ORIGINAL ARTICLES

PULSED WIDE-SPECTRAL PHOTOTHERAPY OF SOFT TISSUE GUNSHOT WOUNDS

Bagrov V.V.[1], Bobin A.N.[2], Bobylev V.A.[2], Volodin L.Y.[1], Davydov D.V.[2,3], Kamrukov A.S.[1], Kondratiev A.V.[1], Nesterova M.V.[2], Pecherskaya M.S.[2], Fateev A.V.[2], Shchedrina M.A.[2], Esaulenko N.B.[2]

[1]Bauman Moscow State Technical University (National Research University), Moscow, Russia
[2]Main Military Clinical Hospital named after Academician N.N. Burdenko of the Ministry of Defense of the Russian Federation, Moscow, Russia
[3]Patrice Lumumba Peoples' Friendship University of Russia, Moscow, Russia

Abstract

A new method has been proposed for the treatment of gunshot wounds complicated by nosocomial microflora. The method is based on the treatment of wounds with high-intensity pulsed optical radiation of a continuous spectrum in the wavelength range from 200 to 1100 nm. A pulsed xenon lamp is used as a radiation source. The effect of high-intensity pulsed wide-spectrum optical radiation and low-intensity continuous UV radiation with a maximum at a wavelength of 272 nm and a half-width of the spectrum of 12 nm on the course of the wound process in a gunshot injury was compared. It has been shown that the effect of such radiation on tissues with signs of purulent-inflammatory process provides an antibacterial effect and stimulates tissue regeneration. At the same time, high-intensity wide-spectral optical radiation has a more pronounced anti-inflammatory effect and contributes to the earlier development of tissue regeneration compared with low-intensity narrow-spectrum UV radiation. However, the use of high-intensity optical radiation requires an individual dosage for each phase of the wound process.

Keywords: pulsed wide-spectrum phototherapy, gunshot wound, optical radiation, antibacterial effect, tissue regeneration

Contacts: Kamrukov A.S., e-mail: kamrukov@bmstu.ru

For citations: Bagrov V.V., Bobin A.N., Bobylev V.A., Volodin L.Y., Davydov D.V., Kamrukov A.S., Kondratiev A.V., Nesterova M.V., Pecherskaya M.S., Fateev A.V., Shchedrina M.A., Esaulenko N.B. Pulsed wide-spectral phototherapy of soft tissue gunshot wouds, *Biomedical Photonics*, 2025, vol. 14, no. 1, pp. 20–28. doi: 10.24931/2413–9432–2025–14–1–20–28

ИМПУЛЬСНАЯ ШИРОКОСПЕКТРАЛЬНАЯ ФОТОТЕРАПИЯ ОГНЕСТРЕЛЬНЫХ РАН МЯГКИХ ТКАНЕЙ

В.В. Багров[1], А.Н. Бобин[2], В.А. Бобылев[2], Л.Ю. Володин[1], Д.В. Давыдов[2,3], А.С. Камруков[1], А.В. Кондратьев[1], М.В. Нестерова[2], М.С. Печерская[2], А.В. Фатеев[2], М.А. Щедрина[2], Н.Б. Эсауленко[2]

[1]Московский государственный технический университет имени Н.Э. Баумана (национальный исследовательский университет), Москва, Россия
[2]Главный военный клинический госпиталь имени академика Н.Н. Бурденко Министерства обороны Российской Федерации, Москва, Россия
[3]Российский университет дружбы народов им. Патриса Лумумбы, Москва, Россия

Резюме

Предложен новый метод для лечения огнестрельных ран, осложненных контаминацией нозокомиальной микрофлорой. Метод основан на обработке ран высокоинтенсивным импульсным оптическим излучением сплошного спектра в диапазоне длин волн от 200 до 1100 нм. В качестве источника излучения используется импульсная ксеноновая лампа. Проведено сравнение влияния на течение раневого процесса при огнестрельной травме высокоинтенсивного импульсного широкоспектрального оптического излучения и низкоинтенсивного непрерывного УФ излучения с максимумом на длине волны 272 нм и полушириной спектра 12 нм. Показано, что воздействие таких излучений на ткани с признаками гнойно-воспалительного процесса обеспечивает антибактериальный эффект и стимулирует регенерацию тканей. При этом высокоинтенсивное широкоспектральное оптическое излучение обладает более выраженным противовоспалительным действием и способствует более раннему развитию регенерации тканей по сравнению с низкоинтенсивным УФ излучением узкого спектра. Однако применение высокоинтенсивного оптического излучения требует индивидуальной дозировки для каждой фазы раневого процесса.

Ключевые слова: импульсная широкоспектральная фототерапия, огнестрельная рана, оптическое излучение, антибактериальный эффект, регенерация тканей.

Контакты: Камруков А.С., e-mail: kamrukov@bmstu.ru

Для цитирования: В.В. Багров, А.Н. Бобин, В.А. Бобылев, Л.Ю. Володин, Д.В. Давыдов, А.С. Камруков, А.В. Кондратьев, М.В. Нестерова, М.С. Печерская, А.В. Фатеев, М.А. Щедрина, Н.Б. Эсауленко. Импульсная широкоспектральная фототерапия огнестрельных ран мягких тканей // Biomedical Photonics. – 2025. – Т. 14, № 1. – С. 20–28. doi: 10.24931/2413–9432–2025–14–1–20–28

Introduction

In modern medicine, one of the issues that remains extremely relevant is the search for methods that increase the effectiveness of local treatment of wounds of various etiologies [1, 2]. This problem has acquired particular significance in connection with the increase in the number of military conflicts and terrorist attacks [3, 4, 5]. In case of gunshot injury, complex pathomorphological processes occur in the body [6]. Polyorganic structural disorders and functional changes resulting from tissue damage and metabolic imbalance combined with inevitable bacterial contamination of gunshot wounds create conditions that increase the incidence of infectious complications in wounded patients by 5-6 times compared with surgical patients [7, 8, 9, 10].

One of the causes of complications due to gunshot wounds are pathogens of nosocomial infections (*S.aureus, P.aeruginosa, E.coli, Klebsiella spp., etc.*), the etiological significance of which has increased significantly in recent years [8]. A distinctive feature of hospital microflora is polyresistance to antibacterial drugs and increased virulence of opportunistic pathogens with relatively low pathogenicity (for example, *Acinetobacter spp.*) against the background of reduced reactivity of the body and inhibition of the reparative regeneration process [6].

