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Regional tissue oximetry of the wound bed as a predictor of skin autograft take in the treatment of deep burns

Регионална ткивна оксиметрија лежишта ране као предиктор прихватања аутотрансплантата коже у лечењу дубоких опекотина

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Регионална ткивна оксиметрија лежишта ране као предиктор прихватања аутотрансплантата коже у лечењу дубоких опекотина

SUMMARY

Introduction/Objective The aim of this study was to assess the prognostic value of regional tissue oxygenation of the burn wound before and after necrectomy for split-thickness skin autograft take.

Methods This single-center observational study included 68 adult patients with burn injuries. Regional hemoglobin oxygen saturation (rSO_2) was measured by near-infrared spectroscopy before and after necrectomy. Values recorded in the prepared wound bed were compared with graft take on postoperative day 5. Categorical data were analyzed with the Fisher–Freeman–Halton exact test; for the rSO_2 threshold of <55%, sensitivity and specificity were calculated with exact Clopper–Pearson 95% confidence intervals (CI).

Results At rSO_2 <55%, an unfavorable outcome was recorded in 9 patients; at rSO_2 55–60%, partial graft take in 10; and at rSO_2 >60%, a favorable outcome in 49. The rSO_2 category was significantly associated with the outcome of skin autografting (Fisher–Freeman–Halton exact test, $p < 0.0001$). For the rSO_2 threshold of <55%, sensitivity was 100% (95% CI 66.4–100%) and specificity was 100% (95% CI 93.9–100%).

Conclusion In the study sample, rSO_2 <55% corresponded to an unfavorable outcome, 55–60% to partial graft take, and >60% to favorable graft take. Regional tissue oximetry may complement the clinical assessment of the wound bed; stand-alone use of these thresholds requires prospective validation.

Keywords: near-infrared spectroscopy; oxygen saturation; debridement; graft survival; skin transplantation

САЖЕТАК

Увод/Циљ Циљ истраживања био је да се процени прогностички значај регионалне ткивне оксигенације опекотинске ране пре и после некректомије за прихватање аутотрансплантата коже делимичне дебљине.

Методе У једноцентрично опсервационо истраживање укључено је 68 одраслих болесника са опекотинском повредом. Регионална сатурација хемоглобина кисеоником (rSO_2) одређивана је методом блиске инфрацрвене спектроскопије пре и после некректомије. Вредности регистроване у припремљеном лежишту ране упоређиване су са прихватањем трансплантата петог постоперативног дана. Категоријски подаци анализирани су Фишер–Фриман–Халтоновим тестом; за праг rSO_2 < 55% израчунате су сензитивност и специфичност са тачним 95% интервалима поверења по Клопер–Пирсоновој методи.

Резултати При rSO_2 <55% неповољан исход регистрован је код девет болесника, при rSO_2 55–60% делимично прихватање код 10, а при rSO_2 >60% повољан исход код 49 болесника. Категорија rSO_2 била је статистички повезана са исходом аутотрансплантације коже (егзактни Фишер–Фриман–Халтонов тест, $p < 0{,}0001$). За праг rSO_2 < 55% сензитивност је износила 100% (95% ИП 66,4–100%), а специфичност 100% (95% ИП 93,9–100%).

Закључак У испитиваној групи rSO_2 <55% био је повезан са неповољним исходом, 55–60% са делимичним, а >60% са повољним прихватањем трансплантата. Регионална ткивна оксиметрија може допунити клиничку процену лежишта ране; самостална примена прагова захтева проспективну валидацију.

Кључне речи: спектроскопија у блиском инфрацрвеном подручју; сатурација кисеоником; дебридман; преживљавање трансплантата; трансплантација коже

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INTRODUCTION

Assessing the severity of burn injury in the early stages of treatment remains one of the most challenging tasks in modern burn care. The choice of treatment strategy, the timing of surgery, and the prognosis of subsequent wound healing largely depend on the results of the initial assessment. The main determinants of the severity of thermal injury are the extent of the burn and the depth of tissue damage [1].

