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Integration of CTA Run-off Score and Systemic Resuscitation Indices to Predict Outcomes in Emergency Lower Extremity Flap Reconstruction: A Retrospective Cohort Study

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AIM: Reconstruction of severe lower extremity trauma with extensive soft tissue defects remains a major microsurgical concern. Unlike elective procedures, emergency reconstruction is plagued by higher rates of necrosis and failure. Current preoperative assessments predominantly focus on local vascular patency, often neglecting systemic physiological disturbances. This gap in the assessment process highlights the need to incorporate whole-body resuscitation indicators. This study aimed to evaluate the predictive value of combining a modified computed tomography angiography (CTA) Run-off Score with systemic resuscitation indices—specifically Central Venous Oxygen Saturation (ScvO2) and preoperative lactate (Lac_Pre)—for emergency flap prognosis.

METHODS: A retrospective cohort study was conducted on 180 patients undergoing emergency free flap transfer for high-energy lower limb trauma between February 1, 2022, and March 31, 2025. Systemic monitoring involved ScvO2 measurement via central venous catheterization and serial lactate analysis. Anatomical assessment included a modified CTA Run-off Score and the measurement of the distance from injury zone to anastomosis site (Dist_Anastomosis). The dataset was divided into the training and validation sets at a 6:4 ratio, which does not represent random clinical allocation. A multivariate logistic regression model was built in the training cohort, with candidate predictors selected based on univariable analyses, collinearity assessment and the clinical relevance supported by previous literature. The model's performance was evaluated through discrimination (Area Under the Curve [AUC]), calibration (calibration curve), and clinical utility (decision curve analysis). For the secondary aesthetic analysis, a total of 163 patients were ultimately included in the 6-month VISIA/Vancouver Scar Scale (VSS)-based analysis after excluding patients with complete flap failure, for whom scar-based assessment was not applicable.

RESULTS: Multivariate logistic regression analysis identified three variables independently associated with flap failure: CTA Run-off Score ($p < 0.001$), Dist_Anastomosis (Odds Ratio [OR] 0.76, $p = 0.006$), and preoperative lactate (Lac_Pre; OR 1.54, $p = 0.014$). The combined prognostic model demonstrated acceptable to good discrimination, with an Area Under the Curve (AUC) of 0.89 (95% Confidence Interval [CI]: 0.82–0.97) in the training set and 0.79 (95% CI: 0.66–0.92) in the validation set. Calibration analysis, assessed via the Brier Score, yielded values of 0.103 for the training set and 0.165 for the validation set, indicating acceptable predictive error and robust model calibration. Secondary analysis revealed that flaps experiencing early adverse events showed significantly higher VISIA-7 Complexion Analysis System–derived "Redness Index" scores at 6 months after surgery ($p = 0.006$).

CONCLUSIONS: Integrating anatomical characteristics and perioperative physiological indicators may provide a useful approach for risk stratification in emergency reconstruction. In this internally validated retrospective cohort, preoperative lactate demonstrated a significant association with adverse acute flap outcomes and should be interpreted as a stratification marker rather than a definitive predictor. Further prospective studies with external validation are required to confirm these findings and evaluate functional recovery outcomes.

Keywords: free tissue flaps; shock; traumatic; computed tomography angiography; esthetics

Introduction

Severe lower extremity trauma resulting from high-energy events such as road traffic accidents or industrial crush injuries poses a major challenge in contemporary reconstructive microsurgery. Although advances in osteosynthesis and critical care have enhanced overall trauma management, extensive soft tissue defects along with exposed neurovascular structures remain a key barrier to successful limb salvage [1,2]. Free flap transfer is widely recognized as a

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primary approach for reconstruction of such complex defects, as it offers robust, well-vascularized tissue that facilitates fracture healing and helps control local infection [3]. In elective transplantation methods, the flap survival rates usually reach 90%. In contrast, emergency reconstruction conducted in acute trauma results in a significantly higher risk of complications. Such a traumatic local environment, characterized by tissue damage, contamination, and vascular instability, increases the risk of partial necrosis, vascular thrombosis, and complete flap failure. Under these adverse circumstances, reported failure rates range from about 10% to 20% [4,5].

The disparity in outcomes observed between elective and emergency approaches suggests that trauma reconstruction occurs within a distinct pathophysiological framework [6]. In routine clinical practice, preoperative assessments predominantly emphasize local anatomical conditions, particularly the patency and quality of recipient blood vessels. Because it offers high spatial resolution and can be conducted non-invasively, computed tomography angiography (CTA) has largely replaced traditional angiography as the primary diagnostic modality for assessing vascular status [7,8]. In vascular surgery, the "Run-off Score" has long been applied as a reliable indicator for predicting bypass graft patency; however, its quantitative application in predicting free flap survival in trauma reconstruction has not been comprehensively explored [9]. Crucially, relying exclusively on local vascular anatomy sometimes overlooks the systemic physiological disturbances that commonly occur in polytrauma patients [10].

High-energy trauma frequently leads to a condition referred to as "occult hypoperfusion", a state of compensated shock in which vital signs may appear within normal limits despite impaired microcirculatory perfusion [11,12]. The Shock Index (SI), determined as the ratio of heart rate to systolic blood pressure, has been proposed as a potential indicator of hemodynamic instability in trauma patients [13,14]. Additionally, blood lactate levels reflect the degree of cumulative anaerobic debt and have been linked to microvascular reperfusion injury [15].

This study proposes that early flap failure should not be viewed merely as technical or surgical; rather, it may indicate a "Double Hit" phenomenon, in which systemic vasoconstriction after trauma interacts with compromised venous outflow at the recipient site, collectively increasing the risk of flap failure. Hence, flap failure may be due to the combined effect of systemic and local physiological stress rather than a surgical issue. Additionally, current outcome measures primarily emphasize flap survival as the principal endpoint. While survival is crucial, this narrow perspective may often overlook long-term concerns, such as aesthetic quality and functional recovery [16]. The VISIA Analysis System, an objective, image-based tool, presents a novel method for quantifying long-term vascular sequelae after reconstruction [17].

The novelty of this study lies in bridging the gap between acute-phase systemic hemodynamic markers, such as Preoperative Lactate (Lac_Pre) and Central Venous Oxygen Saturation (ScvO2), and local anatomical parameters assessed through a modified CTA score. By integrating these parameters, this study aims to develop a more comprehensive framework for predicting surgical outcomes. The primary objective of this retrospective cohort study was to establish and internally validate a prognostic model for acute flap outcomes that integrates both anatomical and systemic indicators. A secondary objective was to explore the association between acute flap outcomes and early postoperative aesthetic results at six months, assessed using the VISIA imaging system together with a traditional scar assessment score.

