



# An experimental study on the effects of the head angle and bullet diameter on the penetration of a gelatin block



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## ABSTRACT

This research conducts 300 small-scale ammunition experiments using moderate bullet speeds and a variety of bullet configurations in order to understand the relationship between penetration behavior and bullet shape. To maximize the survivability of soldiers and reduce their vulnerability and ballistics wounds, it is very important to understand the penetration physics of bullets. Inside human bodies, tumbling and traveling trajectories are important factors to consider when analyzing human injuries due to ballistics. Therefore, many kinds of bullets and armor have been proposed to minimize or maximize human damage. In this study, to support the development of bullets, 10 bullets with different head angle shapes and different diameters were manufactured and fired at speeds less than 200 m/s towards transparent gelatin blocks, and the damage mechanisms, i.e., temporary cavities and permanent cavities, were studied by taking penetration images using a high speed camera. It was found that the tumbling and rotations of bullets are influenced by kinetic energies and the shapes of bullets, and several empirical relationships are derived. The results suggest that the shapes and the diameters are crucial factors for ballistics wounds.

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## 1. Introduction

This research conducted 300 penetration experiments with different bullet shapes in order to understand the relationship between penetration depth and bullet shape. After the development of gun-powder weapons in history, a significant amount of research has been conducted in the military sector to better understand the wound ballistic phenomena associated with a bullet penetrating a human body [1–11]. However, as this occurs over a very short period of time, it was almost impossible to investigate. Recently, with the help of high speed cameras and computational modeling tools, the damage mechanisms are now understood, but are limited to transparent objects such as gelatin or soap [12–19]. To contribute to this research and help the development of bullets for maximizing the survivability of soldiers and civilians, this study manufactures 10 bullets with different head shapes and different diameters and conducts 300 penetration experiments [20,21].

Many relevant studies can be found to better understand the wound ballistic phenomena associated with a bullet penetrating a human body [4,8,11]. The science of projectile behavior inside a target is known as terminal ballistics, and wound ballistics is the study of when a bullet strikes a living tissue, considered as a subfield of terminal ballistics. Wound ballistics and the terminal ballistics are

characterized by very rapid events, high pressures and large deformation rates of soft living tissues and bullets [17,22,23]. With the recent and rapid developments in computers and measurement instruments, it is now much easier to understand this phenomenon [14]. As a bullet begins to penetrate the tissue, the retarding force of the tissue causes it to decelerate and lose kinetic energy [24]. A penetrating bullet causes crushing, scratching, stretching and confusing of the tissue in front and around the site of penetration, as shown in Fig. 1. Between the entrance wound and a stable deformed bullet, it was reported that the entrance wound is not significant; in our experiment with a real gun, it was confirmed that the tissue damage due to the temporary and permanent cavities is significant inside gelatin blocks. After penetrating, the pressure induced by the bullet creates temporary cavities, and its pulsation is shown in Fig. 1 [7,22]. The induced pressure rapidly accelerates and stretches tissues, causing tissue damage. Then, the temporary cavity collapses and re-expands due to the elasticity of the tissue, called pulsation.

After the pulsations of the temporary cavity, the permanent cavities causing serious trauma to humans remain [1–7]. During bullet penetration, the bullet often loses its stability and begins tumbling [25]. Often, the bullet can be deformed, which increases its cross-sectional area in the direction of penetration and results in further tumbling. The increased cross-sectional area transfers more of the bullet's kinetic energy into the tissue. Therefore, it is important to design the shapes of bullets and choose materials that maximize or minimize damage to the human body.

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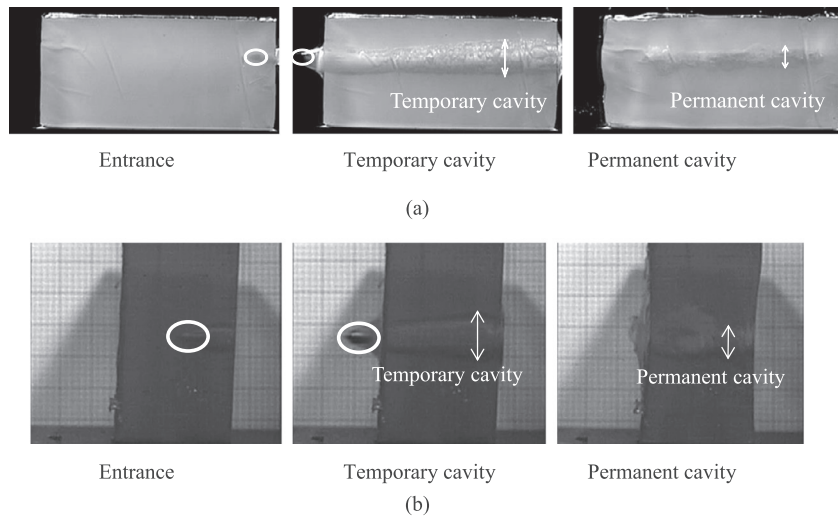


Fig. 1. Gelatin penetration experiments. (a) A real gun experiment and (b) small scale experiment.

To investigate the bullet penetrations, ballistic gelatin blocks are commonly employed for various reasons [12–17,19,22,24,26–32]. First of all, their transparency makes it possible to easily see the temporary cavity using a high speed camera and the permanent cavity. Furthermore, as their compositions and biomechanical properties [17,33,34] are similar to those of humans, it is possible to obtain similar damage patterns inside human tissue. One shortcoming is that its mechanical properties are influenced or deteriorated by humidity and the time difference between penetration experiments, i.e., it is not consistent.

This paper is organized as follows. Section 2 describes the basic equations used in the analysis and the experiment setup for the bullet configurations. In Section 3, we describe our penetration experiment results and present our analyses of the damage inside the gelatin blocks. Section 4 presents our conclusions and some suggestions for future research topics.

## 2. Dissipation of bullet kinetic energy inside ballistic gelatin

### 2.1. Energy dissipation of bullet kinetic energy

During the penetration of a bullet into a gelatin block, a bullet moves the gelatin tissue around, mechanically called the temporary cavity, tearing the tissue in front of it and leaving a wound channel behind, which is called the permanent cavity. Note that the bullet typically erodes or bursts into pieces during impact. The characteristics of the temporary cavity can be investigated via image analysis of the bullet path with a high speed camera. With the obtained images, it is possible to estimate the volume and shape of the temporary cavity depending on bullet type, which is one of the most significant factors in disrupting human tissue.

When a non-rotating bullet impacting target has an impact mass with  $m$  and velocity  $v$ , its kinetic energy  $E$  is defined as follows:

$$E = \frac{1}{2}mv^2. \quad (1)$$

The above energy is used for the impact energy ( $E$ ), and the bullet deformation energy ( $E_{\text{deformation}}$ ) and energy ( $E_{\text{dissipation}}$ ) dissipated into the target are combined as follows:

$$E_r = E - E_{\text{deformation}} - E_{\text{dissipation}}. \quad (2)$$

Here,  $E_r$  is the residual energy and is an important factor when considering the danger of targets. The positive residual energy clearly implies that the corresponding bullet completely penetrates through the target and continues its flight. The deformation energy,  $E_{\text{deformation}}$ , can often be overlooked for less harmful situations, especially for civilians, but it becomes an important factor when trying to increase or decrease the survivability of soldiers [35]. Furthermore, the deformed bullet shape, which is not regular nor aerodynamic, initiates a large pressure or shockwave, causing further tissue failure [9,23]. The kinetic energy dissipation  $E_{\text{dissipation}}$  can be increased by bullet instability, deformation and fragmentation.  $E_{\text{dissipation}}$  is often increased when the spin rate is insufficient to maintain stability in human tissue. When a bullet loses its stabilities, the cross-sectional area in the direction of penetration is increased and the dissipation of kinetic energy inside the surrounding material is also significantly increased, as shown in Fig. 2. The precise penetration depth at which tumbling occurs is somewhat difficult to predict, as it depends on the yaw angle of impact, the properties of the surrounding medium and the internal instabilities of the bullet.

