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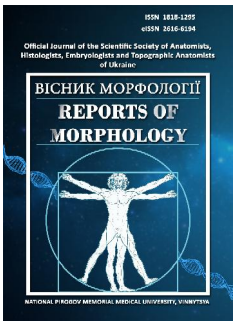

Forensic characteristics of injuries from thermo-baric explosive device

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Since the beginning of the Russian Federation's invasion of Ukraine in 2022, explosive trauma has become an extremely urgent problem, as the main source of bodily injury among both the military in the combat zone and the civilian population in cities has been the impact of explosive devices. The aim of the study is the examination of the forensic characteristics of damage to biological objects that were formed from thermal exposure and shock wave as a result of the explosion of a cumulative munition and in the conditions of an experimental explosion model. The objects of the study were the materials of two examinations on the death of Ukrainian soldiers who died in the war zone (archival "Conclusions of the medical examination" of the Kyiv City Clinical Bureau of Forensic Medical Examination in 2023). Under the conditions of the experiment, studies of pathomorphological changes in the liver and small intestine of 30 white outbred rats from the action of an artificially created air shock wave with an overpressure of 31.62±4.84 kPa were carried out. The injuries were examined macroscopically and using standard laboratory histological techniques. Microscopy of histological sections was performed using an Axio Imager 2 microscope (Zeiss, Germany) at magnifications of x200 and x400. Statistical processing of the obtained quantitative results was carried out using the STATISTICA 6.1 software product. Under the condition of the explosion of the ammunition with the cumulative effect of the rocket-propelled infantry flamethrower "Bumblebee" on sectional incisions of the skin and muscles of the thigh in the projection of areas of redness, a picture of a gelatinous consistency of bright red color was macroscopically determined due to abundant blood impregnation of muscles and subcutaneous fat and partial loss of muscle structure with the release of myoglobin. The bright red color of the skin of the thigh and pelvis without burning the hair may indicate the superficial thermal effect of the explosive device and the protection of the skin by clothing. Diffusely located numerous both paired and single abrasions and shallow wounds, small rounded, oblong, circular in shape, which are the result of fragments of a rocket-propelled grenade equipped with a fire mixture, were also determined. The effect of an air shock wave with an overpressure of 31.62±4.84 kPa on the liver parenchyma of rats was determined by focal hemorrhages with rupture of the terminal central vein of the hepatic lobule, edema of the parasinusoidal spaces, and sludges in the sinusoids. In the wall of the small intestine, acute hemodynamic disorders occurred in the form of vasodilation of arterial vessels, venular and capillary stasis. There was layering and swelling of the small intestine wall, rupture of veins, focal hemorrhage. Thus, the revealed characteristic pathomorphological signs of the destructive effect of overpressure as a result of a blast wave (barotrauma) are typical and common both in the areas of the human thigh and pelvis, and in biological objects of experimental animals. The obtained results are consistent with the pathomorphological manifestations of barotrauma in areas of the human body as a result of the action of an explosive device with a cumulative effect.

Keywords: *forensic medical examination, biological objects, thermo-baric trauma.*

Introduction

Since the beginning of the large-scale invasion of the troops of the Russian federation on the territory of Ukraine in February 2022, the problem of blast-induced trauma has become extremely topical in connection with the use by the enemy of a significant arsenal of explosive devices such as grenades, artillery shells, aerial bombs, rockets, etc. According to the head of the Main Directorate of Mine Action, Civil Protection and Environmental Safety of the Ministry of Defense of Ukraine, since the beginning of the invasion of the russian federation in Ukraine, 950 people have been injured by explosive objects, of which 289 have been killed and 661 have been injured [2].

An explosion is a rapid release of energy due to the action of physical, chemical, nuclear processes with the expansion of the initial explosive substance or products and the formation of extremely high pressure [17]. The damaging and traumatic factors of an explosion are its products (a wave of explosive gases, particles of an explosive substance, soot from an explosion), a shock and sound wave, fragments and particles of explosives, special striking objects (mechanical, chemical, thermal), secondary projectiles [7]. In the literature, considerable attention is paid to morphological changes in biological objects under the influence of fragments and parts of explosive devices that have significant kinetic energy and penetrating ability [23, 24, 30]. It should be noted that the powerful damaging effect of explosive devices is also realized due to the thermo-baric effect, and the shock wave, which acts on the human body as a blunt solid object, accounts for 70 % of the energy of the explosion [25]. As a result, extensive damage to the outer coverings of the body and internal organs, detachment of limbs, parts of the body, and with lower power, barotrauma of the ear, contusion of the lungs, and other internal organs occurs [9, 27]. In a number of clinical and pathomorphological studies based on macro- and microscopic, immunohistochemical, morphometric and microelemental changes, it was found that the brain, lungs, intestines, bladder, and kidneys are the most sensitive to the action of the blast wave in the human body [14, 31].

