ОРИГІНАЛЬНІ ДОСЛІДЖЕННЯ

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FORENSIC CHARACTERISTICS OF PENETRATING WOUNDS AND INJURY FACTORS OCCURRED AFTER THE EXPLOSION OF A BALLISTIC ROCKET

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Abstract. The article presents a forensic characterization of the injuries and traumatic factors that occurred after the explosion of a ballistic missile as manifestations of explosive trauma. The wounds are fatal penetrating injuries caused by blunt, hard objects with a limited contact surface that acted with high kinetic energy and had significant penetrating ability. Micro-X-ray fluorescence spectral analysis revealed the highest amount of iron elements in and around the injuries. The traumatic objects were of the following origin:1) oblong or polygonal rocket fragments with pointed, torn or jagged edges; 2) round or irregularly round objects with a smooth surface and dimensions from 0.6 to 1.7 cm; 3) objects with unevenly pronounced polygonal relief, similar to pebbles, 1-2 cm or larger in size – could be both components of an explosive device (the body/parts of a rocket or cluster munitions for it), and secondary projectiles with layers of metal elements on their surface. The identity of size, shape, surface relief, and high iron (Fe) content among the objects of the second group of non-biological origin give reason to assume that these are cluster munitions, similar to buckshot.

The aim of the study. To describe the forensic medical characterization of penetrating wounds and traumatic factors resulting from the explosion of a ballistic missile.

Materials and methods. Six biological objects (skin flaps) were studied, removed from different parts of the body of a person who died from wounds resulting from the penetrating action of blunt hard objects with a limited contact surface (fragment/element or fragment of an explosive device or secondary projectile) (archive "Conclusions of expert examination" "SSI Kyiv City Bureau of Forensic Medical Examination" 2025), and 34 non-biological objects: 2 removed from the victim's body, and 32 taken from the site of the ballistic missile explosion. The damage was examined visually and using a stereomicroscope "Carl Zeiss stereo Discovery. V12". The study in the ultraviolet region of the spectrum was carried out with the aim of detecting in the areas of the studied wounds any layers and inclusions that can luminescence in ultraviolet rays. To detect the topography of the distribution and qualitative composition of metallization elements in the areas of damage, micro-X-ray fluorescence was used. Spectral analysis was performed using a Bruker (Germany) M4 TORNADO micro-X-ray fluorescence spectrometer aplying standard analytical techniques. Quantitative analysis was performed using standard methods of variational statistics.

Scientific research. This study is the part of research of the Department of Morphology, Clinical Pathology and Forensic Medicine of the P.L. Shupyk National University of Health Sciences "Scientific Substantiation of Modern Pathomorphological Diagnostics and Establishment of Clinical and Morphological Correspondences in Various Diseases" State Registration No. 0116U007906 (2021-2025).

Bioethics. Approved by the Bioethics Commission of the P.L. Shupyk National University of Health Sciences (protocol № 26 dated 18 of June 2025).

Results. Morphological manifestations of explosive trauma were found on the bodies of the corpses of people who died as a result of the penetrating action of ballistic missile fragments. They are mostly identical, as is the elemental content of metals in them, which indicates that the penetrating injuries were caused by the action of a blunt hard object with a limited contact surface (fragment/element or fragment of an explosive device or secondary projectile) that acted with high kinetic energy, while having significant penetration ability.

Conclusions. Forensic macro- and microscopic examination of the injuries resulting from the explosion of a ballistic missile showed that they were fatal penetrating wounds caused by blunt, solid objects with a limited contact surface, which acted with high kinetic energy and had significant penetrating ability. Micro-X-ray fluorescence spectral analysis revealed the highest amount of iron elements in and around the damage. According to their origin, the traumatic objects were divided into groups: 1) rocket fragments of oblong or polygonal shape with pointed, torn or jagged edges; 2) objects of round or irregular shape with a smooth surface and dimensions from 0.6 to 1.7 cm; 3) objects with unevenly pronounced relief polygonal in shape, similar to pebbles, 1-2 cm in size or more – could be both components of an explosive device (the body/parts of a rocket or cluster munitions for it), and secondary projectiles with layers of metal elements on their surface. The identity of size, shape, surface relief, and high iron (Fe) content among the objects of the second group of non-biological origin give reason to assume that these could have been cluster munitions, similar to buckshot. Based on the identity of the quantitative and qualitative morphological features of both wounds and the coincidence of shape, size and high iron content in the objects of the first group of non-biological origin (fragment/element or fragment of an explosive device or secondary projectile), there are reasons to believe that they could have been the traumatic projectiles that caused the victim's death.

Key words: forensic medical examination, bodily injuries, explosive trauma, ballistic missile, cluster munitions.

