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Influence of the Projectile Type on the Energy Density Examination of Airguns

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Abstract

Although airguns are generally thought of low-powered weapons, some of them are able to cause lethal injuries. A literature search yielded many reports of accidental, suicidal, and homicidal penetrating airgun injuries in eye and internal organs of human body. This revealed the potential danger of air weapons. Thus, airguns with kinetic energy above certain legal limits are legally regulated in some countries. In Taiwan, the legal power limit of airguns is 20 J/cm^2 and the chronographic method is used to determine the projectile energy density (ED). In this study, one rifled air pistol was used to perform firing tests. The velocity and ED of sixteen types of Diabolo projectiles with varied nose shape and material composition, one ball-type lead projectile, and one Sheridan cylindrical lead projectile were determined and their variations were investigated. The experimental results indicated that ED values of six types of projectiles were above the Taiwanese legal power limit (20.24–21.66 J/cm^2), while others were below it (16.94–19.94 J/cm^2). Among them, the Diabolo round-nosed lead projectiles had the highest ED values. The results also demonstrated that the projectile velocity is inversely proportional to its mass (R^2 = 0.9323), while projectile ED is influenced by its mass, geometric shape, and material composition. Thus, the legal status of an airgun is likely to be wrongly determined if unsuitable type of projectiles are used for ED examination. We suggest that the Diabolo round-nosed lead projectile is most suitable for the legal status determination of rifled airguns. And we expect the use of suitable type of projectiles will reduce false-negative results and strengthen the reliability and validity of ED examination of suspected illegal airguns.

Keywords: forensic science, firearms examination, airguns, energy density examination, projectile type, Diabolo.

Introduction

Although most airguns are regarded as low-powered weapons, some of them are as powerful as powder firearms and capable of inflicting varied sorts of gunshot wounds. Numerous cases of airgun injuries have been reported in the literature. Jacobs and Morgan reported eleven cases of orbital injuries caused by Diabolo airgun pellets and the projectiles had been retained in the orbit for one month to 26 years [1]. Airgun traumatic cases with heart injury have been recounted in several medical literatures. DeCou et al. published a case report involving life-threatening penetrating airgun injuries to the heart of three boys. All of them recovered uneventfully

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after surgical intervention was used [2]. Bakovic et al. described a case of a young female died after sustaining a penetrating airgun injury in the heart [3]. The involved airgun discharged the Diabolo pellet with an energy density of 190 J/cm^2, which is nearly ten times of the legal power limit (20 J/cm^2) that is assumed to be capable of inflicting lethal injuries in Taiwan [4]. Greenlees et al. presented a case of a 16-year-old male who was shot at close range in the chest with an airgun. The pellet was located at the apex of the left ventricle and retrieved using direct ventriculotomy [5]. Dumencic et al. reported a fatal case caused by an accidentally discharged airgun [6]. The fired pellet penetrated the left lung, heart, and diaphragm after entering the chest of the victim, and was found deep in the liver. Guenther et al. illustrated a case of a 21-year-old male who sustained an airgun injury that led to cardiac tamponade and death [7]. The pellet ran through the left ventricle and anterior esophagus and migrated intraluminally into the stomach. Traumatic cases involving airgun injuries to other parts of the body have also been presented. Krasniqi et al. described a case of a 44-year-old female who sustained an abdominal airgun injury by accident [8]. Tsranchev et al. reported a case involving a self-inflicted airgun injury to the head. The pellet was located in the occipital region of the brain [9]. Simon et al. described a case of a fatal brain injury resulting from accidental airgun shooting to an infant [10]. In addition to accidental and suicidal airgun injuries, homicide using an airgun has also been presented [11,12].

The homicide, suicide and accident cases involving the use of airguns recounted in the literature demonstrate that airguns are potentially lethal weapons. Thus, the purchase, possession, carry, and use of pneumatic weapons are legally regulated in some countries [13-15]. The wounding potential of airguns is strongly related to the kinetic energy imparted by the projectile on the tissues. The amount of kinetic energy of discharged projectile has been used to set the legal power limits of air weapons in many countries [16]. In Taiwan, the legal power limit of energy density for airguns is 20 J/cm^2, the threshold kinetic energy density that a projectile is capable of perforating human skin to inflict a fatal injury [15,17]. Because the legal status of an airgun is evaluated basing on its kinetic energy that is determined by the projectile mass and the square of the velocity, and thus the projectile features that affect the muzzle velocity of an examined airgun are critical to the accurate determination of its legal status.