In these conditions, it is rational to use technologies that allow simultaneous action on various pathogenetic links of the wound process. For this purpose, various methods of local wound treatment have been proposed: chemical, biological, physical and reconstructive-plastic [11].

Active study and development of physical methods of influencing wounds, in particular, optical radiation of various spectral ranges [12, 13], are due to the prospect of their use for targeted regulation of wound process phases. The experimental data available today indicate high efficiency of the biocidal action of high-intensity pulsed optical radiation of a wide spectrum [14, 15, 16, 17]. However, the issue of its effect on reparative tissue regeneration in the area of a gunshot wound is currently insufficiently studied, which complicates the development of new approaches to the treatment of acquired infected defects of soft tissues.

The aim of this work was to study the efficiency of high-intensity pulsed optical radiation of a continuous spectrum in the wavelength range of 200-1100 nm as a new physical factor on the course of the wound process in the treatment of gunshot infected defects of soft tissues and its comparison with the wound healing effect of continuous low-intensity UV radiation.

Materials and methods

Characteristics of the research object

The object of the study were 30 sexually mature male Wistar rats weighing 390±10 g. The animals were kept under standard vivarium conditions in individual cages with free access to food and water. The experiments were conducted in accordance with international and national legislation on compliance with the principles of humane treatment of animals. Permission to conduct the study was obtained from the Independent Ethics Committee of the Burdenko Main Military Clinical Hospital of the Ministry of Defense of the Russian Federation.

Anesthetic support

All manipulations with animals were performed under general anesthesia. The main anesthetic used was Zoletil®100 (VIRBAC, France) (5 mg/kg of animal weight), approved for use in the Russian Federation.

Modeling of an infected gunshot wound

The development and creation of a model of gunshot injury were implemented in the conditions of shooting range of the 111th Main State Center for Forensic and Criminalistic Examinations of the Ministry of Defense of the Russian Federation.

After induction into anesthesia, fixation of the animal in a specially designed device (Fig. 1) and topographic marking

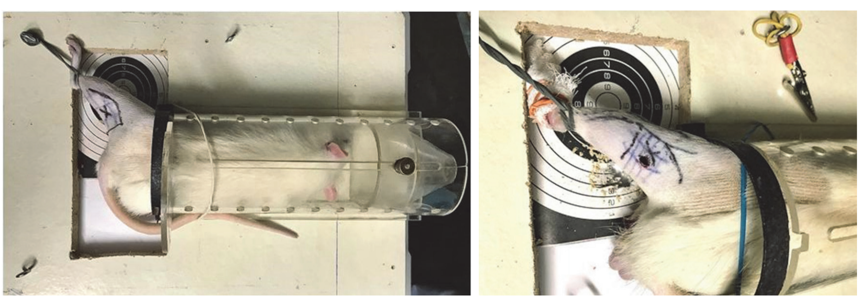

Рис. 1. Формирование модели огнестрельного ранения.
Fig. 1. Formation of a model of a gunshot wound.

Таблица
Распределение животных по группам в зависимости от характера воздействия на сформированную огнестрельную рану

Table
The distribution of animals into groups depending on the nature of the impact on the formed gunshot wound

Группы животных Groups of animals	Вид воздействия на раневую поверхность Type of impact on the wound surface	Количество животных Number of animals
I	Огнестрельная рана (группа I) Gunshot wound (group I)	6
II	Инфицированная огнестрельная рана (контрольная группа II) An infected gunshot wound (control group II)	8
III	Инфицированная огнестрельная рана + высокоинтенсивное импульсное оптическое излучение широкого спектра (аппарат «Зарница-А»). **Параметры облучения:** спектральный диапазон – Δλ=200-1100 нм; энергетическая доза облучения – 1,5 Дж/см^2; доза в УФ-С диапазоне (Δλ=200-280 нм) – 0,15 Дж/см^2; импульсная облученность раны ~200 Вт/см^2; режим воздействия – импульсно-периодический. Infected gunshot wound + high-intensity pulsed optical radiation of a wide spectrum (Zarnitsa-A device) **Irradiation parameters:** spectral range – Δλ=200-1100 nm; energy dose of radiation – 1.5 J/cm^2; the dose in the UV-C range (Δλ=200-280 nm) – 0.15 J/cm^2; the pulse irradiation of the wound ~200 W/cm^2; the exposure mode – pulse-periodic.	8
IV	Инфицированная огнестрельная рана + низкоинтенсивное непрерывное УФ излучение узкого спектра (аппарат «Зарница-Д») **Параметры облучения:** спектральный диапазон λ=272±6 нм; энергетическая доза облучения – 0,29 Дж/см^2; доза в УФ-С диапазоне – 0,23 Дж/см^2; облученность раны ~4 мВт/см^2; режим воздействия – непрерывный. Infected gunshot wound + low-intensity continuous narrow-spectrum UV radiation (Zarnitsa-D device) **Irradiation parameters:** spectral range – λ=272±6 nm; the energy dose of radiation – 0.29 J/cm^2; the dose in the UV-C range – 0.23 J/cm^2; the irradiation of the wound ~4 mW/cm^2; the exposure mode – continuous.	8
	Всего лабораторных животных: Total laboratory animals:	30

of the main anatomical structures located in the area of the back of the left thigh on the skin, each animal received one penetrating gunshot bullet wound. The weapon used was a small-caliber rifle CZ 452-2E ZKM (made in the Czech Republic) with Standard cartridges of 22 caliber (bullet with a diameter of 5.66 mm and a weight of 2.6 g). The rifle was placed in a specialized fixing machine for small arms. The shot was fired from a distance of 1.0 m. The muzzle velocity of the bullet was 320 m/sec; kinetic energy – 133 J.

Depending on the nature of the subsequent impact on the gunshot wound, all animals were divided into four groups (table). In three groups of animals (groups II, III and IV), 2 hours after the gunshot wound, the wounds were infected once with a suspension of *Klebsiella pneumoniae* and *Acinetobacter baumannii* bacteria. In group I, the gunshot wound was not artificially infected.