СУДОВО-МЕДИЧНА ХАРАКТЕРИСТИКА ПРОНИКАЮЧИХ ПОРАНЕНЬ І ТРАВМУЮЧИХ ЧИННИКІВ, ЩО УТВОРИЛИСЯ ПІСЛЯ

ВИБУХУ БАЛІСТИЧНОЇ РАКЕТИ

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Резюме. Наведена судово-медична характеристика ушкоджень і травмуючих чинників, що утворилися після вибуху балістичної ракети, як проявів вибухової травми. Рани є вхідними смертельними пораненнями, заподіяними тупими твердими предметами з обмеженою поверхнею контакту, що діяли з високою кінетичною енергією і мали значну пробивну здатність. Мікрорентгенівський флуоресцентний спектральний аналіз виявив в ушкодженнях та навколо них найбільшу кількість елементів заліза. За походженням травмуючі предмети були: 1) уламками ракети довгастої чи багатокутної форми з загостреними, рваними чи зазубреними краями; 2) предметами округлої чи неправильно округлої форми з гладкою поверхнею і розмірами від 0,6 до 1,7 см; 3) предметами з нерівномірно вираженим рельєфом багатокутної форми, схожими на камінці розмірами 1-2 см і більше – могли бути як компонентами вибухового пристрою (корпусу/деталей ракети чи касетних боєприпасів до неї), так і вторинними снарядами з нашаруваннями елементів металів на своїй поверхні. Тотожність розмірів, форми, рельєфу поверхні та високий вміст заліза (Fe) серед об'єктів другої групи небіологічного походження дають підстави припустити, що це касетні боєприпаси, схожі на картеч.

Мета роботи. Надати судово-медичну характеристику проникаючих поранень і травмуючих чинників, що утворилися після вибуху балістичної ракети.

Матеріали та методи. Досліджено 6 біологічних об'єктів (клаптів шкіри), вилучених із різних ділянок тіла особи, яка загинула від поранень внаслідок проникаючої дії тупих твердих предметів з обмеженою поверхнею контакту (уламок/елемент чи фрагмент вибухового пристрою або вторинного снаряду) (архівні «Висновки експертного дослідження» «ДСУ Київське міське бюро судово-медичної експертизи» 2025 р.), а також 34 небіологічні об'єкти: 2 вилучені з тіла потерпілого та 32 узяті з місця вибуху балістичної ракети. Ушкодження досліджували візуально та за допомогою стереомікроскопа «Carl Zeiss stereo Discovery. V12». Дослідження в ультрафіолетовій ділянці спектра проводили з метою виявлення в ділянках досліджуваних ран будь-яких нашарувань і включень, які можуть люмінесціювати в ультрафіолетових променях. Дослідження виконували за допомогою випромінювача ультрафіолетових променів UV-400 «Spectroline», довжина хвиль випромінення якого становила 320-400 нм, та із запираючим світофільтром ЖС-18. Дослідження в інфрачервоній ділянці спектра проводили з метою виявлення нашарувань та включень, що поглинають інфрачервоні промені, в ділянках досліджуваних ушкоджень за допомогою телекамери «CCD B/W Camera Model: MTC-5C23B», матриця якої чутлива до інфрачервоних променів. Об'єкти освітлювали лампами накалювання (2x100W) з використанням інфрачервоного світлофільтра ІКС-1. Для виявлення топографії розподілу та якісного складу елементів металізації в ділянках ушкоджень був застосований мікрорентгенівський флуоресцентний спектральний аналіз, який був проведений із застосуванням мікрорентгенівського флуоресцентного спектрометру «M4 TORNADO» компанії Bruker (Німеччина) за стандартними аналітичними методиками. Кількісний аналіз проводили з використанням стандартних методів варіаційної статистики.

Науково-дослідна робота. Проведене дослідження є частиною науково-дослідної роботи кафедри морфології, клінічної патології та судової медицини НУОЗУ імені П.Л. Шупика «Наукове обґрунтування сучасної патоморфологічної діагностики та встановлення клініко-морфологічних відповідностей при різних захворюваннях», № державної реєстрації 0116U007906 із терміном виконання впродовж 2021-2025 р.р.

Біоетика. Матеріали роботи схвалено комісією з питань біоетики НУОЗУ імені П.Л. Шупика (протокол № 26 від 18.06.2025).

Результати. На тілі трупів осіб, які загинули внаслідок проникаючої дії уламків балістичної ракети, виявлені морфологічні прояви вибухової травми. Вони переважно тотожні, так само як і елементний вміст металів в них, що свідчить про те, що наскрізні тілесні ушкодження утворилися внаслідок дії тупого твердого предмета з обмеженою поверхнею контакту (уламок/елемент чи фрагмент вибухового пристрою або вторинного снаряду), що діяв з високою кінетичною енергією, маючи при цьому значну пробивну здатність.

Висновки. Судово-медичне макро- і мікроспопічне дослідження ушкоджень, які утворилися внаслідок вибуху балістичної ракети показало, що вони є вхідними смертельними пораненнями, заподіяними тупими твердими предметами з обмеженою поверхнею контакту, що діяли з високою кінетичною енергією і мали значну пробивну здатність. Мікрорентгенівський флуоресцентний спектральний аналіз виявив в ушкодженнях та навколо них найбільшу кількість елементів заліза. За походженням травмуючі предмети були розділені на групи: 1) уламки ракети довгастої чи багатокутної форми з загостреними, рваними чи зазубреними краями; 2) предмети округлої чи неправильно округлої форми з гладкою поверхнею і розмірами від 0,6 до 1,7 см; 3) предмети з нерівномірно вираженим рельєфом багатокутної форми, схожими на камінці розмірами 1-2 см і більше – могли бути як компонентами вибухового пристрою (корпусу/деталей ракети чи касетних боєприпасів до неї), так і вторинними снарядами з нашаруваннями елементів металів на своїй поверхні. Тотожність розмірів, форми, рельєфу поверхні та високий вміст заліза (Fe) серед об'єктів другої групи небіологічного походження дають підстави припустити, що це могли бути касетні боєприпаси, схожі на картеч. Виходячи з тотожності кількісних і якісних морфологічних ознак обох ран та збіг форми, розмірів і високого вмісту заліза в предметах першої групи небіологічного походження (уламок/елемент чи фрагмент вибухового пристрою або вторинного снаряду), є підстави вважати, що саме вони і могли бути травмуючими снарядами, що спричинили смерть потерпілого.

