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PROGNOSTIC ASSESSMENT OF TISSUE PERFUSION IN WOUNDED PATIENTS WITH COMBAT-RELATED COMBINED COLD THERMOMECHANICAL INJURY USING DOPPLER ULTRASONOGRAPHY AND THERMOMETRY

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Combat extremity injuries combined with systemic hypothermia and local cold-induced tissue damage are associated with a high risk of regional ischemia and secondary necrosis, and early objective assessment of tissue viability remains a major clinical challenge. This study included 213 wounded service members with firearm fractures of the extremities accompanied by general hypothermia and local cold injury, in whom regional perfusion was evaluated using venous ultrasound assessment and infrared thermography. Severe impairment of venous outflow was strongly associated with the development of secondary necrosis and was accompanied by a more than threefold increase in relative risk. Venous hemodynamic parameters demonstrated high predictive accuracy and exceeded the prognostic value of temperature asymmetry. The combined use of ultrasound assessment and thermographic analysis improved risk stratification and enabled early identification of critically impaired tissue perfusion. These findings confirm the leading role of venous microcirculatory dysfunction in the progression of ischemic tissue damage and support the use of integrated perfusion assessment in early clinical decision-making.

Key words: combat surgical trauma, frostbite, firearm fracture, osteosynthesis, polytrauma.

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ПРОГНОСТИЧНА ОЦІНКА ТКАНИННОЇ ПЕРФУЗІЇ ТКАНИН У ПОРАНЕНИХ ІЗ БОЙОВОЮ КОМБІНОВАНОЮ ХОЛОДОВОЮ ТЕРМОМЕХАНІЧНОЮ ТРАВМОЮ ЗА ДОПОМОГОЮ ДОПЛЕРОГРАФІЇ ТА ТЕРМОМЕТРІЇ

Бойові ушкодження кінцівок, ускладнені холодовим впливом, характеризуються високим ризиком розвитку тканинної ішемії та вторинного некрозу, а рання оцінка життєздатності тканин залишається складною клінічною проблемою. У дослідження включено 213 поранених військовослужбовців із поєднаною холодовою та вогнепальною травмою кінцівок, у яких проводили оцінку регіонарної перфузії за допомогою ультразвукової оцінки венозного відтоку та інфрачервоної термографії. Виражені порушення венозної гемодинаміки були тісно пов'язані з розвитком вторинного некрозу та супроводжувалися більш ніж триразовим зростанням відносного ризику. Венозні гемодинамічні показники продемонстрували високу прогностичну точність, що перевищувала інформативність температурної асиметрії. Поєднане використання ультразвукової оцінки та термографії дозволило підвищити точність стратифікації ризику та забезпечити раннє виявлення критичних порушень перфузії. Отримані результати підтверджують провідну роль венозної мікроциркуляторної дисфункції у прогресуванні ішемічного ушкодження тканин та обґрунтовують доцільність інтегрованої оцінки перфузії при прийнятті клінічних рішень.

Ключові слова: бойова хірургічна травма, відмороження, вогнепальний перелом, остеосинтез, політравма.

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Combat-related extremity injuries are often accompanied by prolonged exposure to low temperatures, which is characterized by the combination of mechanical tissue damage and cold-induced disturbances of microcirculation and tissue perfusion, leading to the development of combat-related combined cold thermomechanical injury (CRCCTI). Under such conditions, timely and objective assessment of tissue viability is one of the key factors determining treatment strategy and the prognosis of limb preservation [14, 16].

Cold exposure causes vasoconstriction, increased blood viscosity, aggregation of formed elements, and the development of microcirculatory stasis, which leads to decreased tissue perfusion and the development of ischemia [2, 3, 8]. Subsequently, the formation of ice crystals, endothelial injury, and activation of the coagulation cascade result in microthrombosis and impaired venous outflow, which are key mechanisms in the progression of tissue hypoxia and necrosis [3, 7, 8]. At the same time, severe trauma and blood loss lead to systemic hypoperfusion, which further aggravates microcirculatory disturbances and limits the effectiveness of even restored major arterial blood flow [14, 16].

An important feature of cold injury is that clinical signs do not always correspond to the actual depth of ischemic changes. Microcirculatory disturbances, venous congestion, and tissue hypoxia may progress even after hemodynamic stabilization, which significantly complicates the determination of viable tissue boundaries in the early stages of treatment [4, 8]. Microcirculatory dysfunction and impaired venous outflow are considered key factors in the development of irreversible ischemic and necrotic changes in cold injury [1, 3, 7, 8].

