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A hunting rifle with a variable barrel length has been examined in this study. The task addressed was to determine the ballistic indicators of hunting cartridges for different barrel lengths.

A standard deviation in shot distribution on the target and the area of damage by hunting cartridges depending on the length of the hunting rifle barrel were established. The influence of barrel length on the ballistic characteristics of hunting cartridges was investigated by conducting a multifactorial experiment according to the D-optimal Box-Behnken plan.

As a result of experimental studies, it was found that the maximum value of standard deviation in shot distribution at the level of 21 cm is achieved with a barrel length of 150 mm and a shot charge mass of 36 g. At the same time, the gunpowder charge did not have a significant effect on the standard deviation in shot distribution on the target. The standard deviation of shot distribution has maximum values when the powder charge is maximum while the shot mass is minimum.

The area of damage was modeled by increasing the penetration point on the target to the size of the total equivalent diameter of the most vulnerable elements of unmanned aerial vehicles (UAVs) with FPV (First-Person View) piloting. On a target with an equivalent diameter of 8 cm, the area of damage has a maximum value of 1.2 m² with a barrel length of 150 mm, a powder charge mass of 2.28 g and a shot charge mass of 54 g. Reducing the mass of the shot charge and the mass of the powder charge leads to a decrease in the area of damage at any barrel length.

The practical significance of the results is that they could be applied to improve cartridges and individual means of defeating UAVs with FPV piloting. In addition, they might be used in automatic protection systems that are promising for installation on combat vehicles

Keywords: *hunting rifle, powder charge, standard deviation, area of damage, dispersion model*

DETERMINING THE INFLUENCE OF BARREL LENGTH ON THE BALLISTIC CHARACTERISTICS OF HUNTING CARTRIDGES

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1. Introduction

The armed aggression of the Russian Federation against Ukraine has caused significant changes in the strategy and

tactics of conducting combat operations. New organizational structures for conducting combat operations have come to the fore, such as the Forces of Unmanned Systems, whose main basic weapon currently is UAVs with FPV (First-Person View)

technology. This weapon ensures the defeat of both single infantrymen on the front line (gray zone) and ballistic and cruise missile launch systems deep behind enemy lines in real time [1, 2].

The use of UAVs with FPV piloting has made it possible to combine, in fact, 2 systems in one vehicle: a high-precision means of destruction and a target reconnaissance system. Moreover, target reconnaissance can be carried out both traditionally using large UAVs and by a continuous stream of UAVs with FPV piloting [3]. The reserve of flight time allows them not only to clarify the coordinates of the target due to movement but also detect targets within large objects (multi-story buildings, fortification systems, etc.). After detecting a target, the UAV can continue to monitor the area until the battery runs out and only then engage the target, enabling continuous monitoring of the area [4–6].

At the same time, the widespread use of UAVs with FPV piloting necessitates the development of effective countermeasures. Despite the availability of various technical solutions, in particular electronic warfare, their use is not always possible or economically feasible at the level of individual units. In this regard, the search for affordable and relatively inexpensive means of combating small-sized UAVs is relevant [7, 8].

One possible solution to this task is the use of hunting shotguns with appropriate ammunition. The practical range of shotguns is usually from 20 to 50 m, which corresponds to the typical distances of rapprochement of FPV-piloted UAVs with a potential target. Unlike a rifle, which uses a single element of destruction, a shotgun forms a spatial area of damage due to a large number of elements of destruction [9]. However, the effectiveness of this technique largely depends on the parameters of the shot charge and the nature of its dispersion after the shot.

Therefore, research aimed at designing individual means of countering FPV-piloted UAVs is relevant.

2. Literature review and problem statement

Publications on FPV-controlled UAVs are mostly reviews or scientific-journalistic articles. They practically do not reveal the technical aspects of their design and application. Issues of resistance to various countermeasures are especially hidden.

One of the common means of combating small-sized UAVs recently is a 12-gauge smoothbore hunting weapon. A shot charge creates a zone of destruction in space, the area of which corresponds to the probability of hitting moving air objects. Therefore, the patterns of shot dispersion in space directly characterize the effectiveness of combating UAVs. The length of the barrel affects the formation of dispersion characteristics, reducing the length of the barrel decreases the initial velocity of the shot charge. In addition, the density of the distribution of pellets on the target surface changes.

