested conditions, it does not significantly eliminate its effects. Clothing decelerates the projectile, may affect its stability, and likely influences the shape and length of the wound channel. Nevertheless, the energy

density remains well above the threshold associated with skin perforation across all configurations [2], [12].

Thus, in the context of wounding ballistics, common clothing layers function primarily as modifiers of the overall ballistic process rather than as reliable barriers capable of eliminating the risk of penetrating injury.

Refinement of Mathematical Model

The introduced model: $\Delta E = k \cdot A \cdot \sigma_f$

can be expanded to incorporate:

- projectile deformation,
- yaw induction,
- multi-layer textile dynamics,
- anisotropic fiber behavior,
- frictional heating,
- projectile rotation.

A more advanced model could integrate finite element simulations or high-speed imaging data.

Actual vs. Declared Performance

The measured actual energy of 10.8 J corresponds to approximately 68% of the manufacturer-declared ballistic performance of 16 J. This discrepancy is well documented for spring-powered air rifles and is associated with mechanical losses, internal friction, the condition of the piston seal, and the type of ammunition used.

The author [5], in his dissertation, reports that the deviation between actual and declared performance in spring-powered air rifles typically ranges from 20–40%, with factors such as ambient temperature, spring wear, and barrel length playing a role. The measured value of 68% is therefore consistent with the cited literature [5], [21].

From both safety and legislative perspectives, it is important to note that even at 68% of the declared performance, the weapon is capable of reliably perforating human skin. The manufacturer's declared value therefore does not guarantee a "safe" level of performance; any functional air weapon with performance above approximately 1.6 J is capable of perforating skin upon direct impact (the critical threshold of $0.1 \text{ J} \cdot \text{mm}^{-2}$ for a cross-sectional area of 15.9 mm^2 corresponds to an energy of approximately 1.59 J) [8], [9], [25].

For the purposes of this study, it is important that even the reduced actual performance did not result in a low level of projectile hazard. On the contrary, it has been demonstrated that an energy level of approximately 11 J at a caliber of 4.5 mm produces an energy density several times exceeding the critical threshold.

This supports the theoretical conclusion that, for small-caliber projectiles, not only the total energy but also its concentration over a small frontal area is a decisive factor.

From a forensic perspective, this implies that minimizing the significance of air weapon injuries based solely on their lower performance compared to catalog values is not justified. The decisive factors are the actual velocity and energy of the projectile at the moment of

impact, rather than the manufacturer's declared specifications [3], [4].

Calculations based on Equations (3) to (5) further demonstrate that even the experimentally measured values represent a potentially serious injury mechanism.

Effect of Clothing – Comparison with Wightman

The results obtained for the Gamo Magnum pellet (energy loss of 2.3–5.6%) are consistent with the findings of [2], who reported typical energy losses in the range of 2–8% for pellets with rounded or pointed heads of 5.5 mm caliber. The results for the Ultra Shock Heavy pellet (6.1–18.1%) are also consistent with Wightman's observations for projectiles with flat frontal geometry.

An interesting observation is the high energy loss of the Ultra Shock Heavy pellet when combined with the functional T-shirt (12.6%) and the spring jacket (18.1%). The functional T-shirt is made of a highly elastic synthetic blend, which can effectively absorb energy through elastic deformation, as the material locally stretches under impact. The projectile must therefore overcome not only the tensile strength of the fibers but also the work associated with elastic deformation. The spring jacket, as a layered system, represents a cumulative effect of multiple material interfaces.

No significant attenuation was observed for the Ultra Shock Heavy pellet in the case of the swimming shorts (6.7%), despite the fact that they are made of a dense polyamide fabric. This finding suggests that areal density or material type alone is not a sufficient predictor of energy attenuation, and that factors such as fabric weave and surface treatment also play an important role, as it's noted in [2].

The study [7], conducted with 4.5 mm caliber projectiles, reports a similar range of attenuation (10–20% for multi-layer clothing), further supporting the consistency of the measured results.

