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Wounding Potential Evaluation of Low-power Weapons via Ballistic-soap Deformation

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Abstract

Miscellaneous firearms that capable of firing metal projectiles to inflict penetrating injuries are regarded as controlled weapons in Taiwan. Aluminium witness plates have been used to evaluate the wounding potential of airguns by local crime laboratories. In this study, the entrance diameters (d), penetration depths (D), and volumes (V) of gunshot cavities in ballistic soaps were used to evaluate the muzzle energy density (ED), and hence the wounding potential, of airguns and unmodified blank pistols. A series of firing tests were conducted using two airguns and two types of projectiles. The velocity (v), kinetic energy (KE), and energy density of the projectiles fired at ballistic soaps were determined using a ballistic chronograph. The results of correlation analysis between the mean values of d and v, D and ED, and V and KE, respectively, showed that the coefficients of determination (R^2) ranged 0.9411 to 0.9991. The results of verification firing tests using airguns and unmodified blank pistols demonstrate that the linear equations obtained to model the relationship between the mean values of d and v, D and ED, and V and KE, respectively, were all useful for calculating the evaluated impact energy density (ED_E) and the percentage differences between ED and ED_E were found to be ≤ 16.8%, 2.8%, and 11.5%, respectively. The results also indicate that V is more suitable than d and D for use in the firing tests to evaluate the wounding potential of low-power weapons. Additionally, we developed a non-destructive, fast, accurate, and costless method to determine the volume of gunshot cavity in ballistic soap. The results in this study are expected to assist crime laboratories in determining the legal status of low-power weapons with respect to the legal power limit of controlled firearms.

Keywords: firearms examination, airgun, blank pistol, ballistic soap, temporary cavity volume, impact energy density, wounding potential

Introduction

Airguns are pneumatic weapons that use the expanding force of compressed air or other pressurized gases to discharge projectiles. Unmodified blank guns have also been reported to be capable of firing muzzle-loaded projectiles [1]. Most airguns are regarded as low-power weapons and unmodified blank guns are generally considered harmless imitation of real guns. However, because the energy density required for penetrating human skin is relatively low, both of them are capable of causing significant physical injuries [2]. Three cases of life-threatening chest wounds caused by accidental firing of BB airguns were reported by DeCou et al., fortunately, all three child victims recovered uneventfully [3]. Guenther et al. described a 21-year-old man who sustained a penetrating cardiac injury from an airgun that led to cardiac tamponade and death. They also reviewed literatures and identified 39 other cases of penetrating cardiac injuries inflicted by airgun pellets [4]. Mogni

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and Maines reported a homicide case that a man was murdered by an air weapon. On autopsy, a diabolo pellet was found to perforate the anterior pericardial sac and the right ventricle [5]. Two suicide cases and one accident case concerning fatal neck injuries caused by blank pistols were described by Rothschild and Vendura. The high-pressure propellant gases created penetrating injuries and extensive wound cavities in all three cases [6]. Rabl et al. reported a case where a man was shot by an offender with an unmodified blank gun loaded with a metal pin. A 4-cm long wound channel was found in the right temple. The projectile was revealed under radiography examination [7]. In Taiwan, the legal power limit of airguns and miscellaneous firearms is 20 J/cm^2. This is based on the capability of projectiles fired from these weapons to cause skin-penetrating gunshot wounds [8]. Unmodified blank guns are currently categorized as imitation firearms under Taiwanese firearm control laws. However, they are capable of firing muzzle-loaded projectiles with muzzle energy densities above 20 J/cm^2 and are recommended to be legally controlled [1].

In addition to the energy density of fired projectiles, aluminum witness plates have also been used to evaluate the wounding potential of questioned firearms in Taiwan [8, 9]. When a firearm is fired, the projectile penetrates the human body to generate a temporary cavity that results from the transfer of kinetic energy. Subsequently, the human body returns to its original form to leave a permanent cavity [2]. Specifically designed targets, such as ballistic gelatin and ballistic soap, have been used in wound ballistics experiments [10]. Ballistic gelatin is an elastic material, thus the path caused by the penetrating of a projectile in gelatin block represents the permanent cavity of a gunshot wound. However, the limit of elasticity for ballistic soap is very low. Thus, the deformation resulted from the projectile passing through ballistic soap is nearly plastic, and the wound channel would collapse only marginally. This leaves an almost unchanged temporary cavity on which one can easily take measurements of the diameter, penetration depth, and volume of the wound cavity [11]. In this study, we used airguns to conduct a series of firing tests on ballistic soaps at various impact velocities (v). The impact kinetic energy (KE) and impact energy density (ED) of the fired projectiles were calculated. The entrance diameter (d), penetration depth (D), and volume (V) of ballistic-soap deformation were measured and analyzed to propose linear equations relating d to v, D to ED, and V to KE, respectively. The results were further used to evaluate the wounding potential of projectiles discharged from airguns and unmodified blank pistols. The aim of this study was to develop a presumptive test using the ballistic-impact deformations of ballistic soaps to evaluate the wounding potential of low-power guns.