Methods

Recruitment of the Study Participants

This study included 180 patients who underwent emergency free flap transfer for severe limb soft tissue defects. The dataset was divided into the training (n = 108) and validation (n = 72) sets using a 6:4 random split.

Inclusion criteria for patient selection were as follows: (1) age between 18 and 75 years; (2) high-energy lower limb trauma requires emergency free flap reconstruction; (3) preoperative CTA vascular assessment; (4) complete perioperative hemodynamic recording, including Central Venous Oxygen Saturation and blood gas measurements. Participants who meet certain exclusion criteria are excluded from the dataset: (1) pre-existing peripheral vascular disease; (2) critical associated injuries precluding safe anesthesia, such as severe traumatic brain injury requiring urgent neurosurgical intervention or persistent hemodynamic instability necessitating damage-control resuscitation or intensive care stabilization; or (3) incomplete primary outcome data, including cases in which outcome records were unavailable because of patient refusal or loss to follow-up.

Data Acquisition and Clinical Assessments

Radiological Evaluation

Preoperative CTA of the lower extremities was performed using a GE Revolution 256-slice CT scanner (GE HealthCare, Chicago, IL, USA). The scan covered the vascular region from the aortic bifurcation to the toes to allow a comprehensive assessment of both inflow and distal run-off vessels. Imaging parameters included automated tube voltage selection (100–120 kVp) with automatic tube current modulation. Detector collimation was set at 0.625 mm, and images were reconstructed at a slice thickness of 0.625 mm to obtain isotropic voxels favorable for high-quality Three-Dimensional (3D) reformation. A bolus of 100 mL non-ionic iodinated contrast (350 mgI/mL) was injected intravenously at a rate of 4.5 mL/s, followed by a 30 mL saline flush. Arterial phase imaging was achieved using a bolus-tracking method, with the region of interest positioned in the distal abdominal aorta and a trigger threshold set at 120 Hounsfield Units. All image analyses were performed on a dedicated GE AW workstation (GE HealthCare, Chicago, IL, USA).

To examine distal vessel status, a modified run-off scoring system (range 0–3) was employed. The original run-off score [9] was developed to predict bypass graft patency in chronic atherosclerotic disease. However, we modified the scoring criteria to better reflect traumatic vascular alterations commonly occurring in high-energy injuries, such as acute segmental spasm, vasospasm, and focal vessel disruption, all of which may directly affect microsurgical planning. CTA images were evaluated by two independent radiologists, and inter-rater reliability was excellent (Cohen's Kappa = 0.938). The scoring system was defined as follows: a score of 3 (excellent) indicated patent major vessels with rapid distal perfusion; a score 2 (Good) reflected patent vessels with mild wall irregularities; a score 1 (Poor) indicated segmental stenosis or vasospasm; and a score 0 (Very Poor) indicated complete occlusion or vascular discontinuity relying on sparse collateral circulation.

Physiological Monitoring

Systemic physiological status was assessed through several hemodynamic indicators. Hemodynamic stability at admission was determined using the Shock Index (SI), calculated as the ratio of heart rate to systolic blood pressure. For resuscitation and monitoring purposes, all participants underwent central venous catheter (CVC) placement in either the internal jugular or subclavian vein. Central venous blood gas samples were collected at admission (baseline) and again during the intraoperative period. ScvO2 was recorded to evaluate global tissue oxygenation. Additionally, arterial lactate levels were measured at admission and immediately before surgery (Lac_Pre) to evaluate lactate kinetics and systemic metabolic status.

Outcome Measures

Primary Outcome

The primary endpoint of the study was flap prognosis, assessed using a predefined study-specific four-grade flap prognosis grading system (Grades 0–3). Grade 0 indicated uneventful healing, Grade 1 indicated minor complications manageable with conservative treatment, Grade 2 indicated severe complications requiring salvage or surgical re-exploration, and Grade 3 indicated complete flap failure. For the primary analysis, outcomes were further dichotomized into successful outcomes (Grades 0–1) and adverse outcomes (Grades 2–3).

Secondary Outcome (Long-term Aesthetic Analysis)

At the 6-month postoperative follow-up, scar quality and vascular changes were evaluated using the VISIA-7 Complexion Analysis System (version 8.5.2; Canfield Scientific, Parsippany, NJ, USA) together with the Vancouver Scar Scale (VSS) [18]. The 6-month follow-up was selected to capture early tissue remodeling and persistent hyperemia, although final scar maturation typically occurs over a longer period, usually 12–24 months. To account for inter-patient variations in skin tone and lighting conditions, a normalized Redness Index was calculated. This index was determined as the ratio of the absolute "Red Areas" score measured in the flap or scar region to that of the corresponding score obtained from the contralateral healthy skin (Redness Index = Scar Red Score/Control Red Score).

Statistical Analysis

All statistical analyses were performed using R software (version 4.3.0; R Foundation for Statistical Computing, Vienna, Austria). The study cohort was randomly split into the training (n = 108) and validation (n = 72) sets at a 6:4 ratio for internal validation. Use the Shapiro-Wilk test to assess the normality of a continuous variable. Continuous variables were compared using either Student's *t*-test or the Mann-Whitney U test, depending on the distribution of the data. However, categorical variables were analyzed using the Chi-square or Fisher's exact tests, as appropriate.

For predictive model development, variables demonstrating statistical significance ($p < 0.05$) in the univariate logistic regression were selected as candidates for subsequent analysis. Candidate variable consideration was based not only on statistical significance but also on clinical relevance and prior literature. Multicollinearity among variables was assessed using variance inflation factors (VIFs), with values >5 indicating potential collinearity. Given the elevated VIFs for heart rate and systolic blood pressure, and their role as components of the Shock Index, only SI was retained in the multivariable model to improve model stability and interpretability. The remaining significant variables were then included in a multivariate logistic regression model to identify independent predictors of flap outcome. Sensitivity analyses were performed in the training cohort using a more permissive univariable screening threshold ($p < 0.10$) to assess the robustness of variable selection.

Model performance was evaluated in terms of discrimination, calibration, and clinical utility. Discrimination was assessed using the Area Under the Curve (AUC). Calibration was evaluated through calibration curves, with the Brier score reported as an overall indicator of prediction error. The Hosmer–Lemeshow test was also performed as a supplementary assessment of calibration. To reduce potential optimism in model estimates, bootstrap resampling (1000 iterations) was applied for internal calibration validation. Clinical utility was assessed using decision curve analysis (DCA). To enhance clinical interpretation, a nomogram was constructed based on the final model. Furthermore, Shapley Additive exPlanations (SHAP) values were calculated from the final multivariable logistic regression model and were used as an exploratory tool to visualize the relative contribution of each predictor.