Ultrasound Doppler examination is an accessible and noninvasive method for assessing regional hemodynamics, allowing evaluation of venous blood flow characteristics and detection of its impairment, which is important for early diagnosis of ischemia [9, 10, 5]. Infrared thermography enables assessment of tissue functional status based on analysis of the temperature profile, which directly reflects the level of tissue perfusion and metabolic activity [11, 12, 13].

The combined use of ultrasound Doppler assessment and infrared thermography provides the opportunity for objective evaluation of regional perfusion disorders and early detection of ischemic changes, which is critically important for determining treatment strategy and predicting the course of cold-induced extremity injury. However, the diagnostic and prognostic role of these methods in wounded patients with CRCCTI and firearm fractures remains insufficiently studied, which determines the relevance of this research.

The purpose of the study was to determine the diagnostic and prognostic value of ultrasound examination and infrared thermography in wounded patients with early manifestations of combat-related combined cold thermomechanical injury and firearm fractures.

Materials and methods. The study included an analysis of treatment outcomes in 213 wounded service members with combat-related combined cold thermomechanical injury and firearm fractures who underwent diagnostic and therapeutic management at Role 2 medical facilities during the period from 2016 to 2025. The study consisted of a retrospective analysis of 102 patients and a prospective observation of 111 patients.

Exclusion criteria included primary limb amputation, complete destruction of the vascular bundle preventing assessment of blood flow, and inability to perform instrumental examinations in follow-up.

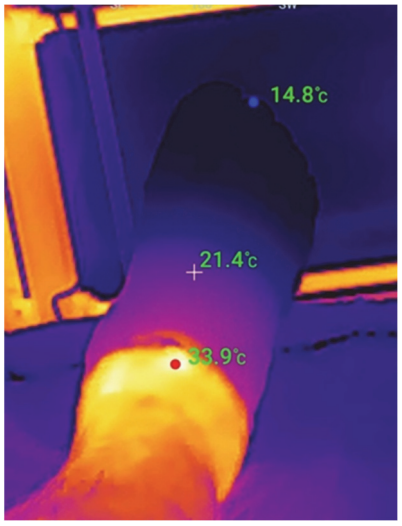
The study was conducted in accordance with the principles of the Declaration of Helsinki and the current legislation of Ukraine. The study protocol was approved by the Ethics Commission of the Ukrainian Military Medical Academy (Protocol No. 12, June 5, 2026).

Clinical parameters of local and systemic cold injury, laboratory indicators, and standard additional diagnostic methods were evaluated. The severity of the condition was determined based on clinical findings, laboratory results, and additional instrumental diagnostic methods, including assessment of systemic hypoperfusion and metabolic disturbances.

For objective evaluation of regional perfusion and detection of venous hemodynamic impairment, ultrasound Doppler examination of the injured extremity was performed using a portable ultrasound Doppler device SonoSite A (Edan Instruments, China) with an 8 megahertz probe and a Mindray DC-40 ultrasound system (Mindray, China) equipped with spectral and color Doppler modes. The presence and characteristics of spontaneous venous blood flow, respiratory phasicity, response to distal compression, compressibility of the venous wall, and symmetry of venous hemodynamics compared with the contralateral limb were assessed. The obtained data were used to evaluate the degree of venous outflow impairment and the severity of microcirculatory disturbances in the injured extremity.

Zones of impaired tissue perfusion were identified using an infrared thermographic camera FLIR C2 (FLIR Systems, United States), with a thermal sensitivity of 0.1 degrees Celsius, as shown in Figure 1. Examinations were performed at a room temperature of 22 to 24 degrees Celsius. Absolute temperature values of the injured segment, temperature asymmetry between the injured and contralateral extremities, and the presence of localized areas of reduced temperature were analyzed.

A



B

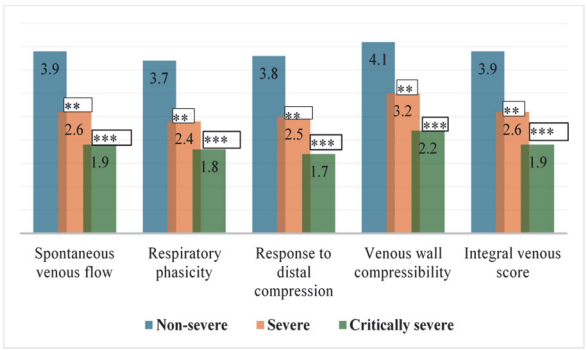
Fig. 1. Identification of zones of impaired perfusion in injured tissues, A – clinical appearance of the injured foot with signs of cold-induced ischemic tissue damage., B – infrared thermographic image demonstrating zones of reduced tissue perfusion and hypothermia.