Materials and methods

Research equipment and materials

The experiments in this study were conducted using two types of multi-stroke pneumatic air pistols (Crosman P1377 4.5-mm caliber and Crosman P1322 5.5-mm caliber) and two types of Turkish Zorkai blank pistols (M906 and M2918, 9 mm P.A.K. caliber and 8.05 mm thread bore diameter). Two lead ball-type projectiles (4.5 mm projectiles measuring 0.53 g and 5.5 mm projectiles measuring 0.99 g) were employed for the firing tests of air pistols. Additionally, one brand of blank cartridges (Walther 9 mm P.A.K., Germany) and 8 mm steel ball bearings (BBs, measuring 2.10 g) were used for the verification tests of blank pistols. Ballistic soaps (Sheng Sing Instrument Co. Ltd., Taiwan) measuring 290 mm × 145 mm × 145 mm were used as the witness targets. A sample ID composed of the pistol model, projectile diameter, and number of pumps for air pistols or manufacturer of blank cartridges was utilized for each firearm, projectile, and cartridge combination. The symbols used for the pistol model were “P1377” for Crosman P1377, “P1322” for Crosman P1322, “M906” for Zoraki M906 and “M2918” for Zoraki M2918. Symbols for the projectile diameter were “45” for 4.5 mm, “55” for 5.5 mm, and “80” for 8.0 mm. Letter P and a number, such as P3, was the symbol of pump number for air pistols. Letter W represents blank cartridges manufactured by Walther. Letter T and a number, such as T1, was the symbol of the verification tests and the firing number. The sample names and their features for the firing tests and verification tests are listed as Tables 1 and 2, respectively.

Table 1 Sample name, airgun model, diameter of projectiles, and number of pumps for firing tests

Sample name	Airgun model	Diameter of projectiles	Number of pumps
P1377-45-P3	Crosman P1377	4.5 mm	3
P1377-45-P4	Crosman P1377	4.5 mm	4
P1377-45-P5	Crosman P1377	4.5 mm	5
P1377-45-P6	Crosman P1377	4.5 mm	6
P1377-45-P8	Crosman P1377	4.5 mm	8
P1377-45-P10	Crosman P1377	4.5 mm	10
P1322-55-P4	Crosman P1322	5.5 mm	4
P1322-55-P6	Crosman P1322	5.5 mm	6
P1322-55-P7	Crosman P1322	5.5 mm	7
P1322-55-P9	Crosman P1322	5.5 mm	9
P1322-55-P11	Crosman P1322	5.5 mm	11
P1322-55-P13	Crosman P1322	5.5 mm	13

Table 2 Sample name, pistol model, diameter of projectiles, and number of pumps or cartridge brand for verification tests

Sample name	Pistol model	Diameter of projectiles	Number of pumps/ Cartridge brand
P1377-45-P5-T1	Crosman P1377	4.5 mm	5
P1377-45-P8-T2	Crosman P1377	4.5 mm	8
P1377-45-P10-T3	Crosman P1377	4.5 mm	10
P1322-55-P7-T4	Crosman P1322	5.5 mm	7
P1322-55-P11-T5	Crosman P1322	5.5 mm	11
P1322-55-P13-T6	Crosman P1322	5.5 mm	13
M906-80-W-T7	Zoraki M906	8.0 mm	Walther
M906-80-W-T8	Zoraki M906	8.0 mm	Walther
M906-80-W-T9	Zoraki M906	8.0 mm	Walther
M2918-80-W-T10	Zoraki M2918	8.0 mm	Walther
M2918-80-W-T11	Zoraki M2918	8.0 mm	Walther
M2918-80-W-T12	Zoraki M2918	8.0 mm	Walther

Experimental method design

All test firings and verification tests were conducted in an indoor ballistic laboratory at an ambient temperature of 23 °C. Two ballistic chronographs were used to measure the impact velocity (*v*) of the fired projectile. The pistol was gripped by a shooter and leveled so that the line of flight of the projectile was perpendicular to the planes defined by the light screens of ballistic chronograph. The impact kinetic energy (KE) and impact energy densities (ED) of the fired projectile were calculated by employing the equations from a previous study [8].

The experimental setup for the firing tests of air pistols is shown in Figure 1. The impact velocities were adjusted by varying the number of pumps for these multi-stroke pneumatic air pistols, as listed in Table 1. The *v* was measured using a Chrono-R2 chronograph (LMBR, Poland). The start and stop sensors of the Chrono-R2 were designed to be 10 cm apart. The start sensor was placed at a distance of 3 cm from the muzzle of the air pistol. The ballistic soap was placed at a distance of 14 cm from the stop sensor. Three repeated firings were conducted for each firing test sample of different pistol, projectile, and pump number combinations. The mean velocity ($\bar{v}$), kinetic energy ($\overline{KE}$), energy density ($\overline{ED}$), and their standard deviations (SDs) for each sample were calculated.