One of the primary objectives of the present study is to investigate the effects of bullet geometry on the kinetic energy dissipation,

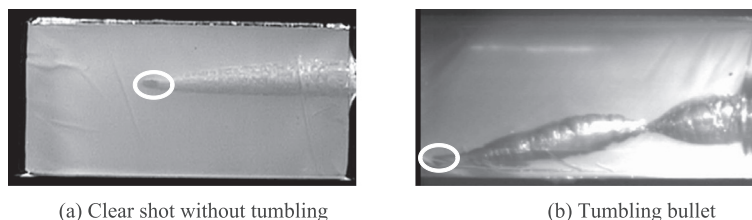


Fig. 2. Stability inside a gelatin block.

$E_{dissipation}$ . Therefore, the experiment configuration in the present study is setup to minimize the residual energy  $E_r$  and the deformation energy of the bullets,  $E_{deformation}$ ; sufficiently large ballistic gelatin blocks are used and bullets are fired over 200 m/s without rotation to prevent the deformations of and maximize the instability of the bullets.

## 2.2. Penetration experiment, bullets and penetration analysis method

### Penetration experiment

Although we also conducted real gun experiments as shown in Fig. 2, it was found that it is difficult to obtain consistent and reproducible experiment results. Partially due to the high kinetic energies of real bullets, the shooter's effects and mainly due to the tight law regulations of the Republic of Korea preventing real gun experiments, we decided to build an in-house launch pad launching in-house bullets. The launch pad in Fig. 3(a) consists of the three main components: the launch device, the ballistic gelatin, and the high speed camera. The launch device has an air compressor replacing the gunpowder, as well as a controller to vary the pressure from 0 bar to 200 bar and regulate pressure fluctuations. For the sake of safety, a remote trigger was also attached to the main table and bullets were fired from a distance using this remote trigger. The stainless steel barrels with various diameters did not have screw marks, i. e., rifling, as we did not try to obtain a special license from the government. However, this maximized the instability as we intended. Ten in-house bullets were accelerated to various speeds by adjusting the gas pressure. "We test the bullet penetration with relatively low velocities because we are interested in the damages of internal organs after hitting bone and penetrating skin. Furthermore, the impact research with low velocities can be useful in developing a less-lethal weapon for police."

For a replacement of human tissue, 10% gelatin blocks composed of a 1:9 ratio of Knox gelatin to water by mass were used, as shown in Fig. 3(b). The size of 10% gelatin is approximately  $11 \times 27 \times 6$  cm. The mechanical properties of gelatin are known to be sensitive to temperature and condition, and we tried to use gelatin blocks with similar manufacturing conditions at a room temperature (spring in South Korea). Before testing, they were aged at a constant temperature inside a refrigerator (approximately 1 day at 4°C). Because of their transparency, the behaviors of projectiles can be investigated via a high-speed camera (more than 10,000 FPS).

### In-house bullets (Bullets for the experiment)

The purpose of the present study is to investigate the effects of the shapes of bullets. For this, 300 experiments with different bullet configurations were conducted with manufactured bullets. With the above launch pad, 10 bullets with different diameters and head shapes, seen in Figs. 4 and 5, were fired. The material of all bullets is brass. In summary, the following conditions are considered.

Condition 1: To see the effects of the head angles of bullets, the bullets with 30°, 60°, 90°, 120° and 150° head angles were manufactured, as seen in Fig. 4. The diameters for all bullets were set to 4 mm and the lengths for the different head angles were 18.64 mm, 15.96 mm, 15 mm, 14.43 mm and 14.03 mm, respectively, so as to make the masses the same (1.3 g).

Condition 2: To see the effects of the diameters of bullets, several bullets with 3 mm, 4 mm, 5 mm, 6 mm, and 7 mm were manufactured, as shown in Fig. 5. The masses of all the bullets were set to 1.3 g. The head angles were set to 90°. In order to make all the masses of the bullets same, the lengths for each diameter were set to 25.3 mm, 15 mm, 10.41 mm, 8.07 mm and 6.8 mm, respectively. To see the effects of the diameter, 3.2 mm, 4.2 mm, 5.2 mm, 6.2 mm and 7.2 mm barrels were made.

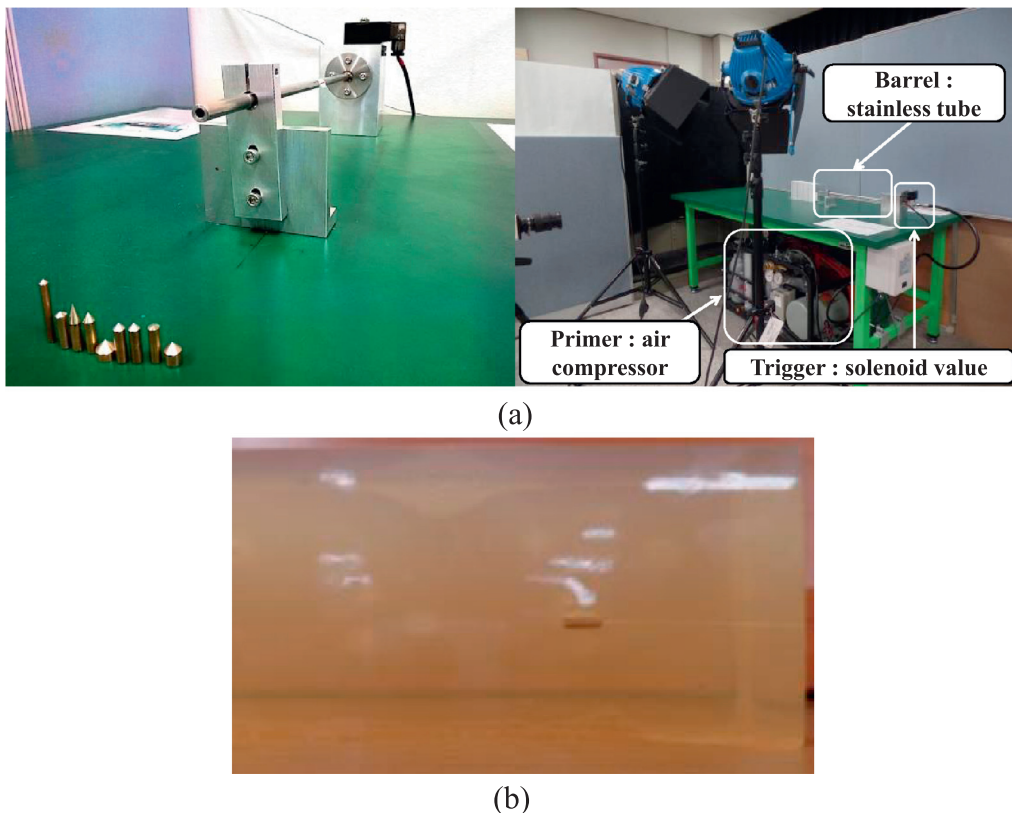


Fig. 3. Experiment device. (a) Launchpad and (b) gelatin block and a bullet.