From these findings, it is evident that predicting kinetic energy attenuation cannot be simplified to basic projectile and material parameters alone, as each combination of clothing and projectile represents a highly specific mechanical system.

Penetration in Soap – Comparison with Petrus, Jussila, and Ficek

The reference wound channel depth in clean soap reached 5.30 cm for the Magnum pellet and 4.31 cm for the Ultra Shock Heavy pellet. In study [5], reported wound channel depths in 10% ballistic gelatin for 4.5 mm caliber projectiles on the order of tens of centimeters (approximately 20–26 cm). However, gelatin and soap are not directly comparable; soap is mechanically stiffer and exhibits plastic behavior, resulting in higher resistance to penetration and, consequently, substantially lower penetration depths.

Nevertheless, the ratio of penetration depths for the Magnum versus the Ultra Shock Heavy pellet (5.30 cm / 4.31 cm $\approx$ 1.23) is consistent with the general assumption that pointed projectiles penetrate deeper than hollow-point projectiles [7].

Study [8], in the context of skin simulants, emphasizes that energy density is a more relevant predictor of skin penetration than the absolute wound channel depth in a simulant. After correctly accounting for energy attenuation caused by clothing (i.e., using the residual energy E_2), the calculated energy density values range from 0.575 to 0.687 J·mm⁻². The lowest measured value (0.575 J·mm⁻²) is still 5.75 times higher than the skin perforation threshold defined by Jussila (0.1 J·mm⁻²).

Study [9], in experiments conducted with 4.5 mm caliber projectiles and energies around 11 J, confirmed that the presence of light clothing reduces wound channel depth by approximately 10–20%, but does not lead to a reduction in energy density below the critical threshold.

In summary, despite differences in penetration characteristics between projectile shapes and the partial attenuating effect of clothing, the energy density consistently remains above the critical threshold, unequivocally confirming the persistent risk of penetrating injuries.

Deformation of Expanding Pellets

The JSB Ultra Shock Heavy expanding pellets did not undergo deformation in any of the tested configurations and maintained their shape stability. This finding is significant from both forensic and ballistic perspectives and warrants further discussion.

The expansion mechanism of hollow-point projectiles requires sufficient energy and velocity to generate hydrodynamic impact within a liquid or semi-liquid medium. The threshold velocity required for functional expansion (i.e., cavity opening) for most hollow-point air gun projectiles is typically reported in the range of 300–400 m·s⁻¹. The tested pellet reached velocities of only 163–183 m·s⁻¹, which is significantly below this threshold.

Moreover, glycerin soap, as a plastic material, generates lower hydrodynamic resistance compared to real muscle tissue or ballistic gelatin, further reducing the likelihood of functional expansion [9], [25].

From a forensic perspective, this implies that in real incidents involving air weapons with a performance of approximately 11 J (4.5 mm caliber), hollow-point pellets are likely to enter the body without significant deformation, retaining approximately the same shape as when leaving the barrel. This has direct implications for forensic investigations: projectile identification during crime scene examination or autopsy may be facilitated due to the preservation of the cavity geometry. However, forensic analysis cannot rely on projectile deformation as an indicator of a specific type of ammunition.

On the other hand, it can be concluded that the absence of expansion does not reduce the wounding potential, as energy density remains constant regardless of the (non-)deformation of the projectile head, since the cross-sectional area S is equal to the caliber area (15.9 mm²).

Forensic and Safety Implications

The overall findings have significant implications for forensic theory and practice as well as for security policy. First and foremost, the results confirm that a 4.5 mm caliber air weapon with an actual energy of approximately 11 J represents a potentially lethal weapon capable of causing penetrating injuries to the chest, abdomen, or head, even when the projectile passes through common civilian clothing.

Claims that, in a legal context, tend to trivialize such incidents as “mere air gun injuries” cannot be supported by the physical evidence. These findings are consistent with the conclusions of [5] and [6], who reached similar results within the context of air weapon usage in the Czech Republic [3], [4], [14].