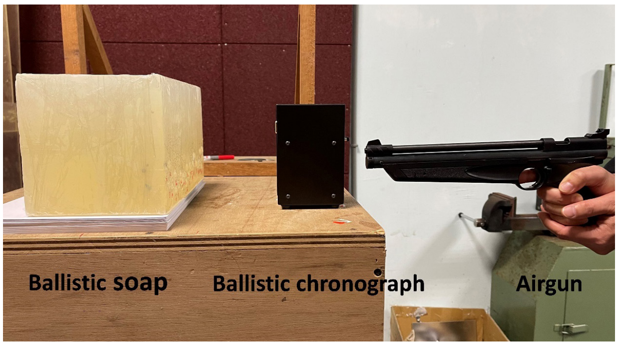

Fig. 1 The experimental setup for airgun firing tests.

The air pistols and blank pistols were subjected to further firing tests, as listed in Table 2, to verify the effectiveness and practicality of the linear equations developed in this study. The aforementioned experimental setup was used for the verification firing tests of air pistols. A BMC 19 chronograph (Kurzzeit, Germany) was used to measure the *v* of projectiles fired from the blank pistols. The start and stop sensors of the BMC 19 were designed to be 34.5 cm apart. The start sensor was placed at a distance of 85 cm from the muzzle of the pistol. The ballistic soap was placed at a distance of 30 cm from the stop sensor. For each verification test of blank pistols, a round of blank cartridge was chambered from the breech and a ball-type projectile was wrapped with a piece of paper and rammed from the muzzle end down the barrel to a point just in front of the barrel obstructions. Subsequently, the chambered blank pistol was fired directly through the light screens of the ballistic chronograph. Three repeated firings were performed for each blank pistol.

The entrance diameter (d) and the penetration depth (D) of gunshot cavity in ballistic soap were measured using a digital caliper (Mitutoyo, Japan). The permanent cavity in ballistic soap (Figure 2) was resulted from a slight collapse of the original temporary cavity, which is regarded as the combination of a truncated cone and a hemisphere of the ball-typed projectile as shown in Figure 3, thus the volume of temporary cavity was calculated using the following equation:

$$V=\pi h(R_1^2 + R_2^2 + R_1R_2)/3 + 2\pi R_2^3/3 \quad (1)$$

where h is the height of truncated cone, R_1 is the radius of cavity entrance; R_2 is the radius of projectile.

The mean entrance diameter ($\bar{d}$), penetration depth ($\bar{D}$), and volume ($\bar{V}$) of temporary cavity in the ballistic soap for each sample and their standard deviations (SDs) were calculated.

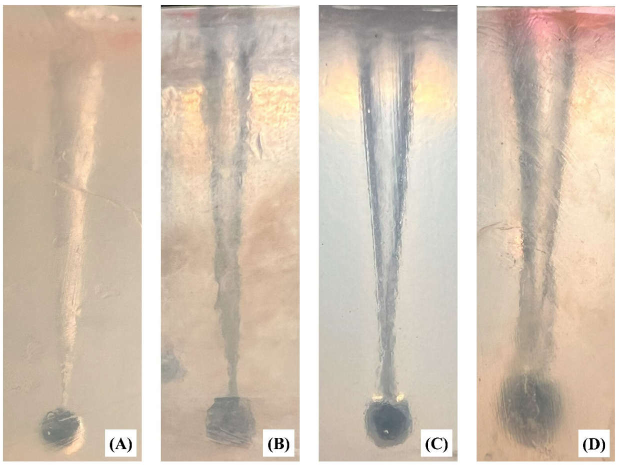

Fig. 2 The deformation cavities created by various firing test samples: (A) P1377-45-P6, (B)P1322-55-P9, (C)M906-80-W-T8, (D)M2918-80-W-T10.

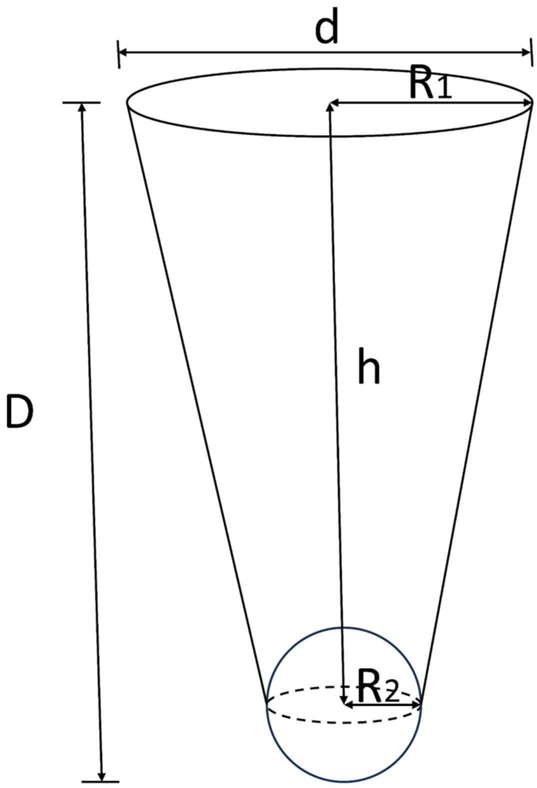

Fig. 3 The original temporary cavity is regarded as the combination of a truncated cone and a hemisphere of the ball-typed projectile.