Ключові слова: судово-медична експертиза, тілесні ушкодження, вибухова травма, балістична ракета, касетні боєприпаси.

Introduction. Despite the end of the Second World War, armed conflicts of varying scales, employing explosive devices (such as artillery shells, mines, aerial bombs, missiles, and others), have continuously occurred in different countries and continents, particularly from the late 20th to the early 21st century. These weapons, due to their destructive capacity and lethal effects, significantly surpass conventional arms [1, 2]. Furthermore, it is essential not to overlook the impact of terrorist acts [3, 4]. The consequences of the use of such weapons, whether manufactured in military factories or under improvised conditions, are hundreds of thousands of casualties [5-8], including children [9-11].

Commencing in February 2022, a large-scale and protracted armed conflict has been ongoing in Ukraine, which has also resulted in a significant number of fatalities and injuries among both military personnel and the civilian population [12-14]. The exceptionally high mortality and injury rates are exacerbated by the aggressor's use of aerial bombs and missiles equipped with cluster munitions.

Within specialized literature, considerable attention is devoted to the characteristics of pathological changes in biological objects following the detonation of explosive devices. For instance, Zara R. Mathews and Alex Koyfman [1], as well as Michael R. Jorolemon, Richard A. Lopez, and Diann M. Krywko [2], categorize blast injuries by mechanism into four groups: *primary* injuries, resulting from the impact of the blast wave itself; *secondary* injuries, caused by fragments or secondary projectiles; *tertiary* injuries, which occur from the displacement of the entire body by the blast wind or through structural collapse; and a *fourth category* of injuries that includes nearly all other mechanisms.

The investigation of blast trauma cases and their expert evaluation is a primary focus of forensic medicine. The legal issues associated with these fatalities are diverse, and forensic experts are often expected to provide an objective medico-legal diagnosis regarding the cause of death and the nature of the injurious agent [15]. This is particularly crucial in the context of an armed conflict involving the use of aerial bombs and missiles equipped with cluster munitions. Among the multitude of challenges posed by warfare, this issue is currently extremely relevant in Ukraine and requires meticulous research.

The aim of the study. To describe the forensic medical characterization of penetrating wounds and traumatic factors resulting from the explosion of a ballistic missile.

Materials and Methods. The study examined 6 biological specimens (skin fragments) collected from various areas of the body of an individual who died from injuries caused by the penetrating action of blunt, solid objects with a limited contact surface (fragments/elements or pieces of an explosive device or secondary projectile) (archival "Expert Research Reports" from the Kyiv City Bureau of Forensic Medical Examination, 2025). Additionally, 34 non-biological objects were studied: 2

recovered from the victim's body and 32 collected from the impact site of a ballistic missile.

The injuries were examined visually and using a "Carl Zeiss Stereo Discovery.V12" stereomicroscope. Examination in the ultraviolet (UV) spectrum was conducted to detect any deposits or inclusions in the investigated wounds that might luminesce under ultraviolet light. This was performed using a "Spectroline UV-400" ultraviolet emitter with a wavelength range of 320-400 nm and a ZHS-18 blocking filter.

Examination in the infrared (IR) spectrum was carried out to identify deposits and inclusions that absorb infrared radiation within the studied injuries. This was done using a "CCD B/W Camera Model: MTC-5C23B" television camera with a matrix sensitive to infrared radiation. The objects were illuminated by incandescent lamps (2x100W) using an IKS-1 infrared filter.

To detect the topography of distribution and the qualitative composition of metallization elements in the injury areas, micro-X-ray fluorescence spectral analysis was applied. This was conducted using a Bruker "M4 TORNADO" micro-X-ray fluorescence spectrometer (Germany) following standard analytical methodologies [5]. Quantitative analysis was performed using standard methods of variation statistics.

Scientific research. This study is the part of research of the Department of Morphology, Clinical Pathology and Forensic Medicine of the P.L. Shupyk National University of Health Sciences “Scientific Substantiation of Modern Pathomorphological Diagnostics and Establishment of Clinical and Morphological Correspondences in Various Diseases” State Registration № 0116U007906 (2021-2025).

Bioethics. Approved by the Bioethics Commission of the P.L. Shupyk National University of Health Sciences (protocol № 26 dated 18 of June 2025).