Equipment for experiments on remote exposure of wounds to optical radiation

Prototypes of phototherapeutic devices of two types were used in the study [1]:

- a high-intensity pulsed optical irradiation device "Zarnitsa-A" based on a pulsed xenon lamp generating continuous spectrum radiation in the wavelength range from 200 to 1100 nm [15, 16];
- a LED device "Zarnitsa-D" providing irradiation of wounds with low-intensity continuous UV radiation of a narrow spectrum with a spectral band width of 12 nm and a maximum at a wavelength of 272 nm [18] (this device can be considered a modern analogue

[1] The Zarnitsa-A and Zarnitsa-D devices were developed and manufactured at the Research Institute of Power Engineering of the Bauman Moscow State Technical University.

of traditional medical devices based on low-pressure mercury lamps).

The Zarnitsa-A device uses a compact pulsed xenon lamp PPF2-5/60 (manufactured by Rider LLC, Russia) with an internal diameter of the quartz shell of 5 mm and an interelectrode gap length of 60 mm, the initial xenon pressure in the lamp is 400 mm Hg. The lamp shell is made of high-quality quartz glass with transmission in the UV region at wavelengths of λ = 210-400 nm of more than 80%. The lamp is mounted on the axis of a conical aluminized reflector with an output quartz window with a light diameter of 50 mm. The average electric power of the lamp is 100 W at a pulse repetition rate of 5 Hz and their duration of ~ 20 µs.

The wound surface was irradiated daily for 21 days, starting from the first day after infection. Before irradiation, the wound was cleaned of necrotic tissue, fibrin and dried.

Irradiation parameters

The Zarnitsa-A device was used to treat gunshot wounds at a distance of 10 cm from the irradiator to the wound surface with a wound irradiation duration of 60 s. The total dose of UV-C radiation (Δλ = 200-280 nm) per irradiation cycle (60 s) was 0.15 J/cm^2; in the integral radiation spectrum (Δλ = 200-1100 nm) ~1.5 J/cm^2 (in the center of the light spot); the diameter of the irradiation zone (light spot) at the half-intensity level was 5 cm. The density of the pulsed power of optical radiation on the object (irradiance) was ~200 W/cm^2.

When irradiating gunshot wounds with the Zarnitsa-D device, the distance from the irradiator to the wound surface was 2 cm; duration of the procedure (1 cycle) of wound irradiation was 72 s; total dose of UV radiation (Δλ= 272±6 nm) per 1 irradiation cycle was 0.29 J/cm^2 (UV-C dose – 0.23 J/cm2), diameter of the irradiation zone (spot) – 5 cm. Radiation power density on the object was about 4 mW/cm^2.

The work with the devices was carried out using UV-protective glasses for the researcher and a protective screen for the eyes of the animals.

Research methods

Clinical studies

Clinical monitoring of the somatic condition of the animals was carried out daily for up to 21 days: the body weight of the animals was measured, the pain component was assessed. Regionally, the course of the wound process was assessed based on clinical markers of inflammation (the degree of hyperemia and tissue edema, the amount and nature of wound discharge), as well as the dynamics of wound healing using photography and video filming.

The presence and severity of pain syndrome in the wound area were determined by changes in the eating behavior of the animals: in case of no changes in the volume of food consumed, it was assumed that pain symptomatology was absent (0 points), and in case of refusal of food, the severity of pain was significant (3 points).

A scoring system was also used to assess the severity of hyperemia and tissue edema: 0 points – pale pink color / no edema; 1 point – mild hyperemia / minor edema; 2 points – moderate hyperemia / moderate edema; 3 points – severe hyperemia/pronounced edema.

Microbiological studies were performed at the Center for Clinical Laboratory Diagnostics of the Federal State Budgetary Institution "N.N. Burdenko Main Military Clinical Hospital" of the Ministry of Defense of the Russian Federation.

In preparation for the described cycle of experiments with a gunshot wound, we preliminarily conducted *in vitro* microbiological studies on the bactericidal properties of the types of optical radiation used – broad-spectrum high-intensity pulsed ("Zarnitsa-A") and narrow-band low-intensity continuous ("Zarnitsa-D"). Six clinically significant strains of microorganisms obtained from the biomaterial of patients were selected as objects of research, including gram-negative strains: *Klebsiella pneumoniae, Escherichia coli, Proteus mirabilis, Acinetobacter baumanii* and gram-positive strains: *Staphylococcus epidermidis, Enterococcus faecalis*. The studies showed a higher bactericidal efficiency of high-intensity pulsed radiation, but did not reveal a significant difference in the photoresistance of the studied types of bacterial microflora to the applied optical radiation. The results of these studies were partially published in [15, 16, 18]. In this regard, two clinical polyresistant strains isolated from the biomaterial of patients in the surgical departments of the hospital and related to gram-negative ESKAPE pathogens were selected as representative exogenous sources of contamination of gunshot wounds: *A.baumanii* and *K.pneumoniae*.

The daily culture of microorganisms was diluted with saline to a concentration of 10^8 CFU/ml, which corresponded to an optical density of 0.5 according to the McFarland turbidity standard for each microorganism. Turbidity was measured using a BD Phoenix Spec nephelometer (Becton Dickinson@Company, USA).

Wound infection in animals of groups II, III and IV was carried out by dropwise introduction of 0.1 ml of a suspension of a mixed bacterial culture of *A.baumanii* and *K.pneumoniae* into the area of the wound channel entrance, which ensured contamination of the wound with ~5.10^6 cells of each microorganism. In group I, the gunshot wound was not artificially infected.

On days 1, 3, 7, 10, 15 and 21 from the moment of gunshot injury and wound infection, microbiological studies of wound discharge with a quantitative determination of each strain of microorganism were performed in all animals.

Pathomorphological studies were conducted in the Department of Pathological Anatomy of the Burdenko Main Military Clinical Hospital of the Russian Ministry of Defense. A 0.5×1.0 cm^2 soft tissue fragment was taken from the entry wound site of a gunshot wound for pathomorphological studies in all experimental groups on days 1, 3, 7, 10, 15, and 21 after injury and infection. A standard protocol was used to process the obtained biological material. Samples were prepared using a Leica ASP6025S automatic vacuum histological processor (Leica Biosystems, USA). All preparations were stained with hematoxylin and eosin. Histological micropreparations were examined at 10x, 20x, and 40x magnification using a Leica DM3000 direct light laboratory microscope (Germany).

Microscopic preparations were scanned on an Aperio AT2 scanning device (manufacturer Leica, USA) at a magnification of 20^x. For morphological analysis, microphotographs were prepared from scanned slides in the Aperio ImageScope (12.3.3) program (developer Leica, USA).