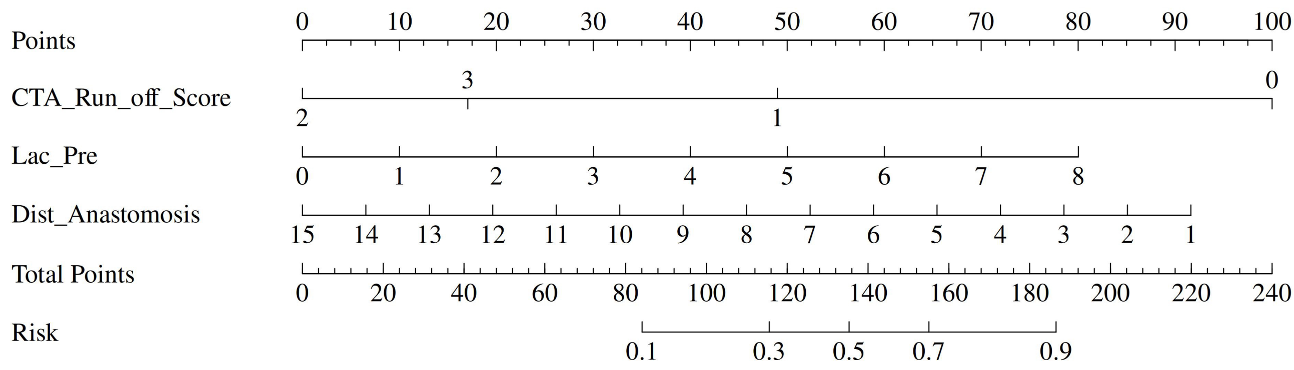

Fig. 1. Predictive nomogram for emergency trauma flap prognosis. A tool to estimate the probability of adverse flap outcomes (necrosis or vascular crisis). Locate the patient's value for each variable on the corresponding axis and draw a vertical line up to the "Points" axis to determine the score. Sum the scores for all variables to obtain the "Total Points", then draw a vertical line down to the "Risk" axis to read the predicted probability. CTA, computed tomography angiography; Lac_Pre, preoperative lactate; Dist_Anastomosis, distance from injury zone to anastomosis site.

Moreover, variations in long-term aesthetic outcomes were analyzed using the Wilcoxon-Holm method. Spearman's rank correlation was used to assess the association between the Redness Index and the VSS score. As this represented a prespecified primary correlation analysis, no additional adjustment for multiple comparisons was applied. Statistical significance was established at a two-sided p-value < 0.05.

Results

Comparison of Baseline Characteristics Between the Training and Validation Cohorts

As detailed in Table 1, the training and validation cohorts were comparable across the baseline characteristics. No significant differences were found between the two cohorts regarding Injury Severity Score (ISS), ischemia time, or baseline physiological parameters, including SI and ScvO2. These observations indicate that the random grouping method produced two comparable cohorts for further analysis.

Stratified Analysis of Prognostic Determinants

Stratifying patients according to outcome severity (Grade 0–3) revealed distinct trends across several clinical variables (Table 2).

Metabolic Status

Preoperative lactate (Lac_Pre) demonstrated the most significant difference across outcome groups. Individuals with successful outcomes (Grade 0) exhibited a median Lac_Pre of 0.75 mmol/L. Those with flap failure (Grade 3) had significantly elevated levels, with a median of 1.55 mmol/L. The patient experiencing severe complications (Grade 2) showed the highest levels, reaching a median of 3.20 mmol/L (p = 0.004).

Systemic Oxygenation

Preoperative ScvO2 differed significantly across the four flap prognosis grades (overall p = 0.010). The median ScvO2 Pre values were 76.75%, 74.70%, 74.55%, and 70.50% in Grade 0, Grade 1, Grade 2, and Grade 3, respectively, suggesting a trend toward lower systemic oxygenation with worsening flap prognosis.

Zone of Injury

Dist_Anastomosis differed significantly across the four prognosis grades (overall $p < 0.001$) and decreased progressively with worsening prognosis. Median values were 10.25 cm, 5.95 cm, 4.25 cm, and 2.85 cm for Grades 0, 1, 2, and 3, respectively.

Identification of Independent Predictors

In univariable analyses, preoperative ScvO2 showed a statistically significant association with adverse outcomes, whereas SI did not demonstrate any substantial link. However, after accounting for lactate- and anatomy-related variables in a multivariable model, the effect of ScvO2 was attenuated, and it was not retained in the final model (Table 3). The final identified three independent predictors. First, the CTA Run-off Score emerged as a protective factor, with a higher score associated with better outcomes ($p < 0.001$). Second, the Dist_Anastomosis was also a protective factor (Odds Ratio [OR] 0.76, 95% Confidence Interval [CI]: 0.62–0.92, p = 0.006), indicating that each 1 cm increase in distance from the injury zone was linked to approximately 24% reduction in the risk of flap failure. Third, preoperative lactate (Lac_Pre) was identified as a risk factor (OR 1.54, 95% CI: 1.09–2.16, p = 0.014), suggesting that each 1 mmol/L increase in preoperative lactate corresponded to an estimated 54% increase in the risk of failure.

Table 1. Comparison of baseline characteristics between the training and validation cohorts.