For an airgun-projectile combination, the projectile velocity is determined by the initial velocity and the downrange loss of velocity. The initial velocity is depending on the pressure of propelling gas, the sealing and friction forces between projectile and barrel, and the projectile mass [18], while the downrange loss of velocity is predominantly due to the drag force [19]. Frank et al. published a couple of papers using unusual type of projectiles, such as plastic-sleeved composite projectiles [20] and sub-caliber discarding sabot airgun projectiles [21], to demonstrate the muzzle velocity of airguns are related to the shape, material composition, and mass of the projectiles. Salimipour et al. used simulation methods to investigate and compare the ballistic performance of some airgun projectiles with modified nose shapes and the computed results revealed that the change in projectile shape influenced the mass, initial velocity and drag forces of a projectile [22]. Since the velocity and energy density of a fired projectile is influenced by its geometric shape, mass, and material composition, an airgun is still illegal if the value of its energy density is beyond the legal power limit with one type of projectile but not with another. Therefore, it is the aim of this study to investigate the most suitable projectile type for the energy density examination of suspected illegal airguns through the firing tests of one air pistol using a number of conventional types of airgun projectiles with varied geometric shapes, masses, and material compositions.

Materials and methods

Research equipment and materials

In this study, a series of firing tests were performed using one 4.5 mm caliber rifled single-stroke pneumatic air pistol (Beeman P17, USA). Additionally, one ball-type projectile (4.5 mm lead ball), one Sheridan cylindrical projectile (4.5 mm lead pellet) and sixteen Diabolo projectiles with varied nose shapes (4.5 mm round-nosed, pointed, wadcutter, and hollow-pointed) and material compositions (lead , copper-coated lead, and tin) (H&N, Germany, see Fig. 1) were used. A sample ID composed of letters and numbers was utilized for each type of projectile. The symbols used for geometric shape were “P” for Diabolo pointed, “R” for Diabolo round-nosed, “W” for Diabolo wadcutter, “H” for Diabolo hollow-pointed, “B” for ball-type, and “C” for Sheridan cylindrical. Symbols for material composition were “Pb” for lead, “Cu (Pb)” for copper-coated lead and “Sn” for tin. The sample ID, projectile type, material composition, and mass of 18 H&N airgun projectiles used in this study are presented in Table1. The elemental composition of each type of airgun projectiles was analysed using a JSM-IT300 scanning electron microscope (SEM, Jeol, Japan) combined with MaxN energy dispersive X-ray spectrometer (EDS, Oxford, UK).

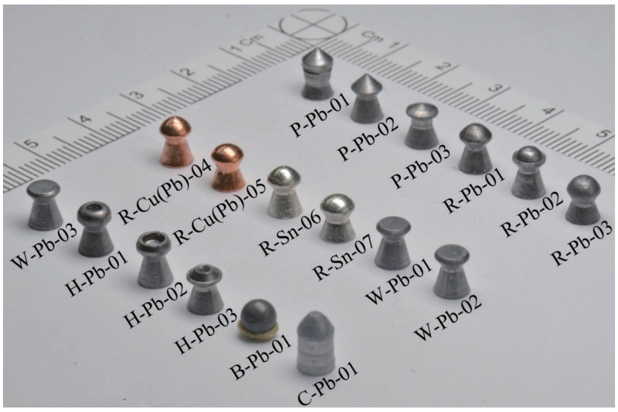

Fig. 1 Photograph of the shapes and sample IDs of 18 H&N airgun projectiles.

Table 1 Sample ID, type, material composition, and mass of airgun projectiles.