Results

Somatic condition assessment

Starting from day 3 to day 15 of observation, a decrease in body weight was noted in all laboratory animals in all groups (Fig. 2). The greatest loss of body weight (15.7%) was recorded in animals of group III; the smallest (5%) was noted in groups I and IV. After day 15, most animals in all groups gained weight, reaching the initial indicators by day 21.

Pain syndrome assessment

Gunshot injury was accompanied by pain syndrome, the intensity of which in animals in all groups was greatest on the 3rd day after the start of the experiment (1.13±0.2 points in group I, 2.5±0.16 points in group II, 1.92±0.24 points in group III, 1.58±0.2 points in group IV).

During the entire subsequent observation period, a gradual decrease in the intensity of the pain syndrome was recorded, and the average pain intensity values in points in animals of group II were always higher than in animals of groups III and IV, which indicates that broad-spectrum optical and short-wave UV irradiation reduce pain syndrome in the case of infected wounds.

Evaluation of the degree of tissue hyperemia and edema

In all groups, the maximum degrees of tissue hyperemia/edema developed by the 3rd day of observation, with the most pronounced ones occurring in animals of groups II and III (Fig. 3).

By the 10th day, the color of the perifocal tissues and the degree of edema in the laboratory animals of group I returned to normal values, in the other groups the severity of hyperemia/edema gradually decreased, remaining to the greatest extent in the group with an infected gunshot wound (group II). On the 15th day, hyperemia and edema were noted only in the group with an infected gunshot wound (group II).

The purulent-hemorrhagic nature of the wound discharge persisted for up to 7 days in all groups. Starting from the 7th day, in laboratory animals in groups I, III and IV, the nature of the wound discharge was serous-hemorrhagic.

Thus, the greatest severity and duration of the inflammatory process in the area of the gunshot wound were observed in the experimental animals of group II (infected gunshot wound). Exposure to high-intensity continuous-spectrum optical radiation (group III) and low-

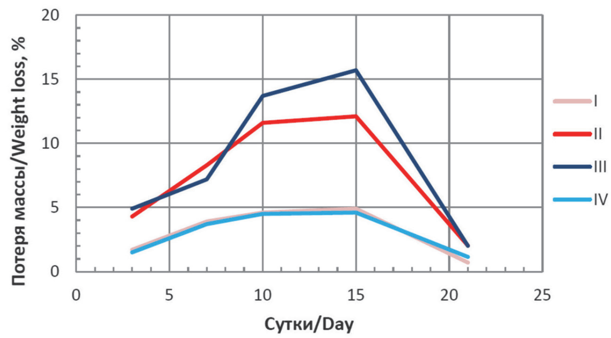

Рис. 2. Динамика уменьшения массы тела лабораторных животных в ходе эксперимента (римские цифры соответствуют номерам экспериментальных групп животных).
Fig. 2. Dynamics of decrease in body weight of laboratory animals during the experiment (Roman numerals correspond to the numbers of experimental groups of animals).

intensity continuous narrow-spectrum UV radiation (group IV) reduced the duration and activity of the inflammatory process in an infected wound, bringing the dynamics of the wound process closer to the nature of the course in an uninfected wound (group I).

Results of microbiological studies

In experimental groups III and IV, where the corresponding types of optical radiation exposure to the wound surface were applied, there was no growth of *K.pneumonia* and *A.baumannii* strains, starting from the first day. In group II, the growth of the declared pathogenic strains (K.pneumonia and A.baumannii) persisted for up to 17 days with a gradual decrease in concentration to 10^3 CFU/ml by the specified time.

Analysis of the results of microbiological examination of wound discharge in animals with a gunshot infected wound demonstrated a stable bactericidal effect of high-intensity optical radiation of the continuous spectrum of the Zarnitsa-A device and low-intensity continuous UV radiation of the narrow spectrum of the Zarnitsa-D LED device on gram-negative bacteria *K.pneumoniae* and *A.baumannii*. This effect was expressed throughout the study.

Results of morphological studies

The dynamics of the wound process at the cellular and tissue levels was studied by microscopic examination of the material obtained as a result of a lifetime biopsy of soft tissues from the zone of the gunshot defect in animals of all experimental groups. A brief description of the results obtained is given below.

Fig. 4 shows micropreparations of the animal wound on the 3rd day of treatment.

In the wound injuries of animals of groups I and II on the third day, the prevalence of necrobiotic changes remained the same as on the first day, namely: cellular detritus with diffusely expressed dense segmented nuclear infiltration, a large number of neutrophilic leukocytes (75-80%) in a state of degeneration and destruction (in the form of karyopyknosis and karyorrhexis, cytolysis). The remaining 20-25% of the cellular composition is represented by

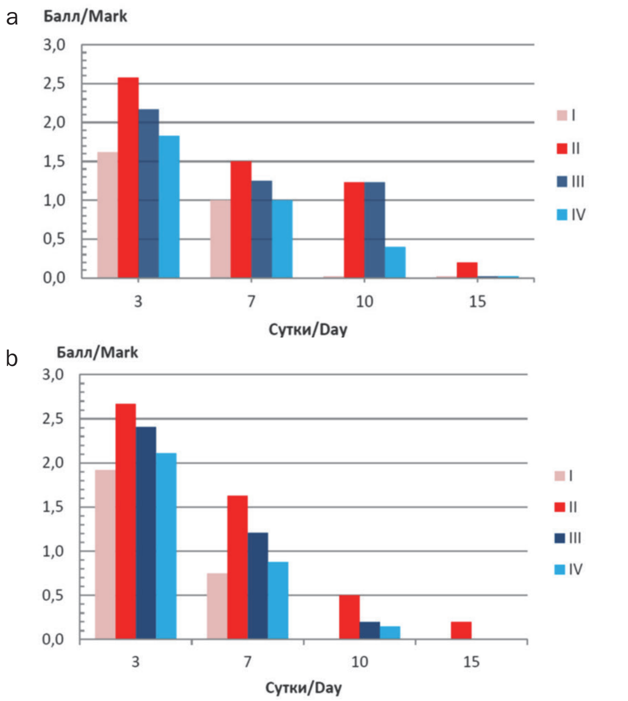

Рис. 3. Динамика развития гиперемии (а) и отека (б) у лабораторных животных в ходе эксперимента (римские цифры соответствуют номерам экспериментальных групп животных)
Fig. 3. Dynamics of hyperemia (a) and edema (б) in laboratory animals during the experiment (Roman numerals correspond to the numbers of experimental groups of animals)

lymphocytes, monocytes and individual macrophages and polyblasts. In general, the nature of changes in soft tissues in these groups on the third day of observation corresponded to the first phase of the wound process and did not have significant morphological and morphometric differences in intergroup comparison.