Variable	Total (n = 180)	Test cohort (n = 72)	Training cohort (n = 108)	Statistic	*p*-value
SBP (mmHg), Mean ± SD	136.37 ± 13.63	135.22 ± 14.58	137.13 ± 12.97	$t = -0.92$	0.359
BMI (kg/m²), Mean ± SD	25.79 ± 3.50	25.38 ± 3.33	26.06 ± 3.60	$t = -1.27$	0.206
SI, M (Q_1, Q_3)	0.82 (0.75, 1.04)	0.79 (0.72, 1.04)	0.83 (0.75, 0.94)	Z = –0.27	0.786
HR (beats/min), M (Q_1, Q_3)	106.00 (102.00, 133.50)	105.00 (102.00, 135.00)	108.50 (102.00, 133.00)	Z = –0.45	0.652
ISS, M (Q_1, Q_3)	26.00 (19.00, 34.25)	25.50 (20.00, 33.25)	27.50 (18.75, 36.00)	Z = –0.46	0.644
Hgb (g/dL), M (Q_1, Q_3)	10.90 (9.70, 11.60)	10.80 (9.97, 11.43)	11.00 (9.47, 11.60)	Z = –0.32	0.752
Ischemia Time (min), M (Q_1, Q_3)	158.00 (150.00, 175.00)	160.00 (152.50, 176.75)	158.00 (148.75, 172.00)	Z = –1.19	0.234
Op time (min), M (Q_1, Q_3)	415.00 (402.00, 435.00)	414.00 (403.50, 435.00)	416.50 (401.75, 431.50)	Z = –0.19	0.848
Lac_Init (mmol/L), M (Q_1, Q_3)	1.50 (1.10, 3.00)	1.55 (1.08, 2.60)	1.50 (1.10, 3.35)	Z = –0.68	0.498
Lac_Pre (mmol/L), M (Q_1, Q_3)	1.25 (0.60, 3.02)	1.30 (0.60, 3.10)	1.05 (0.60, 2.70)	Z = –0.64	0.524
ScvO2 Pre (%), M (Q_1, Q_3)	75.35 (70.77, 77.62)	75.45 (70.38, 77.53)	75.20 (70.97, 77.70)	Z = –0.14	0.887
ScvO2 Intra (%), M (Q_1, Q_3)	72.45 (68.57, 74.93)	72.30 (68.50, 74.82)	72.55 (68.60, 75.00)	Z = –0.65	0.519
Alarms (n), M (Q_1, Q_3)	1.00 (0.00, 1.00)	1.00 (0.00, 1.00)	1.00 (0.00, 1.00)	Z = –1.20	0.232
Dist_Anastomosis (cm), M (Q_1, Q_3)	6.45 (4.40, 9.90)	6.10 (4.50, 9.45)	6.55 (4.18, 10.03)	Z = –0.07	0.941
Smoking, n (%)				$\chi^2 = 0.63$	0.429
No	89 (49.44)	33 (45.83)	56 (51.85)		
Yes	91 (50.56)	39 (54.17)	52 (48.15)		
Diabetes, n (%)				$\chi^2 = 1.08$	0.299
No	154 (85.56)	64 (88.89)	90 (83.33)		
Yes	26 (14.44)	8 (11.11)	18 (16.67)		
CTA Run-off Score, n (%)				$\chi^2 = 3.49$	0.322
Very Poor	28 (15.56)	12 (16.67)	16 (14.81)		
Poor	23 (12.78)	13 (18.06)	10 (9.26)		
Good	60 (33.33)	21 (29.17)	39 (36.11)		
Excellent	69 (38.33)	26 (36.11)	43 (39.81)		
Flap Type, n (%)				$\chi^2 = 0.13$	0.715
Fasciocutaneous	87 (48.33)	36 (50.00)	51 (47.22)		
Muscle/myocutaneous	93 (51.67)	36 (50.00)	57 (52.78)		
Anast type, n (%)				$\chi^2 = 0.05$	0.828
End-to-end	139 (77.22)	55 (76.39)	84 (77.78)		
End-to-side	41 (22.78)	17 (23.61)	24 (22.22)		
OUT multi class, n (%)				$\chi^2 = 0.76$	0.858
Uneventful healing	49 (27.22)	21 (29.17)	28 (25.93)		
Minor complication	82 (45.56)	30 (41.67)	52 (48.15)		
Severe complication requiring salvage	32 (17.78)	14 (19.44)	18 (16.67)		
Flap failure	17 (9.44)	7 (9.72)	10 (9.26)		
OUT binary, n (%)				$\chi^2 = 0.23$	0.632
Success (Uneventful healing and minor complication)	131 (72.78)	51 (70.83)	80 (74.07)		
Adverse (Severe complication requiring salvage and flap failure)	49 (27.22)	21 (29.17)	28 (25.93)		

Note: Data are presented as Mean ± Standard Deviation (SD) for normally distributed continuous variables, Median (Interquartile Range) [M (Q_1, Q_3)] for non-normally distributed variables, or frequency (percentage) for categorical variables. *p*-values were calculated using the independent Student's *t*-test (*t*) for normal distributions, the Mann-Whitney U test (Z) for skewed distributions, and the Chi-square test (χ^2) for categorical data. There were no statistically significant differences between the two cohorts ($p > 0.05$), indicating good comparability.

Abbreviations: SBP, Systolic Blood Pressure; BMI, Body Mass Index; SI, Shock Index; HR, heart rate; ISS, Injury Severity Score; Hgb, Hemoglobin; ScvO2, Central Venous Oxygen Saturation; CTA, computed tomography angiography; OUT, outcome; Op, Operative; Pre, Preoperative; Intra, Intraoperative; Init, Initial.

Table 2. Comparison of clinical and operative variables stratified by flap prognosis severity in the training cohort (n = 108).