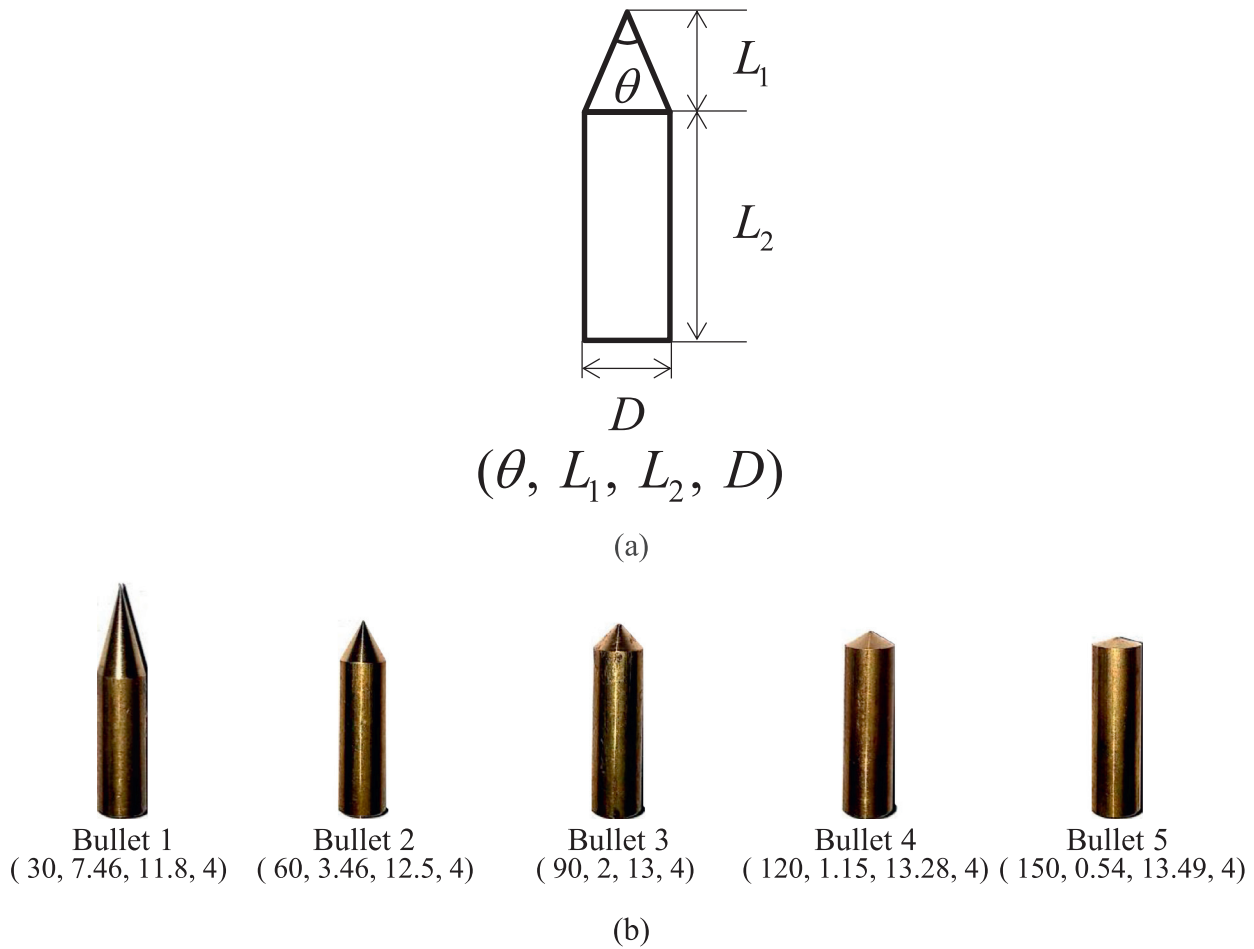


Fig. 4. Bullet types of different bullet angles. (a) Bullet diagram representing bullet sizes ( $\theta$ (Degrees),  $L_1$ (mm),  $L_2$ (mm),  $D$ (mm)) and (b) bullets used in the experiment.

Note that except for one case, all the bullets remain inside gelatin blocks. In other words,  $E = E_{dissipation}$  in the present study except for one case.

#### Penetration analysis

To analyze the penetration behaviors of the bullets, a high-speed camera is mainly used. The images are analyzed by an automatic image analyzer, TRACKER (<http://physlets.org/tracker>). A typical example is shown in Fig. 6, with Bullet 1 ( $30^\circ$ ) at 111 (m/s). In the analysis software, the head and bottom of the bullets can be semi-automatically marked, and this information is analyzed for the positions, velocities and accelerations of the bullets. When the displacement of the bullet is marked using the tracker program, the displacement of the bullet is generally recognized by the automatic recognition. When the images from the high speed camera are blurred, we should set the trajectories manually. Red, cyan and green points represent the head, bottom and center of the bullets, respectively.

### 3. Experiment and correlation analysis of bullet penetrations

#### 3.1. Effect of head angle on penetration depth

First of all, the effects of the five head angles,  $30^\circ$ ,  $60^\circ$ ,  $90^\circ$ ,  $120^\circ$  and  $150^\circ$ , on penetration depth were tested by varying the speed and the penetration depth, and all 150 experiments are plotted and summarized in Fig. 7. For the experiments considering head angle, the diameters of all the bullets were set to 4 mm. The speeds were directly measured just before the impacts using a high speed camera. Despite the same speeds being used for the bullets, the

penetration depths have some variations due to the different impact angles and other unclear reasons.

For the sake of illustration, Fig. 7 plots the penetration depths for the five bullets in Fig. 4. The following are observed.

- 1) Due to the viscosity of gelatin blocks, the curves of the penetration depths with respect to kinetic energy become nonlinear functions.
- 2) Bullets with sharp head angles tend to penetrate more compared to blunt bullets, as the areas of the contact surfaces with sharp head angles are smaller than those with blunt head angles. However, the kinetic energy dissipations due to tumbling, i.e., bullets with  $30^\circ$  and  $60^\circ$ , result in less penetrations.

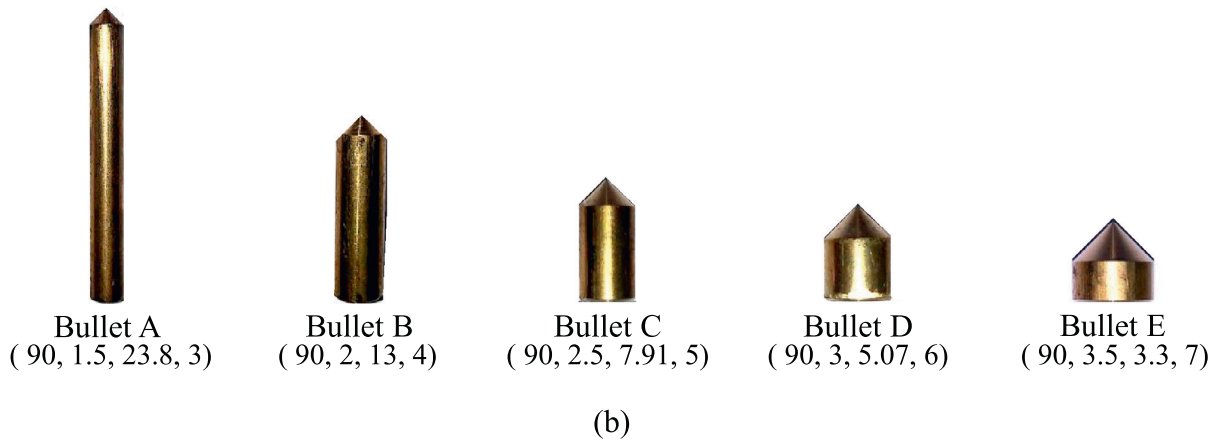
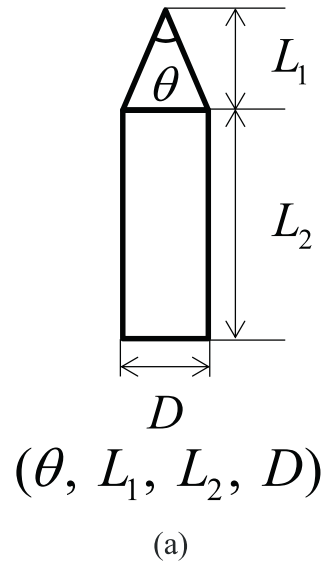
In [36], the following correlation equation between the penetration depth and the speed was proposed:

$$\text{Square law: } \ln v = -C_1 s + C_2, a = -C_3 v^2, \Rightarrow s \propto \ln \frac{v}{v_{ad}}, \quad (3)$$

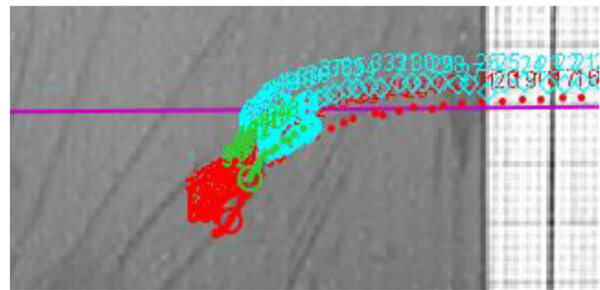
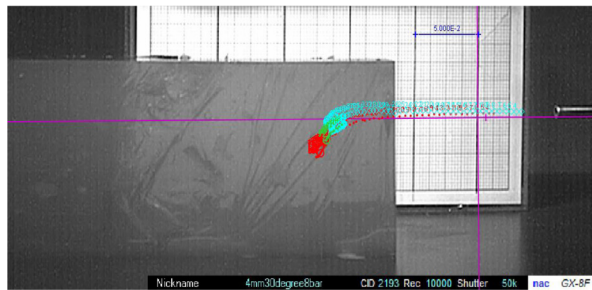
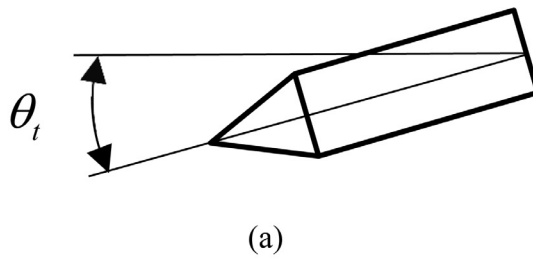
where the penetration depth and the entry speed of a bullet are denoted by  $s$  and  $v$ , respectively, the residual velocity is  $v_{ad}$ , the deceleration coefficient is denoted by  $a$ ,  $C_1$ ,  $C_2$  and  $C_3$  are parameters. The above equation can be further summarized with the coefficients  $C_1$  and  $C_2$  as follows:

$$\text{Square law: } v = e^{-C_1 s + C_2}. \quad (4)$$

From our experiments, the coefficients can be found by interpolating data, and the interpolated curves are plotted and