In scientific papers, the issue of relationship between the length of the barrel of a smoothbore weapon and the characteristics of shot dispersion is not sufficiently covered, especially in the context of defeating small-sized objects.

In [10], a study was conducted on the effect of changing the barrel length of 12-gauge shotguns on shot dispersion. The results showed that the distance to the target has a greater effect on dispersion than the barrel length. One of the factors that could have led to this result is the use of shot number 4. In addition, the picture of shot dispersion given in the paper indicates the use of containers, which has a greater effect on dispersion than other factors.

Work [11] reports dispersion diagrams for establishing shot distances when conducting forensic ballistic examinations. It was found that the dispersion of both lead and steel shot increases with decreasing its size if all other relevant parameters remain unchanged.

In [12], the possibility of using plastic wads for forensic ballistics is considered. This study confirms their importance for the formation of shot peals.

The application of deep machine learning methods for automated interpretation of shot peals is investigated in [13]. The results showed that the trained models are capable of detecting complex patterns in shot distributions that are not always obvious during visual analysis.

Study [14] demonstrated that cartridges loaded with grain have a much wider distribution over targets at the same shooting distance with the same and similar barrel length compared to conventional cartridges containing lead shot.

Paper [15] considers experimental determination of the ballistic characteristics of hunting shot cartridges. Shot dispersion was determined taking into account the mass of gunpowder, the mass of the shot charge, and the size of the shot. Unlike other studies, non-standard hunting cartridges were used and the results of hits on the target were recorded. Three-factor dependences were obtained, which make it possible to choose a charge option that provides maximum shot dispersion at a distance of 20 m.

In paper [16], the effect of temperature on shot dispersion along the trajectory was studied. However, it turned out that the temperature of the sleeve has a greater effect. This conclusion is logical due to the change in the burning rate of gunpowder when its temperature changes, but the practical significance of such a conclusion is minimal.

The issue of shot dispersion was also studied in work [17]. Various types of 12-gauge weapons and the results of hits at distances of 10, 18 and 25 meters were considered. The shooting results showed a uniform distribution of the shot at a level of 65% to 80% relative to the center.

Existing research in the field of ballistics of shotgun cartridges mainly focuses on hunting applications and does not take into account the specifics of defeating small-sized air targets, in particular, FPV-piloted UAVs. Specifically, the issues of the influence of the barrel length and the mass of the shot and powder charge on the formation of the density and uniformity of the hit pattern, which directly determines the probability of hitting the target, remain insufficiently studied.

Taking into account the above, it can be concluded that the methods given in the reviewed literature [10–17] only partially make it possible to determine the characteristics of hunting cartridges intended for defeating FPV-controlled UAVs. In this regard, the scientific task of devising a methodology for defining the characteristics of such cartridges taking into account the length of a weapon barrel, the mass of the shot, and the powder charge, arises.

All this allows us to state that it is advisable to conduct a study aimed at determining the standard deviation in the distribution of shot on the target and the area of damage in given ranges of barrel lengths, shot charge mass, and gunpowder.

3. The aim and objectives of the study

The purpose of our study is to determine the ballistic performance of hunting cartridges for defeating UAVs with FPV piloting depending on the length of a hunting rifle barrel.

This will give an opportunity to provide rational values for the length of the hunting rifle barrel and directions for further improvement of means for defeating UAVs with FPV piloting.

To achieve the goal, the following tasks were set:

- to determine the standard deviation in the distribution of shot on the target;
- to determine the area of impact with hunting cartridges.

4. The study materials and methods

4.1. The object and hypothesis of the study

The object of our study is a hunting rifle with a variable barrel length.

The principal hypothesis assumes that by determining the root-mean-square characteristics of shot distribution and analyzing the area of damage, it is possible to quantitatively assess the effectiveness of defeating FPV-piloted UAVs when using hunting cartridges. This should make it possible to establish rational values of the barrel length and determine the directions for further improvement of means for defeating such UAVs.

When planning the experiment, it was assumed that the use of the D-optimal Box-Behnken plan would make it possible to most accurately approximate the measurement results. The justification for this was the desire to obtain a regression model that minimizes the variance between empirical data and predicted values. To simplify the experimental planning, three factors were selected, which, according to our expert assessment, are the most significant for characterizing the effectiveness of defeating FPV-piloted UAVs.