Sample ID	Projectile type	Material composition	Mass (g)
P-Pb-01	Diabolo pointed	Lead	0.74
P-Pb-02	Diabolo pointed	Lead	0.55
P-Pb-03	Diabolo pointed	Lead	0.55
R-Pb-01	Diabolo round-nosed	Lead	0.67
R-Pb-02	Diabolo round-nosed	Lead	0.57
R-Pb-03	Diabolo round-nosed	Lead	0.56
R-Cu(Pb)-04	Diabolo round-nosed	Copper-coated lead	0.68
R-Cu(Pb)-05	Diabolo round-nosed	Copper-coated lead	0.57
R-Sn-06	Diabolo round-nosed	Tin	0.42
R-Sn-07	Diabolo round-nosed	Tin	0.36
W-Pb-01	Diabolo wadcutter	Lead	0.53
W-Pb-02	Diabolo wadcutter	Lead	0.49
W-Pb-03	Diabolo wadcutter	Lead	0.48
H-Pb-01	Diabolo hollow-pointed	Lead	0.67
H-Pb-02	Diabolo hollow-pointed	Lead	0.58
H-Pb-03	Diabolo hollow-pointed	Lead	0.46
B-Pb-01	Ball-type	Lead	0.55
C-Pb-01	Sheridan cylindrical	Lead	0.99

Experimental method design

One of each type of airgun projectiles was subjected to elemental analysis using SEM/EDS without prior coating. Three randomly selected areas were analysed for each lead projectile, each tin projectile, and the coating and core of each copper coated lead projectile. Computer software, built into the SEM/EDS, was employed to calculate the weight percentages of detected metal elements of each sample. The mean and standard deviation (SD) of the weight percentages of detected metal elements of each sample were calculated.

The experimental setup for the firing tests is shown in Fig. 2. The velocity of projectile was measured using a ballistic chronograph equipped with two infrared light screens suitable for all light conditions (Model-57, OEHLER, USA). The start and stop sensors on the light screens were designed to be 200 cm apart. The start sensor was placed at a distance of 50 cm from the muzzle of the air pistol. The air pistol was mounted on a rigid rack and leveled so that the line of flight of the projectile is perpendicular to the planes defined by the light screens of ballistic chronograph. All test firings were conducted in an indoor ballistic laboratory at temperature 26 °C and relative humidity 76%. Ten repeated firings were conducted for each type of projectile. Furthermore, the kinetic energy and energy density of the fired projectile were calculated by employing the equations from a previous study [4]. The mean, standard deviation and coefficient of variation of measured velocities of each set of firing test were calculated.

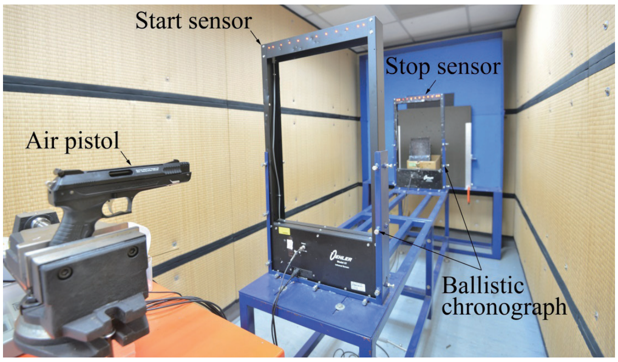

Fig. 2 The experimental setup for firing tests.

Results and discussion

The weight percentage data of all airgun projectile samples are listed in Table 2. Typical EDS spectra obtained from the elemental analysis of a lead projectile (P-Pb-01), a copper-coated lead projectile (R-Cu(Pb)-4), and a tin projectile (R-Sn-06) are shown in Fig. 3. As observed from Table 2 and Fig. 3, all types of lead projectiles were made out of lead to which antimony had been added to increase the hardness of the alloy. The weight percentages of lead and antimony of different types of lead projectiles ranged from 93.9% to 98.3% and 1.7% to 6.1%, respectively. All types of tin projectiles were made out of pure tin metal. Every type of copper-coated lead projectiles had pure lead cores coated with copper-aluminium alloy where the weight percentages of aluminium were less than 9%. The lead signals observed in the EDS spectrum of the coating of copper-coated lead projectile were generated from the lead core due to the penetration of electron beam through the copper-aluminium coating into the lead core.

Table 2 Sample ID and weight percentage data of all airgun projectile samples.