The results of Doppler examination and thermography were compared with clinical data, the course of the wound process, and subsequent treatment outcomes to determine their diagnostic value in assessing tissue viability. The degree of perfusion impairment was determined based on a combination of clinical and instrumental findings, with classification into compensated, subcompensated, and critical blood supply disorders.

Statistical analysis was performed using licensed STATISTICA version 13.0 software (StatSoft Inc., United States). Normality of distribution was assessed using the Shapiro–Wilk test. Quantitative variables were compared using the Student t test or the Mann–Whitney test depending on distribution characteristics, and qualitative variables were analyzed using the chi square test. Differences were considered statistically significant at a probability value less than 0.05.

Results of the study. Assessment of venous hemodynamics was performed in 78 wounded patients (70.3 %) whose general condition allowed extended ultrasound examination after restoration of arterial inflow. Venous circulation was analyzed at the level of the proximal major veins of the injured extremity with comparison to the contralateral intact limb.

Analysis of baseline venous hemodynamic parameters demonstrated a clear association between the severity of the general condition and the degree of venous outflow impairment in the injured limb, as shown in Fig. 2– A.



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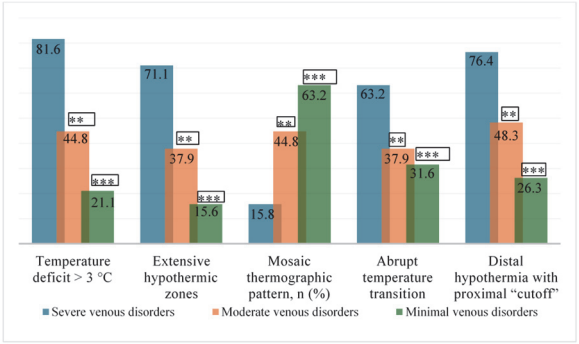

B

Fig. 2. A – distribution of venous hemodynamic parameters according to injury severity. Data are presented as mean values. **p < 0.01 and ***p < 0.001 compared with the non-severe group. B – distribution of thermographic characteristics according to the severity of venous hemodynamic disorders. **p < 0.01 and ***p < 0.001.

In patients with non-severe condition, the mean integral venous score was 3.9±0.5 points, corresponding to relatively preserved venous patency and moderate microcirculatory changes. In this group, spontaneous venous blood flow was preserved in 6 of 7 patients (85.7 %), respiratory phasicity was present in 5 (71.4 %), and an adequate response to distal compression was observed in 6 (85.7 %).

In severely injured patients, the integral venous score decreased to 2.6±0.7 points. Signs of significant venous outflow impairment (integral score ≤2 points) were identified in 21 patients (39.6 %). Reduced spontaneous venous flow (≤2 points) was recorded in 29 patients (54.7 %), impaired respiratory phasicity in 27 (50.9 %), weakened or absent response to distal compression in 24 (45.3 %), and decreased venous wall compressibility in 18 patients (34.0 %).

The most pronounced changes were observed in critically injured patients, in whom the integral venous score was only 1.9±0.6 points. In this category, 25 patients (49.0 %) had scores not exceeding 2 points.

Absence or marked suppression of spontaneous venous blood flow was detected in 31 patients (60.8 %), loss of respiratory phasicity in 29 (56.9 %), negative response to distal compression in 28 (54.9 %), and decreased venous wall compressibility in 22 (43.1 %).

Simultaneous presence of three or more pathological venous signs was observed in 33 severely and critically injured patients (42.3 % of those examined). Ultrasound criteria consistent with deep vein thrombosis were identified in 9 patients (11.5 %), predominantly in the critically injured group.

During initial examination, decreased surface temperature of the injured limb compared with the intact limb was detected in 79 of 86 patients (91.9 %). The mean temperature difference between symmetrical segments was 3.1±1.4 degrees Celsius, ranging from 1.2 to 6.7 degrees Celsius. In 48 patients (55.8 %), the temperature deficit exceeded 3 degrees Celsius, which was interpreted as pronounced regional hypoperfusion, as shown in Fig. 2–B.

Hypothermic zones demonstrated different configurations. In 34 patients (39.5 %), they were localized predominantly distal to the level of firearm injury; in 29 (33.7 %), they extended to the entire limb segment; and in 16 (18.6 %), they had a mosaic pattern with alternating areas of reduced and relatively preserved temperature. The latter variant was more frequently observed in patients with partially preserved venous blood flow according to Doppler findings.

A sharp temperature transition between proximal and distal segments of the limb was detected

in 41 patients (47.7 %) and was predominantly associated with low venous flow scores (0 to 2 points on the semi-quantitative scale). A gradual temperature gradient was observed in 45 patients (52.3 %) and correlated with partial preservation of venous outflow (3 to 4 points).