The severity of damage to these organs is influenced by the distance from the epicenter of the explosion to the biological object, the power of the explosion, the presence of obstacles, the peculiarities of the body position, the presence of protective equipment [7, 11].

Thus, at the time of our research, a whole series of literature information is already known, in which the clinical, pathomorphological and pathogenetic traumatic and post-traumatic processes, as well as changes in internal organs after exposure to a shock wave, are sufficiently fully covered. However, some issues related to the morphological features and the mechanism of action of the blast wave on biological objects with thermo-baric effect remain insufficiently elucidated and require further research.

The aim of the study is the examination of the forensic characteristics of damage to biological objects that were formed from thermal exposure and shock wave because of the explosion of a cumulative munition and in the conditions of an experimental explosion model.

Materials and methods

The material of the study was "Conclusions of a medical expert examination" from the archive of the Kyiv City Clinical Bureau of Forensic Medical Examination, which related to 2 cases of death of servicemen in the combat zone from explosive devices, in particular, from the reactive infantry flamethrower "Bumblebee", which is a thermobaric reactive grenade. equipped with a fire mixture (Fig. 1). Studies in forensic medicine were performed in accordance with current Ukrainian legislation, in particular Order No. 6 of the Ministry of Health from 1995 [22].

In addition, in order to increase the objectivity of study, an experiment was conducted, namely, studies of pathomorphological changes in the liver and small intestine of purebred white rats weighing 177.5±15.8 g as a result of the action of an artificially created air shock wave with an excess pressure of 31.62±4.84 kPa. The generation of the shock wave was carried out on a self-made device. The animals were kept in the vivarium of the Dnipro State Medical University. During the study we followed the requirements of the "General Ethical Principles of Animal Experiments" adopted by the Fifth National Congress on Bioethics (Kyiv, 2013), the recommendations of the European Convention for the Protection of Vertebrate Animals (Strasbourg, 2005), and the Law of Ukraine "On the Protection of Animals from harsh treatment". The work was approved at a meeting of the Commission on Bioethics of Dnipro State Medical University (Protocol № 12 dated October 23, 2024). All animals (n=30) were randomly divided into three groups: 1 group consisted of intact rats (n=6), 2 - control (halothane anesthesia with fixation) (n=12), 3 (n=12) - experimental animals (halothane anesthesia with fixation, traumatic single action of an air shock wave with excess pressure 31.62±4.84 kPa). The objects for the study were fragments of the liver and intestine of 30 male rats, which were removed on the first day of the post-traumatic period after euthanasia of the animals (decapitation under halothane anesthesia). The pieces were fixed in a 10 % solution of neutral formalin (pH 7.4) with exposure for 24 hours. The samples were then dehydrated in increasing concentrations of ethanol, cleared

Fig. 1. Jet infantry flamethrower "Bumblebee" of Soviet production (Wikipedia).

Table 1. Point assessment of signs of traumatic injuries.

Morphological sign		Characteristics of the sign	Point assessment
1	Post-traumatic hemorrhages	absent in all fields of vision	0
		diapedesis hemorrhages	1
		small focal hemorrhages	2
		large focal hemorrhages	3
2	Intratissue traumatic ruptures of layers, membranes, vessels	absent in all fields of vision	0
		tears in the walls of capillaries, venules	1
		ruptures of arterioles, interstitial tears	2
		multiple tears of all tissue components	3
3	Expression of post-traumatic edema	absent in all fields of view	0
		moderate perivascular edema	1
		foci of perivascular and pericellular edema	2
		widespread perivascular and pericellular edema	3
4	Alterative post-traumatic cell changes	there are no signs of irreversible cell changes	0
		necrosis, apoptosis	2

in xylene, and embedded in paraffin. After that, the paraffin-soaked fragment of soft tissues was embedded in paraffin blocks, from which serial sections with a thickness of no more than 4 μm were obtained using a Thermo HM 355S microtome (Thermo Scientific, Germany). Sections of each tissue sample were used for general histological tissue staining with hematoxylin and eosin. Before staining, sections were deparaffinized in xylene, rehydrated in descending (100, 95, 70 %) concentrations of ethanol and placed in Bouin's fluid (10 % formalin in saturated picric acid solution) for additional fixation to enhance nuclear staining for 1 hour. Then samples were dehydrated in increasing concentrations of alcohol, clarified in xylene and placed in the final medium under coverslips glasses. Microscopy of histological sections was carried out using an Axio Imager 2 microscope (Zeiss, Germany) at magnifications of x100, x200 and x400. In each group, based on the results of histological examination of the liver and small intestine, the integral index of traumatic injury was calculated in accordance with Table 1.