Sample ID	Weight percentage of elements (mean ± SD %)
P-Pb-01	Pb (98.0 ± 0.4), Sb (2.0 ± 0.4)
P-Pb-02	Pb (97.5 ± 0.6), Sb (2.5 ± 0.6)
P-Pb-03	Pb (97.1 ± 0.3), Sb (2.9 ± 0.3)
R-Pb-01	Pb (96.4 ± 1.4), Sb (3.6 ± 1.4)
R-Pb-02	Pb (98.2 ± 0.2), Sb (1.8 ± 0.2)
R-Pb-03	Pb (98.3 ± 0.1), Sb (1.7 ± 0.1)
R-Cu(Pb)-04/Core	Pb (100.0)
R-Cu(Pb)-04/Coating	Cu (92.5 ± 0.7), Pb (4.8 ± 0.7), Al (2.7 ± 0.7)

Sample ID	Weight percentage of elements (mean ± SD %)
R-Cu(Pb)-05/Core	Pb (100.0)
R-Cu(Pb)-05/Coating	Cu (89.8 ± 1.1), Pb (1.6 ± 0.9), Al (8.6 ± 2.0)
R-Sn-06	Sn (100.0)
R-Sn-07	Sn (100.0)
W-Pb-01	Pb (98.2 ± 0.3), Sb (1.8 ± 0.3)
W-Pb-02	Pb (96.3 ± 0.7), Sb (3.7 ± 0.7)
W-Pb-03	Pb (96.5 ± 1.7), Sb (3.5 ± 1.7)
H-Pb-01	Pb (95.9 ± 0.4), Sb (4.1 ± 0.4)
H-Pb-02	Pb (97.1 ± 0.6), Sb (2.9 ± 0.6)
H-Pb-03	Pb (96.9 ± 0.7), Sb (3.1 ± 0.7)
B-Pb-01	Pb (93.9 ± 2.7), Sb (6.1± 2.7)
C-Pb-01	Pb (97.0 ± 0.5), Sb (3.0 ± 0.5)

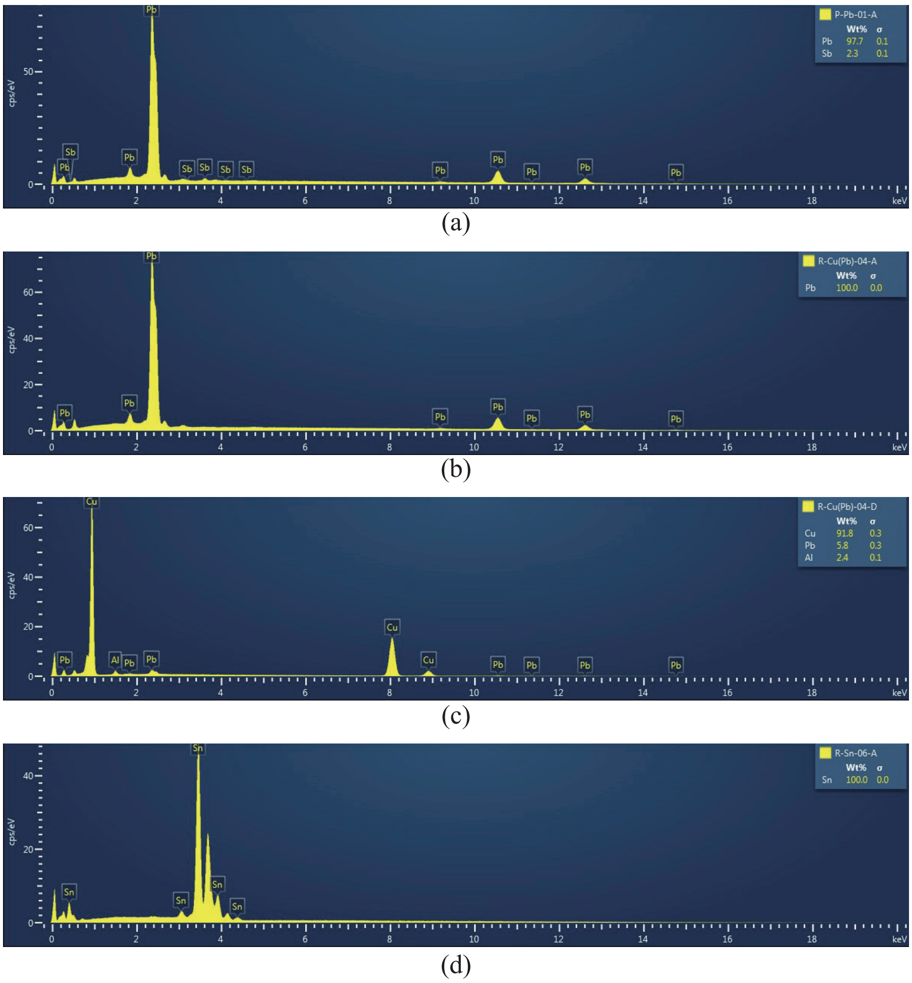

Fig. 3 Energy dispersive X-ray spectra obtained from the elemental analysis of (a) pellet P-Pb-01, (b) the core and (c) coating of pellet R-Cu(Pb)-4, and (d) pellet R-Sn-06.