Variable	Total (n = 108)	Grade 0 (n = 28)	Grade 1 (n = 52)	Grade 2 (n = 18)	Grade 3 (n = 10)	Statistic	*p*-value
SBP (mmHg), Mean ± SD	137.13 ± 12.97	135.89 ± 11.86	137.10 ± 12.48	136.67 ± 13.91	141.60 ± 17.37	F = 0.48	0.696
BMI (kg/m^2), Mean ± SD	26.06 ± 3.60	24.84 ± 3.11	27.24 ± 3.66	24.98 ± 3.13	25.26 ± 3.90	F = 3.93	0.011
SI, M (Q_1, Q_3)	0.83 (0.75, 0.94)	0.79 (0.75, 0.91)	0.83 (0.75, 0.91)	0.96 (0.75, 1.08)	0.77 (0.65, 1.03)	H = 4.45	0.217
HR (beats/min), M (Q_1, Q_3)	108.50 (102.00, 133.00)	104.00 (102.00, 124.00)	114.00 (102.00, 133.00)	131.50 (104.25, 139.00)	104.00 (104.00, 127.75)	H = 6.06	0.109
ISS, M (Q_1, Q_3)	27.50 (18.75, 36.00)	18.50 (14.00, 30.00)	29.00 (21.00, 37.00)	25.50 (18.25, 27.75)	37.50 (32.25, 42.00)	H = 18.34	<0.001
Hgb (g/dL), M (Q_1, Q_3)	11.00 (9.47, 11.60)	11.85 (10.28, 12.57)	11.00 (9.40, 11.50)	10.65 (9.47, 11.07)	10.45 (9.17, 11.40)	H = 9.53	0.023
Ischemia time (min), M (Q_1, Q_3)	158.00 (148.75, 172.00)	150.50 (145.75, 161.50)	161.50 (151.75, 177.25)	157.50 (147.00, 162.00)	163.00 (152.00, 183.50)	H = 6.89	0.076
Op time (min), M (Q_1, Q_3)	416.50 (401.75, 431.50)	406.00 (397.75, 424.00)	421.50 (405.75, 438.25)	416.50 (403.25, 419.00)	420.50 (407.75, 442.50)	H = 5.13	0.162
Lac_Init (mmol/L), M (Q_1, Q_3)	1.50 (1.10, 3.35)	0.95 (0.67, 1.95)	1.50 (1.10, 3.00)	3.90 (1.57, 5.10)	3.35 (2.40, 5.10)	H = 24.54	<0.001
Lac_Pre (mmol/L), M (Q_1, Q_3)	1.05 (0.60, 2.70)	0.75 (0.50, 1.15)	0.85 (0.60, 2.07)	3.20 (1.30, 4.88)	1.55 (0.80, 3.30)	H = 13.42	0.004
ScvO2 Pre (%), M (Q_1, Q_3)	75.20 (70.97, 77.70)	76.75 (74.97, 78.55)	74.70 (71.15, 77.60)	74.55 (69.62, 76.45)	70.50 (69.75, 74.28)	H = 11.42	0.010
ScvO2 Intra (%), M (Q_1, Q_3)	72.55 (68.60, 75.00)	74.60 (71.88, 76.40)	72.00 (68.42, 74.70)	72.05 (68.58, 73.83)	69.70 (68.53, 73.02)	H = 8.71	0.033
Alarms (n), M (Q_1, Q_3)	1.00 (0.00, 1.00)	0.00 (0.00, 1.00)	1.00 (0.00, 1.00)	1.00 (0.00, 4.00)	0.00 (0.00, 4.00)	H = 6.04	0.110
Dist_Anastomosis (cm), M (Q_1, Q_3)	6.55 (4.18, 10.03)	10.25 (9.00, 11.98)	5.95 (4.47, 7.60)	4.25 (3.55, 6.33)	2.85 (2.05, 4.88)	H = 36.07	<0.001
Smoking, n (%)						H = 22.54	<0.001
No	56 (51.85)	25 (89.29)	19 (36.54)	9 (50.00)	3 (30.00)		
Yes	52 (48.15)	3 (10.71)	33 (63.46)	9 (50.00)	7 (70.00)		
Diabetes, n (%)						-	0.003
No	90 (83.33)	28 (100.00)	37 (71.15)	16 (88.89)	9 (90.00)		
Yes	18 (16.67)	0 (0.00)	15 (28.85)	2 (11.11)	1 (10.00)		
CTA Run-off Score, n (%)						-	<0.001*
Very Poor	16 (14.81)	1 (3.57)	2 (3.85)	9 (50.00)	4 (40.00)		
Poor	10 (9.26)	2 (7.14)	4 (7.69)	2 (11.11)	2 (20.00)		
Good	39 (36.11)	9 (32.14)	26 (50.00)	2 (11.11)	2 (20.00)		
Excellent	43 (39.81)	16 (57.14)	20 (38.46)	5 (27.78)	2 (20.00)		
Flap type, n (%)						H = 27.70	<0.001
Fasciocutaneous	51 (47.22)	24 (85.71)	20 (38.46)	7 (38.89)	0 (0.00)		
Muscle/Myocutaneous	57 (52.78)	4 (14.29)	32 (61.54)	11 (61.11)	10 (100.00)		
Anast type, n (%)						-	<0.001
End-to-End	84 (77.78)	28 (100.00)	51 (98.08)	5 (27.78)	0 (0.00)		
End-to-Side	24 (22.22)	0 (0.00)	1 (1.92)	13 (72.22)	10 (100.00)		

Note: Patients were stratified into four prognostic grades: Grade 0 (Success), Grade 1 (Minor Complication), Grade 2 (Severe Complication/Salvage), and Grade 3 (Failure). Significance was tested using One-way analysis of variance (ANOVA, F) for normally distributed data, Kruskal-Wallis H test (H) for non-normally distributed data, and Chi-square test (χ^2) or Fisher's exact test (-) for categorical variables. *Indicates *p*-values derived using Monte Carlo simulation due to sparse data cells. CTA Run-off Score was treated as an ordinal variable ranging from 0 to 3.

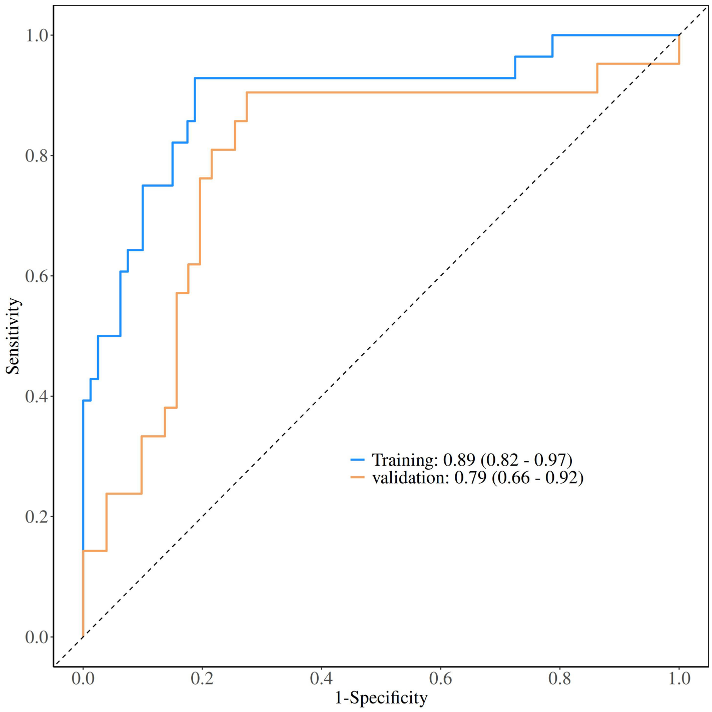

Fig. 2. Performance of the predictive model. Receiver operating characteristic (ROC) curves for the training cohort (blue line) and the validation cohort (orange line). The Area Under the Curve (AUC) was 0.89 (95% Confidence Interval [CI]: 0.82–0.97) in the training set and 0.79 (95% CI: 0.66–0.92) in the validation set, indicating acceptable to good discriminative performance.

In sensitivity analyses using a more permissive screening threshold ($p < 0.10$), Body Mass Index (BMI) entered the multivariable model but did not reach statistical significance ($p = 0.065$). Notably, the core predictors and the pattern of their effect remained unchanged, reinforcing the stability of the final model (**Supplementary Table 1**).