Mathematical and statistical processing of the obtained quantitative results was carried out using the software product STATISTICA 6.1 (StatSoftInc., serial number AGAR909E415822FA), Excel program (Microsoft Office, USA). The significance of differences between groups was assessed using the Mann-Whitney U-test for a confidence level of at least 95 %, ($p<0.05$).

Results

Macroscopically, redness of the skin of a local nature was detected - areas of the outer and inner surfaces of the right and left thigh, as well as the pelvic area (Fig. 2). They were bright red in color with no hair burning, which may indicate superficial thermal effects and skin protection by clothing. In addition, diffusely located numerous both paired and single abrasions and shallow wounds, small in size of rounded, oblong, circular shape (see Fig. 2), which were the result of the action of fragments of a rocket-propelled grenade, were determined. On the sections of the skin and muscles of the thigh in the projection of areas of redness, macroscopically, there was blood impregnation of muscles and subcutaneous fat, as well as a partial loss of muscle structure, presumably with the release of myoglobin, which gave them a state of gelatinous consistency of bright red color (Fig. 3).

Microscopic qualitative analysis of histological sections of the liver and intestine of rats exposed to an air shock wave revealed a number of structural changes at both the cellular and tissue levels. In most of the studied objects of the liver, typical changes were damage of the vascular system. Thus, in the liver of experimental rats, at the border of media of different densities, small focal hemorrhages occurred as a result of rupture of microvessels, ruptures of the terminal central vein of the hepatic lobule. The endotheliocytes of the sinusoidal capillaries thinned and acquired a spindle-like shape, the parasinusoidal spaces expanded, the sinusoidal capillaries in this part of the liver

Fig. 2. Local redness of the skin of the outer and inner surfaces of thigh after the action of a thermobaric reactive grenade equipped with a fire mixture.

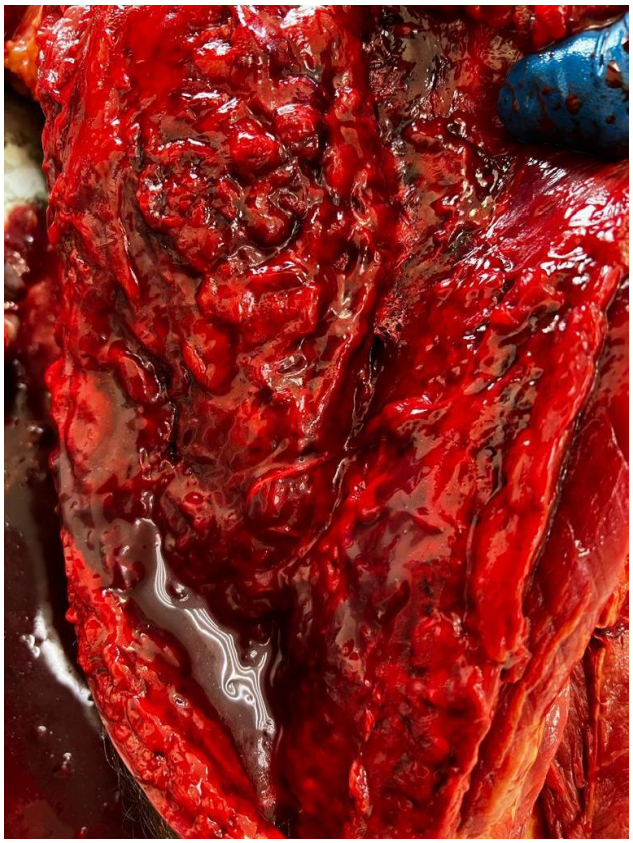

Fig. 3. Macropreparation. Blood seepage of the muscles and subcutaneous fatty tissue of the right and left thigh areas after the action of a thermobaric reactive grenade equipped with a fire mixture.