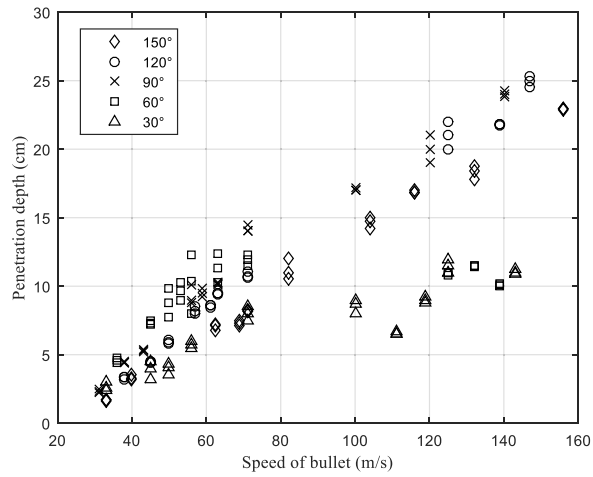


**Fig. 5.** Bullet types of different bullet diameters. (a) Bullet diagram representing bullet sizes ( $\theta$ (Degrees),  $L_1$ (mm),  $L_2$ (mm),  $D$ (mm)) and (b) bullets used in the experiment.








**Fig. 6.** Penetration analysis (Penetration of Bullet 1 (30°) at 111 m/s; red mark: head, cyan mark: bottom, green marker: center of bullet). (a) The angle measure, (b) the trajectory analysis and (c) the detailed image of figure (b). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)





(a)

 Bullet 1 (30,7.46,11.8,4)	Velocity(m/s)		33	45	50	56	71	100	111	119	125	143
	Depth (cm)	1 <sup>st</sup>	2.6	4.5	3.5	5.7	8	8.7	6.5	9	11.5	11
		2 <sup>nd</sup>	3	4	4.3	6	7.5	8	8.8	6.7	11.9	11.2
		3 <sup>rd</sup>	2.4	3.2	4.1	5.5	8.5	9	9.2	6.5	11	10.9
		Average	2.7	3.9	4.0	5.7	8.0	8.6	8.2	7.4	11.5	11.0
		Standard deviation	0.25	0.54	0.34	0.21	0.41	0.42	1.19	1.13	0.37	0.12
 Bullet 2 (60,3.46,12.5,4)	Velocity(m/s)		36	45	50	53	56	63	71	125	132	139
	Depth (cm)	1 <sup>st</sup>	4.6	7.3	8.8	9.7	10.4	11.3	11.9	7.8	11.5	10
		2 <sup>nd</sup>	4.4	7.5	7.7	9	8	10.3	11.5	11	11.4	10.2
		3 <sup>rd</sup>	4.8	7.2	9.8	10.3	12.3	12.4	12.3	11	11.5	10.1
		Average	4.6	7.3	8.8	9.7	10.2	11.3	11.9	9.9	11.5	10.1
		Standard deviation	0.16	0.12	0.86	0.53	1.76	0.86	0.33	1.51	0.05	0.08
 Bullet 3 (90,2,13,4)	Velocity(m/s)		31	38	43	56	59	63	71	100	120	140
	Depth (cm)	1 <sup>st</sup>	2.3	4.4	5.3	8.8	9.5	10.1	14	17	20	24
		2 <sup>nd</sup>	2.2	4.5	5.2	10.1	9.8	10.3	14.5	17.2	21	23.8
		3 <sup>rd</sup>	2.5	4.4	5.4	9	9.2	10.2	14	17	19	24.3
		Average	2.3	4.4	5.3	9.3	9.5	10.2	14.2	17.1	20.0	24.0
		Standard deviation	0.12	0.05	0.08	0.57	0.24	0.08	0.24	0.09	0.82	0.21
 Bullet 4 (120,1.15,13.28,4)	Velocity(m/s)		38	45	50	57	61	63	71	125	139	147
	Depth (cm)	1 <sup>st</sup>	3.2	4.4	6.1	8.2	8.4	9.4	11.1	21	21.8	25
		2 <sup>nd</sup>	3.4	4.5	5.9	8	8.6	9.5	10.7	22	21.7	24.5
		3 <sup>rd</sup>	3.4	4.5	5.8	8.5	8.6	9.5	10.6	20	21.8	25.3
		Average	3.3	4.5	5.9	8.2	8.5	9.5	10.8	21.0	21.8	24.9
		Standard deviation	0.09	0.05	0.12	0.21	0.09	0.05	0.22	0.82	0.05	0.33
 Bullet 5 (150,0.54,13.49,4)	Velocity(m/s)		33	40	62.5	69	71	82	104	116	132	156
	Depth (cm)	1 <sup>st</sup>	1.7	3.3	7.1	7.3	8.2	11	14.7	16.8	18.4	23
		2 <sup>nd</sup>	1.7	3.2	6.8	7.5	8.2	12	14.2	17	17.8	23
		3 <sup>rd</sup>	1.6	3.5	7.2	7.1	8.3	10.5	15	16.8	18.8	22.9
		Average	1.7	3.3	7.0	7.3	8.2	11.2	14.6	16.9	18.3	23.0
			Standard deviation	0.05	0.12	0.17	0.16	0.05	0.62	0.33	0.09	0.41

(b)

**Fig. 7.** Penetration depth with respect to various bullet angles (Bullet diameter: 4 mm). (a) Penetration depths with respect to the bullet's speed and (b) the detailed data.

