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Influence of Ambient Temperature on the Legal Status Determination of Airguns

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Abstract

Airguns employ pressurized air or vapors of liquefied gases to discharge projectiles, and thus are usually considered to be harmless. However, some of them are capable of inflicting lethal injuries. Thus, a legal power limit of 20 J/cm^2 is given to regulate the dangerous airguns in Taiwan. And the legal status of airguns is determined through muzzle energy density (ED) examination. The muzzle EDs of pneumatic and spring-piston airguns have been reported to be affected by ambient temperature. However, the influence of ambient temperature on the muzzle EDs of liquefied-gas airguns has not been investigated. In this study, a series of firing tests were conducted using one spring-piston, three pneumatic, and three liquefied-gas airguns to investigate the influence of temperature on their muzzle EDs. The results indicated that over an increase of 7 °C in ambient temperature, the liquefied CO_2 airgun obtained the most increase of muzzle ED, followed by the liquefied propane airguns and the pneumatic airguns, whereas the spring-piston airgun had the least increase of muzzle ED. The results of a *t*-test using a confidence level of 90% showed that the differences between the EDs obtained at different temperatures were statistically significant for all types of airguns tested. The interior ballistic fundamentals of the influence of ambient temperature on the muzzle EDs of different types of airguns are discussed in detail. The muzzle ED examination results of one experimental pneumatic airgun and one actual-case liquefied CO_2 airgun verified that an airgun was probable to have muzzle EDs lower than the legal power limit at lower temperature while higher than the legal limit at higher temperature. This reveals that the ambient temperatures of forensic laboratories shall be carefully controlled to accurately determine the legal status of a suspicious airgun.

Keywords: forensic science, firearms examination, airguns, legal status, ambient temperature, muzzle energy density.

Introduction

An airgun is an air-powered device that employs the expansion of pressurized air or gas to accelerate a projectile down the barrel. The power systems of airguns can be broadly categorized into three groups: spring-piston, pneumatic type, and liquefied-gas. A spring-piston airgun uses a compressed spring driving a piston to compress the air in the cylinder to propel the projectile down the barrel. In a pneumatic airgun, atmospheric air is pumped and pressurized into a storage chamber. The compressed air is released to drive the missile down the barrel when the trigger is pulled. For airguns using liquefied gas as power source, the vaporized gas is used to discharge the projectile when ambient temperature is below the critical temperature of the gas. Carbon dioxide (CO_2) is currently the most commonly used liquefied gas in airguns, followed by liquefied propane. The critical temperatures of CO_2 and propane are 31.1°C and 97°C, respectively.

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Low-powered smoothbore airguns are generally regarded as toys and used for firearms training, funfair shooting games, paintball shootings, and survival games [1,2]. Rifled airguns that have higher muzzle energy are regarded as weapons and used for sport and hunting. Although airguns are usually considered to be harmless, some of them are as dangerous as conventional powder firearms that are able to perforate skin and soft tissue and injure deeper structures [3-5]. Thus, the legal power limits in the values of muzzle kinetic energy (KE) or energy density (ED) are given to regulate the dangerous airguns in some countries. In Taiwan, the legal muzzle ED limit of airguns is 20 J/cm^2. The reason for this ED limit is that a projectile must perforate skin and soft tissue to inflict lethal injury [6,7]. In Japan, airguns are regulated by two legal power limits, the higher one is 20 J/cm^2 for the potential of endangering human life and the other is 3.5 J/cm^2 for the capability of injuring a person [8]. In Hong Kong, the applicable KE limit of airguns is 2 J [9]. In Germany, the legal KE limit of airguns is 7.5 J, whereas in Ireland, it is 1 J [10].

In Taiwan, the legal status of an airgun is determined basing on the results of muzzle ED examination. It has been reported that the muzzle ED of an airgun is not an invariable even for a specific airgun-projectile combination, but is dependent on ambient temperature [11]. However, the aforementioned study had conducted firing tests only on pneumatic and spring-piston airguns that used compressed air as the power source. Although one Chinese-language literature has addressed a postulation that ambient temperature would also affect the muzzle EDs of airguns powered by liquefied CO_2 [12], no firing tests have been performed to verify the postulation in this literature. To the best of our knowledge, there are no literatures mentioned the influence of ambient temperature on the muzzle ED of an airgun powered by liquefied propane. To evaluate the influence of varied ambient temperatures on the muzzle EDs of airguns with different types of power sources, we conducted a series of firing tests using seven airguns of different types. The objective of the current study was to prove the importance of controlling the ambient temperatures of forensic laboratories to the reliable determination of legal status of suspicious illegal airguns.