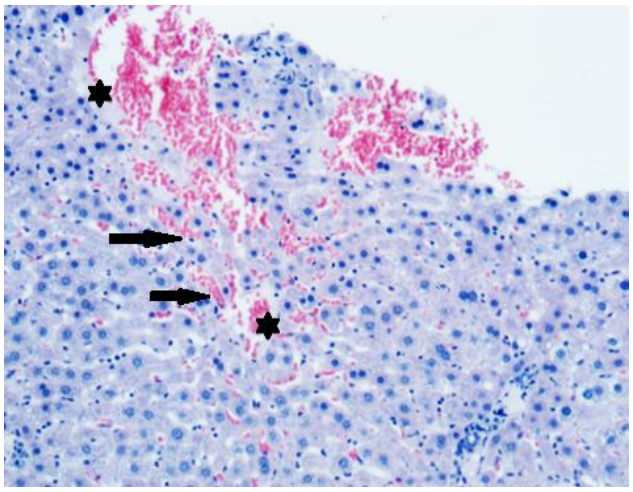

Fig. 4. Focal hemorrhages with rupture of the terminal central vein of the hepatic lobe (asterisks), swelling of the parasinusoidal spaces and sludge in the sinusoids (arrows) of the rat liver after exposure to an air shock wave. Hematoxylin and eosin staining. x100.

were empty (Fig. 4). The nuclei of the endothelial cells of the sinusoidal capillaries in some places protruded into the lumen of the sinusoids, which were full of blood with the phenomena of sludge syndrome. The lumen of the interlobular veins was increased compared to the control and intact groups. Inflammatory infiltrates with polymorphonuclear leukocytes formed around the interlobular vessels. Individual hepatocytes were destroyed, the swelling of stromal components grew rapidly, the sizes of parasinusoidal and periportal spaces increased.

The intercellular spaces increased not only in the area of the lateral but also the apical surfaces of hepatocytes. There were areas with a violation of the beam structure of the liver lobules with focal small foci of parenchymal destruction.

Acute hemodynamic disturbances in the form of vasodilatation of arterial vessels, venular and capillary

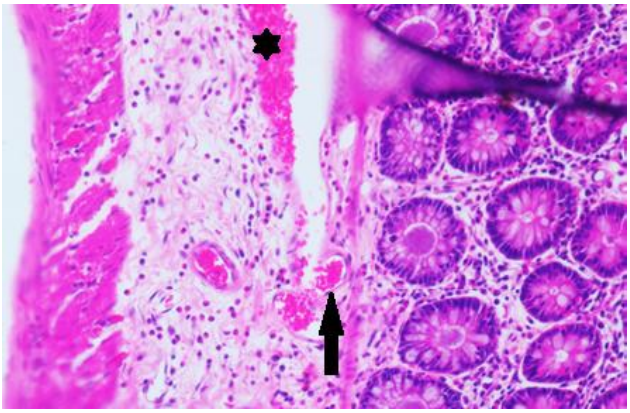

Fig. 5. Layering and swelling of the wall of the small intestine of a rat. Rupture of venules (asterisk). Focal hemorrhage (arrow). Hematoxylin and eosin staining. x100.

Table 2. The results of calculating the integral indicator of traumatic damage to the liver and small intestine (M±σ).

Characteristics of groups	Integral indicator of damage, conventional units
Control, liver	1.672±0.490
Experiment, liver	4.830±1.113*
Control, small intestine	1.834±0.391
Experiment, small intestine	5.421±1.440**

Notes: * - differences with the corresponding control group are statistically significant ($p<0.01$); ** - differences with the corresponding control group are statistically significant ($p<0.01$).

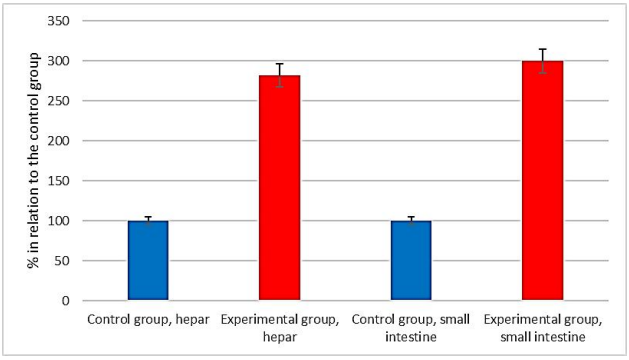

Fig. 6. The effect of shock airwave on changes in the integral index of damage to the liver and small intestine of rats in the experiment.

stasis also occurred in the wall of the small intestine on the background of alterative changes (Fig. 5). Hemodynamic disturbances were accompanied by an increase in the edematous component. There were delamination and swelling of the intestinal wall, rupture of a vein, focal hemorrhage.