**Table 1**

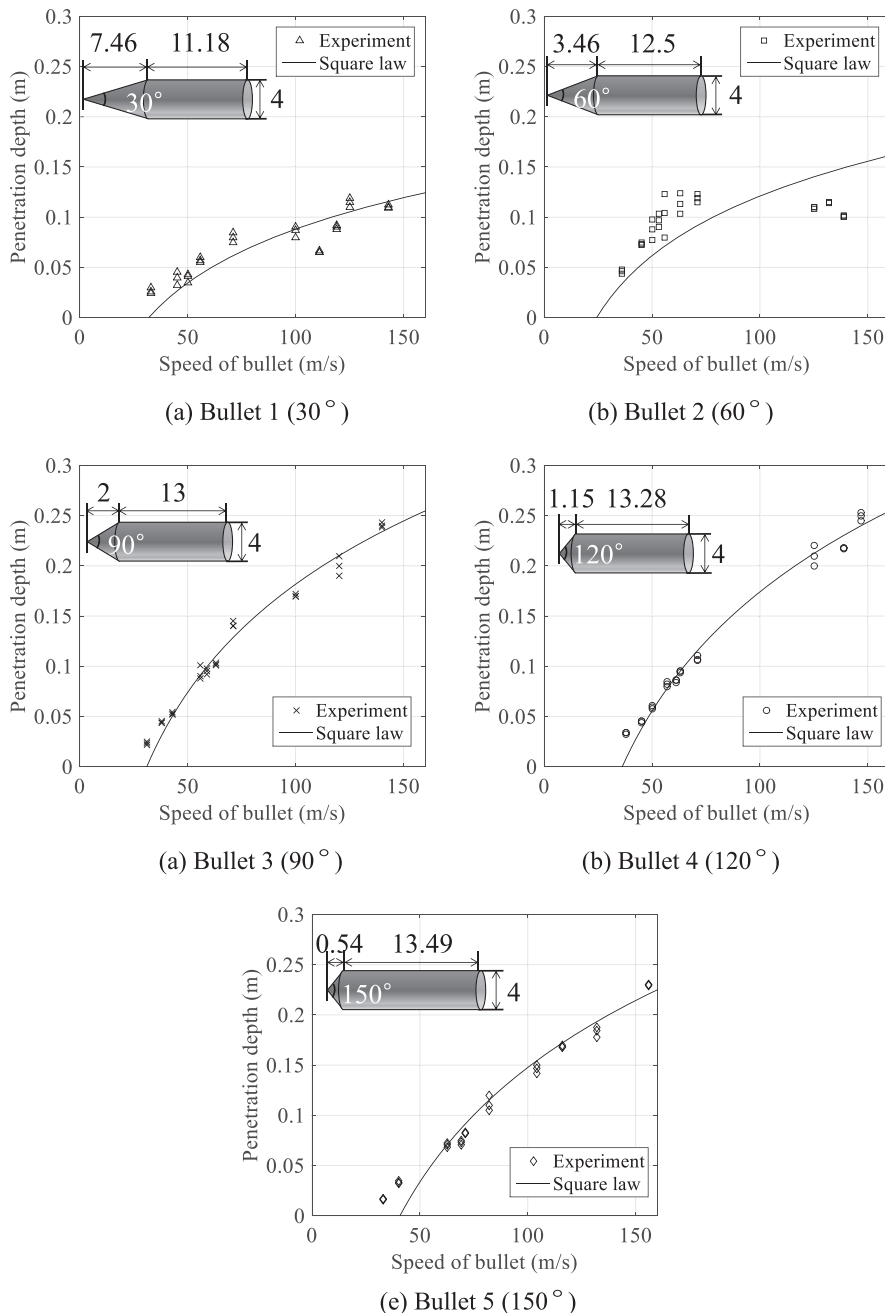
Penetration parameters of (4) calculated using experiment data (Bullet diameter: 4 mm).

Angle	30°	60°	90°	120°	150°
$C_1$	-12.950	-11.680	-6.440	-5.841	-6.081
$C_2$	3.464	3.191	3.435	3.588	3.707

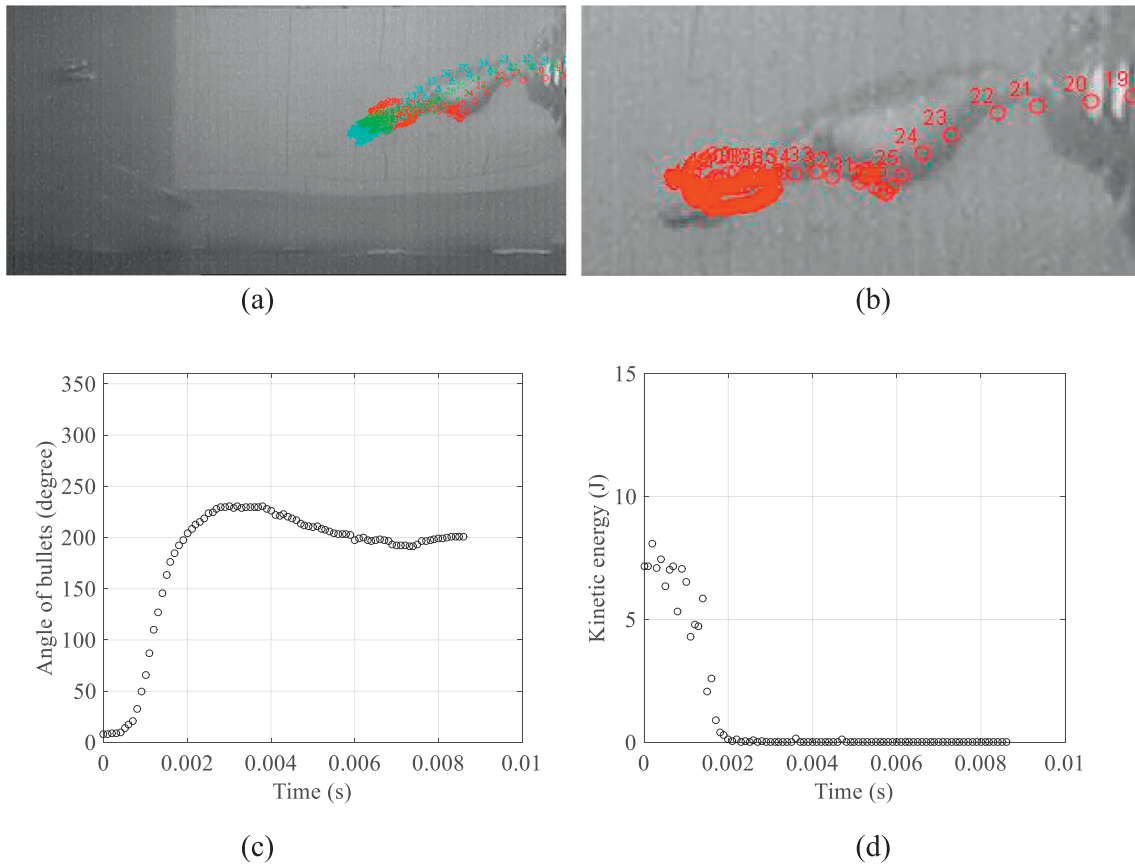
compared with the experimental data in Fig. 8. It was observed that the slopes of the curves increased for the blunt bullets. This is partially due to that the lift forces of the sharp bullets are higher than those of the blunt bullets (causing tumbling), and the resistance forces of the large length bullets are higher than those of the short length bullets. The three typical penetration analyses are plotted in Figs. 9–11. The kinetic energies are

transferred from the bullets to the gelatin tissues in the form of pressure waves creating temporary cavities, shown in Figs. 9–11. The kinetic energies are released from the bullets to the gelatin tissues via the pressure wave field. The temporary cavities soon collapse, but it is known that this also causes damage to the gelatin tissues along the permanent cavities.

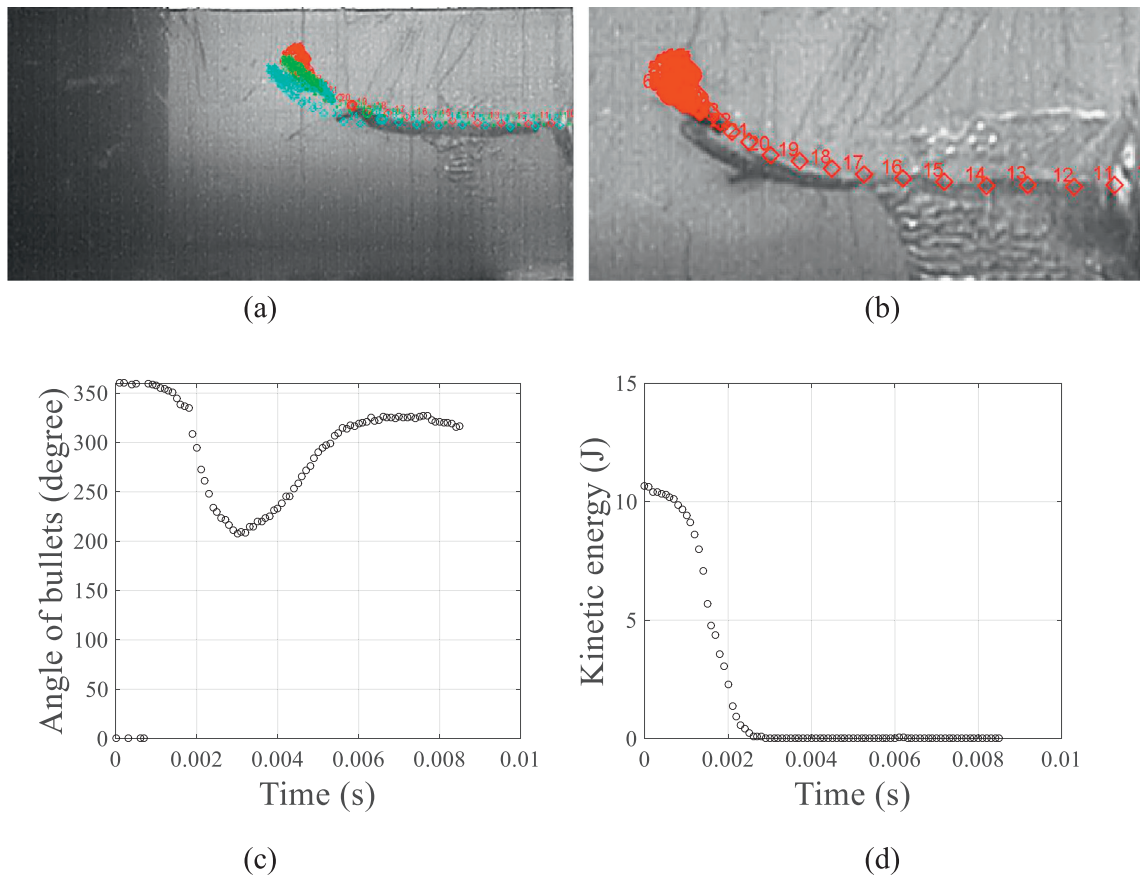
There are two reasons for the damage due to these temporary cavities. The human tissue lying closer to the wound channel is exposed to higher pressure and higher deformation, resulting in more severe damage. Due to this, it was sometimes recommend for a surgeon to carve out a cylinder of tissue at least 10 to 40 times the diameter of the projectile in the 1975 edition of the NATO handbook: Emergency War Surgery. However, some reports also suggested that they will heal if left alone [37]. Due to the tumbling of the bullet, the temporary cavity of Fig. 9 is larger than that of Fig. 11. In case of the impact inside human tissue, this temporary cavity is filled with