The mean and standard deviation (SD) of velocity (V), kinetic energy (KE), and energy density (ED) data and the coefficient of variation (CV) of velocity of each type of projectiles are presented in Table 3 in the sequence of energy density values.

Table 3 Velocity, kinetic energy, and energy density data of each type of projectiles.

Sample ID	V ± SD (m/s)	CV of V	KE ± SD (J)	ED ± SD (J/cm^2)
R-Pb-01	101.4 ± 0.52	0.51%	3.44 ± 0.04	21.66 ± 0.22
R-Pb-03	108.3 ± 0.48	0.45%	3.28 ± 0.03	20.65 ± 0.18
R-Pb-02	107.2 ± 0.63	0.59%	3.27 ± 0.04	20.59 ± 0.24
P-Pb-01	93.8 ± 0.63	0.67%	3.26 ± 0.04	20.47 ± 0.28
P-Pb-03	108.5 ± 0.53	0.49%	3.24 ± 0.03	20.36 ± 0.20
P-Pb-02	108.2 ± 0.63	0.58%	3.22 ± 0.04	20.24 ± 0.24
H-Pb-01	97.3 ± 0.48	0.50%	3.17 ± 0.03	19.94 ± 0.20
W-Pb-02	113.5 ± 0.53	0.46%	3.16 ± 0.03	19.84 ± 0.18
W-Pb-01	108.7 ± 0.82	0.76%	3.13 ± 0.05	19.69 ± 0.30
W-Pb-03	113.5 ± 1.08	0.95%	3.09 ± 0.06	19.44 ± 0.37
H-Pb-02	102.9 ± 0.99	0.97%	3.07 ± 0.06	19.31 ± 0.37
B-Pb-01	105.6 ± 0.52	0.49%	3.07 ± 0.03	19.28 ± 0.19
H-Pb-03	113.8 ± 0.79	0.69%	2.98 ± 0.04	18.73 ± 0.26
R-Sn-06	117.0 ± 0.94	0.81%	2.87 ± 0.05	18.08 ± 0.29
R-Sn-07	125.5 ± 1.08	0.86%	2.84 ± 0.05	17.83 ± 0.31
R-Cu(Pb)-05	99.2 ± 1.55	1.56%	2.81 ± 0.09	17.64 ± 0.55
C-Pb-01	74.4 ± 0.97	1.30%	2.74 ± 0.07	17.23 ± 0.45
R-Cu(Pb)-04	89.0 ± 1.49	1.67%	2.69 ± 0.09	16.94 ± 0.57

As observed from Table 3, the mean velocity of different types of projectiles ranged from 74.4 m/s for the Sheridan cylindrical lead projectile (C-Pb-01) to 125.5 m/s for the Diabolo round-nosed tin projectile (R-Sn-07). The mass values of projectile C-Pb-01and R-Sn-07 were 0.99 g and 0.36 g, respectively. The results revealed that the velocity of projectile was inversely proportional to projectile mass as shown in Fig. 4. A correlation analysis was performed to obtain the correlation coefficient (R) and the coefficient of determination (R^2) and investigate the correlation strength between the velocity and the mass of projectile fired from the air pistol. The correlation analysis results showed that the R value and R^2 value were -0.9656 and 0.9323, respectively. The corresponding t-score was -14.85, while the p-value was 8.88×10^{-11}, and thus the correlation between the velocity and the mass of projectile was considered to be significantly strong. For pneumatic type airguns, gas is compressed via a cocking lever into a high-pressure reservoir. Airguns employ the compressed air instead of the combustion gases generated by gunpowder to propel projectile within the barrel. When the trigger is pulled, the compressed air (pressure P) expands into the barrel (of cross-sectional area A), pushing out the projectile (mass m). The force (F) acting upon the projectile is thus

$F = A \times P$ (1)

According to the Newton's second law of motion the applied force equals to the mass multiplied by the acceleration (a) of the accelerated projectile.