Model Performance and Visualization

The nomogram (Fig. 1), which integrates these three variables, exhibited strong predictive performance. In the training cohort, the mode demonstrated strong discrimination, yielding an AUC of 0.89 (95% CI: 0.82–0.97). In the validation cohort, the AUC was 0.79 (95% CI: 0.66–0.92), suggesting consistent predictive power across datasets (Fig. 2). Calibration analysis further reinforced the accuracy of the model. The Brier scores were 0.103 for the training cohort and 0.165 for the validation cohort, indicating acceptable levels of predictive error and agreement between predicted and observed outcomes (Fig. 3). Additionally, the clinical utility of the model was evaluated using DCA (Fig. 4), which confirmed that the model offers a superior net benefit compared to strategies based on treating all patients or treating none. Model interpretability was further explored using SHAP analysis (Fig. 5), which revealed that the CTA run-off score primarily determines the baseline risk, while Dist_Anastomosis and Lac_Pre provide essential individualized adjustments to the overall risk estimates.

Long-term Aesthetic Outcomes

VISIA and VSS assessments at the 6-month follow-up were available for 163 patients. Patients who experienced complete flap failure (outcome Grade 3) were excluded from the long-term aesthetic analysis because scar evaluation was not applicable in these cases. At the 6-month follow-up, VISIA-7 analysis revealed significant differences between outcome groups. The Redness Index, derived from VISIA-7 analysis, was substantially higher in patients who experienced adverse postoperative courses compared to the uneventful healing group, even among salvaged flaps ($p < 0.05$, Fig. 6A). Furthermore, a modest but statistically significant positive correlation was observed between the objective Redness Index and the subjective VSS vascularity score (Spearman $\rho = 0.238$, $p = 0.002$, Fig. 6B), indicating concordance between objective optical assessment and clinical scar evaluation.

Discussion

This study identifies critical determinants of emergency flap failure by integrating both anatomical features and systemic metabolic indicators. Our findings challenge the sole reliance on vascular patency. By analyzing 180 cases, we identified a prognostic triad: the CTA Run-off Score, the distance from the injury zone to the anastomosis site, and preoperative lactate levels.

Our results support the established concept of the "Zone of Injury" risk and provide a more objective and quanti-

Table 3. Univariate and multivariate logistic regression analysis for predictors of adverse flap outcomes.

Variable	Univariate					Multivariate				
	β	S.E	Z	*p*-value	OR (95% CI)	β	S.E	Z	*p*-value	OR (95% CI)
Smoking, n (%)										
No					1.00 (Reference)					
Yes	0.49	0.44	1.10	0.270	1.63 (0.68∼3.88)					
Diabetes, n (%)										
No					1.00 (Reference)					
Yes	–0.65	0.67	–0.97	0.333	0.52 (0.14∼1.95)					
CTA Run-off Score, n (%)										
Very Poor					1.00 (Reference)					1.00 (Reference)
Poor	–1.87	0.91	–2.06	0.040	0.15 (0.03∼0.91)	–2.19	1.09	–2.01	0.044	0.11 (0.01∼0.95)
Good	–3.64	0.83	–4.38	<0.001	0.03 (0.01∼0.13)	–4.29	1.04	–4.13	<0.001	0.01 (0.00∼0.11)
Excellent	–3.10	0.76	–4.07	<0.001	0.04 (0.01∼0.20)	–3.56	0.91	–3.92	<0.001	0.03 (0.00∼0.17)
SI	2.18	1.43	1.53	0.126	8.86 (0.54∼145.32)					
BMI	–0.11	0.06	–1.65	0.099	0.90 (0.79∼1.02)					
ISS	0.03	0.02	1.37	0.171	1.03 (0.99∼1.08)					
Hgb	–0.28	0.16	–1.73	0.084	0.76 (0.56∼1.04)					
Ischemia time	0.01	0.01	0.92	0.357	1.01 (0.99∼1.04)					
Op time	0.00	0.01	0.32	0.746	1.00 (0.98∼1.03)					
Lac_Init	0.50	0.13	3.75	<0.001	1.64 (1.27∼2.13)					
Lac_Pre	0.39	0.13	3.10	0.002	1.48 (1.16∼1.90)	0.43	0.17	2.46	0.014	1.54 (1.09∼2.16)
ScvO2 Pre	–0.15	0.06	–2.59	0.010	0.86 (0.76∼0.96)					
ScvO2 Intra	–0.03	0.03	–0.96	0.335	0.97 (0.92∼1.03)					
Alarms	0.05	0.03	1.36	0.174	1.05 (0.98∼1.12)					
Dist_Anastomosis	–0.26	0.08	–3.24	0.001	0.77 (0.66∼0.90)	–0.28	0.10	–2.72	0.006	0.76 (0.62∼0.92)

Note: The outcome variable was binary (Success [Grades 0–1] vs. Adverse Outcome [Grades 2–3]). Candidate variables for multivariable analysis were selected based on univariable associations ($p < 0.05$) and collinearity assessment, as described in the Methods. Variables not retained in the final multivariable model are shown with univariate results only. Categorical variables were presented as follows: smoking and diabetes (0 = no, 1 = yes); CTA Run-off Score was treated as an ordinal variable ranging from 0 to 3. β, Regression Coefficient; S.E., Standard Error; OR, Odds Ratio; CI, Confidence Interval; Ref, Reference Category.