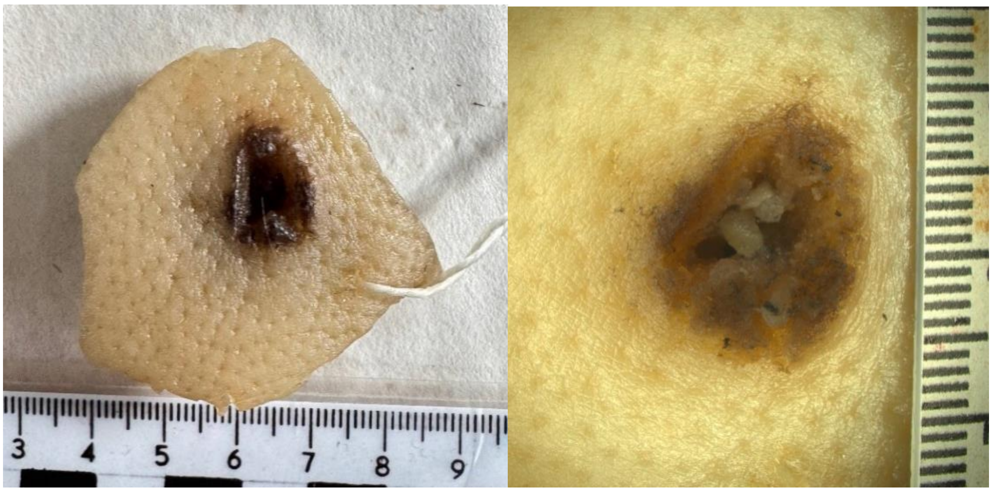
Results. On January 18, 2025, another ballistic missile strike by the aggressor country targeted the central district of the city of Kyiv. A 26-year-old man died as a result of penetrating wounds to vital organs, which were incompatible with life. During the forensic autopsy, penetrating wounds were identified on the posterior surface of the thoracic cavity on the right side (Wound №1) and on the right lateral surface of the thoracic cavity (Wound №2) (Fig. 1).

Fig.1. Penetrating wounds on the posterior surface of the thoracic cavity on the right (Wound №1) and on the right lateral surface of the thoracic cavity (Wound №2).

Macroscopic and stereomicroscopic examination of two skin fragments containing the wounds, extracted from Wound № 1 and Wound № 2, revealed that both were through-and-through, of an irregular oval shape, measuring 1.3x1.6 cm and 1.3x1.2 cm, respectively, with an elongated tissue defect in each.

In Wound № 1, the right edge was smooth, while the left edge was somewhat serrated due to superficial lacerations and partially crushed (Fig. 2 a, b). Two superficial lacerations extended from the lower edge of the wound; the wound edges were unevenly abraded, with the maximum width along the lower edge; the walls were somewhat uneven, with the left wall being smooth and vertical, and the right wall slightly sloping towards the center (Fig. 2 a, b).

Stereomicroscopic examination of Wound № 1 revealed the presence of embedded black textile fibers.



a b

Fig. 2. General view of the skin fragment with Wound № 1 (a) and its microscopic view (b).