Statistical analysis

A correlation analysis was used to measure the correlation strengths between the values of $\overline{\mathrm{d}}$ and $\overline{v}$, $\overline{\mathrm{D}}$ and $\overline{\mathrm{ED}}$, and $\overline{\mathrm{V}}$ and $\overline{\mathrm{KE}}$ for the firing test samples, respectively. Simple linear regression analysis was also performed to model the relationship between $\overline{\mathrm{d}}$ and $\overline{v}$, $\overline{\mathrm{D}}$ and $\overline{\mathrm{ED}}$, and $\overline{\mathrm{V}}$ and $\overline{\mathrm{KE}}$ for the firing test samples, respectively. The obtained linear equations for $\overline{\mathrm{d}}$ and $\overline{v}$, $\overline{\mathrm{D}}$ and $\overline{\mathrm{ED}}$, and $\overline{\mathrm{V}}$ and $\overline{\mathrm{KE}}$ were utilized in the verification firing tests to calculate the evaluated impact velocity (v_E), impact energy density (ED_E), and impact kinetic energy (KE_E), respectively. The acquired values of v_E and KE_E were then further calculated to obtain their corresponding ED_Es, respectively.

The percentage difference between ED and ED_E of verification firing tests was calculated by dividing the difference between ED and ED_E by the mean of ED and ED_E and multiplying the quotient by 100%.

Results and discussion

Correlation analysis between entrance diameter and impact velocity

The values of $\overline{v}$, $\overline{\mathrm{KE}}$, $\overline{\mathrm{ED}}$, $\overline{\mathrm{d}}$, $\overline{\mathrm{D}}$, and $\overline{\mathrm{V}}$ and their standard deviations (SDs) for each firing test sample are presented in Table 3. Ottoson pointed out that when a target is penetrated by ballistic impacts, the diameter of temporary cavity is proportional to the velocity of projectiles having the same sectional density [12]. Kneubuehl et al. [2] established a proportional relationship between d and v during ballistic impacts that can be stated as the following equations:

$$\mathrm{d}^2 \propto \mathrm{KE/q} \quad (2)$$

where q is the sectional density of projectile, which is given by

$$\mathrm{q = m/A} \quad (3)$$

where m and A are the mass and sectional area of projectile, respectively.

$$\mathrm{KE} = \mathrm{m}v^2/2 \quad (4)$$

$$\mathrm{A} = 2\pi \mathrm{r}^2 \quad (5)$$

where r is the radius of projectile.

Combines Equations 2, 3, 4, and 5 gives

$$\mathrm{d} \propto \mathrm{v \cdot r} \quad (6)$$

Equation 6 shows that the diameter of cavity entrance in the target of a ballistic impact is proportional to the impact velocity and the radius, and hence the diameter, of the projectile.

As observed from Table 3, for the projectiles having the same mass and diameter, that also representing the same sectional density; $\overline{\mathrm{d}}$ tended to increase as $\overline{v}$ increased. The $\overline{v}$ values of the 4.5 mm and 5.5 mm projectiles ranged from 109.0 m/s to 172.3 m/s and 97.7 m/s to 148.3 m/s, respectively. The $\overline{\mathrm{d}}$ values of deformation cavity in ballistic soap created by 4.5 mm and 5.5 mm projectiles ranged from 5.79 mm to 7.69 mm and 7.10 mm to 8.77 mm, respectively. The results of correlation analysis between $\overline{\mathrm{d}}$ and $\overline{v}$ indicated that the coefficients of determination, denoted by R^2, between $\bar{d}$ and $\bar{v}$ for the ballistic impacts by the 4.5 mm and 5.5 mm projectiles were 0.9411 and 0.9918, respectively. These results agree well with the findings described by Ottoson [12]. The linear equations obtained to model the relationship between $\bar{d}$ and $\bar{v}$ for the ballistic impacts of 4.5 mm and 5.5 mm projectiles were $\bar{d} = 0.0277\,\bar{v} + 2.6983$ and $\bar{d} = 0.0334\,\bar{v} + 3.8066$, respectively, as shown in Figure 4. The results indicate that the diameters of deformation entrances in the ballistic soaps were linearly related to the impact velocities when the fired projectiles had the same diameter.