In group III of animals, against the background of a decrease in morphological markers of inflammation, cases of formation of immature granulation tissue were noted. Enhanced angiogenesis with proliferation of vascular endothelium was observed (in different rats from 19 to 26 vessels per 1 mm^2). In the structure of the cellular composition, a decrease in the content of neutrophilic leukocytes to 65-50% and an increase in the number of macrophages were observed.

In group IV, all laboratory animals in biopsy specimens still showed a predominance of necrobiotic changes, namely: cellular detritus with pronounced dense segmented nuclear infiltration and a large number of neutrophilic leukocytes (70-60%). However, the severity of the inflammatory process decreased.

By the seventh day, animals of group I showed signs of transition of the wound process to the regeneration phase and decreased severity of inflammation, as evidenced by changes in the cellular composition: a 1.6-2.5-fold decrease (compared to the first three days) in the number of neutrophilic leukocytes, an increase in the number of regeneration predictors: macrophages, mast cells, fibroblast proliferation, increased angiogenesis (in different rats from 9 to 16 vessels per 1 mm^2), as well as the development of immature granulation tissue.

In animals of group II, a pronounced inflammatory process persisted: the predominant elements of the cellular composition were neutrophilic leukocytes (70-80%); angiogenesis was poorly developed, fibrin thrombi persisted in some vessels.

In animals of groups III and IV, regression of inflammatory reactions and activation of reparative regeneration due to external exposure to optical radiation were clearly observed. Formation of mature granulation tissue was clearly visible in biopsies. Formation of vertically located vessels with endothelial proliferation was observed (from 10 to 15 per 1 mm^2). In the structure of the cellular composition, tissue undifferentiated polyblasts, fibroblasts, lymphocytes, as well as macrophages and mast cells predominated (70-80%). The content of neutrophilic leukocytes was 20-30%, which indicates a significant decrease in the severity of the inflammatory process, mainly in group III (Zarnitsa-A device). In general, the nature of changes in soft tissues in groups III and IV corresponded to the second phase of the wound process – the regeneration phase.

On the 10th day, the majority of laboratory animals in three of the four experimental groups – I, III and IV – showed a morphological picture reflecting the progression of regeneration in the area of the gunshot wound.

In all animals in groups III and IV, whose wounds were irradiated with optical radiation, the biopsy specimens clearly showed the formation of mature granulation tissue, the formation of vertically located vessels with endothelial proliferation (from 10 to 12 per 1 mm^2); stroma with signs of

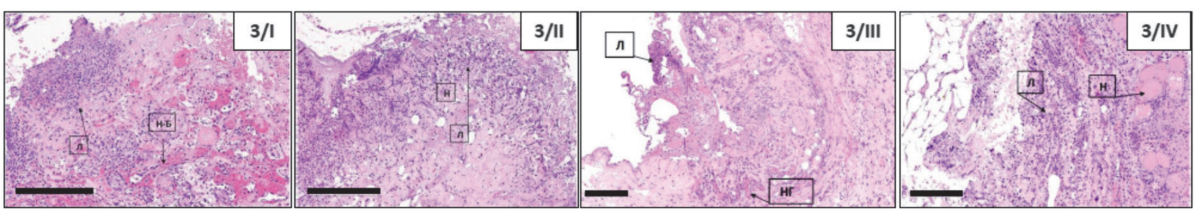

Рис. 4. Микропрепараты раны животных на 3-й день лечения (3/I – 1-я группа; 3/II – II-я группа; 3/III – III-я группа; 3/IV – IV-я группа): Л – сегментоядерные лейкоциты; Н – некроз мягких тканей; Н-Б – некроз мягких тканей с кровоизлиянием; НГ – незрелая грануляционная ткань, развитие ангиогенеза с очаговой пролиферацией эндотелия. Масштабная метка – 200 мкм; окраска – гематоксилин-эозин.
Fig. 4. Micro-preparations of animal wounds on the 3rd day of treatment (3/I – 1st group; 3/II – II group; 3/III – III group; 3/IV – IV group): Л – segmented leukocytes; Н – necrosis of soft tissues; Н-Б – necrosis of soft tissues with hemorrhage; НГ – immature granulation tissue, development of angiogenesis with focal proliferation of the endothelium. The scale label is 200 microns; the color is hematoxylin-eosin.

fibrosis. In the structure of the cellular composition, fibroblasts, macrophages and mast cells predominated (75-80%). The content of neutrophilic leukocytes was 20-25%, indicating an insignificant severity of the inflammatory process.

In group II of animals, a pronounced inflammatory process persisted by the 10th day. There were no trends towards activation of the connective tissue regeneration process in the area of the infected gunshot wound. In all the biopsies examined from the area of the gunshot wound, immature granulation tissue with a predominance of neutrophilic leukocytes in the structure of the cellular composition was determined. Angiogenesis was poorly developed, fibrin thrombi were noted.

On the 15th day, the positive dynamics of the wound healing process in Group I was generally maintained, in particular, a partial transition from the regeneration phase to the phase of scar reorganization (reparation) and epithelialization (phase III of the wound process) was noted.

In Group II, positive dynamics were also noted compared to the previous morphological picture: five animals showed pronounced activity of the tissue regeneration process in the area of the gunshot infected wound. Morphologically, granulation tissue formation was observed in biopsies, the number of vessels decreased (up to 15 per 1 mm^2), the vessels took a vertical position, and the endothelium showed signs of proliferation. In the structure of the cellular composition, the content of neutrophilic leukocytes was 35-45%. However, in the other three animals of the group, regeneration was less pronounced: immature granulation tissue, active angiogenesis (the number of vessels up to 25 per 1 mm^2), and stroma with minimal signs of collagenization were determined. The cellular composition is represented by 50-60% neutrophilic leukocytes.