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Timely and objective assessment of burn depth is of particular clinical importance, since this parameter largely determines treatment strategy, including the indications for surgery. Superficial and full-thickness burns are usually not difficult to diagnose. However, the differential diagnosis of intermediate-depth burns, especially early after injury, remains a challenging clinical task.

In routine practice, burn depth is traditionally assessed on the basis of a combination of visual and palpatory signs, including the color and moisture of the wound surface, the presence and pattern of capillary refill, pain and tactile sensation, and the condition of the epidermis and dermis. Although clinical assessment is simple and readily available, its results depend largely on the clinician's experience and inevitably contain a subjective component. Consequently, even when patients are examined by experienced burn surgeons, the accuracy of burn depth assessment, particularly for borderline injuries early after trauma, may be insufficient for an unequivocal choice of surgical strategy.

The limited objectivity of conventional assessment becomes particularly important when choosing the timing and extent of surgical treatment. The decision to perform early excision of nonviable tissue followed by restoration of skin coverage should be based on the most accurate possible assessment of the viability of the injured area. Misinterpretation of burn depth may lead either to unnecessary surgery or to a delay in necessary surgery [2]. Therefore, an important area of research is the development of quantitative methods that allow objective assessment of the depth and viability of burn wound tissue at an early stage of treatment. One approach is the use of instrumental technologies based on recording the structural, optical, and hemodynamic characteristics of injured tissue [3–6]. A wide range of additional diagnostic methods has been proposed to complement conventional clinical assessment of burn depth, including histological examination of biopsy specimens, photographic documentation with digital image analysis,

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infrared thermography, indocyanine green angiography, laser Doppler techniques for assessing microcirculation, and ultrasound examination of tissue. These technologies provide additional objective information on the structural condition of tissue, its perfusion, and microcirculation, which may improve the accuracy of burn depth assessment and of predicting the viability of injured tissue.

Thus, the need for objective early assessment of tissue viability justifies further study of near-infrared spectroscopy in burn care. Quantitative recording of regional tissue oxygenation may be considered an additional tool for assessing the depth of thermal injury and could potentially guide subsequent surgical management. The use of near-infrared spectroscopy to assess burn depth has been described previously [7–9], and patented approaches to diagnosing burn wound depth have also been proposed [10].

The objective of this study was to determine the prognostic value of regional tissue oxygenation of the burn wound before and after necrectomy for predicting split-thickness skin autograft take.

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METHODS

This prospective single-center observational study was conducted at the Department of Thermal Injuries of the Saint Petersburg I. I. Dzhanelidze Research Institute of Emergency Medicine in 2025–2026. The study protocol was approved by the Local Ethics Committee of the Saint Petersburg I. I. Dzhanelidze Research Institute of Emergency Medicine (Ethics Committee approval, protocol No. 1-02, dated February 11, 2025). The study was conducted in accordance with the ethical principles of the World Medical Association Declaration of Helsinki (2024 revision). All participants provided written informed consent before enrollment. The study included 68 patients of both sexes with skin burns. The distribution of cases by burn etiology

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is presented in Table 1, and the characteristics of the study sample in Table 2.

Examination of the burn wound started at the periphery, corresponding to the zone of superficial injury, after which the sensor was moved sequentially toward the deeper areas of the wound. At each site, after signal stabilization, regional tissue oxygenation values were recorded, characterizing local tissue oxygenation along the sensor path.

All patients underwent serial monitoring of regional tissue oxygenation by near-infrared spectroscopy (NIRS). Regional hemoglobin oxygen saturation (rSO_2, %) was recorded as the quantitative measure of tissue oxygenation.