4.2. Methodology for determining the influence of barrel length on ballistic performance of hunting cartridges

The influence of barrel length on ballistic characteristics of hunting cartridges intended for defeating FPV-piloted UAVs was studied by conducting a multifactorial experiment according to the D-optimal Box-Behnken design for three main factors [18]. The adequacy of the resulting regression models was checked using the Fisher criterion. The level of variance in experimental data was assessed using the Cochran criterion, and the significance of coefficients in the regression equation was assessed using the Student criterion. All statistical criteria were calculated for a 95 percent confidence level. The change intervals and levels of variation in the independent variables used in the study are given in Table 1.

Table 1

Intervals of magnitude of and variations in the levels of the studied factors

Factor ID	Designation	Level of variation in factors			Variance interval
		-1	0	+1	
Barrel length, mm	l_C	150	410	670	260
Weight of shot charge, g	p_D	36	45	54	9
Amount of gunpowder in the charge, g	p_C	1.52	1.9	2.28	0.38

Fire tests were conducted on a white paper target measuring 1.9×2.5 m at a distance of 20 m. Shooting was carried out indoors under artificial lighting at a temperature of 20°C and normal atmospheric pressure; the air velocity in the experimental area was practically zero. The angle of the shot

remained unchanged due to the fixation of the rifle in the clamps to ensure stability of the position.

A 12-gauge IZH-54 hunting rifle (barrel diameter 21.2 mm) was used for the experiments. The ammunition was formed according to the D-optimal Box-Behnken plan for the three studied factors and variation intervals given in Table 1; all cartridges contained pellets with a diameter of 3.75 mm.

The physical appearance of the used rifle samples is shown in Fig. 1. The tests were carried out on the ballistic track at the National University of Defense of Ukraine (Kyiv). Each shot was fired at a separate target: after one shot, the target was changed, and the coordinates of individual shot hits on the hit target were recorded.

The coordinates of the scattered shots were digitized using the PlotDigitizer program [19], from which the root-mean-square deviation of the shot from the center of scattering was calculated (Fig. 2).



Fig. 1. General view of rifle samples used during the research with barrel lengths: a – 150 mm; b – 410 mm; c – 670 mm

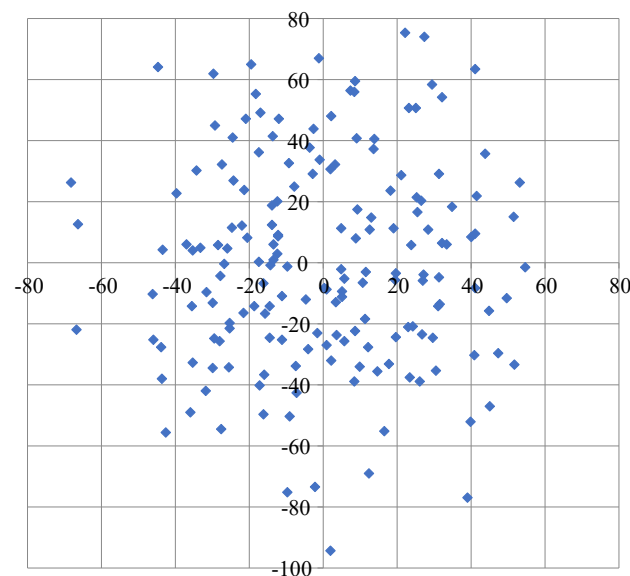


Fig. 2. Sample of scattered shot on a target with a barrel length of 150 mm, a shot mass of 54 g, and a powder charge mass of 1.9 g

The area of damage was simulated by scaling the penetration point on the target to the size of the total equivalent diameter of the most vulnerable FPV-UAV components. In the study, the equivalent diameter of the targets was taken to be 8 cm (Fig. 3).