Thermographic mosaic pattern was recorded in 31 patients (36.0 %) and was characterized by alternating areas of hypothermia and relative normothermia within the same segment. This phenomenon was most frequently observed in patients with incomplete tourniquet compression and preserved fragmentary venous blood flow, corresponding to uneven microcirculatory distribution.

In critically ill patients with second to third degree shock, thermographic findings were characterized by a significantly greater temperature deficit (mean 4.2±1.3 degrees Celsius) and extensive hypothermic zones involving distal and middle limb segments. In the severely injured group, the mean temperature difference was 2.8±1.1 degrees Celsius, whereas in the non-severely injured group it was 1.6±0.7 degrees Celsius.

To objectively assess the relationship between venous hemodynamic status and the severity of cold-ischemic tissue changes, correlation analysis of venous ultrasound parameters and thermographic indices was performed. Eighty-six patients were included in the analysis, in whom both diagnostic methods could be performed during the early hospital period after primary stabilization and controlled restoration of blood flow in the injured limb, as shown in Fig. 3.

Correlation analysis revealed statistically significant associations between venous hemodynamic parameters and thermographic characteristics of the injured limbs. All evaluated venous parameters demonstrated moderate to strong negative correlation with temperature deficit and the extent of hypothermic zones (r from −0.49 to −0.68; p<0.01), indicating the determining role of venous outflow in the development of cold-ischemic changes.

The strongest correlation was observed for the integral venous score, which correlated with temperature deficit at r=−0.68 (p<0.01) and with the extent of hypothermic zones at r=−0.61 (p<0.01). This indicates that worsening venous hemodynamics was accompanied by proportional increase in temperature asymmetry and expansion of cold-affected areas.

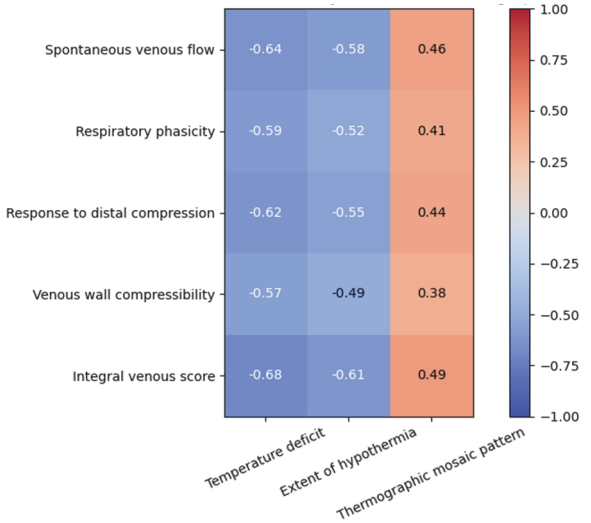

Fig. 3. Correlation between venous hemodynamic parameters and thermographic characteristics.

To quantitatively compare the prognostic performance of venous ultrasound examination and thermography, receiver operating characteristic analysis was performed with subsequent comparison of areas under the curves using the DeLong method. For each method, the area under the receiver operating characteristic curve, standard error, 95 % confidence interval, Z statistic, and significance level were calculated, as presented in Table 1.

Table 1

Comparative receiver operating characteristic characteristics in necrosis prediction

Method	AUC	SE	95 % CI	Z (DeLong)	p
Duplex scanning	0.90	0.04	0.82–0.96	2.17	0.03
Thermography	0.84	0.05	0.75–0.92	–	–

The area under the receiver operating characteristic curve for venous ultrasound assessment was 0.90±0.04 (95 % confidence interval 0.82 to 0.96), corresponding to high prognostic performance. For thermography, the area under the curve was 0.84±0.05 (95 % confidence interval 0.75 to 0.92), indicating good but lower predictive accuracy.

Comparison of the curves using the DeLong method revealed a statistically significant difference between the methods (Z=2.17; p=0.03), confirming the superiority of venous ultrasound examination in predicting secondary necrosis development, as shown in Fig. 4.

Note. The area under the curve for venous ultrasound assessment was 0.90 (95 % confidence interval 0.82 to 0.96), for thermography 0.84 (95 % confidence interval 0.75 to 0.92), and for the combined model 0.86 (95 % confidence interval 0.78 to 0.93). The difference between venous ultrasound and thermography was statistically significant (p=0.03 by DeLong).