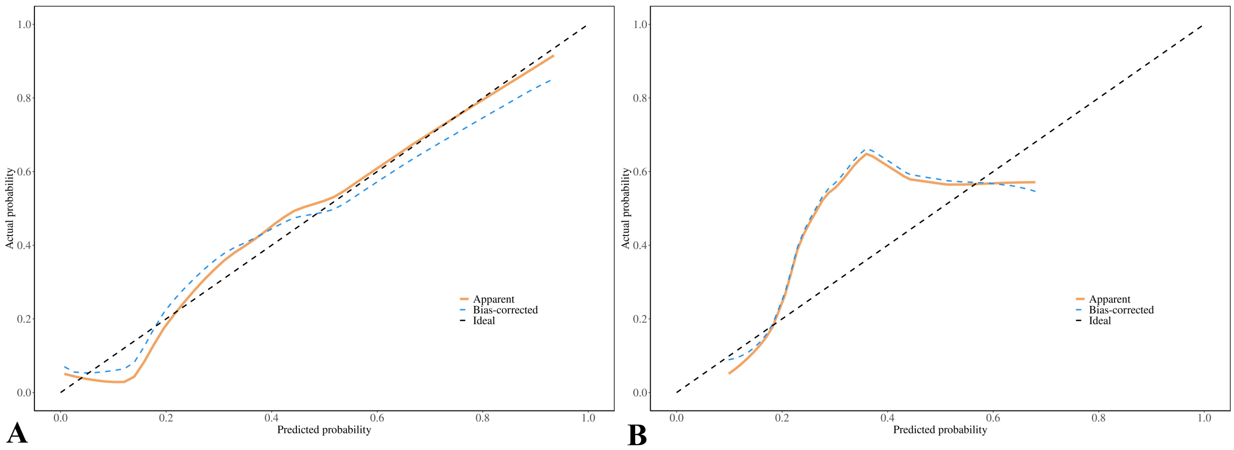

Fig. 3. Calibration plots of the nomogram. Calibration curves for (A) the training cohort and (B) the validation cohort. The x-axis represents the nomogram-predicted probability of flap failure, and the y-axis represents the actual observed probability. The diagonal dashed line represents an ideal prediction. The solid orange line indicates the apparent performance, and the dashed blue line represents bias-corrected performance (bootstrapping B = 1000). The Hosmer-Lemeshow test yielded non-significant *p*-values (p = 0.150 for training; p = 0.417 for validation), and Brier Scores (Training: 0.103; Validation: 0.165), suggesting good model fit.

tative perspective. However, this concept has been defined largely in quantitative terms [19]. In this study, Dist_Anastomosis was identified as an independent predictor of flap outcome (OR 0.76). The findings indicate that

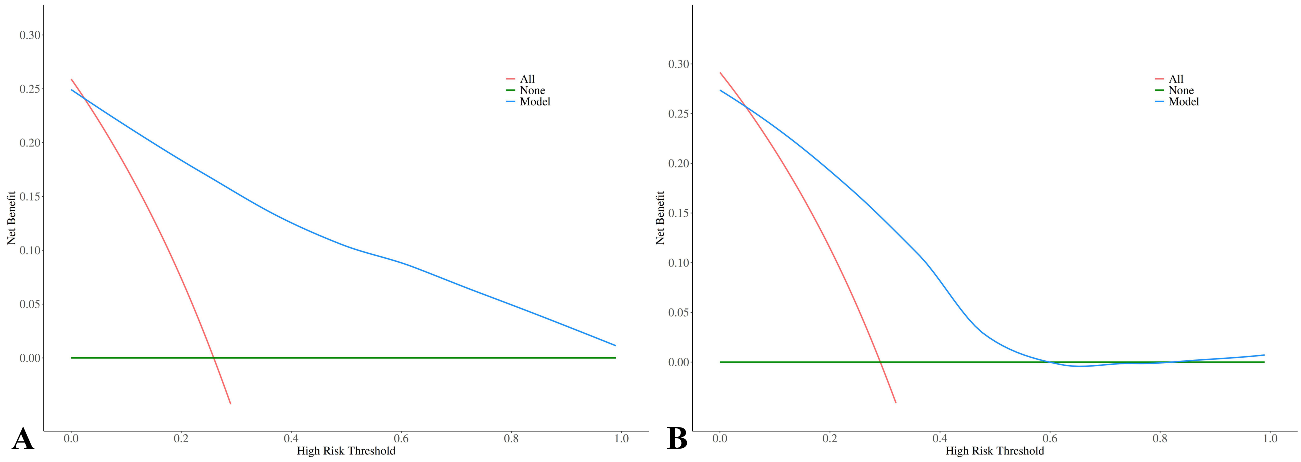

Fig. 4. Decision curve analysis (DCA) of the model. DCA plots (A) the training cohort and (B) the validation cohort, assessing the clinical utility of the model. The y-axis measures the net benefit. The blue line represents the predictive nomogram. The red line represents the assumption that all patients have adverse outcomes ("Treat All"), and the green line assumes no patients have adverse outcomes ("Treat None"). The model demonstrates a higher net benefit across a wide range of threshold probabilities compared to the default strategies.

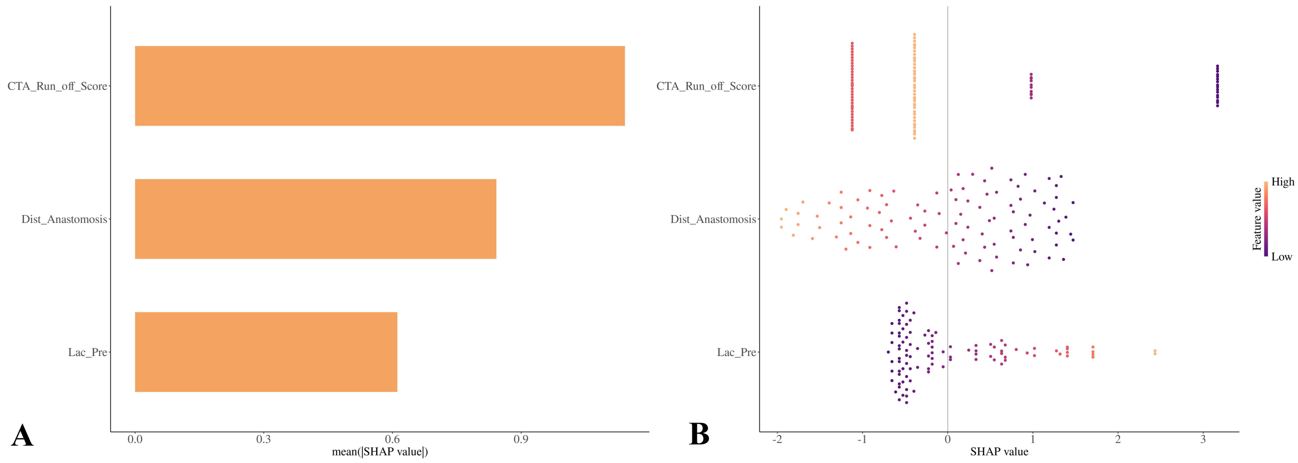

Fig. 5. SHAP visualization of feature importance. (A) SHAP Summary Bar Plot: Ranking of features based on their mean absolute SHAP values, indicating global importance. (B) SHAP Beeswarm Plot: Visualizing the directionality of feature impact. Each dot represents a single patient. The color spectrum indicates the feature value (Red = High, Purple = Low). The horizontal position indicates the SHAP value (positive values increase risk, negative values decrease risk). SHAP, Shapley Additive exPlanations.

performing vascular anastomosis within about 3 cm of the injury zone, a pattern observed in the failure group, is associated with a substantially increased risk. This observation likely reflects the presence of subclinical endothelial injury and a pro-thrombotic, inflammatory microenvironment that may extend beyond the visible trauma [20,21]. From a surgical perspective, these results support approaches that relocate the anastomosis to a "healthy zone", for example, through the use of a vein graft, rather than relying on vessels located within the compromised injury zone [22].