$F = m \times a$ (2)

Combines Equations 1 and 2 gives

$P = (m/A) \times a$ (3)

Equation 3 shows that the acceleration of the projectile is inversely proportional to its cross-sectional density (*m/A*) when the pressure of compressed air is constant. Since the cross-sectional area of the projectile and the barrel length are constant in this study, the mass of the projectile should be as small as possible to obtain high muzzle velocity.

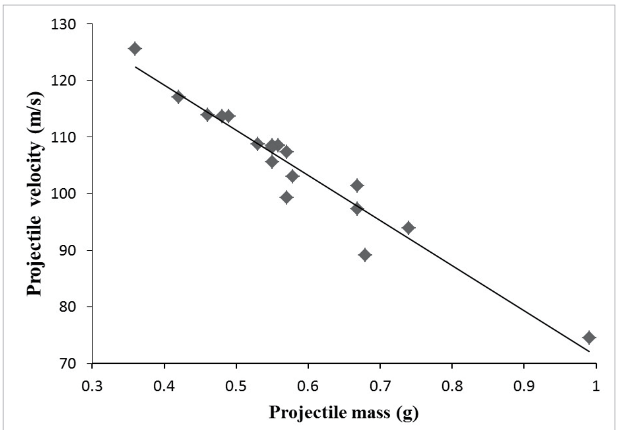

Fig. 4 Inversely proportional relationship between projectile velocity and projectile mass.

With the exception of projectiles R-Cu(Pb)-04, R-Cu(Pb)-05, and C-Pb-01, the CV values of velocity were all smaller than 1.0%, as observed from the values given in Table 3. The skirt of a Diabolo projectile is designed to be expanded by the high-pressure gas to seal the bore when an airgun is fired [18]. The deformation of skirt can be easily achieved for Diabolo lead pellets and the base rim is forced into the barrel rifling grooves to properly seal the high-pressure gas. However, since the hardness of copper is greater than that of lead, the copper layer of the Diabolo copper-coated lead pellets, such as R-Cu(Pb)-04 and R-Cu(Pb)-05, may cause varied degree of sealing and lead to greater CV values of the velocity. For the Sheridan cylindrical lead projectile (C-Pb-01), its base rim could not be efficiently expanded to tightly seal the bore, and thus its CV value of the velocity was greater than those of all Diabolo lead projectiles.

As can be further observed from Table 3, the ED values of different types of projectiles ranged from 16.94 J/cm^2 to 21.66 J/cm^2. The percentage difference between the maximum ED value (ED_{max}) and minimum ED value (ED_{min}) was calculated by dividing the difference between ED_{max} and ED_{min} by the mean of ED_{max} and ED_{min} and multiplying the quotient by 100. The percentage difference between ED_{max} and ED_{min} was 24.46%, indicating that the use of different types of projectiles would significantly affect the ED values of an airgun. In Taiwan, the threshold value of ED for evaluating the legal status of airguns is 20 J/cm^2. Airguns with ED values above this legal limit are regarded as controlled weapons and cannot be purchased, possessed, carried, or used without legitimate permission. Although all of the projectiles used in this study were fired from the same air pistol, the ED values of six out of eighteen types of projectiles were greater than 20 J/cm^2, ranged from 20.24 J/cm^2 to 21.66 J/cm^2, and the ED values of other types of projectiles were lower than the legal limit, ranged from 16.94 J/cm^2 to 19.94 J/cm^2. This finding reveals that the use of suitable type of projectiles is extremely important for the ED examinations in order to accurately determine the legal status of airguns.

For the fourteen types of lead projectiles, with the exception of H-Pb-03, we found that the Diabolo lead projectiles had the highest ED values (19.31–21.66 J/cm^2), followed by the ball-type lead projectile (19.28 J/cm^2), while the Sheridan cylindrical lead projectile had the lowest energy density (16.94 J/cm^2). This further demonstrates that the expansion of the skirt of Diabolo lead projectile would properly seal the gap between projectile and barrel and result in higher ED value. The ball-type projectile had a narrow circular bearing surface that could not be expanded by the high-pressure gas, and thus the sealing was looser than the sealing of Diabolo projectiles. This resulted in a lower ED value. The greatest bearing surface of the Sheridan cylindrical projectile led to the greatest friction forces and resulted in the lowest ED value. As for the hollow-pointed projectile (H-Pb-03) that had an unusual nose shape as shown in Fig. 1, the aerodynamic drag acting on its front face during the free flight would significantly slow down the velocity. It is postulated that the decreased velocity and the smallest mass among all Diabolo lead projectiles resulted in a lower ED value for H-Pb-03 compare to the ED value of the ball-type lead projectile (B-Pb-01).