Table 3 The means of the impact velocity ($\bar{v}$), impact kinetic energy ($\overline{KE}$), impact energy density ($\overline{ED}$), diameter of cavity entrance ($\bar{d}$), penetration depth of cavity ($\bar{D}$), and volume of temporary cavity ($\bar{V}$) and their standard deviations (SDs) for each firing test sample

Sample name	$\bar{v}$ ± SD (m/s)	$\overline{KE}$ ± SD (J)	$\overline{ED}$ ± SD (J/cm^2)	$\bar{d}$ ± SD (mm)	$\bar{D}$ ± SD (cm)	$\bar{V}$ ± SD (cm^3)
P1377-45-P3	109.0±2.0	3.15±0.12	19.80±0.73	5.79±0.08	2.12±0.13	0.420±0.032
P1377-45-P4	125.7±1.2	4.18±0.08	26.31±0.48	6.28±0.04	2.80±0.05	0.616±0.016
P1377-45-P5	137.7±0.6	5.02±0.05	31.58±0.27	6.47±0.00	3.27±0.04	0.751±0.010
P1377-45-P6	147.3±3.1	5.75±0.23	36.18±1.50	6.54±0.04	3.78±0.08	0.884±0.024
P1377-45-P8	160.3±2.1	6.81±0.17	42.84±1.11	7.06±0.30	4.30±0.10	1.114±0.084
P1377-45-P10	172.3±2.1	7.87±0.19	49.49±1.20	7.69±0.15	4.94±0.10	1.432±0.065
P1322-55-P4	97.7±2.3	4.72±0.22	19.88±0.94	7.10±0.03	2.26±0.06	0.667±0.023
P1322-55-P6	116.3±2.1	6.70±0.24	28.20±1.00	7.63±0.18	3.18±0.20	1.035±0.094
P1322-55-P7	123.7±0.6	7.57±0.07	31.87±0.30	7.90±0.02	3.53±0.06	1.204±0.026
P1322-55-P9	134.7±1.5	8.98±0.20	37.79±0.86	8.39±0.01	4.14±0.05	1.530±0.020
P1322-55-P11	142.7±0.6	10.07±0.08	42.41±0.35	8.52±0.01	4.64±0.07	1.754±0.027
P1322-55-P13	148.3±0.6	10.89±0.09	45.85±0.36	8.77±0.01	5.08±0.14	2.001±0.057

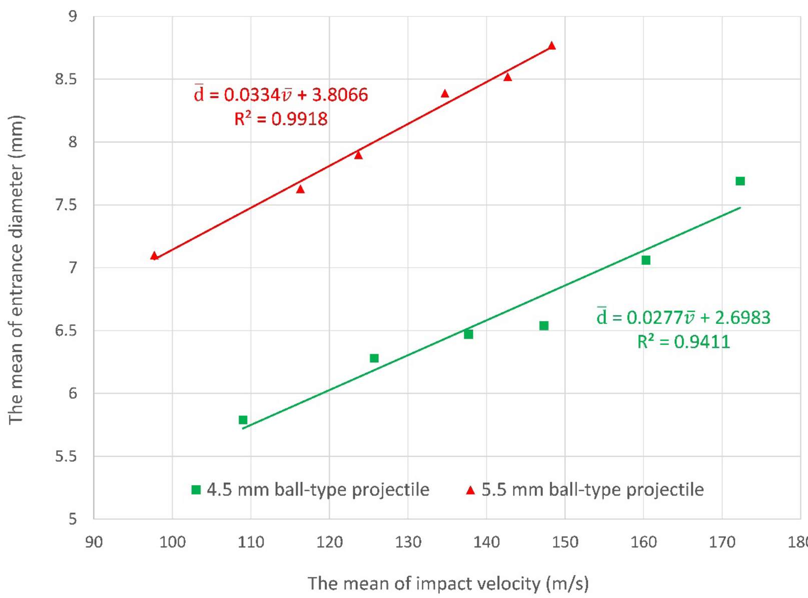

Fig. 4 Linear relationships between the mean of entrance diameter ($\bar{d}$) of deformation cavity and the mean of impact velocity ($\bar{v}$) of 4.5 mm and 5.5 mm projectiles, respectively.

In the verification firing tests of 4.5 mm and 5.5 mm air pistols, the d values obtained from firing tests were used to calculate the corresponding v_E values using the aforementioned linear equations, respectively. Subsequently, ED_E values and the values of percentage differences (PD_{ED}) between ED_E and ED were calculated. The data for d, v, ED, v_E, ED_E, and PD_{ED} between ED_E and ED are listed in Table 4. As inferred from Table 4, with the exception of the CP1377-45-P8-T2 sample which has a PD_{ED} value of 16.8%, the ED_E data obtained from the other five verification firing tests agree well with the corresponding ED data, and their PD_{ED} values are all less than 9.5%.