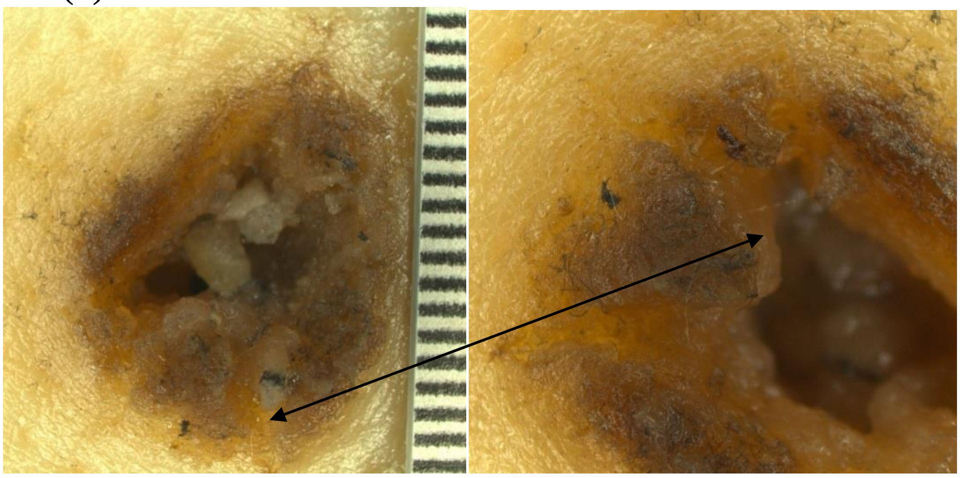


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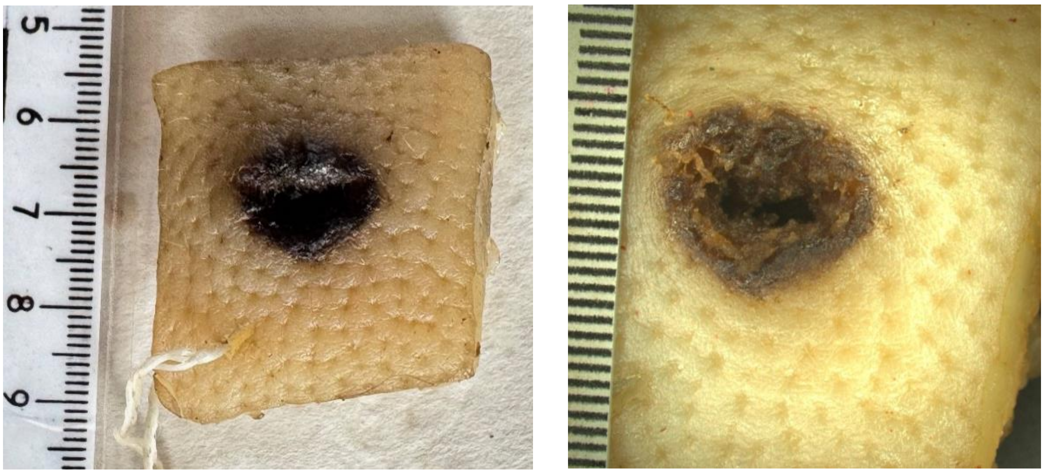
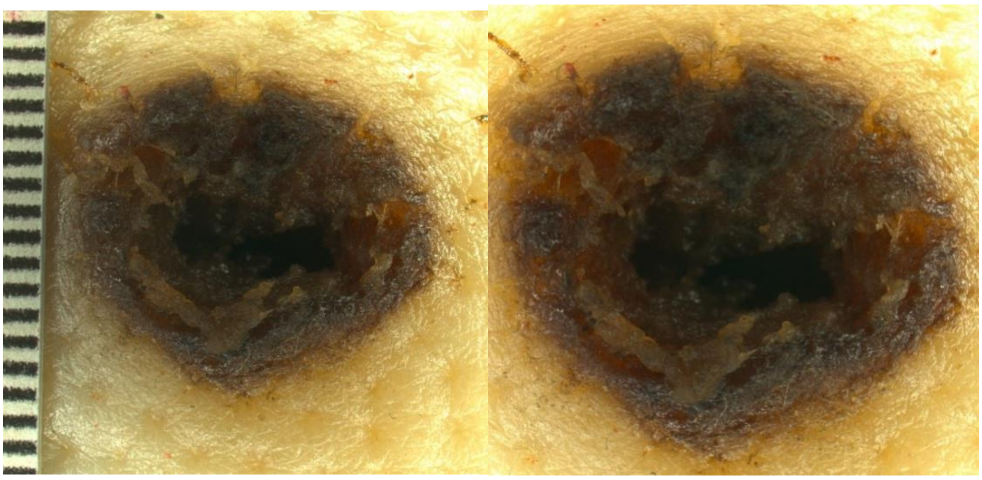
Fig. 3. Microscopic view of Wound № 1, showing the tissue defect and lacerations along the upper edge (the arrows indicate the lacerations and the area of maximum abrasion).

In Wound № 2, the upper edge was serrated due to three linear, superficial lacerations turned upward, while the lower edge was relatively smooth (Fig. 4a). A single, minor superficial laceration extended from each the right and left edges; the wound edges were uniformly abraded around the perimeter, with the maximum width along the upper edge; the walls were nearly vertical and relatively smooth, the lower one more so (Fig. 4b). Stereomicroscopic examination of the wound did not reveal any inclusions.



a b

Fig. 4. General view of the skin fragment with Wound №2 (a) and its microscopic view (b).

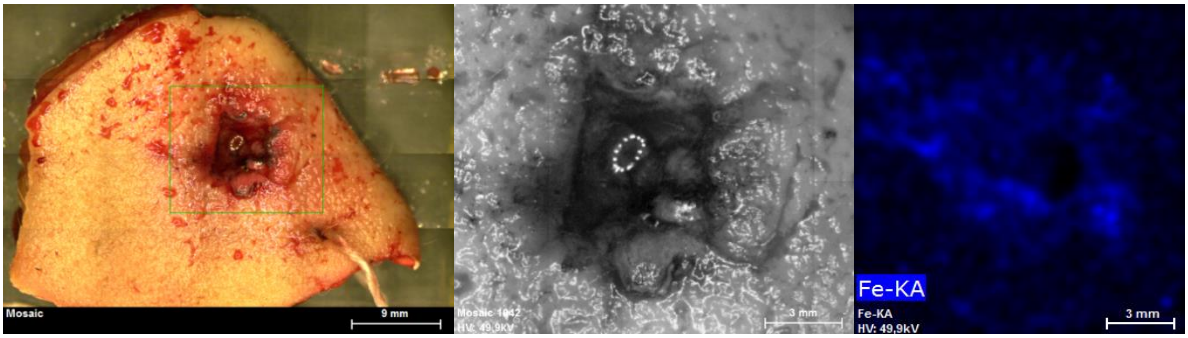


a b

Fig. 5. Microscopic view of Wound № 2, showing the tissue defect and lacerations along the upper edge.

Examination of the wounds on the skin fragments at the extreme ends of the spectrum, using the "Spectroline" UV-400 ultraviolet emitter and the "CCD B/W Camera Model: MTC-5C23B" television camera with a matrix sensitive to infrared radiation, did not reveal any deposits or inclusions in Wounds № 1 and 2 capable of luminescing under ultraviolet light and/or absorbing infrared light.

To identify the elemental composition of the injurious projectile, micro-X-ray fluorescence spectral analysis (XRF) was applied to both skin fragments using a Bruker "M4 TORNADO" spectrometer (Germany). As a result, spectra for the element iron (Fe) were obtained from the scanning area of Wound № 1 (Fig. 6 a, b, c) and Wound № 2 (Fig. 7 a, b, c), both within the damaged areas and in the surrounding regions.