Materials and methods

Research equipment and materials

The firing tests in this study were conducted using seven models of airguns including three pneumatic airguns(4.5 mm caliber), one spring-piston airgun (4.5 mm caliber), two liquefied propane airguns (6 mm caliber), and one liquefied CO_2 airgun (6 mm caliber). A sample ID composed of airgun type and model was utilized for each airgun. The symbols used for airgun type were “P” for pneumatic, “S” for spring-piston, “C” for carbon dioxide, and “G” for propane. The sample ID, type, brand, model, and caliber of airguns used are presented in Table 1. Additionally, one ball-type copper-coated steel projectile (6 mm steel ball measuring 0.88 g) and one Diabolo round-nosed lead pellet (4.5 mm JSB Exact projectiles measuring 0.54 g) were used. The elemental composition of the copper-coated steel ball and the lead pellet were analyzed using JSM-IT300 scanning electron microscope (SEM, Jeol, Japan) and MaxN energy dispersive X-ray spectrometer (EDS, Oxford, UK).

Table 1 Sample ID, type, brand, model, caliber, and testing temperatures of airguns used.

Sample ID	Type	Brand	Model	Caliber	Temperatures
C-M84	Liquefied CO_2 Pistol	WG	M84	6 mm	22 & 29 °C
G-MK1	Liquefied Propane Pistol	KJWorks	MK1 Carbine	6 mm	23 & 30 °C
G-M93R	Liquefied Propane Pistol	KSC	M93R	6 mm	22 & 29 °C
P-TCX	Pre-charged Pneumatic Rifle	Listone	Taichi X	4.5 mm	23 & 30 °C
P-840C	Multi-pump Pneumatic Rifle	Daisy	840C	4.5 mm	22 & 29 °C
P-P17	Single-pump Pneumatic Pistol	Beeman	P17	4.5 mm	23 & 30 °C
S-AF10	Spring-piston Pistol	Gamo	AF10	4.5 mm	22 & 29 °C

Experimental method design

The experimental setup for the firing tests is shown in Fig. 1. The muzzle velocity was measured using a ballistic chronograph (Model-57, Oehler, USA). The start and stop sensors of the Model-57 were designed to be 200 cm apart. The start sensor was placed at a distance of 50 cm from the muzzle of the airgun. The airgun 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 Model-57. All test firings were conducted in an indoor ballistic laboratory at a lower temperature of 22 °C or 23 °C and a higher temperature of 29 °C or 30 °C, as shown in Table 1. Twenty repeated firings were performed for each airgun. Because the temperature of the airgun would decrease when the liquefied gas evaporated, the firings of all liquefied-gas airguns used in this study were performed at intervals of at least 30 seconds to minimize the influence of the temperature drop. Furthermore, the kinetic energy and ED of the fired projectile were calculated by employing the equations from a previous study [13]. The mean and standard deviation (SD) of muzzle velocities (v) and muzzle EDs of firing tests for each airgun were calculated. To examine the influence of ambient temperature on the muzzle ED of airguns, an independent sample t-test was used to establish the significance of the differences between mean EDs obtained at different temperatures of each airgun. Two confidence levels of 95% and 90% (p-value = 0.05 and 0.10, respectively) were chosen for the t-test.