**Fig. 8.** Comparisons between experiment results and the penetration relationship equation.

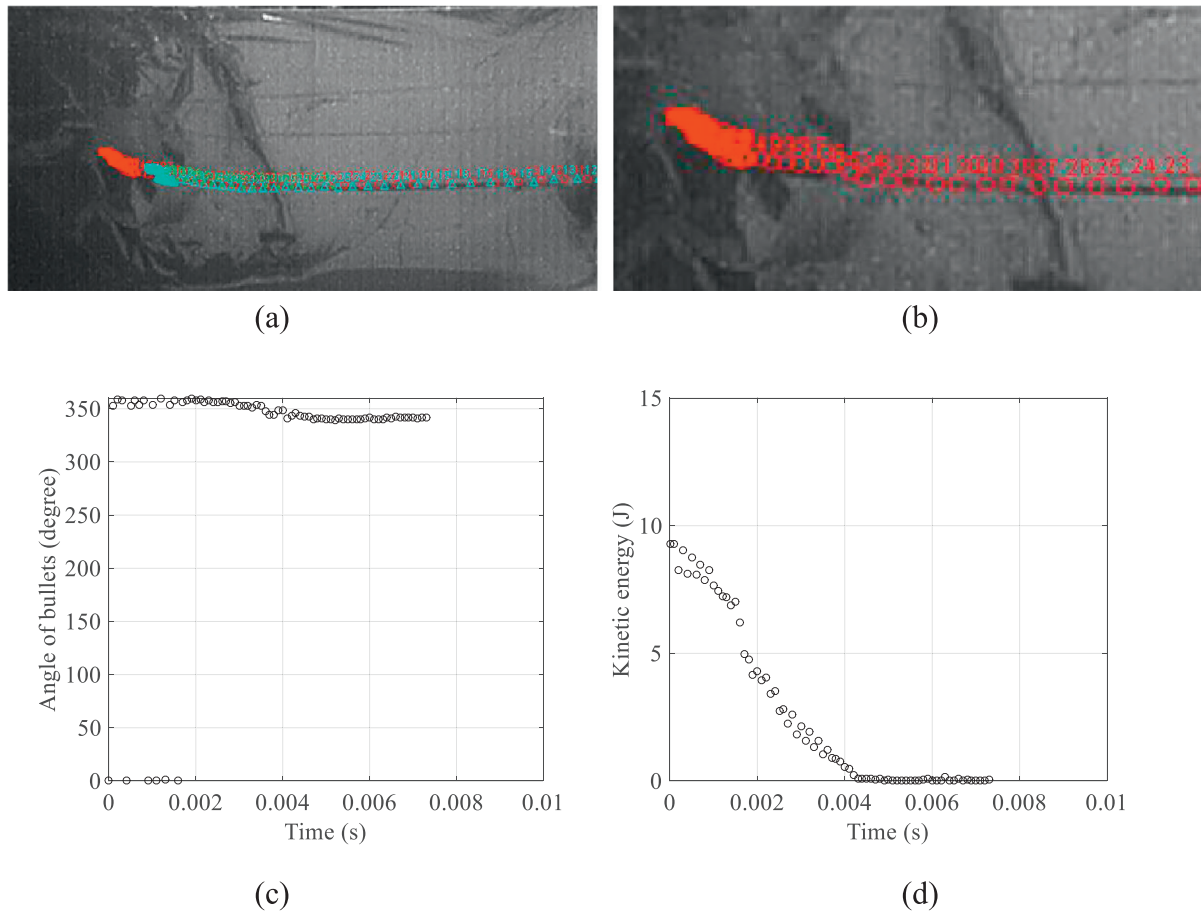


**Fig. 9.** Tumbling phenomenon of Bullet 1 ( $30^\circ$ ) at 111 m/s. (a) The head, tail and center trajectories, (b) the head trajectory, (c) the angle of bullet and (d) the kinetic energy distributions.



**Fig. 10.** Tumbling phenomenon of Bullet 1 ( $60^\circ$ ) at 132 m/s. (a) The head, tail and center trajectories, (b) the head trajectory, (c) the angle of bullet and (d) the kinetic energy distributions.





**Fig. 11.** Tumbling phenomenon of Bullet 5 (150°) at 116 m/s. (a) The head, tail and center trajectories, (b) the head trajectory, (c) the angle of bullet and (d) the kinetic energy distributions.

blood, tissue debris, and contaminants brought in from the wound surface.

### 3.2. Effect of the diameter on penetration depth

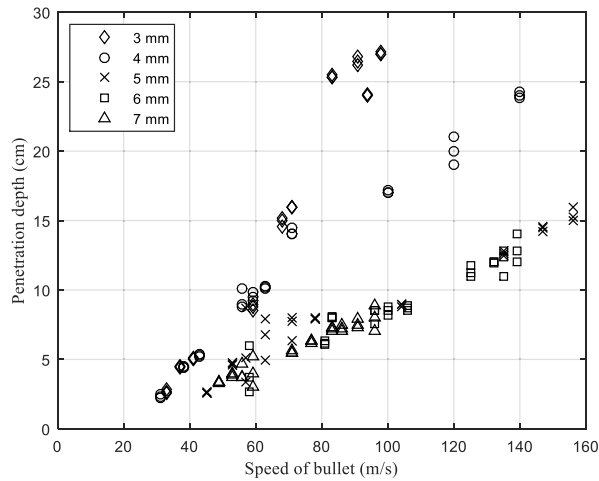
It is a common-sense that large bullets cause more injuries in tissue and are more likely to strike vascular structures, which has been confirmed from the investigations based on real wounds and patients in trauma centers. However, it is not clear whether “large bullet” is to be interpreted as having larger diameters or heavier masses. To make it clearer, this subsection tested the effect of the diameter.

For the second test, the bullet diameter is varied from 3 mm to 7 mm, as seen in Fig. 12. As expected, bullets having higher kinetic energies penetrate ballistic gelatin blocks deeper. As the drag forces of bullets with relatively larger diameters are higher than those with smaller diameters, the bullets having large diameters penetrate less compared with the small diameter bullets. Table 2 shows the computed coefficients of Eq. (4) and the detailed curves are shown in Fig. 13. It is interesting to note that the slopes of the curves become smaller with increasing diameter. This observation suggests that bullets with large diameters are good for controlling the penetration depth via the entry speed. On the other hand, bullets with smaller cross sections tended to travel in straighter trajectories. From a survival point of view, these characteristics play an important role. Some representative penetration behaviors are illustrated in Figs. 14 and 15. As stated, the common-sense belief is that large-diameter handgun bullets cause more serious injury compared with small






bullets, but the experiments of this sub-section suggest that it is only valid for large-diameter bullets.