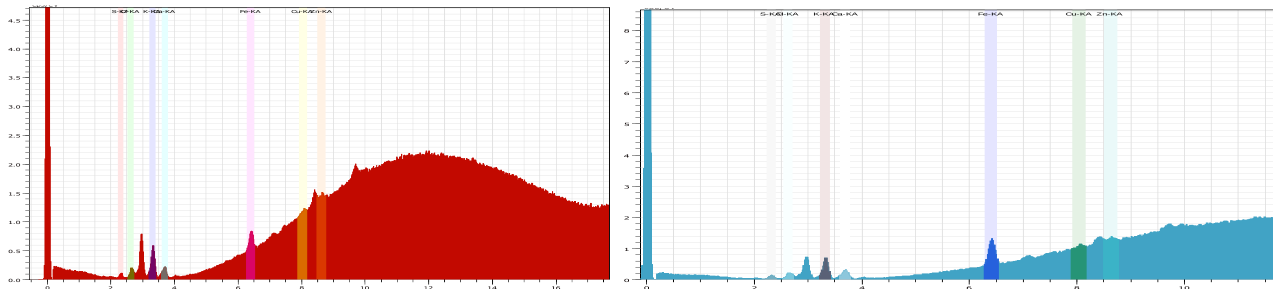


a b c

Fig. 6. Video image of the skin fragment with Wound № 1 (a), its scanning area (b), and the elemental distribution map of the scanning plane showing an elevated content of iron elements along the edges of the injury and in the surrounding area (c).

a b c

Fig. 7. Video image of the skin fragment with Wound No. 2 (a), its scanning area (b), and the elemental distribution map of the scanning plane showing an elevated content of iron elements along the edges of the injury and in the surrounding area (c).



a b

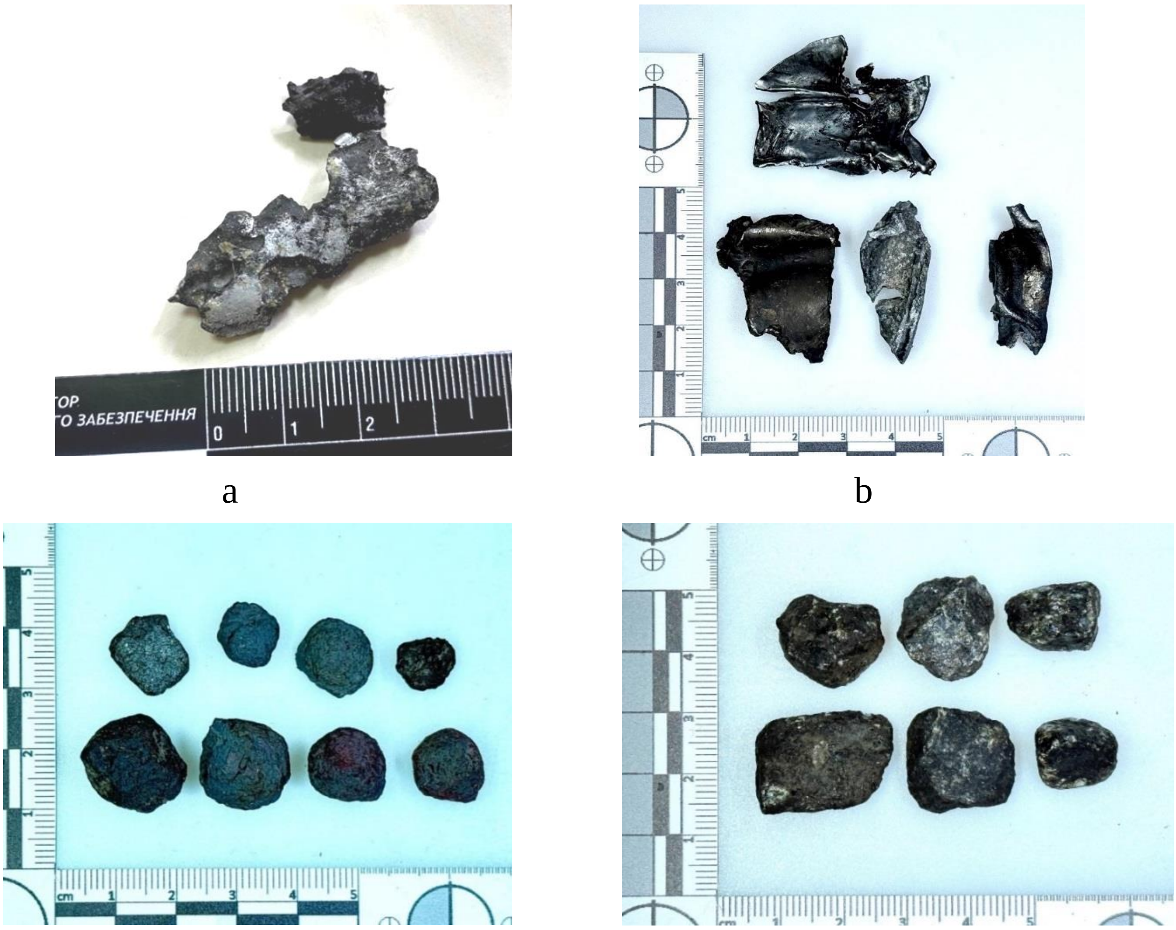
Fig. 8. Spectra of metallic elements from selected areas of the scanning of Wound №1 (a) and Wound №2 (b).