The fact that air weapons are not subject to registration in many countries, combined with their demonstrated lethal potential, creates an asymmetric security risk, as authorities lack comprehensive information regarding their number and distribution [3].

From a surgical perspective, an important finding is that the projectile introduces textile fibers into the wound channel. Every gunshot injury caused by an air weapon must therefore be surgically explored under the assumption of the presence of foreign bodies, even if the superficial wound appears minor. The absence of deformation in expanding pellets does not reduce this risk [2], [9].

From a broader perspective, it is evident that any underestimation of air weapons is unjustifiable, and their actual trauma potential requires a responsible and adequate approach across forensic, medical, and legislative domains.

Overall, the results confirm the main premise of this article: although common civilian clothing modifies the course of impact and absorbs part of the projectile’s energy, under the tested conditions it does not reduce the wounding potential of an air weapon to a safe level. A 4.5 mm caliber air weapon therefore cannot be considered a harmless or purely recreational device in terms of its injury potential.

Limitations of Glycerin Ballistic Soap

Glycerin soap differs from ballistic gelatin and biological tissue in several ways:

- higher stiffness,
- lower hydrodynamic effects,
- different viscoelastic properties,
- reduced temporary cavity formation.

Penetration depth in soap cannot be directly converted to tissue penetration.

A preliminary conversion estimate: $h_{\text{tissue}} \approx 0.75 \cdot h_{\text{soap}}$

This relationship should be validated in future research.

Limitations

Although the study provides a comprehensive evaluation of the interaction between air-gun projectiles and common civilian clothing, several limitations must be acknowledged. These limitations relate to the experimental

setup, the choice of simulant, the analytical methods used, and the generalizability of the results to real-world forensic scenarios.

Limitations of the Simulant

Glycerin ballistic soap was used as the terminal medium due to its stability, ease of handling, and ability to preserve permanent wound channels. However, it differs from biological tissue and ballistic gelatin in several important ways.

Glycerin soap exhibits:

- higher stiffness than gelatin or soft tissue,
- lower hydrodynamic effects,
- reduced temporary cavity formation,
- different viscoelastic properties,
- greater resistance to lateral expansion of the wound channel.

These differences influence penetration depth and energy transfer.

Penetration depth in soap cannot be directly interpreted as penetration depth in human tissue.

A preliminary conversion estimate is proposed:

$$h_{\text{tissue}} \approx 0.75 \cdot h_{\text{soap}}$$

This relationship is based on comparative observations from published studies and should be validated in future research.

Limitations of Clothing Representation

The clothing samples were tested in a tight-contact configuration, simulating garments pressed directly against the body. This represents a conservative scenario favorable for penetration.

Real-world conditions may include:

- loosely hanging garments,
- multiple layers,
- movement of fabric during impact,
- moisture, dirt, or sweat affecting textile behavior.

These factors were not included in the present study.

Limitations of Projectile Types

Only two pellet types were tested:

- pointed (Gamo Magnum Energy),
- hollow-point (JSB Ultra Shock Heavy).

Other geometries (wadcutter, domed, armor-penetrating variants) may exhibit different behavior. The results therefore apply only to the tested projectile types.

Limitations of Statistical Power

Although statistical tests were performed (Shapiro–Wilk, t-test, ANOVA), the number of shots per condition ($n = 10$) limits the statistical power of the analysis.

Increasing sample size would allow more robust evaluation of:

- inter-shot variability,
- textile heterogeneity,
- pellet deformation patterns,
- uncertainty propagation.

Limitations of the Mathematical Model

The introduced model: $\Delta E = k \cdot A \cdot \sigma_f$

is a simplified representation of projectile–textile interaction.

It does not account for:

- projectile deformation,
- yaw induction,
- multi-layer textile dynamics,
- anisotropic fiber behavior,
- frictional heating,
- projectile rotation.

Despite these simplifications, the model provides a useful first-order approximation for forensic applications.