## 4. Conclusions

This research experimentally investigates the effects of the shapes of bullets on 10% ballistic gelatin. From various studies, it is known that wounding is significantly determined to a great extent by the physical configurations of bullets. In other words, the configuration and shape of bullets can change the penetration behaviors inside tissues. Particularly, this study investigates the specific penetration behavior and penetration depth of bullets resulting from changing the head angle and bullet diameter. For this, a launch pad firing a bullet at around 200 m/s was used. For the first experiment, the head angles are varied for the five bullets with the same mass, i.e., from 30° to 150°, and 150 experiments were conducted. The geometries of the bullets were adjusted to make the masses of the bullets same. A high speed camera was placed in order to observe the penetration behaviors. Using an automated analysis program, TRACKER, the velocities and positions of the bullets were analyzed. For the square law, the coefficients are computed to see the relationship between the penetration depth and the bullet speed. From the second experiment, the diameters of in-house barrels are incrementally raised by 1 mm to 7.2 mm from 3.2 mm for the five bullets whose diameters varied from 3 mm to 7 mm. It was observed that by decreasing the diameter of the bullet, the bullets penetrate deeper because they are less penetration resistance. The instant images by the high speed camera reveal that the bullet



(a)

 Bullet 1 ( 90,1.5,23.8,3)	Velocity(m/s)		33	37	41	59	68	71	83	91	94	98
	Depth (cm)	1 <sup>st</sup>	2.8	4.5	5	8.8	15	16	25.3	26.5	24	27
		2 <sup>nd</sup>	2.6	4.5	5	8.5	14.6	16	25.3	26.8	24	27
		3 <sup>rd</sup>	2.7	4.4	5.1	9	15.2	16	25.5	26.2	24.1	27.2
		Average	2.7	4.5	5.0	8.8	14.9	16.0	25.4	26.5	24.0	27.1
		Standard deviation	0.08	0.05	0.05	0.21	0.25	0	0.09	0.24	0.05	0.09
 Bullet 2 ( 90,2,13,4)	Velocity(m/s)		31	38	43	56	59	63	71	100	120	140
	Depth (cm)	1 <sup>st</sup>	2.3	4.4	5.3	8.8	9.5	10.1	14	17	20	24
		2 <sup>nd</sup>	2.2	4.5	5.2	10.1	9.8	10.3	14.5	17.2	21	23.8
		3 <sup>rd</sup>	2.5	4.4	5.4	9	9.2	10.2	14	17	19	24.3
		Average	2.3	4.4	5.3	9.3	9.5	10.2	14.2	17.1	20.0	24.0
		Standard deviation	0.12	0.05	0.08	0.57	0.24	0.08	0.24	0.09	0.82	0.21
 Bullet 3 ( 90,2.5,7.91,5)	Velocity(m/s)		45	53	57	63	71	78	104	135	147	156
	Depth (cm)	1 <sup>st</sup>	2.6	4.7	5.1	6.8	8	7.9	8.8	12.5	14.5	15.3
		2 <sup>nd</sup>	2.7	4.8	3.4	4.9	6.3	7.9	9	12.6	14.6	16
		3 <sup>rd</sup>	2.6	4.6	8.7	7.9	7.7	8	9	12.8	14.2	15
		Average	2.6	4.7	5.7	6.5	7.3	7.9	8.9	12.6	14.4	15.4
		Standard deviation	0.05	0.08	2.21	1.24	0.74	0.05	0.09	0.12	0.17	0.42
 Bullet 4 ( 90,3,5.07,6)	Velocity(m/s)		58	81	83	96	100	106	125	132	135	139
	Depth (cm)	1 <sup>st</sup>	3.7	6.2	8.1	7.6	8.8	8.9	11.8	11.9	11	12
		2 <sup>nd</sup>	2.7	6.1	8	8.5	8.5	8.7	11	12	12.8	12.8
		3 <sup>rd</sup>	6	6.3	8	8.2	8.2	8.5	11.2	12	12.4	14
		Average	4.1	6.2	8.0	8.1	8.5	8.7	11.3	12.0	12.1	12.9
		Standard deviation	1.38	0.08	0.05	0.37	0.24	0.16	0.34	0.05	0.77	0.82
 Bullet 5 ( 90,3,5,3,3,7)	Velocity(m/s)		49	53	56	59	71	77	83	86	91	96
	Depth (cm)	1 <sup>st</sup>	3.4	3.9	4.7	5.2	5.5	6.3	7.3	7.5	7.9	8.9
		2 <sup>nd</sup>	3.4	4	3.7	3	5.5	6.2	7	7	7.5	7
		3 <sup>rd</sup>	3.3	3.7	3.7	4	5.6	6.3	7.2	7.2	7.3	8
		Average	3.4	3.9	4.0	4.1	5.5	6.3	7.2	7.2	7.6	8.0
		Standard deviation	0.05	0.12	0.47	0.90	0.05	0.05	0.12	0.21	0.25	0.78

(b)

Fig. 12. Penetration depths according to bullet diameters (Bull et angle: 90°).

**Table 2**

Penetration parameters of (4) calculated using experiment data (Bullet angle: 90°).

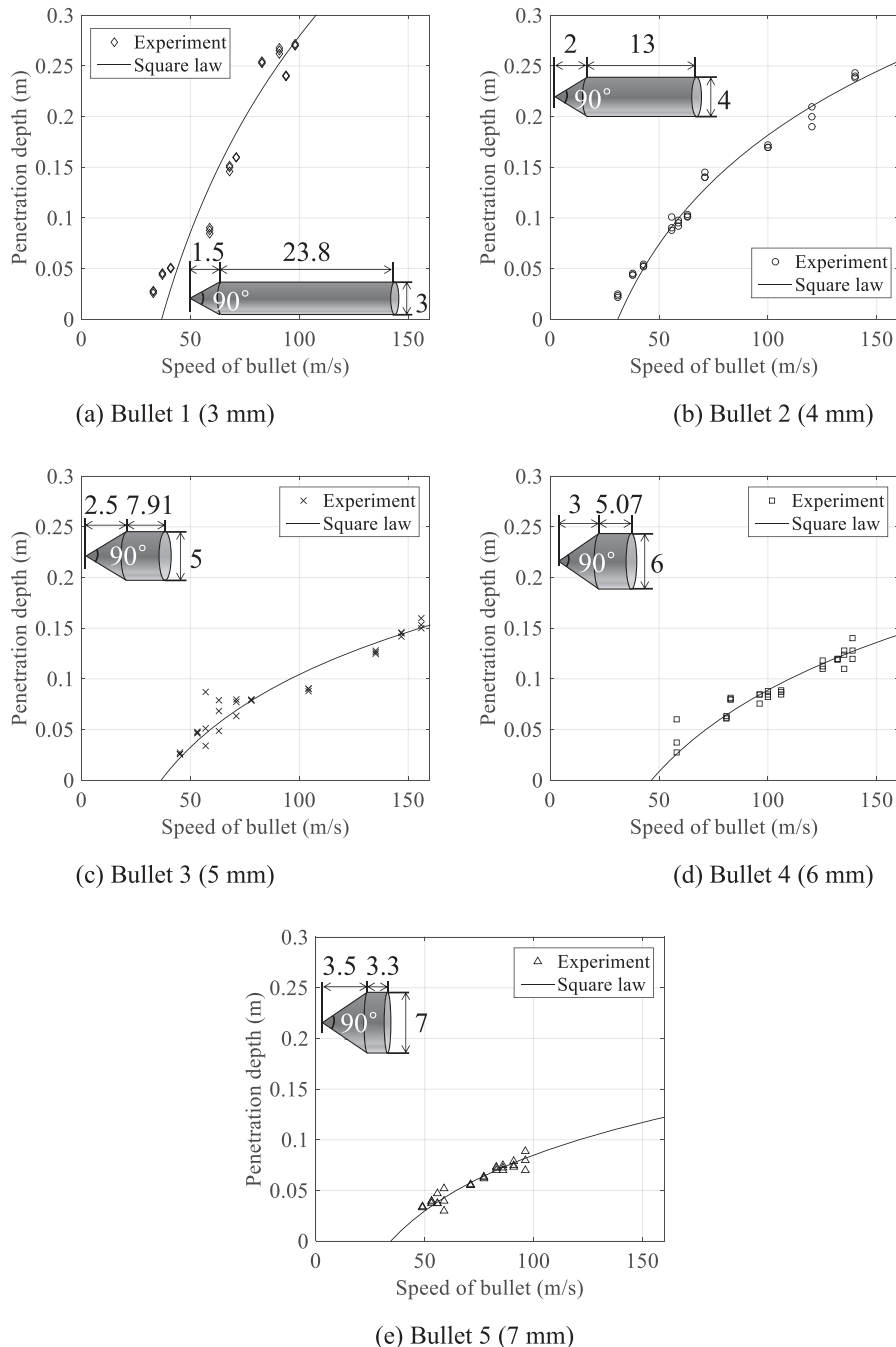
Diameter	3 mm	4 mm	5 mm	6 mm	7 mm
$C_1$	-3.580	-6.440	-9.652	-8.612	-12.580
$C_2$	3.605	3.435	3.598	3.839	3.537

with a 3-mm diameter tends to go straight compared to the other bullets; the tumbling behaviors of the bullets with a 7-mm diameter are more significant. To determine the effect of the diameter at the same mass, the length of the bullet was set differently in Fig. 5(b). In case of the bullets with 7 mm, the length of bullet was shorter than 3 mm and the shorter bullets showed unstable behavior such as tumbling. These tumbling behaviors