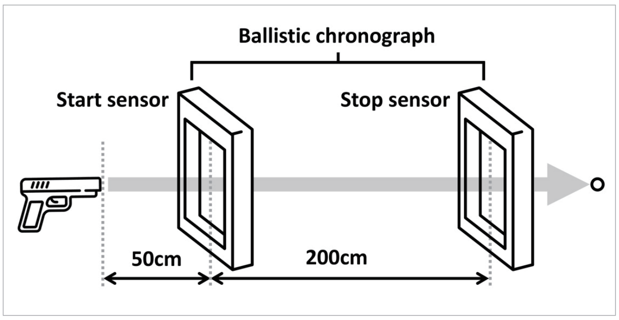


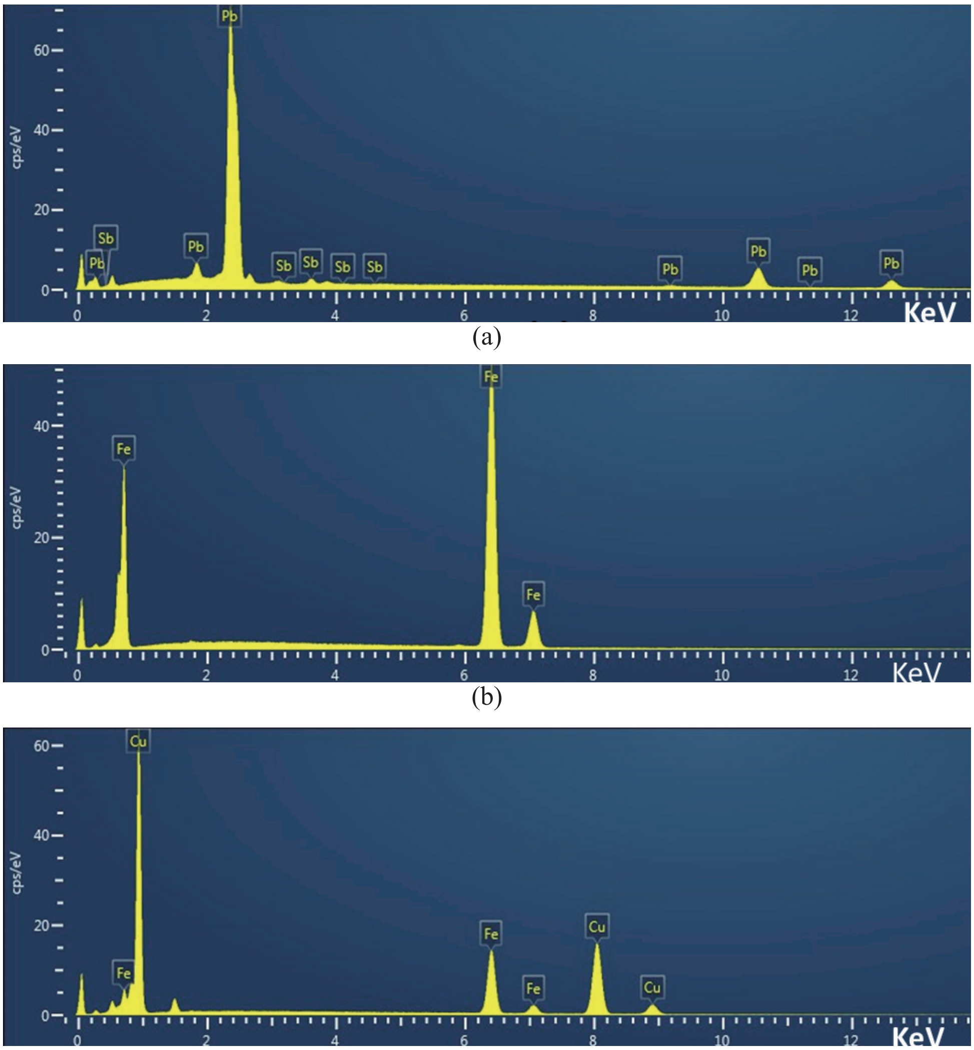
Fig. 1 The experimental setup for firing tests.