Measurements of rSO_2 were obtained in the burn wound area at different stages of surgical treatment, including in the prepared wound bed after necrectomy. To determine the prognostic value of regional tissue oxygenation, post-necrectomy rSO_2 values were compared with subsequent split-thickness skin autograft take. The analysis was performed according to the rSO_2 ranges recorded in the prepared wound bed.

Inclusion criteria:

- thermal burn; time from injury to enrollment no more than 5 days;
- burn extent: superficial burns covering ≥30% and deep burns covering ≥10% of the total body surface area (TBSA);
- age 18–55 years;
- planned surgical necrectomy; for the prognostic analysis, free skin autografting performed during the same operation.

Exclusion criteria:

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- diseases of the central or peripheral nervous system;
- clinically significant cardiovascular or peripheral arterial disease;
- use of vasopressors or vasodilators at the time of measurement;
- inhalation injury, hypoxemia, or carbon monoxide or combustion product poisoning;
- inability to obtain a stable NIRS signal in the study area.

Regional tissue oximetry protocol

Regional tissue oxygenation was assessed by NIRS using a somatic sensor of the INVOS 5100C system (Medtronic, Minneapolis, MN, USA). Regional hemoglobin oxygen saturation (rSO_2, %) was recorded as the quantitative measure. Measurements were performed sequentially in the burn area under study, on visually intact skin on the burned side, and on a symmetrical area of intact skin on the contralateral side. The sensor was placed in firm contact with the skin surface without excessive compression of the underlying tissue. The rSO_2 value was recorded after signal stabilization; recording at each measurement point lasted at least 20 s.

Depending on the clinically presumed burn depth, the study sites were classified into the following categories: S, superficial burn; M, intermediate-depth burn; D, deep burn. In addition, measurements were performed on visually intact skin on the burned side (NB) and on a symmetrical area of intact skin on the contralateral side (H) (Table 3).

The rSO_2 value recorded at site H was used as the individual reference level. To quantify the change in regional tissue oxygenation at the study site relative to the individual reference, the difference in rSO_2 values was calculated in percentage points:

$$\Delta rSO_2 = rSO_2(\text{study site}) - rSO_2(H),$$

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where rSO_2(study site) is the regional hemoglobin oxygen saturation recorded at site S, M, D, or NB, and rSO_2(H) is the rSO_2 value recorded on the symmetrical area of intact skin on the contralateral side.

A negative ΔrSO_2 value indicated lower regional tissue oxygenation at the study site than the individual reference level, a value of zero indicated no difference, and a positive value indicated a higher rSO_2 than in the intact contralateral skin.

Surgical treatment and outcome assessment

Surgical necrectomy was performed in stages until clinical signs of tissue viability were achieved and a wound bed suitable for skin autografting was prepared. After each excision step, rSO_2 was recorded at the center of the prepared wound bed. The values obtained were compared with the individual reference rSO_2 level recorded on the symmetrical area of intact contralateral skin (H), and ΔrSO_2 was calculated as described above.

After completion of necrectomy, once the clinical criteria of wound bed readiness had been met, free skin autografting with a split-thickness skin autograft was performed.

The outcome of skin autografting was assessed on postoperative day 5. Graft take was defined as the viable skin autograft area as a percentage of the total grafted area. A five-point scale was used for standardization: 90–100%, 5 points; 80–89%, 4 points; 70–79%, 3 points; 60–69%, 2 points; <60%, 1 point. For the analysis, outcomes were grouped into three predefined clinical categories: favorable outcome, 4–5 points (graft take ≥80%); partial graft take, 2–3 points (60–79%); unfavorable outcome, 1 point (<60%).

Skin autograft take was compared with the rSO_2 values of the prepared wound bed recorded

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after completion of necrectomy to assess the relationship between regional tissue oxygenation and the outcome of skin autografting.