Ladommatos found that the aerodynamic drag acting on the projectile nose playing a dominant role in the overall drag for non-spherical projectiles [23]. Salimipour et al. reported that the round-nosed projectiles had the lowest drag coefficients, followed by the sharp nose (pointed) projectiles, while the flat nose (wadcutter) projectiles had the highest drag coefficients [22]. And the cavity nose (hollow-pointed) projectiles had been reported to have similar drag coefficients to flat nose (wadcutter) projectiles [23]. The lower drag coefficient would reduce the downrange loss of velocity and result in higher ED value for the projectile. And the ED examination results for the twelve Diabolo lead projectiles used in this study agree well with the aforementioned relationship between the nose shape and the drag coefficients (and hence ED values) of projectiles. As listed in Table 3, the Diabolo round-nosed lead projectiles had the highest ED values (20.59–21.66 J/cm^2), followed by the Diabolo pointed lead projectiles (20.24–20.47 J/cm^2), while the Diabolo wadcutter and hollow-pointed lead projectiles had the lowest ED values (18.73–19.94 J/cm^2 and 19.44–19.84 J/cm^2, respectively) and the ranges of their ED values were overlapping with each other. This demonstrates that the Diabolo round-nosed projectiles had a better aerodynamic shape than other types of projectiles.

Regarding the influence of different material composition on the ED values of sixteen Diabolo projectiles, the lead projectiles had the highest ED values (18.73–21.66 J/cm^2), followed by the tin projectiles (17.83 and 18.08 J/cm^2), while the copper-coated lead projectiles had the lowest ED values (16.94and 17.64 J/cm^2). As we mentioned earlier, the copper is harder than lead. Hence, it was more difficult for the copper layer of the copper-coated lead projectiles to be deformed to firmly seal the gap between projectile and barrel. The gas escaped through the gap would reduce the power of the high-pressure gas, and thus resulted in the lowest ED values. Considering the exterior ballistic performance, the projectile's cross-sectional density should be high to reduce the downrange loss of velocity and kinetic energy. The cross-sectional densities of Diabolo tin projectiles were smaller than those of Diabolo lead projectiles. And the lower ED values of Diabolo tin projectiles observed in this study would be resulted from their smaller cross-sectional densities.

The results of this study showed that the projectile velocity (and hence the ED) of an airgun is actually not an invariable, but is dependent on the mass, geometric shape, and material composition of projectiles used. Owing to the variations of the geometric shape and material composition within a fixed projectile caliber, the projectile mass varies between different projectile designs. The demands of projectile mass are contradictory between the realms of interior ballistics and exterior ballistics. Considering the interior ballistic performance, the projectile mass should be low to obtain high velocity; while under exterior ballistic considerations, the projectile mass should be high to reduce the ballistic coefficient and the loss of velocity [24]. The projectile mass is primarily influenced by its material composition and geometric shape. Furthermore, the geometric shape (especially nose shape) would dominate the overall aerodynamic drag acting on the projectile, and thus affect the exterior ballistic performance. The tail shape and material composition would also affect the degree of sealing between projectile and barrel, and thus influence the interior ballistic performance of the projectile. The results of firing tests performed in this study demonstrated that for a 4.5 mm caliber rifled airgun, the Diabolo round-nosed lead projectile with a mass of 0.67 g is the most suitable type of projectile for the determination of ED.

Conclusion

This study verified that the projectile velocity is inversely proportional to the projectile mass when an airgun is fired, and the projectile ED is affected by the mass, geometric shape, and material composition of the projectile. Depending on the type of projectiles used, an airgun may obtain some ED values above the legal power limit while others below the legal power limit. Thus, the legal status of an airgun is likely to be wrongly determined if unsuitable types of projectiles are used for the ED examination. This reveals that it is very crucial to use proper type of projectiles to accurately determine the legal status of airguns. Based on the findings of this study, the Diabolo round-nosed lead projectile is most suitable for the firing tests to determine the legal status of rifled airguns. We expect that the use of proper type of projectiles will reduce false-negative results of the ED examination of suspected illegal air weapons.

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