Table 4 The d, v, ED, v_E, ED_E, and PD_{ED} values for the verification firing tests of 4.5 mm and 5.5 mm air pistols

Sample name	d (mm)	v (m/s)	ED (J/cm^2)	v_E (m/s)	ED_E (J/cm^2)	PD_{ED} (%)
P1377-45-P5-T1	6.35	131	28.59	131.8	28.94	1.2
P1377-45-P8-T2	6.67	156	40.55	143.4	34.26	16.8
P1377-45-P10-T3	7.46	164	44.81	171.9	49.24	9.4
P1322-55-P7-T4	7.89	123	31.52	122.3	31.16	1.1
P1322-55-P11-T5	8.39	136	38.54	137.2	39.22	1.7
P1322-55-P13-T6	8.53	144	43.20	141.4	41.66	3.6

Correlation analysis between penetration depth and impact energy density

For ballistic impacts which created deformation cavities, Kneubuehl et al. [2] established a proportional relationship between the ratio of penetration depth/sectional density (D/q) and the impact kinetic energy (KE) of spheroid missiles that can be stated as the following equation:

$$D/q \propto KE \tag{7}$$

Combines Equations 3 and 7 gives

$$D \propto (KE/A)\cdot m \tag{8}$$

where KE/A is the impact energy density (ED), thus Equation 8 can be rewritten as following:

$$D \propto ED\cdot m \tag{9}$$

Equation 9 shows that the penetration depth of deformation cavity during a ballistic impact is proportional to the impact energy density and the mass of the projectile.

As can be further observed from Table 3, for the projectiles having the same mass $\overline{D}$ tended to increase with the increase of $\overline{ED}$. In the case of 4.5 mm projectiles, the data of $\overline{D}$ and $\overline{ED}$ ranged from 2.12 cm to 4.94 cm and 19.80 J/cm^2 to 49.49 J/cm^2, respectively. In the case of the 5.5 mm projectiles, the corresponding values of $\overline{D}$ and $\overline{ED}$ ranged from 2.26 cm to 5.08 cm and 19.88 J/cm^2 to 45.85 J/cm^2, respectively. The results of correlation analysis between $\overline{D}$ and $\overline{ED}$ demonstrated that the R^2 between $\overline{D}$ and $\overline{ED}$ for the ballistic impacts by the 4.5 mm and 5.5 mm projectiles were 0.9983 and 0.9991, respectively. These results indicate that, in the penetrating ballistic impacts of ballistic soaps, the correlation strengths between $\overline{D}$ and $\overline{ED}$ were significantly higher than those between $\overline{d}$ and $\overline{v}$ for both 4.5 mm and 5.5 mm projectiles.

The linear equations obtained to model the relationship between $\overline{D}$ and $\overline{ED}$ for the ballistic impacts of 4.5 mm and 5.5 mm projectiles were $\overline{D} = 0.0944\ \overline{ED} + 0.2895$ and $\overline{D} = 0.107\ \overline{ED} + 0.1332$, respectively, as shown in Figure 5. The results demonstrate that the penetration depths of deformation cavities in the ballistic soaps were linearly related to the impact energy densities when the fired projectiles had the same mass.

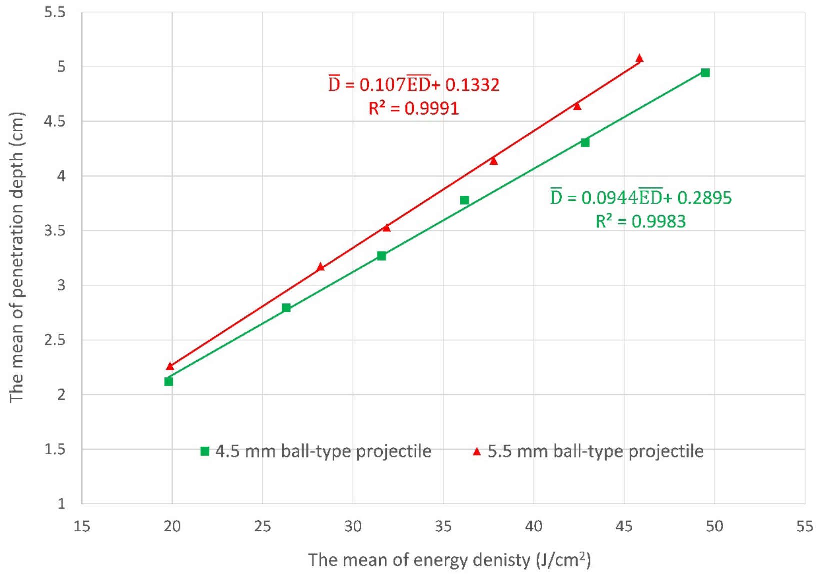

Fig. 5 Linear relationships between the mean of penetration depth ($\overline{D}$) of deformation cavity and the mean of energy density ($\overline{ED}$) of 4.5 mm and 5.5 mm projectiles, respectively.