The calculation of the integral indicator of traumatic damage to the liver and small intestine showed significant changes in comparison with the control group (Table 2, Fig. 6).

Discussion

Therefore, as a result of the conducted research, a pronounced destructive effect on the biological objects of the human body (regions of the thigh and pelvis) and experimental animals (liver and small intestine of rats) of the shock wave with excess pressure, which was formed as a result of the explosion of ammunition with a cumulative effect, was revealed as well, as after the action of the experimental model of the explosive device. The explosion of the rocket-propelled infantry flamethrower "Bumblebee" is accompanied by the formation of very compressed, high-temperature gas jets, which penetrate at high speed into a room, vehicle, or other space, forming overpressure and high temperature. Overpressure creates a shock wave that acts on biological objects like a blunt object. Its short-term pulsed, centripetal and unilateral action can last from 0.1 to 0.001 seconds, causing a variety of injuries: from abrasions and bruises to the separation of body parts, and the thermal effect is accompanied by the formation of skin burns of varying degrees. In both cases, the blast wave acted on biological objects as a blunt object, the main mechanism of which was the shock, which was accompanied by the destruction of the vascular bed, thigh muscles, liver parenchyma and small intestine. The thermal effect of the ammunition with a cumulative effect was accompanied by skin burns.

As it turns out from the literature, the use of explosive devices is a fairly common negative form of impact on the health and life of people, ranging from suicides [26, 29], to accidents [18, 20] and terrorist attacks [8, 12]. They are most common in military conflicts [1, 25]. It should be noted that since February 2022, over the past three years, in the context of the armed conflict on the territory of Ukraine, the hot phase of hostilities has been going on, the victims of which are both military personnel and civilians. At the same time, the number of victims is constantly increasing, and the dominant lesions are blast trauma, which is accompanied by bodily injuries of varying severity, high-risk somatic and mental illnesses [3, 28].

Practice has shown that explosive devices, such as grenades, mines and others, have both a blast wave and penetrating shrapnel wounds, and the severity of injuries in a mine-blast wound depends on the location of a person at the time of the explosion, which coincides with the opinion of Kalebi A. Y. and Olumbe A. K. [19], Chopna V. V. et al. [5], as well as the authors Christensen A. M. and Smith V. A. [6]. The obtained own data on numerous paired and single abrasions and wounds of the skin of small sizes of rounded, oblong, circular shape, as well as the bright red color of the skin of the thigh and pelvis, which were the result of the action of fragments of a rocket-propelled grenade equipped with a fire mixture, correspond to the features of injuries given in the literature [9, 13, 15].

During the explosion of the rocket-propelled infantry flamethrower "Bumblebee", a shock wave was formed, with a short-term pulse, centripetal and unilateral effect on the body or part of the human body as a blunt object. The consequences of such a destructive effect on the areas of the thigh and pelvis were the loss of the integrity of the vascular bed and the impregnation of muscles and subcutaneous fat with blood, as well as a partial loss of muscle structure, which generally gave them a gelatinous consistency of bright red color. Manifestations of the destructive effect of overpressure as a result of a blast wave (barotrauma) were also typical on biological objects of experimental animals.

In general, the results obtained by us regarding the destructive effect of a blast wave with a thermal effect on biological objects are original and consistent with the data of known literature sources [4, 10, 17, 25].

The microscopically changes in the liver and small intestine identified and evaluated by us after exposure to an airborne shock wave under experimental conditions are generally consistent with the experimental results of other researchers [16, 21], but there are still debates about the degree and duration of reactive changes in parenchymal-stromal and vascular elements, which may be of significant importance in determining the age of the damage.

Conclusions

1. The established pathomorphological signs of the destructive effect of overpressure as a result of a blast wave (barotrauma) were typical and common both in the areas of the human hip and pelvis, and in biological objects of experimental animals. In particular, during the explosion of ammunition with a cumulative effect of the rocket infantry flamethrower "Bumblebee" on sectional incisions of the skin and muscles of the thigh in the projection of areas of redness, a picture of a gelatinous consistency of bright red color was macroscopically determined due to abundant blood impregnation of muscles and subcutaneous fat and partial loss of muscle structure, with the release of myoglobin.

2. The bright red color of the skin of the thigh and pelvis without burning the hair may indicate the superficial thermal effect of the explosive device and the protection of the skin by clothing.