In group III, all examined biopsies showed the presence of mature granulation tissue, vertically oriented vessels, and endothelium with signs of proliferation. Angiogenesis activity was reduced: the number of vessels was up to 10 per 1 mm^2. The stroma was compacted with collagenization. However, compared to the previous morphological picture, in this group, on the 15th day, a slowdown in the rate of tissue regeneration with an increase in the activity of the inflammatory process was observed. In the structure of the cellular composition, the content of neutrophilic leukocytes increased from 20-25% to 40-50%; the remaining 50-60% of cells are represented by tissue undifferentiated polyblasts, fibroblasts, lymphocytes, as well as macrophages and mast cells.

Unlike group III, laboratory animals of group IV did not show any increase in the activity of the inflammatory process and maintained a stable sequence of early interphase transition in the dynamics of the wound process, namely, the transition from the regeneration phase to the scar reorganization and epithelialization phase. In the cellular composition, the proportion of neutrophilic leukocytes was 20-30%, tissue undifferentiated polyblasts, fibroblasts, lymphocytes, as well as macrophages and mast cells formed 70-80%. Formation of mature granulation tissue was clearly visible in the wound. Angiogenesis activity was reduced: the number of vessels was up to 10 per 1 mm^2. The vessels were located vertically, the endothelium showed signs of proliferation.

Fig. 5 shows micropreparations of the animal wound on the 21st day of treatment.

When analyzing the dynamics of the wound process on the 21st day, it was noted that in groups I and IV, the wound process entered the phase of scar reorganization and epithelialization in all laboratory animals. In group II, the process of transition to the third phase was not completed in most animals, but maintained positive dynamics. In the structure of the cellular composition, the content of neutrophilic leukocytes was 30-40%. In group III, no significant differences in the dynamics of the wound process were observed compared to the previous morphological picture – the rate of tissue regeneration in the wound area was slowed down against the background of the continued activity of the inflammatory process.

Discussion of the results

The conducted studies of reparative regeneration of soft tissues in the area of infected gunshot injury allow to make the following clinical conclusions.

The slowest development of the regeneration process was observed in Group II (infected gunshot wound). This is

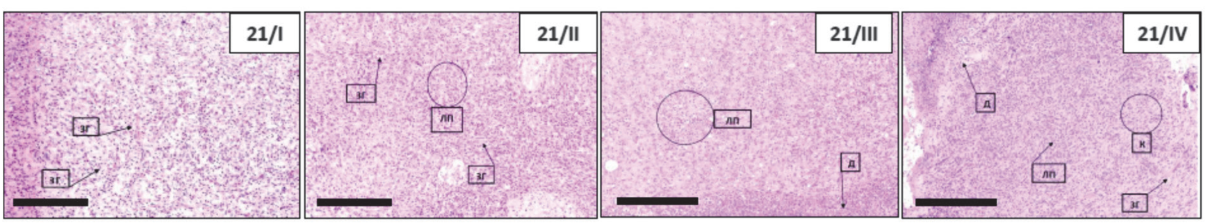

Рис. 5. Микропрепараты раны животных на 21-й день лечения (21/I – 1-я группа; 21/II – II-я группа; 21/III – III-я группа; 21/IV – IV-я группа): ЗГ – формирование зрелой грануляционной ткани с началом образования вертикально расположенных сосудов с пролиферацией эндотелия; ЛП – воспаление представлено рассеянными лейкоцитами, лимфоцитами и плазмоцитами; Д – клеточный детрит; К – пролиферация фибробластов, тучных клеток и макрофагов. Масштабная метка – 200 мкм; окраска – гематоксилин-эозин.

Fig. 5. Micro-preparations of animal wounds on the 21st day of treatment (21/I – 1st group; 21/II – II group; 21/III – III group; 21/IV – IV group): ЗГ – formation of mature granulation tissue with the onset of formation vertically located vessels with endothelial proliferation; ЛП – inflammation is represented by scattered leukocytes, lymphocytes and plasmocytes; Д – cellular detritus; К – proliferation of fibroblasts, mast cells and macrophages. The scale label is 200 microns; the color is hematoxylin-eosin.

due to the presence of long-term (up to 10 days) bacterial inflammation.

The effect of high-intensity optical radiation of a wide spectrum and low-intensity continuous UV radiation of a narrow spectrum on the tissues of infected gunshot wounds accelerates the transition between the inflammatory and regenerative phases of the wound process. Compared with Group II, the regeneration process in the area of the infected wound began 7-10 days faster, and compared with Group I (uninfected gunshot wound) – 3-5 days faster.

When analyzing the wound-healing effects of various types of optical radiation, it was found that high-intensity broad-spectrum optical radiation has a more pronounced anti-inflammatory effect in the first phase of the wound process and ensures earlier development of tissue regeneration compared to low-intensity continuous narrow-spectrum UV radiation.

However, at prolonged application (more than 10 days) high-intensity pulsed optical radiation of wide spectrum with the dosage selected in this work caused slowing down of tissue regeneration process in the area of wound damage, which should be taken into account when carrying out therapeutic procedures.

It should be noted that in the described experiments the dosage of the optical radiation used was set based on the results of previously conducted *in vitro* microbiological studies, which determined the bactericidal effectiveness of various types of optical radiation against clinically significant strains of pathogenic microorganisms [15, 16, 18]. The doses used reduced the initial level of bacterial contamination of the surface of the nutrient media by more than 6 decimal orders. Thus, the magnitude of the energy dose in these experiments was determined by the requirement to ensure a bactericidal effect in the wound. It was believed that effective suppression of bacterial flora activity is one of the main factors determining the nature of the course and duration of the wound process.

In this regard, it can be assumed that the observed effect of inhibition of regenerative histogenesis in the wound with a simultaneous increase in the activity of the inflammatory process in the case of long-term use (more than 10 days) of sufficiently high energy doses of pulsed optical irradiation is associated with an overdose of such an effect on the granulation tissues and epithelial layers that arise during regeneration. An overdose of optical radiation, and primarily its short-wave UV component (UV-C and UV-B components) is accompanied by increased concentrations of photochemical destruction products of intracellular structures (proteins, lipids, nucleic acids, etc.). These destruction products are, in fact, photoinduced antigens and should be neutralized and removed as a result of the inflammatory process. This can explain the prolonged nature of inflammation and inhibition of reparation observed in the experiments after 10 days of irradiation with the Zarnitsa-A device. Thus, the use of high-intensity pulsed irradiation for wound therapy requires strict methodological justification of the regime parameters and, first of all, the applied dose characteristics for each phase of the wound process.