X-ray fluorescence spectral analysis of the wounds revealed the highest quantity of iron elements within the injury areas and their immediate surroundings (Fig. 8).

Consequently, the macro- and microscopic examination of Wounds № 1 and 2 demonstrated that their morphology corresponds to the characteristic features of entry wounds formed by a combined mechanism of action from the penetrating projectiles: perforating (due to the high kinetic energy of the element) and cutting/lacerating (due to the presence of well-defined edges in their configuration). These characteristics match those of the injurious projectiles extracted from the body during the autopsy (Fig. 9a). The study of non-biological objects included three groups: 1) fragments of elongated or polygonal shape with sharp, torn, or serrated edges, recovered from the victim's body (Fig. 9a) and found at the missile explosion site (Fig. 9b); 2) objects of round or irregularly round shape with a smooth surface, measuring from 0.6 to 1.7 cm (Fig. 9c); 3) objects with an unevenly pronounced, polygonal relief, resembling pebbles, sized 1-2 cm or larger (Fig. 9d).

Elemental composition analysis of the surface of the first group of objects – elongated or polygonal fragments from the missile explosion site - using micro-X-ray fluorescence spectral analysis, revealed spectra containing the elements Ca, Ti, Cr, Mn, Ni, Cu, Zn, and Fe. However, the dominant elemental values in these objects varied. For instance, in some, molybdenum (Mo) was predominant at 99.38% (Table 1), while in others, copper (Cu) at 59.60% or nickel (Ni) at 78.74% were dominant.

These qualitative and quantitative indicators provide grounds to conclude that these objects are fragments of the missile's casing or internal components, which were composed of non-ferrous metals.



a b

c d

Fig. 9. Objects recovered from the victim's body (a) and from the missile explosion site (b): elongated or polygonal fragments with sharp, torn, and serrated edges; irregularly rounded objects (c); and objects resembling rectangular pebbles (d).

Table 1

Percentage of detected elements in elongated or polygonal objects

Spectrum:

El	AN	Series	Net	unn. C [wt.%]	norm. C [wt.%]	Atom. C [at.%]	Error (1 Sigma) [wt.%]
Ca	20	K-series	6290	0,21	0,47	1,12	0,00
Fe	26	K-series	15073	0,07	0,15	0,26	0,00
Mo	42	K-series	4207988	44,35	99,38	98,62	0,00
			Total:	44,63	100,00	100,00	

Among the objects of the second group, recovered from the site of the rocket explosion – irregularly rounded in shape, spectra were obtained with almost identical quantitative indicators in percentages: Fe and Ca, of which iron (Fe) accounted for 99.83%, and calcium (Ca) for 0.17% (Fig. 10, Table 2).

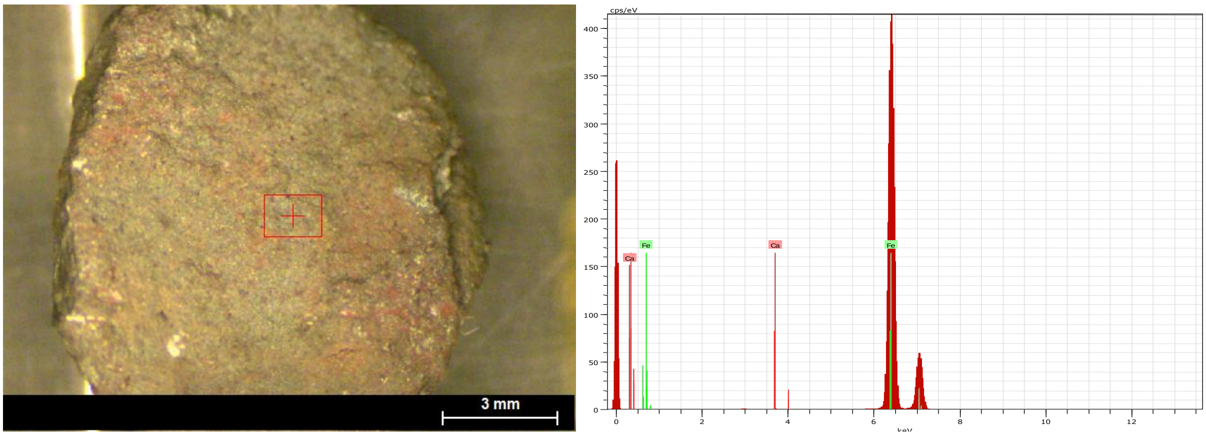


Fig. 10. The object of study (point in the area of maximum peak concentration) and spectrum from the scanning surface.

Table 2

Percentage ratio of elements detected in the composition of the irregularly rounded objects.

Spectrum:

El	AN	Series	Net	unn. C [wt.%]	norm. C [wt.%]	Atom. C [at.%]	Error (1 Sigma) [wt.%]
Ca	20	K-series	7400	0,07	0,17	0,24	0,00
Fe	26	K-series	8627401	40,66	99,83	99,76	0,00
			Total:	40,73	100,00	100,00	

The third group of objects recovered from the site of the rocket explosion, resembling pebbles, contained spectra with almost identical quantitative indicators: K, Al, Si, Ti, Mn, Cu, Zn, Fe, and Ca, of which the largest component was iron (Fe) – 53.41-67.90% (Table 3).