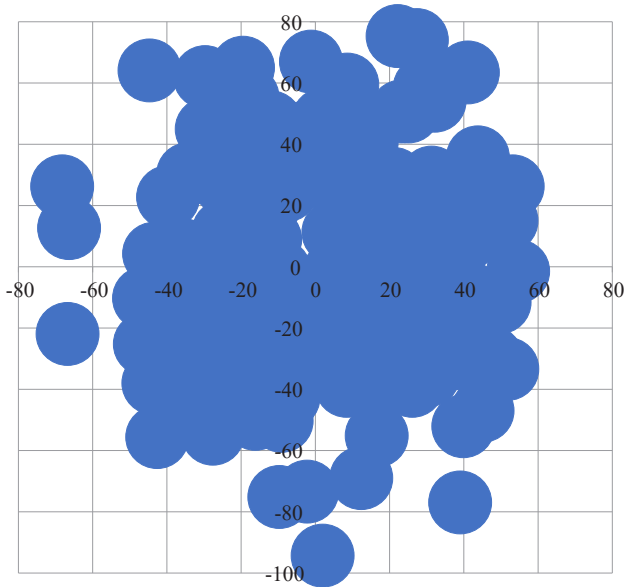


Fig. 3. Example of determining the area of damage with an equivalent target diameter of 8 cm, a barrel length of 150 mm, a shot weight of 54 g, and a powder charge weight of 1.9 g

The general view of the affected area (Fig. 2, 3) shows that the resulting variant of shot dispersion has a uniform dispersion with no central accumulation of shots.

5. Results of determining the influence of barrel length on the ballistic performance of hunting cartridges

5.1. Determining the standard deviation in shot distribution on the target

The standard deviation (for three repetitions) of shot distribution on the target depending on the value of the experimental factors is given in Table 2.

Table 2

Standard deviation in the distribution of shots on the target depending on the value of the experimental factors

Barrel length, mm	Shot charge weight, g	Amount of gunpowder in the charge, g	Mean value of standard deviation in the distribution of shots on the target, cm
670	54	1.90	15.09
150	36	1.90	21.91
670	36	1.90	13.86
150	54	1.90	18.19
670	45	2.28	16.15
150	45	1.52	19.07
670	45	1.52	13.52
150	45	2.28	17.76
410	54	2.28	17.30
410	36	1.52	13.69
410	54	1.52	12.82
410	36	2.28	13.81
410	45	1.90	11.91
670	54	1.90	12.04
150	36	1.90	12.67

The regression equation that describes the standard deviation in the distribution of shots on the target, taking into account significant regression coefficients, takes the following form

$$\delta = 77.468 - 0.077 \cdot l_C - 1.853 \cdot p_D + 0.0001 \cdot l_C^2 + 0.018 \cdot p_D^2 + 0.0005 \cdot l_C \cdot p_D, \quad (1)$$

where δ is the standard deviation in shot distribution on the target, cm; l_C is the barrel length, mm; p_D is the weight of shot charge, g; p_C is the powder charge, g.

The regression equation (1) is graphically represented in Fig. 4-6.

Thus, it can be stated that the results from determining the standard deviation of the shot distribution on the target were obtained by taking into account the given range of barrel length, shot charge mass, and gunpowder.

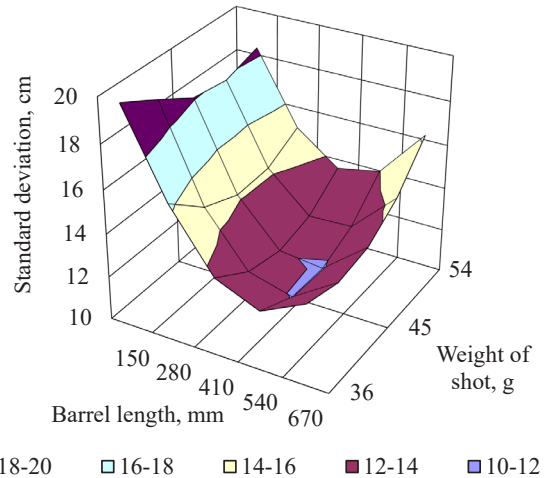


Fig. 4. Standard deviation in shot distribution on the target depending on barrel length and shot mass with a powder charge of 1.9 g