Based on the results of the study, we can make a preliminary conclusion about the need for a gradual reduction in the doses of pulsed broad-spectrum optical irradiation in the phases of regeneration and reorganization of the scar (II and III phases of the wound process) to a preventive level of exposure, which is 10-20% of the initial dose, providing an anti-inflammatory (bactericidal) effect.

The experiments also showed that low-intensity UV radiation from LEDs, even at higher energy doses compared to pulsed optical radiation, has a smaller photochemical effect in biological tissues and, under the modes used in these experiments, did not cause any pronounced negative effects. Nevertheless such radiation accelerated the development of the phases of regeneration and reorganization of the scar and epithelialization.

Conclusion

The research proposes a new approach to the treatment of gunshot wounds complicated by nosocomial microflora. The essence of the method lies in the effect on the wound surface of high-intensity pulsed optical radiation of a wide spectrum, continuously covering the entire UV range (from 200 to 400 nm), visible and near infrared spectral regions. A pulsed xenon lamp is used as a radiation source, on the basis of which the Zarnitsa-A device was created. A comparison was made of the effect on the course of the wound process in gunshot trauma of high-intensity pulsed broad-spectrum optical radiation and low-intensity continuous UV radiation of a LED device emitting a narrow-band emission spectrum with a maximum at a wavelength of 272 nm and a half-width of 12 nm. It has been shown that high-intensity optical radiation of a broad spectrum has a more pronounced anti-inflammatory effect in the first phase of the wound process and ensures earlier development of tissue regeneration compared to low-intensity continuous UV radiation of a narrow spectrum. However its use requires justification of dose characteristics for each phase of the wound process.

Based on the results of the studies, it is recommended to gradually reduce the dosage of pulsed broadband optical irradiation in phases II and III of the wound process to a preventive level of exposure, which is 10-20% of the dose that provides a bactericidal effect. The results of the studies show the potential for using optical irradiation devices such as "Zarnitsa-A" and "Zarnitsa-D" for the treatment of infected gunshot wounds for the purpose of targeted action on the phases of the wound process and accelerating healing.

Funding of the work

The work was carried out with the financial support of Oniko-M LLC.

REFERENCES

1. Dai T., Vrahas M.S., Murray C.K., Hamblin M.R. Ultraviolet C irradiation: an alternative antimicrobial approach to localized infections? *Expert Rev. Anti Infect. Ther*, 2012, Vol.10(2), pp.185-195.
2. Klochkov H.D. et al. // In the collection *«Experience of medical support for troops in Afghanistan 1979-1989: Organization and volume of surgical care for the wounded»*, edited by I.A. Yeryukhin, V.I. Frailkin. – M.: GVKG im. Academician N.N. Burdenko, 2002, Vol. 2, pp. 68-131.
3. Stewart S., Tunstall C., Stevenson T. Gunshot wounds in civilian practice: a review of epidemiology, pathophysiology and management. *Orthopaedics and Trauma*, 2023, Vol. 37(4), pp. 216-221. https://doi.org/10.1016/j.mporth.2023.05.002.
4. Trukhan A.P. Gunshot wounds and explosive trauma in peacetime. Features, organization and provision of surgical care (clinical and experimental research). *Dissertation of the Doctor of Medical Sciences (Military Medical Academy named after S.M. Kirov" of the Ministry of Defense of the Russian Federation*, *St. Petersburg*, 2022.
5. Chizh I.M. et al. // Experience of medical support for troops in internal armed conflict in the North Caucasus region of the Russian Federation in 1994-1996 and 1999-2002. *Edited by Fisuna A.Ya. (Rostov-on-Don: Rostov State Medical University of the Russian Ministry of Health*, 2014, Vol. 1, pp. 223-234.
6. Martin M.J., Eastridge B., Ruggero J.M. Combat trauma care: Lessons learned from recent combat operations. Current Therapy of Trauma and Surgical Critical Care *(Third Edition)*. Editors: Asensio J.A., Meredith J.W.,2024, Elsevier. https://doi.org/10.1016/B978-0-323-69787-3.00109-X.
7. Ataev A.R., Ataeva L.A., Ataev E.A. and others. Comprehensive treatment of wound infection in gunshot wounds and its objective criteria of effectiveness. *Practical medicine*, 2022, Vol. 20(4), pp.7-12.
8. Military field surgery: textbook. – 2nd ed., ed. and supplement / Ed. by E.K. Gumanenko. – M.: GEOTAR-Media, 2008, p.768. ISBN 978-5-9704-0911-4
9. Trishkin D.V., Kryukov E.V., Chuprina A.P. and others. Methodological recommendations for the treatment of combat surgical trauma. *Military Medical Academy named after S.M. Kirov. Saint Petersburg*, 2022, p. 373.
10. Plotnikov A.V. Infectious complications of gunshot wounds. *Thesis. LXX International Scientific and practical Conference "Actual problems of modern medicine and pharmacy", edited by* A.V. Sikorsky, O.K. Doronina. Minsk: BSMU, 2016, pp. 846-847.
11. Obolensky V.N. Modern methods of treatment of chronic wounds. *Medical Council*, 2016, Vol.10, pp.148-154.
12. Rasulov M.M., Motorina I.G., Yushkov G.G., and others. The effect of short-wave ultraviolet radiation on the healing of burn wounds (experimental study). *Issues of balneology, physiotherapy and therapeutic physical culture*, 2016, Vol.93(5), pp.38 42.
13. Motorina I.G., Rasulov M.M., Gukasov V.M., Myakinkova L.L. The effectiveness of phototherapy in the treatment of long-term non-healing wounds. *Innovation and expertise*, 2017, Vol. 2(20), pp. 225-234.
14. Arkhipov V.P., Bagrov V.V., Byalovsky Yu.Y. and others. Organization of preclinical studies of the bactericidal and wound-healing effects of the Zarya pulsed phototherapy apparatus. *Problems of social hygiene, public health and the history of medicine*, 2021, Vol. 29(5), 1156-1162. http://dx.doi.org/10.32687/0869-866X-2021-29-5 – 1156-1162
15. Bagrov V.V., Bukhtiyarov I.V., Volodin L.Y. et al. A High-Intensity Optical Irradiation Device for the Treatment of Wounds and Wound Infections. *Biomedical Engineering*, 2023, Vol. 57, pp. 77-80. https://doi.org/10.1007/s10527-023-10272-0.
16. Bagrov V.V., Bukhtiyarov I.V., Volodin L.Y. at al., Preclinical Studies of the Antimicrobial and Wound-Healing Effects of the High-Intensity Optical Irradiation «Zarnitsa-A» Apparatus. *Applied Sciences*, 2023, Vol. 13, pp. 10794. https://doi.org/10.3390/app131910794 V.13. – 10794.
17. Abduvosidov H.A., Chudnykh S.M., Egorov V.S. and others. Bactericidal efficiency of using high–intensity pulsed broadband radiation in the treatment of infected wounds // Biomedical Photonics, 2024, Vol. 13(2), pp. 26-33. https://doi.org/10.24931/2413-9432-2023-13-2-26-33
18. Bagrov V.V., Volodin L.Y., Kamrukov A.S. at al. LED device of short-wave ultraviolet irradiation. *Biomedical Engineering*, 2023. https://doi.org/10.1007/s10527-023-10307-6.