To verify the influence of ambient temperature on the legal status determination of suspicious airguns, one airgun (WinGun 321, 6 mm caliber) collected from an actual case was subjected to firing tests. One ball-type steel projectile (6 mm steel balls measuring 0.88 g) was used. The tested air gun used a liquefied CO_2 cartridge measuring 12 g as power source, as shown in Fig. 2. The standard operating temperature used for the airgun muzzle ED examination conducted in Taiwan's Forensic Science Laboratories is 25 ± 2 °C. The firing tests of the actual-case airgun were performed at three different ambient temperatures: two of them were below the standard operating temperature (17 °C and 20 °C) and the other was at 25 °C. The muzzle velocity was measured by a ballistic chronograph (BMC 19, Kurzziet, Germany) with the start and stop sensors being 34.5 cm apart. The start sensor was placed at 100 cm away from the airgun muzzle. Five repeated firings were performed at each temperature. An independent sample t-test with a confidence level of 95% was used to investigate the significance of the differences between the mean EDs obtained at each compared pair of temperatures.

Fig. 2 Photograph of the actual-case liqueified CO_2 airgun.

Results and discussion

The results of elemental composition analysis showed that the Diabolo-type lead pellet was made out of lead to which antimony had been added to increase the hardness of the alloy. And the steel projectile was a steel ball with a thin coating of copper. The energy dispersive X-ray spectra obtained from the analysis of the lead pellet and the core and the coating of the steel ball are shown in Fig. 3.



(a)

(b)

(c)

Fig. 3 Energy dispersive X-ray spectra obtained from the analysis of: (a) the Diabolo-type lead pellet; (b) the core of the copper-coated steel ball; (c) the coating of the copper-coated steel ball.

The mean and SD of the muzzle velocities and the percentage difference (PD) between the mean muzzle velocities obtained at the higher temperature (v_{ht}) and the lower temperature (v_{lt}) of each airgun are presented in Table 2. As observed from Table 2, the mean projectile velocity measured at the higher temperature was higher than that measured at the lower temperature for every airgun regardless of the type of power source utilised in the airgun. The PD values between v_{ht} and v_{lt} varied from 0.6% for the spring-piston pistol (S-AF10) to 9.0% for the liquefied CO_2 pistol (C-M84). The results revealed that over a range of 7 °C increase in ambient temperature, the liquefied CO_2 airgun had the most increase of mean muzzle velocity with a PD value of 9.0%, followed by the liquefied propane airguns (PD values were 4.1% and 2.8% for G-MK1 and G-M93R, respectively) and the pneumatic airguns (PD values were 3.7%, 2.6%, and 2.1% for P-TCX, P-840C, and P-P17, respectively), while the spring-piston airgun had the least increase of mean muzzle velocity with a PD value of 0.6%. While the PD of absolute temperature between the higher temperature and the lower temperature was 2.3%. The percentages of the increase of muzzle velocities over the same range of increase of ambient temperature varied with the types of the airguns tested and were not consistent with the percentage of the increase of absolute temperature. The rationale underlying the above results is as discussed below.

Table 2 Sample ID, muzzle velocity data, and PDs between v_{ht} and v_{lt} of airguns tested.

Sample ID	v_{lt} ± SD (m/s)	v_{ht} ± SD (m/s)	PD (%)
C-M84	79.36 ± 1.20	84.09 ± 2.54	9.0
G-MK1	94.35 ± 0.81	98.30 ± 0.47	4.1
G-M93R	50.66 ± 2.91	52.09 ± 2.03	2.8
P-TCX	71.05 ± 0.76	73.70 ± 0.92	3.7
P-840C	78.71 ± 1.01	80.80 ± 1.20	2.6
P-P17	108.10 ± 0.78	110.35 ± 0.67	2.1
S-AF10	73.35 ± 1.03	73.85 ± 0.73	0.6

The mean and SD of the muzzle EDs and the PD value and the p-value of the *t*-test between the mean muzzle EDs obtained at the higher temperature (ED_{ht}) and the lower temperature (ED_{lt}) of each airgun are presented in Table 3. The results showed that the values of ED_{lt} and ED_{ht} ranged from 4.01 J/cm^2 to 19.84 J/cm^2 and 4.23 J/cm^2 to 20.67 J/cm^2, respectively. The ED_{lt} values of all airguns tested were smaller than the legal power limit of Taiwan (20 J/cm^2). The ED_{ht} values of all airguns tested were higher than their respective ED_{lt} values. Among the seven airguns tested, only the single-pump pneumatic pistol P-P17 had the ED_{ht} value higher than 20 J/cm^2. Furthermore, although the mean ED value of the P-P17 airgun tested at 23 °C was 19.84 J/cm^2, there were six out of the twenty repeated firings had ED values higher than 20 J/cm^2. The Student's t-distribution curves for the ED values of the P-P17 tested at 23 °C and 30 °C are shown in Fig. 4. Basing on the t-distribution curves, the probabilities of the ED higher than 20 J/cm^2 for the P-P17 airgun tested at 23 °C and 30 °C were 28.0% and 99.3%, respectively. The results demonstrated that an airgun was probably determined to be a non-restricted airgun at a lower temperature, but was evaluated to be a restricted weapon at a higher temperature.