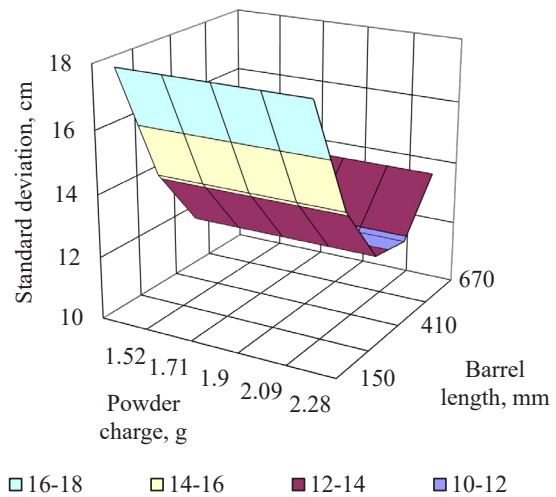


Fig. 5. Standard deviation in shot distribution on the target depending on barrel length and powder charge with a shot charge mass of 45 g

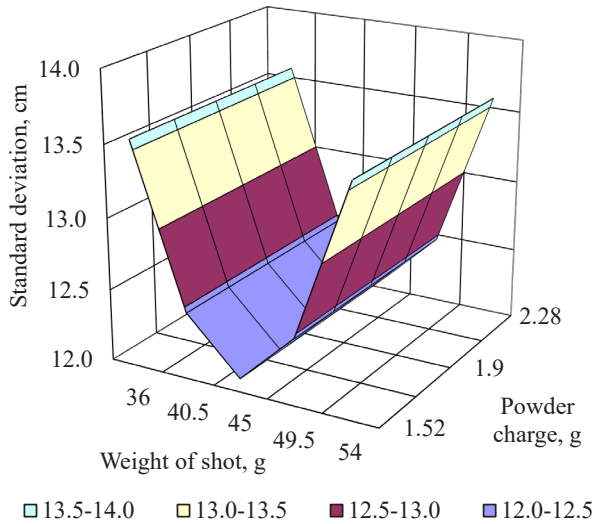


Fig. 6. Standard deviation in shot distribution on the target depending on shot mass and powder charge with a barrel length of 410 mm

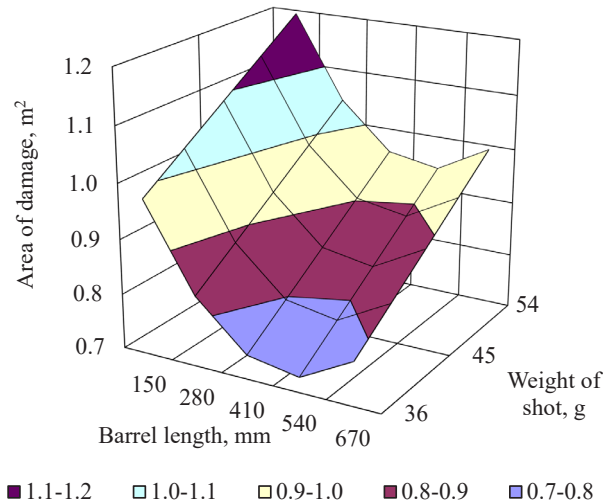


Fig. 7. Target area with an equivalent diameter of 8 cm depending on the mass and length of the barrel with a charge of 1.9 g of gunpowder

5.2. Determining the area of damage by hunting cartridges

The area of damage (for three repetitions) by hunting cartridges depending on the value of the experiment factors is given in Table 3.

Table 3

Area affected by hunting cartridges depending on the value of the experiment factors

Barrel length, mm	Shot charge mass, g	Amount of gunpowder in the charge, g	Average area of damage, m²
670	54	1.90	0.87
150	36	1.90	1.03
670	36	1.90	0.65
150	54	1.90	1.35
670	45	2.28	1.05
150	45	1.52	0.95
670	45	1.52	0.85
150	45	2.28	0.90
410	54	2.28	0.96
410	36	1.52	0.73
410	54	1.52	0.77
410	36	2.28	0.69
410	45	1.90	0.85
670	54	1.90	0.83
150	36	1.90	0.87

The regression equation that describes the target area, taking into account significant regression coefficients, takes the following form

$$S = 1.32 - 0.003 \cdot l_C - 0.02 \cdot p_D + 0.39 \cdot p_C + 0.000002 \cdot l_C^2 - 0.344 \cdot p_C^2 + 0.0006 \cdot l_C \cdot p_C + 0.017 \cdot p_D \cdot p_C, \tag{2}$$

where *S* is the area of damage on the target, m².

The regression equation (2) is graphically represented in Fig. 7–9.