3. The effect of an air shock wave with an excess pressure of 31,62±4,84 kPa on the liver parenchyma of rats was primarily determined by destructive changes in its vascular system, namely, focal hemorrhages with

rupture of the terminal central vein of the hepatic lobe, swelling of the parasinusoidal spaces, sludge in the sinusoids. In the wall of the small intestine, there were acute hemodynamic disturbances in the form of vasodilatation of arterial vessels, venular and capillary stasis, delamination and swelling of the intestinal wall, rupture of veins, focal hemorrhage. And all this is consistent with the pathomorphological manifestations of barotrauma on parts of the human body as a result of the action of an explosive device with a cumulative effect.

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СУДОВО-МЕДИЧНА ХАРАКТЕРИСТИКА УШКОДЖЕНЬ ВІД ТЕРМОБАРИЧНОЇ ДІЇ ВИБУХОВОГО ПРИСТРОЮ

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З початку вторгнення російської федерації на територію України у 2022 р., вибухоіндукована травма стала надзвичайно актуальною проблемою, оскільки основним джерелом тілесних ушкоджень як серед військових в зоні бойового зіткнення, так і цивільного населення в містах, стала дія вибухових пристроїв. Мета роботи - вивчення судово-медичної характеристики ушкоджень біологічних об'єктів, які утворились від термічного впливу та ударної хвилі внаслідок вибуху боєприпасу з кумулятивною дією та в умовах експериментальної моделі вибуху. Об'єктами дослідження були матеріали двох експертиз з приводу смерті українських військових, які загинули в зоні бойових дій (архівні "Висновки експертного дослідження" Київського міського клінічного бюро судово-медичної експертизи за 2023 р.). В умовах експерименту були проведені дослідження патоморфологічних змін печінки та тонкої кишки 30 білих безпородних щурів від дії штучно створеної повітряної ударної хвилі з надлишковим тиском 31,62±4,84 кПа. Ушкодження досліджували макроскопічно та за допомогою стандартних лабораторних гістологічних методик. Мікроскопію гістологічних зрізів проводили за допомогою мікроскопу Axio Imager 2 (Zeiss, Німеччина) на збільшеннях х200 та х400. Статистичну обробку отриманих кількісних результатів проводили за допомогою програмного продукту STATISTICA 6.1. За умови вибуху боєприпасу з кумулятивною дією реактивного піхотного вогнемету "Джміль" на секційних розрізах шкіри і м'язів стегна в проекції ділянок почервоніння макроскопічно визначалась картина драглистої консистенції яскраво-червоного кольору за рахунок рясного просочування кров'ю м'язів і підшкірно жирової клітковини та часткової втрати структурованості м'язів із виходом міоглобіну. Яскраво-червоний колір шкіри стегна і таза без обгоряння волосся може свідчити про поверхневу термічну дію вибухового пристрою та захист шкіри одягом. Також визначались дифузно розташовані чисельні як парні, так і поодинокі садна та неглибокі рани, невеликих розмірів округлої, довгастої, циркулярної форми, які є наслідком дії уламків реактивної гранати, спорядженої вогневою сумішшю. Вплив повітряної ударної хвилі з надлишковим тиском 31,62±4,84 кПа на паренхіму печінки щурів визначався вогнищевими крововиливами з розривом кінцевої центральної вени печінкової часточки, набряком парасинусоїдальних просторів та сладжами в синусоїдах. У стінці тонкої кишки відбувалися гострі порушення гемодинаміки у вигляді вазодилятації артеріальних судин, венулярного та капілярного стаза. Мали місце розшарування та набряк стінки кишки, розрив вен, вогнищевий крововилив. Таким чином, виявлені характерні патоморфологічні ознаки руйнівної дії надлишкового тиску внаслідок вибухової хвилі (баротравми) є типовими і загальними як на ділянках стегна і таза людини, так і на біологічних об'єктах експериментальних тварин. Отримані результати узгоджуються з патоморфологічними проявами баротравми на ділянках тіла людини в результаті дії вибухового пристрою з кумулятивною дією.

Ключові слова: *судово-медична експертиза, біологічні об'єкти, термобарична травма.*

Author's contribution

Mykhaylenko O. V. - conceptualization, research, review writing and editing.
Mishalov V. D. - project administration, research, methodology and writing of the original draft, formal analysis and validation.
Kozlov S. V. - data visualization.
Varfolomeiev Y. A. - software, resources.