Table 3 Sample ID, muzzle ED data, and PDs and p-values of *t*-tests between ED_{ht} and ED_{lt} of airguns tested.

Sample ID	ED_{lt} ± SD (J/cm^2)	ED_{ht} ± SD (J/cm^2)	PD (%)	p-Value
C-M84	9.80 ± 0.30	11.01 ± 0.67	11.6	5.71×10^{-7}
G-MK1	13.85 ± 0.24	15.04 ± 0.14	8.2	3.67×10^{-11}
G-M93R	4.01 ± 0.46	4.23 ± 0.32	5.3	0.083
P-TCX	8.57 ± 0.18	9.22 ± 0.23	7.3	4.60×10^{-12}
P-840C	10.52 ± 0.27	11.08 ± 0.33	5.2	5.97×10^{-7}
P-P17	19.84 ± 0.29	20.67 ± 0.25	4.1	6.72×10^{-12}
S-AF10	9.14 ± 0.26	9.26 ± 0.18	1.3	0.087

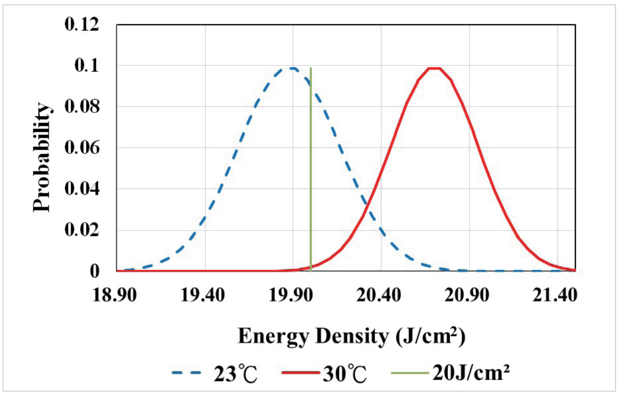


Fig. 4 Student's *t*-distribution curves for the ED values of the P-P17 airgun tested at 23 °C and 30 °C.

As listed in Tables 2 and 3, the PDs between ED_{ht} and ED_{lt} of all airguns tested are greater than their respective PDs between v_{ht} and v_{lt}. This is resulted from that the muzzle ED of an airgun is determined by the square of the muzzle velocity as the equations shown in a previous study [13]. As can be further observed from Table 3, the liquefied CO_2 airgun acquired the most increase of mean ED (PD was 11.6%), followed by the liquefied propane gas airguns (PDs were 8.2% and 5.3%) and the pneumatic-type airguns (PDs were 7.3%, 5.2%, and 4.1%), whereas the spring-piston airgun obtained the least increase of mean ED (PD was 1.3%) when the ambient temperature increased over a range of 7°C.

With the exception of G-M93R and S-AF10, the p-values of the *t*-tests for the comparison of ED_{ht} and ED_{lt} of airguns tested were all less than 0.05. This reveals that the increase of muzzle ED for five out of seven airguns tested is statistically significant at a confidence level of 95% as the temperature rose by 7°C. The p-values for G-M93R and S-AF10 were 0.083 and 0.087, respectively, which were less than 0.10. Thus, if a confidence level of 90% (p-value = 0.10) instead of 95% was chosen for the *t*-test, the differences between ED_{ht} and ED_{lt} of airguns tested would be all statistically significant. This indicates that the muzzle EDs of airguns are significantly affected by the testing temperature, and thus the ambient temperatures of the forensic laboratories should be carefully controlled while conducting muzzle ED examinations for determining the legal status of airguns.