The findings convincingly demonstrate that impaired venous outflow is one of the key mechanisms in the progression of ischemic-necrotic changes in combat-related combined cold thermomechanical injury of the extremities. A significant decrease in the integral venous score was observed according to injury severity, from 3.9±0.5 points in non-severely injured patients to 1.9±0.6 points in critically injured patients (p<0.001). Critical

venous outflow impairment (≤2 points) was associated with a significantly higher incidence of secondary necrosis (76.3 % versus 23.3 %; relative risk 3.3; odds ratio 10.5; p<0.001).

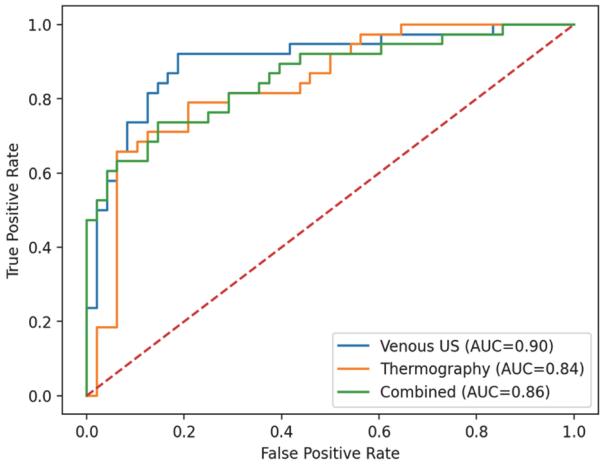

Fig. 4. Comparative receiver operating characteristic curves in wounded patients.

Discussion. These data are consistent with current concepts of cold injury pathogenesis, which emphasize that not only reduced arterial inflow but also microcirculatory dysfunction and impaired venous outflow are key factors in necrosis development [1, 3, 7, 8]. Endothelial injury, microthrombosis, and venous stasis increase tissue pressure, restrict capillary perfusion, and promote progression of tissue hypoxia even after restoration of major arterial flow [3, 7, 16]. Recommendations of the Wilderness Medical Society highlight that microcirculatory dysfunction determines tissue viability after cold injury [1, 15].

The high prognostic value of venous ultrasound assessment was confirmed by receiver operating characteristic analysis (area under the curve 0.90; p<0.001). At a threshold value of ≤2 points, sensitivity was 82.1 % and specificity 85.4 %, enabling effective identification of patients at high risk of necrotic complications. Similar findings were reported by Perkins and colleagues regarding the diagnostic value of Doppler examination in traumatic limb ischemia [9, 10].

The strong correlation between the integral venous score and temperature asymmetry (r=−0.68; p<0.001) confirms the pathophysiological link between venous hemodynamics and tissue perfusion. Infrared thermography demonstrated good predictive value (area under the curve 0.84; p<0.001), although lower than ultrasound examination, as thermography reflects functional consequences of impaired perfusion whereas ultrasound directly evaluates venous blood flow [11, 12, 13].

The combined use of ultrasound Doppler examination and thermography significantly improved prediction of ischemic-necrotic complications (odds ratio 24.1; p<0.001), confirming the complementary nature of these methods. Combined structural and functional perfusion assessment enables more accurate identification of patients at high risk of necrosis.

The findings have important clinical implications, supporting the leading role of venous disorders in ischemic complications and justifying the use of venous ultrasound assessment as an effective method of early diagnosis and risk stratification in combat-related cold and traumatic limb injury [1, 8, 9, 11].

Conclusion

In wounded patients with combat-related combined cold injury of the extremities, impairment of venous hemodynamics is one of the leading mechanisms in the development of ischemic-necrotic tissue changes, as confirmed by a significant decrease in the integral venous score and its strong correlation with the development of secondary necrosis (r=−0.68; p<0.001).

Ultrasound assessment of venous blood flow demonstrates high diagnostic and prognostic value for predicting ischemic-necrotic complications (area under the curve 0.90; 95 % confidence interval 0.82–0.96; p<0.001; sensitivity 82.1 %; specificity 85.4 %) and exceeds infrared thermography in accuracy, although thermography also represents an informative noninvasive method for evaluating tissue perfusion (area under the curve 0.84; p<0.001).

Combined application of ultrasound assessment of venous hemodynamics and infrared thermography improves the accuracy of predicting ischemic-necrotic changes (area under the curve 0.86; 95 % confidence interval 0.78–0.93; p<0.001) and enables objective identification of wounded patients at high risk of ischemia progression to support further treatment strategy decisions.

Prospects for further research. Further studies should focus on the development and validation of integrated prognostic models combining ultrasound, thermographic, and clinical indicators for early prediction of tissue viability and optimization of treatment strategies in wounded patients with combat-related combined cold thermomechanical injury.

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Conflict of interest. The authors have no conflicts of interest to declare.

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