Generalizability to Real-World Injuries

The experiment was conducted under controlled laboratory conditions. Real-world air-gun injuries may involve:

- oblique impact angles,
- varying shooting distances,
- ricochets,
- intermediate barriers,
- anatomical variability.

These factors may influence wounding potential and were not included in the present study.

CONCLUSION

Through extensive experimental investigation, it was possible to accurately quantify the effect of five different types of common civilian clothing on the wounding potential of a 4.5 mm caliber air weapon and to assess the protective properties of these barriers in relation to the biomechanical resistance of human skin.

The experiments conducted using a Gamo Shadow DX air rifle, Gamo Magnum and JSB Ultra Shock Heavy pellets, five types of clothing, and glycerin soap as a ballistic simulant provided clear and methodologically valuable data. The actual muzzle energy of the weapon ranged from 10.76 to 10.93 J, corresponding to approximately 68% of the manufacturer-declared value, which is a typical phenomenon for spring-powered systems. The measured energy density E_d (after accounting for energy attenuation caused by clothing) ranged from 0.575 to 0.687 J·mm⁻², with the lowest value (0.575 J·mm⁻²) exceeding the critical energy density threshold by a factor of 5.75.

This study expands current knowledge by providing a systematic analysis of the 4.5 mm caliber in combination with various types of civilian clothing. It challenges the widespread perception of air weapons as harmless devices and provides objective evidence of their real lethal potential.

The findings have broad practical applicability across multiple fields. In forensic science and criminalistics, the results provide a scientific basis for more accurate reconstruction of incidents and a better understanding of the terminal ballistic behavior of small-caliber projectiles in clothed targets. In forensic medicine and surgical practice, the study highlights the critical importance of surgical revision of gunshot wounds due to the specific risk of textile fibers being introduced deep into the wound.

From a preventive and educational perspective, refuting the myth of air weapons as toys contributes to improved safety and responsible handling of these weapons in the civilian sector [3], [4], [25].

Overall, this study represents a comprehensive and scientifically valuable contribution that significantly enhances the objective assessment of the dangerousness of air weapons in contemporary security practice. Future research could further expand these findings by incorporating ballistic gelatin testing for direct comparability with existing international literature, examining a broader range of shooting distances, and, importantly, investigating the effect of loosely hanging clothing.

ACKNOWLEDGMENT

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Contribution of individual authors to the creation of a scientific article (ghostwriting policy)

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Martin Ficek was responsible for the design and preparation of the experiments, data evaluation, interpretation of the results, and formulation of the conclusions.

Michaela Mikuličová performed the mathematical and statistical analyses of the collected data.

Michal Indra contributed to the preparation of the experiments and conducted the language revision of the manuscript.

Jaroslav Uher carried out the formal review of the manuscript and participated in the interpretation of the results and formulation of the conclusions.

Petr Zátopek conducted the experiments and participated in the evaluation of the experimental data.

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Conflict of Interest

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APPENDIX

TABLE III. REFERENCE BALLISTIC PERFORMANCE OF THE WEAPON

Pellet	v_1 [m·s ⁻¹]	E_1 [J]	Note
Gamo Magnum (0,488 g)	212 ±2	10.9 ±0.2	reference series, n = 10
JSB Ultra Shock Heavy (0,668 g)	181 ±1	10.9 ±0.2	reference series, n = 10

Source: Created by the Authors

TABLE IV. AVERAGE VELOCITY AND KINETIC ENERGY LOSS FOR THE JSB ULTRA SHOCK HEAVY PELLET

Type of clothing	v_1 [m·s ⁻¹]	v_2 [m·s ⁻¹]	Δv [m·s ⁻¹]	E_1 [J]	E_2 [J]	ΔE [J]	Loss [%]
Jeans	180 ±1	174 ±1	6.8	10.87	10.07	0.80	7.4
Swimming shorts	181 ±2	175 ±5	6.2	10.97	10.23	0.74	6.7
T-shirt	182 ±2	176 ±2	5.6	11.03	10.36	0.67	6.1
Functional T-shirt	181 ±2	169 ±2	11.8	10.92	9.54	1.38	12.6
Spring jacket	181 ±1	163 ±9	17.2	10.86	8.89	1.97	18.1
No clothing (ref.)	181 ±1	181 ±1	0.2	10.93	10.91	0.02	0.2