ЛИТЕРАТУРА

1. Dai T., Vrahas M.S., Murray C.K., Hamblin M.R. Ultraviolet C irradiation: an alternative antimicrobial approach to localized infections? // Expert Rev. Anti Infect. Ther. – 2012. – Vol.10(2). – P.185-195.
2. Клочков Н.Д. и др. // В сб. «Опыт медицинского обеспечения войск в Афганистане 1979-1989 гг.: Организация и объем хирургической помощи раненым», под ред. И.А. Ерюхина, В.И. Хрупкина. – М.: ГВКГ им. акад. Н. Н. Бурденко. – 2002. – Т.2, С. 68-131.
3. Stewart S., Tunstall C., Stevenson T. Gunshot wounds in civilian practice: a review of epidemiology, pathophysiology and management // Orthopaedics and Trauma. – 2023. – Vol. 37, No. 4. – С. 216-221. https://doi.org/10.1016/j.mporth.2023.05.002.
4. Трухан А.П. Огнестрельные ранения и взрывная травма мирного времени. Особенности, организация и оказание хирургической помощи (клинико-экспериментальное исследование) // Диссертация доктора медицинских наук (Военно-медицинская академия имени С.М. Кирова» Министерства обороны Российской Федерации, СПб. – 2022.
5. Чиж И.М. и др. // Опыт медицинского обеспечения войск во внутреннем вооруженном конфликте на территории Севера Кавказского региона Российской Федерации в 1994-1996 гг. и 1999-2002 гг. Под ред. Фисуна А.Я.. (Ростов-на-Дону: ГБОУ ВПО РостГМУ Минздрава России. – 2014, Т.1. – С. 223-234.
6. Martin M.J., Eastridge B., Ruggero J.M. Combat trauma care: Lessons learned from recent combat operations. Current Therapy of Trauma and Surgical Critical Care (Third Edition) // Editors: Asensio J.A., Meredith J.W. – 2024. – Elsevier. https://doi.org/10.1016/B978-0-323-69787-3.00109-X.
7. Атаев А.Р., Атаева Л.А., Атаев Э.А. и др. Комплексное лечение раневой инфекции при огнестрельных ранениях и ее объективные критерии эффективности // Практическая медицина. – 2022. – Т.20, №4. – С.7-12.
8. Военно-полевая хирургия: учебник. – 2-е изд., изм. и доп. / Под ред. Е.К. Гуманенко. – М.: ГЭОТАР-Медиа. – 2008. – С.768. ISBN 978-5-9704-0911-4
9. Тришкин Д.В., Крюков Е.В., Чуприна А.П. и др. Методические рекомендации по лечению боевой хирургической травмы // Военно-медицинская академия имени С.М. Кирова. Санкт-Петербург. – 2022. – С. 373.
10. Плотников А.В. Инфекционные осложнения огнестрельных ран // Тез. докл. LXX Международная научно-практическая конференция «Актуальные проблемы современной медицины и фармации», под ред. А.В. Сикорского, О.К. Дорониной. Минск: БГМУ. – 2016. – С. 846-847.
11. Оболенский В.Н. Современные методы лечения хронических ран // Медицинский Совет. – 2016. – №10. – С.148-154.
12. Расулов М.М., Моторина И.Г., Юшков Г.Г., и др. Влияние коротковолнового ультрафиолетового облучения на заживление ожоговых ран (экспериментальное исследование) // Вопросы курортологии, физиотерапии и лечебной физической культуры. – 2016. – Т.93, №5. – С.38-42.
13. Моторина И.Г., Расулов М.М., Гукасов В.М, Мякинькова Л.Л. Эффективность фототерапии при лечении длительно незаживающих ран //Инноватика и экспертиза. – 2017. – №. 2(20). – С. 225-234.
14. Архипов В.П., Багров В.В., Бяловский Ю.Ю. и др. Организация доклинических исследований бактерицидного и ранозаживляющего действия аппарата импульсной фототерапии "Заря" // Проблемы социальной гигиены, здравоохранения и истории медицины. – 2021. –Т. 29, №5. – 1156-1162. http://dx.doi.org/10.32687/0869-866X-2021-29-5- 1156-1162
15. Bagrov V.V., Bukhtiyarov I.V., Volodin L.Y. et al. A High-Intensity Optical Irradiation Device for the Treatment of Wounds and Wound Infections // Biomedical Engineering. – 2023. Vol. 57. – P. 77-80. https://doi.org/10.1007/s10527-023-10272-0.
16. Bagrov V.V., Bukhtiyarov I.V., Volodin L.Y. at al., Preclinical Studies of the Antimicrobial and Wound-Healing Effects of the High-Intensity Optical Irradiation «Zarnitsa-A» Apparatus // Applied Sciences. – 2023. – Vol. 13. – P. 10794. https://doi.org/10.3390/app131910794 V.13. – 10794.
17. Абдувосидов Х.А., Чудных С.М., Егоров В.С. и др. Бактерицидная эффективность использования высокоинтенсивного импульсного широкополосного облучения при лечении инфицированных ран // Biomedical Photonics. – 2024. – Vol. 13(2). – P. 26-33. https://doi.org/10.24931/2413-9432-2023-13-2-26-33
18. Bagrov V.V., Volodin L.Y., Kamrukov A.S. at al. LED device of short-wave ultraviolet irradiation // Biomedical Engineering. – 2023. https://doi.org/10.1007/s10527-023-10307-6.