Statistical analysis

Statistical analysis was performed for 68 patients. Categorical variables are presented as absolute frequencies and proportions (%); two-sided exact Clopper–Pearson 95% confidence intervals (CI) were calculated for proportions. To test the main hypothesis of an association between the rSO_2 category of the prepared wound bed (<55%, 55–60%, >60%) and the outcome category of skin autografting (unfavorable, partial graft take, favorable), a 3 × 3 contingency table was constructed and the Fisher–Freeman–Halton test was applied. The p-value was calculated by complete exact enumeration of all 3 × 3 tables with fixed marginal totals (2,420 tables in total) based on the multivariate hypergeometric distribution; no permutation or Monte Carlo approximations were used. The level of statistical significance was set at $\alpha = 0.05$. For the rSO_2 threshold of <55%, the sensitivity and specificity for detecting an unfavorable outcome were also calculated with exact Clopper–Pearson 95% CI. Calculations were performed in Python: the exact p-value with a custom complete-enumeration script, and the confidence intervals with SciPy version 1.17.0.

The rSO_2 threshold of <55% was considered a research criterion for an unfavorable outcome and was not used in isolation to determine the extent of necrectomy or to decide on skin autografting. The optimal cut-off value was not selected retrospectively from the data of this sample. rSO_2 values were interpreted together with the clinical assessment of the wound bed. Pre-necrectomy measurements and ΔrSO_2 calculation were performed as part of the study protocol; however, the present analysis of the prognostic relationship used the rSO_2 values of the prepared wound bed after completion of necrectomy.

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RESULTS

The analysis included 68 patients. The cause of the burn was flame in 34 (50.0%; 95% CI 37.6–62.4%), scald in 30 (44.1%; 95% CI 32.1–56.7%), and contact in 4 (5.9%; 95% CI 1.6–14.4%) patients. Descriptive comparison of post-necrectomy wound bed rSO_2 ranges with the outcomes of free skin autografting yielded the distribution presented in Table 4.

At rSO_2 <55%, an unfavorable outcome of skin autografting was observed in 9 patients; at rSO_2 55–60%, partial graft take was recorded in 10 patients; and at rSO_2 >60%, a favorable outcome was observed in 49 patients. In the 3 × 3 contingency table, all observations fell on the diagonal of the corresponding categories. The association between the rSO_2 category and the outcome of skin autografting was statistically significant (Fisher–Freeman–Halton exact test, $p < 0.0001$). For the rSO_2 threshold of <55%, the sensitivity for detecting an unfavorable outcome was 100% (9/9; 95% CI 66.4–100%) and the specificity was 100% (59/59; 95% CI 93.9–100%). These estimates of diagnostic accuracy should be interpreted with caution given the small number of unfavorable outcomes and the lack of external validation.

Thus, in the study sample, the rSO_2 category of the prepared wound bed was significantly associated with the category of skin autograft take.

DISCUSSION

This study found a statistically significant association between the rSO_2 category of the wound bed prepared by necrectomy and the category of subsequent split-thickness skin autograft take. Unfavorable outcomes were recorded at rSO_2 <55%, partial graft take at 55–60%, and favorable outcomes at >60%. The exact concordance of categories in this sample resulted in high estimates of the diagnostic performance of the <55% threshold; however, the small number of

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unfavorable outcomes and the single-center design limit the precision and generalizability of these estimates.

These findings are consistent with current research on the instrumental assessment of burn wounds. In a clinical study, Kim et al. [8] showed that functional near-infrared spectroscopy can distinguish burn areas of different depth from intact skin. Yin et al. [9] demonstrated in an experimental model that burn depth can be quantified by NIRS. In the studies by Schulz et al. [4], Promny et al. [5], and Korzeniowski et al. [6], objective optical and perfusion-based methods were used to assess burn depth, tissue viability, and healing potential. Zinoviev et al. [2] related the outcome of skin grafting to microcirculation parameters of the burn wound. Unlike these approaches, the present study focused on the rSO_2 of the wound bed already prepared by necrectomy and its association with subsequent autograft take. This extends the potential application of tissue oximetry from assessing burn depth to assessing wound bed readiness, but requires independent prospective confirmation.