Source: Created by the Authors

TABLE V. AVERAGE VELOCITY AND KINETIC ENERGY LOSS FOR THE GAMO MAGNUM PELLET

Type of clothing	v_1 [m·s ⁻¹]	v_2 [m·s ⁻¹]	Δv [m·s ⁻¹]	E_1 [J]	E_2 [J]	ΔE [J]	Loss [%]
Jeans	209 ±2	205±3	3.8	10.63	10.25	0.38	3.6
Swimming shorts	210 ±2	207±2	2.4	10.74	10.5	0.24	2.3
T-shirt	209 ±1	204±2	4.6	10.66	10.2	0.47	4.4
Functional T-shirt	209 ±2	203±4	6.0	10.61	10.01	0.60	5.6
Spring jacket	209 ±1	204±2	5.6	10.72	10.16	0.57	5.3
No clothing (ref.)	210 ±2	210±2	0.0	10.76	10.76	0.0	0.0

Source: Created by the Authors

TABLE VI. PENETRATION IN BALLISTIC SOAP FOR THE GAMO MAGNUM PELLET

Type of clothing	v [m·s ⁻¹]	E_1 [J]	E_2 [J]	E_d [J·mm ⁻²]	h [cm]
Clean soap	212 ±1	10.92	10.92	0.687	5.3 ±0.1
Jeans	212 ±2	10.92	10.53	0.662	5.0 ±0.2
Swimming shorts	211 ±2	10.85	10.60	0.667	4.9 ±0.3
T-shirt	212 ±2	10.89	10.41	0.655	5.0 ±0.1
Functional T-shirt	211 ±2	10.84	10.23	0.643	5.2 ±0.2
Spring jacket	213 ±2	11.02	10.44	0.657	4.9 ±0.1

Source: Created by the Authors

TABLE VII. PENETRATION DEPTH IN BALLISTIC SOAP FOR THE JSB ULTRA SHOCK HEAVY PELLET

Type of clothing	v [m s ⁻¹]	E_1 [J]	E_2 [J]	E_d [J·mm ⁻²]	h [cm]
Clean soap	181 ±1	10.89	10.89	0.685	4.3 ±0.2
Jeans	181 ±1	10.93	10.12	0.636	3.5 ±0.2
Swimming shorts	183 ±2	11.2	10.45	0.657	4.0 ±0.1
T-shirt	181 ±1	10.93	10.26	0.645	3.6 ±0.4
Functional T-shirt	181 ±1	10.89	9.52	0.599	3.7 ±0.3
Spring jacket	183 ±1	11.17	9.15	0.575	4.0 ±0.1

Source: Created by the Authors

TABLE VIII. RELATIVE WOUNDING POTENTIAL

Pellet	Configuration	Residual E_2 [J]	h [cm]	RWP [J·cm ⁻¹]
Gamo Magnum	Clean soap	10.88	5.30	2.05
Gamo Magnum	Jeans	10.53	4.96	2.12
Gamo Magnum	Swimming shorts	10.6	4.86	2.18
Gamo Magnum	T-shirt	10.41	4.98	2.09
Gamo Magnum	Functional T-shirt	10.23	5.16	1.98
Gamo Magnum	Spring jacket	10.44	4.89	2.13
JSB Ultra Shock	Clean soap (ref.)	10.89	4.31	2.53
JSB Ultra Shock	Jeans	10.12	3.45	2.93
JSB Ultra Shock	Swimming shorts	10.45	4.03	2.59
JSB Ultra Shock	T-shirt	10.26	3.64	2.82
JSB Ultra Shock	Functional T-shirt	9.52	3.69	2.58
JSB Ultra Shock	Spring jacket	9.15	4.00	2.29

Source: Created by the Authors