In the verification firing tests of 4.5 mm and 5.5 mm air pistols, the D values obtained from firing tests were used to calculate the corresponding evaluated ED_E values using the aforementioned linear equations, respectively. The values PD_{ED} between ED_E and ED were then calculated. The data for D, ED, ED_E, and PD_{ED} are listed in Table 5. As inferred from Table 5, the ED_E data of all six verification firing tests agree well with the corresponding ED data, and their PD_{ED} values are all ≤ 2.8%.

Table 5 The data for D, ED, ED_E, and PD_{ED} for the verification firing tests of 4.5 mm and 5.5 mm air pistols

Sample name	D (cm)	ED (J/cm^2)	ED_E (J/cm^2)	PD_{ED} (%)
P1377-45-P5-T1	3.064	28.59	29.39	2.8
P1377-45-P8-T2	4.109	40.55	40.46	0.2
P1377-45-P10-T3	4.443	44.81	44.00	1.8
P1322-55-P7-T4	3.478	31.52	31.26	0.8
P1322-55-P11-T5	4.207	38.54	38.07	1.2
P1322-55-P13-T6	4.871	43.20	44.28	2.5

Correlation analysis between cavity volume and impact kinetic energy

The kinetic energy of a projectile is dissipated by the projectile, target, and friction during an unperforated ballistic impact. The energy dissipated by undeformed solid projectile and friction is negligible [13]. Thus, the deformation of ballistic soap would be the dominant mechanism to dissipate the energy and the volume of temporary cavity would be proportional to the impact kinetic energy for the firing tests in this study. This can be verified by the linear equation proposed by Kneubuehl et al. for the volume of the temporary cavity [2]:

$$V = \mu \cdot E_{ab} \qquad (10)$$

Where μ is the proportionality factor, E_{ab} is the kinetic energy absorbed by the impacted target.

It can be observed from Table 3 that the $\overline{V}$ of all the firing test samples tended to increase with the increase of $\overline{KE}$, regardless the caliber and the mass of projectiles.

The $\overline{KE}$ values of the 4.5 mm and 5.5 mm projectiles ranged from 3.15 J to 7.87 J and 4.72 J to 10.89 J, respectively. The $\overline{V}$ values of temporary cavity created by 4.5 mm and 5.5 mm projectiles ranged from 0.420 cm^3 to 1.432 cm^3 and 0.667 cm^3 to 2.001 cm^3, respectively. The results of correlation analysis between $\overline{V}$ and $\overline{KE}$ for all test firing samples indicated that the R^2 between $\overline{V}$ and $\overline{KE}$ was 0.9897. The linear equation obtained to model the relationship between $\overline{V}$ and $\overline{KE}$ for the ballistic impacts by 4.5 mm and 5.5 mm projectiles was $\overline{V} = 0.2025\,\overline{KE} - 0.2618$ as shown in Figure 6. The results indicate that the volumes of temporary cavities in the ballistic soaps were linearly related to the impact kinetic energies, regardless the diameter and the mass of projectiles used.

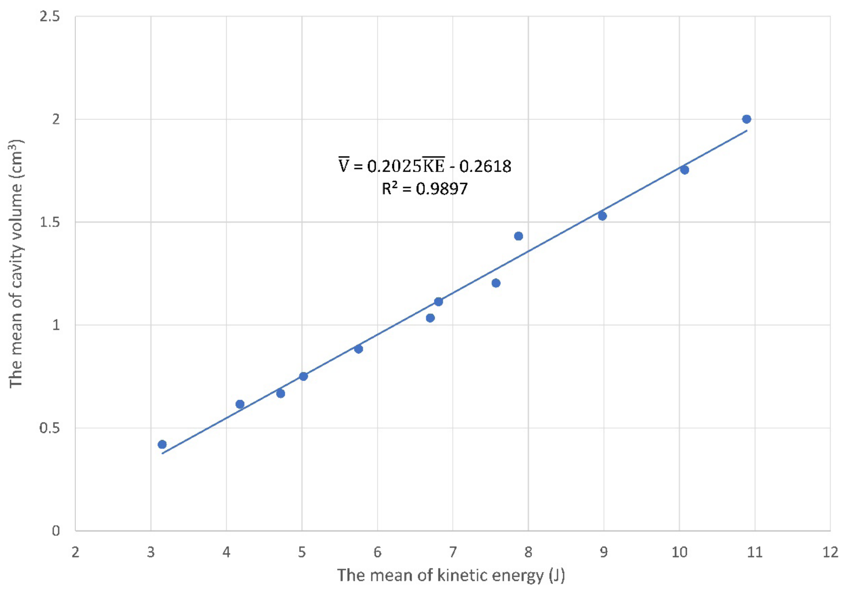

Fig. 6 Linear relationships between the mean of cavity volume ($\overline{V}$) and the mean of kinetic energy ($\overline{KE}$) of all airgun projectiles.