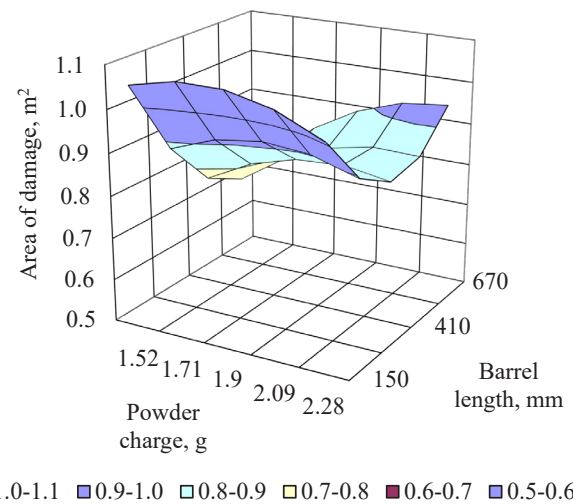


Fig. 8. Target area with an equivalent diameter of 8 cm depending on the powder charge and barrel length with a shot charge weight of 45 g

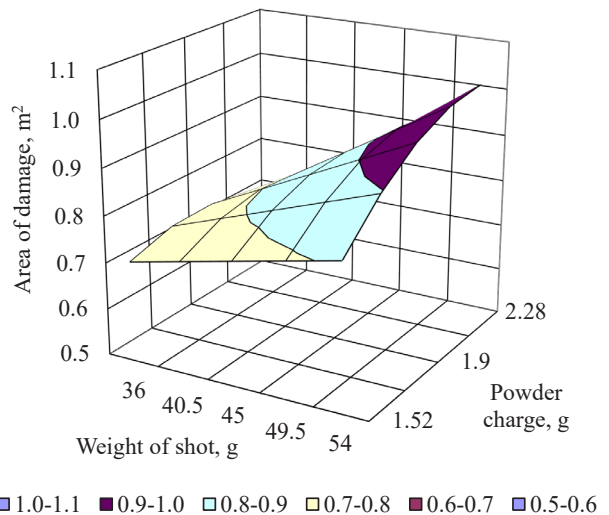


Fig. 9. Target area with an equivalent diameter of 8 cm depending on the powder charge and shot mass with a barrel length of 410 mm

Thus, the results from determining the area of damage of a target with an equivalent diameter of 8 cm were obtained depending on the given barrel length, mass of shot charge, and gunpowder.

6. Discussion of the results of determining the influence of barrel length on the ballistic performance of hunting cartridges

The use of hunting weapons and cartridges to combat FPV-piloted UAVs is common under war conditions. The basis for such use is the experience of combat operations.

We have determined characteristics of hunting cartridges for defeating FPV-piloted UAVs, namely the mean square deviation of the shot from the center of the target and the area of destruction. This was achieved by applying the planning of experiments using the D-optimal Box-Benkin design for the three factors under study: shot diameter, mass of powder and shot [18].

Unlike papers [10–17], our study has established the influence of barrel length on the ballistic performance of hunting cartridges for defeating FPV-piloted UAVs, namely the mean square deviation of the shot from the center of the target and the area of destruction.

The plot characterizing the standard deviation of the shot distribution on the target depending on the barrel length and shot mass is shown in Fig. 4. One can see that the maximum value of the standard deviation in shot distribution at the level of 21 cm occurs at a barrel length of 150 mm and a shot charge mass of 36 g. A smaller peak of the standard deviation in shot distribution at the level of 18 cm is also observed at a barrel length of 150 mm, but at a shot charge mass of 54 g. The maximum shot cluster on the target occurred in almost the entire range of shot mass and a barrel length of 410 mm.

The standard deviation in shot distribution on the target depending on the barrel length and the powder charge is shown in Fig. 5. From Fig. 5 it is seen that the maximum value of the standard deviation in shot distribution at the level of 18 cm occurs at a barrel length of 150 mm and any mass of the powder charge. A smaller peak of the standard deviation in shot distribution at the level of 13 cm is observed at a barrel length of 670 mm and also at any mass of the powder charge.