Table 3

Percentage composition of detected elements in polygonal, pebble-like objects

Spectrum:

El	AN	Series	Net	unn. C [wt.%]	norm. C [wt.%]	Atom. C [at.%]	Error (1 Sigma) [wt.%]
Al	13	K-series	412	0,98	3,50	6,30	0,00
Si	14	K-series	3921	1,36	4,86	8,41	0,00
K	19	K-series	2261	0,04	0,14	0,18	0,00
Ca	20	K-series	34797	0,32	1,15	1,40	0,00
Ti	22	K-series	1692257	9,99	35,79	36,30	0,00
Mn	25	K-series	50969	0,28	1,00	0,89	0,00
Fe	26	K-series	3160766	14,90	53,41	46,44	0,00
Cu	29	K-series	462	0,00	0,01	0,01	0,00
Zn	30	K-series	7385	0,04	0,13	0,09	0,00
			Total:	27,90	100,00	100,00	

Therefore, the results of macroscopic examination and micro-X-ray fluorescence spectral analysis of the non-biological objects recovered from the missile explosion site suggest that the items from the first two groups most likely represent components of a ballistic missile, specifically fragments of its casing or internal parts, and cluster munitions. The third group most probably consisted of objects that were secondary projectiles in origin, namely pebbles from the road surface and curbs, formed as a result of the explosion. The presence of iron can be explained by its ionization from these objects during the explosion of the ballistic missile.

Particular attention is drawn to the items of the second group, which were characterized by a predominantly round or irregularly round shape, a smooth surface, and approximately uniform dimensions. Some exhibited deformations and surface flattening; however, the iron (Fe) content in all of them was 99.83%. Consequently, the identity of their size, shape, surface relief, and high iron (Fe) content provide grounds to classify these objects as cluster munitions, similar to shrapnel.

Summarizing the above research results, it can be concluded that both injuries are entry wounds, formed by the action of a blunt, solid object with a limited contact surface (a fragment/element, or piece of an explosive device or secondary projectile) that acted with high kinetic energy, possessing significant penetrating capability. Furthermore, since the wounds had identical morphological features: an irregular oval shape and nearly identical dimensions, an elongated tissue defect, and the highest content of iron (Fe) elements was found within and around the injury areas, there is reason to believe that these specific iron-based objects were the injurious projectiles that caused the victim's fatal injuries.

Discussion. Therefore, the pathomorphology of explosion-related deaths is complex and governed by multiple factors affecting biological objects, primarily the blast wave, high temperatures, and the impact of fragments from both the explosive device itself and secondary projectiles formed during the explosion [16, 17]. These factors manifested as penetrating body wounds, massive tissue defects, traumatic amputations, comminuted fractures, among others [18-21]. In this regard, the results of our own studies on individuals who died as a result of a ballistic missile equipped with cluster munitions are consistent with the data from the authors cited above.

However, to ensure a high-quality forensic investigation and subsequent assessment of the explosion-related cause of death, a comprehensive approach is recommended. This should include not only forensic histology but also X-ray fluorescence spectral analysis [22], and injury assessment using modern optical examination methods [23]. The analysis and identification of the specific injurious agents that directly caused death are also crucial components of this integrated investigation [23-26].

Cusack D, Ferrara SD, Keller E, Ludes B, Mangin P, Väli M et al. [27] posit that successful forensic-medical examination necessitates the use of investigation protocols based on precise post-mortem analysis procedures. Post-mortem virtopsy allows for the acquisition and preservation of information for subsequent evaluations [28]. Furthermore, it provides evidence that can guide the forensic expert during the autopsy of individuals who have died from blast trauma [29, 30].

Conclusions.

1. The forensic medical macroscopic and microscopic examination of injuries resulting from the explosion of a ballistic missile established that they constitute fatal entry wounds. These were inflicted by blunt, solid objects with a limited contact surface, which acted with high kinetic energy and possessed significant penetrating capability. Micro-X-ray fluorescence spectral analysis revealed the highest concentration of iron elements within and surrounding these injuries.

2. Based on their origin, the injurious objects were categorized into three groups:

Group 1: Elongated or polygonal missile fragments with sharp, torn, or serrated edges.

Group 2: Objects of round or irregularly round shape with a smooth surface, measuring from 0.6 to 1.7 cm.

Group 3: Objects with an unevenly pronounced, polygonal relief, resembling pebbles sized 1-2 cm or larger.

These objects could be either components of the explosive device (such as parts of the missile casing/internal components or associated cluster munitions) or secondary projectiles with metallic element deposits on their surfaces.

3. The uniformity in size, shape, surface relief, and the high iron (Fe) content among the objects in the second non-biological group suggest that these were likely cluster submunitions, similar to shrapnel balls.

4. Based on the identical quantitative and qualitative morphological features of both wounds, along with the correlation with the shape and size of the objects in the first non-biological group (missile fragments), there is substantiated reason to conclude that these specific fragments were the injurious projectiles that caused the victim's fatal injuries.

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