Using a symmetrical contralateral area of intact skin as an individual reference may help account for interindividual differences in tissue oxygenation. However, the comparability of measurements may be affected by soft tissue thickness, the severity of edema, the anatomical location of the injury, limb position, and other local factors. Therefore, standardization of rSO_2 recording conditions is essential for improving the reproducibility of the method.

Of particular interest is the serial assessment of tissue oxygenation before and after removal of the burn eschar. Repeat rSO_2 recording after necrectomy may reflect changes in tissue perfusion and the extent to which a viable wound bed has been prepared. A promising direction for further research is the assessment of the absolute rSO_2 value in combination with its change relative to the baseline value and the contralateral reference (ΔrSO_2).

These results suggest that rSO_2 may be considered a potential additional objective indicator of

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wound bed condition and of the prognosis of skin autograft take. However, the identified ranges, including an rSO_2 value of <55%, should not be regarded as a stand-alone criterion for changing surgical strategy until they have been prospectively validated.

Thus, the results of this study indicate the potential of regional tissue oximetry for the comprehensive assessment of the wound bed prepared by necrectomy. The method may help objectify the assessment of tissue viability and identify patients at increased risk of an unfavorable outcome of skin autografting.

The method for assessing tissue viability and predicting the outcomes of free skin autografting developed on the basis of this regional oximetry principle is protected by Russian Federation Patent No. 2868607, "Method for predicting the outcomes of free skin autografting with a split-thickness skin graft in the treatment of deep burns" (application No. 2025127925 of October 8, 2025; Zinoviev E.V., Dzeranov V.Z., et al.) [11].

The effect of somatic oximetry on the rate of repeat surgical interventions was not assessed in this observational study.

The clinical benefit of oximetry-guided changes in management should be tested in a separate study.

The threshold values should be regarded as preliminary and interpreted together with the clinical assessment of the wound bed.

Proposed practical algorithm

1. Baseline assessment.

Before necrectomy, rSO_2 is recorded in the central zone of the presumed deep burn. To determine the individual reference level, rSO_2 is simultaneously recorded on a symmetrical area

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of intact skin.

2. Intraoperative monitoring.

After removal of the burn eschar, rSO_2 of the prepared wound bed is recorded again in the same anatomical zone once the device readings have stabilized. In staged necrectomy, the measurement should be repeated after each stage of excision of nonviable tissue.

3. Assessment of changes in regional tissue oxygenation.

The post-necrectomy rSO_2 value is compared with the baseline value in the burn area and with the individual contralateral reference. An increase in rSO_2 after removal of nonviable tissue indicates improved regional tissue oxygenation of the prepared wound bed.

4. Interpretation of results.

According to the results of this study, wound bed rSO_2 values >60% are associated with a favorable outcome of skin autografting. The 55–60% range should be regarded as borderline, associated with partial skin autograft take and a possible need for additional treatment. In the study sample, rSO_2 values <55% were associated with an unfavorable outcome of skin autografting; individual risk assessment requires analysis of primary data and external validation.

5. Surgical decision-making.

The rSO_2 value should be used as an additional objective criterion for assessing the viability of the prepared wound bed, together with clinical signs of its readiness for skin autografting. Until the identified thresholds have been prospectively validated, decisions to extend necrectomy, perform additional tissue excision, or change the timing of skin autografting should not be based solely on the rSO_2 value.

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6. Assessment of skin autografting outcome.

The outcome of free skin autografting is assessed on postoperative day 5 as the viable, adherent skin autograft area as a percentage of the total grafted area, using a single standardized assessment approach.

Limitations. This single-center study included only 68 patients, with 9 unfavorable outcomes. The observed complete concordance between rSO_2 categories and outcomes may lead to overestimation of diagnostic performance in the study sample. External validation, multivariable adjustment for potential confounders, and analysis of measurement reproducibility were not performed. Therefore, the sensitivity and specificity of the <55% threshold should be regarded as estimates for this sample rather than as a definitively validated diagnostic threshold.