In the verification firing tests of air pistols and blank pistols, the V values obtained from firing tests were used to calculate the corresponding KE_E values utilizing the aforementioned linear equation. Subsequently, ED_E values and the values of PD_{ED} between ED_E and ED were calculated. The data for V, ED, KE_E, ED_E, and PD_{ED} are listed in Table 6. As inferred from Table 6, the ED_E data of all six verification firing tests by air pistols agree well with the corresponding ED data, and their PD_{ED} values are all ≤ 4.5%. The PD_{ED} values are still ≤ 11.5%, even when the 8 mm projectiles fired from two blank pistols were used for the verification firing tests. The results demonstrate that the linear equation obtained using the data of cavity volume and impact kinetic energy for the firing tests of 4.5 mm and 5.5 mm airgun projectiles can also be employed to evaluate the impact energy density of 8 mm projectiles fired from blank pistols. However, linear equations that related d to v and D to ED, respectively, can only be used to calculate ED_E values when the projectiles used in the firing tests have the same caliber and mass.

Table 6 The data for V, KE, ED, KE_E, ED_E, and PD_{ED} between ED_E and ED of each verification sample fried from air pistols and blank pistols

Sample name	V (cm^3)	KE (J)	ED (J/cm^2)	KE_E (J)	ED_E (J/cm^2)	PD_{ED} (%)
P1377-45-P5-T1	0.687	4.55	28.59	4.69	29.46	3.0
P1377-45-P8-T2	0.987	6.45	40.55	6.17	38.78	4.5
P1377-45-P10-T3	1.165	7.13	44.81	7.05	44.30	1.1
P1322-55-P7-T4	1.219	7.49	31.52	7.31	30.78	2.4
P1322-55-P11-T5	1.555	9.16	38.54	8.97	37.76	2.0
P1322-55-P13-T6	1.848	10.26	43.20	10.42	43.85	1.5
M906-80-W-T7	2.882	17.04	33.90	15.52	30.89	9.3
M906-80-W-T8	3.476	19.39	38.58	18.46	36.72	4.9
M906-80-W-T9	3.238	17.50	34.82	17.28	34.38	1.3
M2918-80-W-T10	3.273	17.53	34.88	17.46	34.73	0.4
M2918-80-W-T11	2.414	14.60	29.05	13.21	26.29	9.9
M2918-80-W-T12	2.770	16.80	33.42	14.97	29.79	11.5

In order to measure the cavity volume, the cavity in ballistic soap is usually longitudinally cut in half and both halves are filled with forensic silicone. The two dried silicone moulds are then introduced into a container filled with water and the moulds volume is calculated using the Archimedes principle, where the moulds volume equals to the volume of water displaced by the moulds [14]. This method is invasive, destructive, and time-consuming, furthermore, small spaces in the cavity may remain unfilled or even overfilled by silicone and thus the volume of the cavity being sub-/overestimated. As a non-destructive method, computed tomography (CT) has also been used to measure the deformation cavity in ballistic soap. It is faster, more precise, and more sensitive than the silicone moulds method. However, CT instrumentation is expensive and unavailable in forensic ballistic laboratories. Therefore, the method developed in this study is more practical and efficient than the silicone-casting and CT methods for forensic practitioners to determine the cavity volumes in ballistic soap. However, the aforementioned Equation 1 cannot be used to calculate the volume of irregularly shaped cavities resulted from the deformation, fragmentation, and tumbling of projectiles during the ballistic impacts. Therefore, we recommend that steel ball- and lead ball-type projectiles, which would not tumble, deform, and fragment in ballistic soap, are most suitable for the wounding potential evaluation of low-power weapons using the volume of gunshot cavity in ballistic soap.

Conclusion

This study verified that the features of deformation cavities in ballistic soap are strongly correlated with wounding potential of low-power weapons during ballistic impacts. The experimental results indicate that the entrance diameters and penetration depths of cavities are linearly correlated with the impact velocities and energy densities, respectively. The results of verification firing tests also demonstrate that the obtained linear equations are useful for evaluating the impact energy densities of fired airguns. However, this is only true when projectiles having the same caliber and mass are used in ballistic-impact tests. Thus, their applications are limited to the evaluation of wounding potential of firearms having the same caliber and using the type of projectiles. On the other hand, the cavity volumes are verified to be linearly correlated with the impact kinetic energies and the obtained linear equation are useful for calculating the values of ED_E, regardless the caliber and the type of projectiles used in the ballistic impacts. Considering the aforementioned results, we can conclude that the cavity volume is more suitable than the entrance diameter and penetration depth for use in the firing tests at ballistic soap to evaluate the wounding potential of low-power weapon. Additionally, we expect that the non-destructive, fast, accurate, and costless volume calculating method developed in this study will assist forensic ballistic laboratories to determine the of volume temporary cavity in ballistic soap in energy density evaluation of questioned firearms. Furthermore, to reduce the influence of the tumbling, deformation, and fragmentation of projectiles, we recommend the use of steel ball- and lead ball-type projectiles to conduct firing tests.

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