The standard deviation in shot distribution on the target depending on the mass of the shot and the powder charge is shown in Fig. 6. It shows that the maximum values of the standard deviation in shot distribution are practically identical at 13.5 cm for shot weights of 36 g and 54 g, and the minimum is 12 cm for a shot charge weight of 45 g.

Thus, our analysis of the standard deviation in shot distribution on the target depending on the barrel length and shot weight, as well as the powder charge, revealed the following. The maximum value of standard deviation in shot distribution at 21 cm occurs with a barrel length of 150 mm and a shot charge weight of 36 g. The powder charge weight in this study had no effect on the value of the standard deviation.

The area of damage to a target with an equivalent diameter of 8 cm (Fig. 7–9) at the level of 1.2 m² has a maximum value at a barrel length of 150 mm, a powder charge mass of 2.28 g, and a shot charge mass of 54 g. A decrease in the mass of the shot charge and the mass of the powder charge leads to a decrease in the area of damage at any barrel length.

The regression equation, which describes the standard deviation of the distribution of the shot on the target, shows that it lacks powder charge coefficients. They turned out to be

insignificant. This may be due to the fact that the dispersion is more related to the interaction of the shot with the barrel walls, which limits the departure angle, and the powder charge affects mainly the speed of the shot. At the same time, the area of damage is more related to the uniformity of the dispersion of the shot, so there is an increase in the area of damage due to the increase in speed, and accordingly, the powder charge is a significant parameter.

The standard deviation in the distribution of shot has maximum values in the case when the powder charge is maximum, and the mass of the shot is minimal. This is due to the fact that, in this case, the speed of the shot is maximum and, accordingly, the factor of increasing aerodynamic resistance is triggered, which, in combination with deviations in the shape of the shots, leads to an increase in dispersion. At the same time, the area of damage will have minimum values due to the small number of striking elements.

The proposed method for determining the characteristics of hunting cartridges for defeating UAVs with FPV piloting, unlike existing ones, allows one to establish the influence of barrel length on the ballistic performance of hunting cartridges. It also provides the opportunity to devise rational options for means for effective combat against UAVs with FPV piloting.

Thus, when determining the influence of barrel length on the ballistic performance of hunting cartridges for defeating UAVs with FPV piloting, the mean square deviation in the shot from the center of the target and the area of impact were established. The results of our study enabled determining those parameters of the impact means that would make it possible to defeat UAVs with FPV piloting to the greatest extent.

The derived equations (1), (2) and experimental dependences (Fig. 4–9) are new in that they determine the influence of the barrel length on the ballistic performance of hunting cartridges for defeating UAVs with FPV piloting. In addition, these data were obtained in combination with the powder charge and the weight of the shot. Such results were not reported in the reviewed literary sources.

The practical significance of our research results is that they could be used to improve cartridges for hunting rifles used to defeat FPV-piloted UAVs. In addition, they might be used in automatic protection systems that are installed on combat vehicles [20] in the conditions of modern combat operations.

The limitations of the research include their conduct for a specific type of means of destruction, and the results are limited by the conditions of the experiment.

The disadvantages include the fact that the research was conducted on the existing database of characteristics of means of destruction, which does not fully meet the conditions of combat with FPV-piloted UAVs.

7. Conclusions

1. We have found that the maximum value of standard deviation in shot distribution at the level of 21 cm occurs at a barrel length of 150 mm and a shot charge mass of 36 g. At the same time, the powder charge did not have a significant effect on the standard deviation in the shot distribution on the target.

2. It was found that the area of impact of a target with an equivalent diameter of 8 cm has a maximum value of 1.2 m² at a barrel length of 150 mm, a powder charge mass of 2.28 g, and a shot charge mass of 54 g. Reducing the mass of the shot charge and the mass of the powder charge leads to a decrease in the area of impact at any barrel length.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

The data will be provided upon reasonable request.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

Authors' contributions

Victor Golub: Conceptualization, Methodology, Investigation, Writing – original draft; **Serhii Bisyk:** Methodology, Formal analysis; **Gennadii Golub:** Formal analysis, Validation, Writing – review & editing; **Ihor Zozulevych:** Investigation, Data curation; **Oleksandr Kuprinenko:** Investigation; **Leonid Davydov'skyi:** Software, Visualization; **Sviatoslav Sedov:** Supervision, Funding acquisition; **Oleh Aristarkhov:** Investigation, Funding acquisition.

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