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CONCLUSION

Regional tissue oximetry allows objective assessment of the wound bed prepared by necrectomy and may be used as an additional instrumental method in patients with deep burns.

A statistically significant association was found between the regional tissue oxygenation category of the prepared wound bed and the outcome of subsequent free skin autografting (Fisher–Freeman–Halton exact test, $p < 0.0001$). In the study sample, rSO_2 <55% corresponded to unfavorable outcomes, 55–60% to partial graft take, and >60% to favorable outcomes.

In this sample, the rSO_2 threshold of <55% had a sensitivity of 100% (95% CI 66.4–100%) and a specificity of 100% (95% CI 93.9–100%) for detecting an unfavorable outcome. These values require confirmation in an independent prospective sample.

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Post-necrectomy rSO_2 measurement complements the clinical assessment of the wound bed and may be used as part of a comprehensive approach to determining its readiness for free skin autografting. The use of the identified thresholds as stand-alone criteria for surgical decision-making requires further prospective validation.

ETHICS APPROVAL

The study protocol was approved by the Local Ethics Committee of the Saint Petersburg I. I. Dzhanelidze Research Institute of Emergency Medicine (Ethics Committee approval, protocol No. 1-02, dated February 11, 2025). The study was conducted in accordance with the World Medical Association Declaration of Helsinki (2024 revision). All participants provided written informed consent to participate in the study.

DATA AVAILABILITY

The availability of de-identified primary data is determined by the research team and the requirements of the local ethics committee.

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Table 1. Distribution of cases by burn etiology

Burn etiology	n	Proportion, %	95% CI, %
Flame	34	50	37.6–62.4
Scald	30	44.1	32.1–56.7
Contact	4	5.9	1.6–14.4
Total	68	100	—

CI – confidence interval (exact Clopper–Pearson method)

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Table 2. Characteristics of the study sample

Characteristic	**Value**
Number of patients, n	68
Age, years (inclusion criterion)	18–55
Sex, male/female, n (%)	38 (55.9) / 30 (44.1)
Superficial burn area, % TBSA (inclusion criterion)	≥ 30
Deep burn area, % TBSA (inclusion criterion)	≥ 10
Study period	March 2025 – March 2026

TBSA – total body surface area; for age and burn area, the limits defined by the inclusion criteria are shown

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Table 3. Stages of regional tissue oxygenation assessment of the burn wound

Study stage	Measurement site	Parameter and purpose
Before necrectomy	S, M, D, NB, H	Recording of baseline rSO_2 values according to the clinically presumed burn depth; determination of the individual reference level
After necrectomy	Prepared wound bed, H	Recording of rSO_2 in the prepared wound bed; calculation of ΔrSO_2 relative to the individual contralateral reference
After skin autografting, postoperative day five	Skin autograft area	Assessment of the skin autograft take area and comparison with the post-necrectomy wound bed rSO_2 value

S – superficial burn; M – intermediate-depth burn; D – deep burn; NB – visually intact skin on the burned side; H – symmetrical area of intact skin on the contralateral side; rSO_2 – regional hemoglobin oxygen saturation; ΔrSO_2 – difference between the rSO_2 value at the study site and the individual reference rSO_2(H) value

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Table 4. Contingency table of rSO_2 categories and skin autografting outcomes

Post-necrectomy rSO_2, %	Unfavorable outcome, n	Partial graft take, n	Favorable outcome, n	Total, n
< 55	9	0	0	9
55–60	0	10	0	10
> 60	0	0	49	49
Total	9	10	49	68

rSO_2 – regional hemoglobin oxygen saturation; the association between categories is statistically significant (Fisher–Freeman–Halton exact test, $p < 0.0001$)

Paper accepted

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