For the interior ballistics of airguns using the power source of liquefied gas, the force (F) that acts on the projectile is determined by the vapor pressure (p_{vap}) of the liquefied gas and the sectional area (A) of the projectile as

$$F = p_{vap}A \tag{1}$$

The muzzle velocity of an airgun depends on the acceleration (a) of the projectile propelled in the barrel. The acceleration is determined by the force and the mass of the projectile (m_p) as follows:

$$F = m_p a \tag{2}$$

Combines Equations 1 and 2 gives

$$a = p_{vap}A/m_p \tag{3}$$

If the acceleration is assumed to be constant, we can calculate the muzzle velocity (v) of the projectile using the following equation:

$$v = v_0 + at \tag{4}$$

where v_0 is the velocity at time t = 0.

Since $v_0 = 0$ when an airgun is fired, we can rewrite Equation 4 as

$$v = at \tag{5}$$

Combines Equations 3 and 5 gives

$$v/t = p_{vap}A/m_p \tag{6}$$

Equation 6 shows that the projectile's muzzle velocity is proportional to the vapor pressure of the liquefied gas. Because the p_{vap} of a liquefied gas increases with temperature as shown in Table 4, the muzzle velocity (and hence ED) of a liquefied gas airgun increases as ambient temperature rises. The vapor pressures of liquefied CO_2 and liquefied propane at different testing temperatures (T) of each airgun used in this study are listed in Table 4.

Table 4 The p_{vap} of liquefied gases used in different airguns at different testing temperatures.

Sample ID	Gas	p_{vap} (psi) / T (°C)	p_{vap} (psi) / T (°C)
C-M84	CO_2	871 / 22	1023 / 29
G-MK1	Propane	131 / 23	156 / 30
G-M93R	Propane	128 / 22	153 / 29

For the interior ballistics of pneumatic type and spring-piston airguns, the compressed air in the chambers is regarded as ideal gas to keep discussion simple.

There are many versions of ideal gas law that differ in unit. One of them is

$$pV = m_g RT \tag{7}$$

where p is the pressure of the gas, V is the volume the gas occupies, m_g is the mass of the gas, R is the specific gas constant, T is the absolute temperature.

The work (W) done on the projectile by the compressed air in the airgun barrel is defined as follows:

$$W = \int F\,dx \qquad (8)$$

In Equation 8, work is defined as the product of the force and the distance over which the force acts.

The force acts on the projectile is the product of the gas pressure and the cross sectional area (A) of the projectile that gives

$$F = pA \qquad (9)$$

Using Equation 9, we can rewrite Equation 8 as

$$W = \int pA\,dx \qquad (10)$$

Furthermore, we can write Equation 10 in terms of the pressure and the volume of the gas as

$$W = \int p\,dV \qquad (11)$$

Combines Equations 7 and 11 gives

$$W = m_g RT(dV/V) \qquad (12)$$

If we assume that all of the work done by the compressed air is converted into the kinetic energy (KE) of the projectile, then Equation 12 can be rewritten as

$$KE = m_g RT(dV/V) \qquad (13)$$

Equation 13 shows that the KE (and hence ED) of the projectile is directly proportional to the absolute temperature when it is fired from an airgun using compressed air as the power source.

Although the compressed air were used by both spring-piston and pneumatic airguns as their power sources, the values of PD listed in Table 3 showed that the tested pneumatic airguns had more increase of muzzle ED than spring-piston airgun as ambient temperature increased. The reason for this is discussed as follows.

For a spring-piston airgun, the air is pulled into the compression chamber when the piston is withdrawn. When the airgun is fired, the spring drives the piston forward and compresses the air in front of it. And the compressed air presses directly on the projectile loaded in the barrel. The projectile does not move down the barrel until the force of the compressed air overcomes the projectile's friction resistance. Thus, when a spring-piston airgun is fired, the magnitude of the force (and hence the air pressure) that starts to drive the projectile down the barrel is mainly determined by the projectile's friction resistance rather than the change of ambient temperature. As a consequence, a spring-piston airgun obtains less increase of muzzle ED than a pneumatic airgun when the ambient temperature rises.