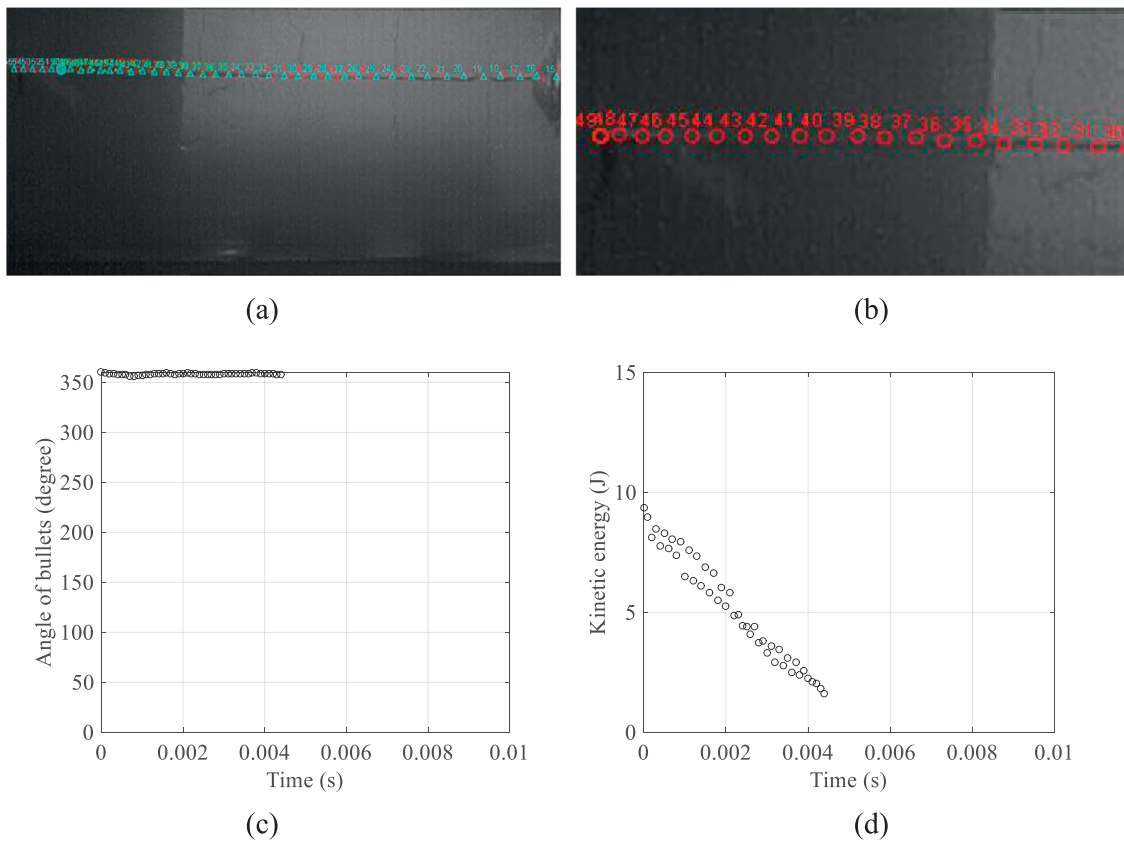
change their orientations by becoming unstable and yawing or turning sideways, relative to the line of flight. Such behavior in tissue greatly affects tissue disruption. In conclusion, to investigate the effects of the geometric configurations of bullets, the head angles and the diameters were changed and the 300 penetration behaviors of the bullets were investigated. However, note that these results are only valid when the bullets have the same mass, which is a limitation of this study.

### Acknowledgement

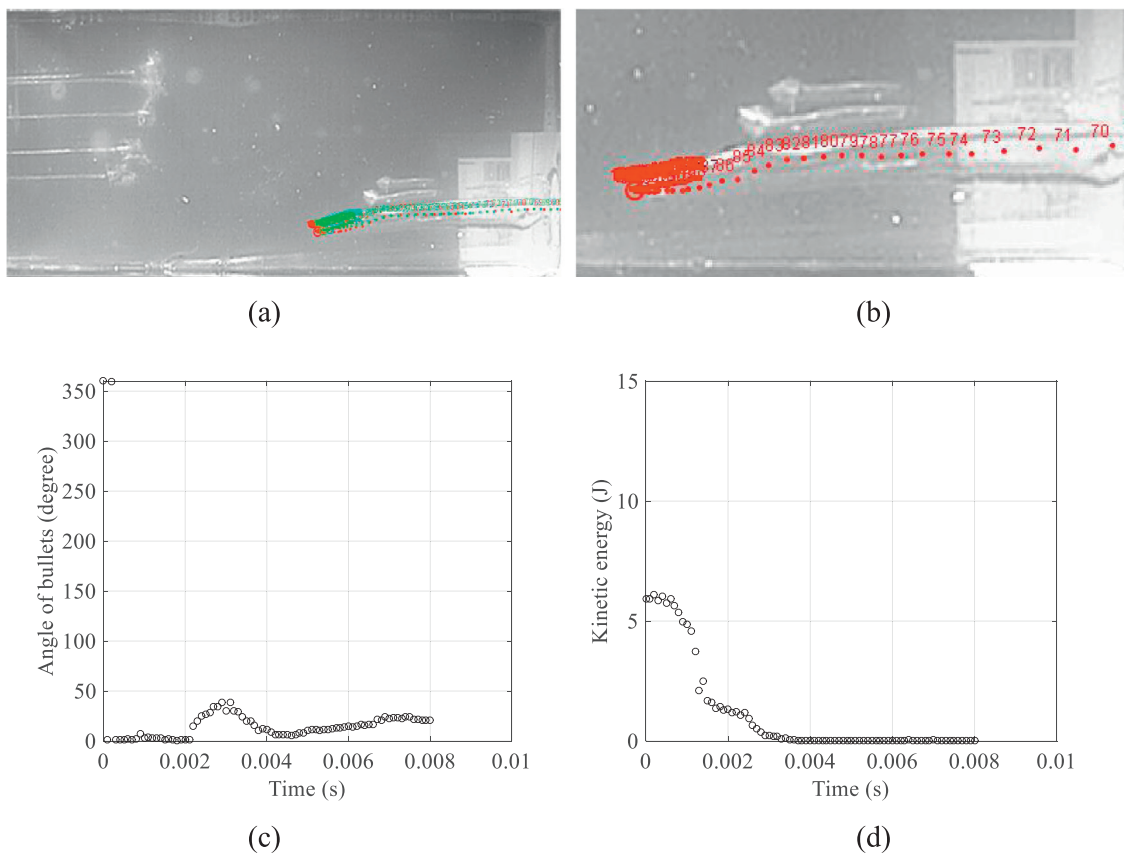
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**Fig. 13.** Comparisons between experiment results and the penetration equation.



**Fig. 14.** Bullet penetration without tumbling (Bullet 1 (3 mm) at 98 m/s). (a) The head, tail and center trajectories, (b) the head trajectory, (c) the angle of bullet and (d) the kinetic energy distributions.



**Fig. 15.** Bullet penetration with tumbling (Bullet 5 (7 mm) at 96 m/s). (a) The head, tail and center trajectories, (b) the head trajectory, (c) the angle of bullet and (d) the kinetic energy distributions.

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