In the firing tests of the actual-case airgun, the data of muzzle velocity (v) and muzzle ED and the p-values of ED higher than 20 J/cm^2 obtained at varied temperatures (T) are listed in Table 5. The mean of muzzle EDs obtained at 17 °C, 20 °C, and 25 °C were 18.76 J/cm^2, 19.68 J/cm^2, and 21.34 J/cm^2, respectively. The mean ED obtained at the standard operating temperature was higher than the legal power limit while the mean EDs obtained at lower temperatures were less than 20 J/cm^2. The p-values of the *t*-tests of the mean EDs between paired testing temperatures of 17 °C and 20 °C, 20 °C and 25 °C, and 17 °C and 25 °C were 0.046, 0.0006 and 4.0×10^{-5}, respectively. The above *t*-test results revealed that, for the actual-case airgun powered by liquefied CO_2, the increase of ED was statistically significant at a confidence level of 95% even when the increase of ambient temperature was only 3 °C. The Student's *t*-distribution curves for the ED values of the actual-case airgun tested at 17 °C, 20 °C and 25 °C are shown in Fig. 5. It can be observed from Table 5 and Fig. 5 that the probabilities of obtaining an ED higher than the legal power limit for the actual-case airgun tested at 17 °C, 20 °C, and 25 °C were 6.1%, 31% and 99%, respectively. The results demonstrated that, for an actual-case airgun, although its muzzle ED was higher than the legal power limit when it was tested at standard operating temperature, the probability of being wrongly determined to be a legal airgun as being tested at lower temperatures was high. This further demonstrates that the ambient temperatures of forensic laboratories shall be carefully controlled when firing tests are performed for the determination of the legal status of airguns.

Table 5 Muzzle velocity and ED data and p-values of ED higher than 20 J/cm^2 of the actual-case airgun tested at varied temperatures (T).

T (°C)	v ± SD (m/s)	ED ± SD (J/cm^2)	p-Value of ED > 20 J/cm^2
17	109.16 ± 1.92	18.76 ± 0.63	0.061
20	111.78 ± 1.69	19.68 ± 0.60	0.31
25	116.42 ± 0.94	21.34 ± 0.32	0.99

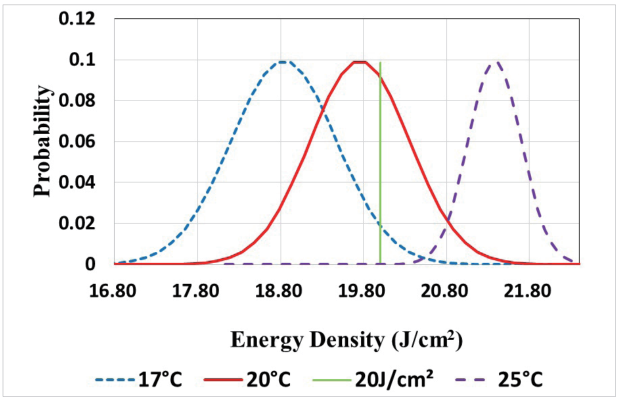


Fig. 5 Student's t-distribution curves for the ED values of the actual-case airgun tested at 17 °C, 20 °C and 25 °C.

Conclusion

This study verified that the muzzle velocity and energy density of an airgun are affected by ambient temperature regardless of the type of power source used in the airgun. We found that the liquefied CO_2 airgun had the most increase of muzzle ED, followed by the liquefied propane airguns and the pneumatic-type airguns, whereas the spring-piston airgun had the least increase of muzzle ED as ambient temperature increased by 7 °C. And the differences between the muzzle EDs obtained at the higher temperature and those obtained at the lower temperature were statistically significant for all airguns tested when a confidence level of 90% was chosen for the *t*-test. This reveals that the ambient temperatures of forensic laboratories shall be carefully controlled to accurately determine the muzzle ED of airguns tested. The results of the firing tests using actual-case airgun demonstrated that it was highly probable that an airgun would have muzzle ED lower than 20 J/cm^2 at a lower temperature while above the legal power limit at a higher temperature. Thus, it is crucial that the testing temperature is accurately controlled to strengthen the reliability of the legal status determination of airguns.

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