In the present study, ScvO2 monitoring was introduced as a measure of global oxygen balance. The univariate analysis confirmed that patients with low ScvO2 values (systemic oxygen debt) tended to have worse outcomes. However, when multiple indicators were considered together, preoperative lactate emerged as the stronger independent predictor of flap prognosis [23]. ScvO2 reflects real-time balance between oxygen delivery and tissue extraction, which can fluctuate rapidly during resuscitation or fluid therapy [24]. In contrast, lactate levels represent the cumulative burden of anaerobic metabolism, indicating oxygen debt and cellular metabolic stress that has not yet been resolved [25]. In the context of microsurgical reconstruction, elevated lactate levels imply the presence of tissue acidosis. Acidosis can impair coagulation pathways, promote neutrophil adhesion to the endothelium, and exacerbate ischemia-reperfusion injury after clamps are released [26]. Overall, these results indicate that while ScvO2 serves as a dynamic physiological indicator of the global oxygen supply-demand balance, preoperative lactate more accurately reflects the cumulated

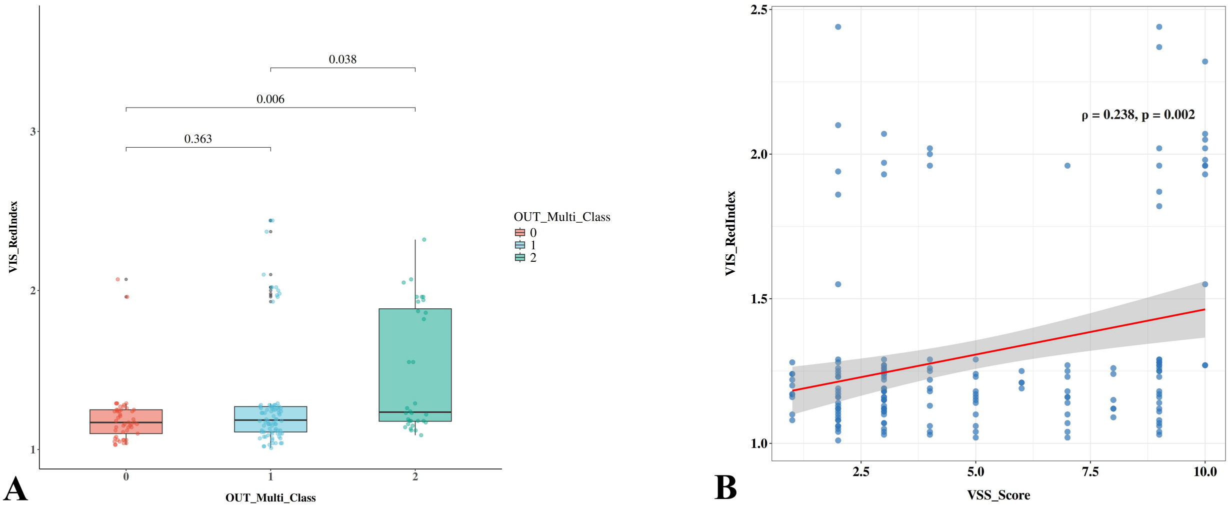

Fig. 6. Long-term aesthetic outcomes 6 months after surgery. (A) Comparison of the VISIA-derived Redness Index (VIS_RedIndex) across prognostic outcome groups using the Wilcoxon–Holm test. Outcome groups were defined as follows: Group 0, successful healing without complications; Group 1, minor complications not requiring surgical salvage; and Group 2, severe adverse outcomes requiring salvage procedures. Patients in Group 2 exhibited significantly higher Redness Index values compared with Group 0 (p = 0.006) and Group 1 (p = 0.038). (B) Spearman rank correlation analysis demonstrating a significant positive correlation between the objective Redness Index and the subjective Vancouver Scar Scale (VSS) vascularity score (p = 0.002), supporting the utility of optical analysis in quantifying scar vascularity.

metabolic stress experienced by tissues. In this study, the persistently increased lactate emerged as a superior independent predictor of flap outcomes. However, we must emphasize that preoperative lactate should be interpreted as a strong associative prognostic marker, rather than a prescriptive decision threshold for surgical intervention. Given the observational design of the study, it would be premature to consider increased lactate as a categorical "stop sign" for reconstruction. Instead, it should be regarded as a critical warning signal indicating the need for careful resuscitation and optimization of the physiological status before starting microsurgery.

Our results are consistent with the concept of "Anatomical-Metabolic Coupling", in which flap survival is not only determined by anatomical features or physiological status alone, but by the interaction between the two. A patient with favorable vascular outflow (CTA run-off score of 3) may still tolerate a relatively short anastomotic distance between the injury zone and the anastomosis. However, in the presence of metabolic acidosis (High Lactate), the tolerance for anatomical compromise becomes much smaller (Low CTA Score or Short Distance). Under such conditions, factors such as poor vascular run-off or a short anastomotic distance may elevate the risk of flap failure. The nomogram constructed in this study captures this interaction and translates it into a clinically useful tool. By combining both anatomical and metabolic indicators, this model may assist surgeons in deciding between immediate flap reconstruction versus "damage control strategy" (debridement and vacuum therapy), allowing time for metabolic optimization and clearer definition of the injury zone.

Although our nomogram showed good discrimination in the training set (AUC 0.89), its performance declined in the validation set (AUC 0.79). This variation may reflect a degree of model overfitting, which is a common limitation of single-center retrospective analysis, particularly when the number of adverse events is relatively limited. The calculated Brier scores (0.103 and 0.165) provide a reliable measurement of prediction error, indicating acceptable calibration. Robustness could be further enhanced by increasing validation cohort sizes or evaluating dynamic physiological predictors, such as lactate clearance.

A novel aspect of this study is the observed association between acute flap prognosis and subsequent scar characteristics, as evaluated through VISIA imaging. Flaps that experienced complications during the acute postoperative period, even when successfully salvaged, exhibited significantly higher Redness Indices at the 6-month follow-up. This objective optical metric also showed a positive correlation with the subjective VSS vascularity score, indicating consistency between digital imaging analysis and conventional clinical scar assessment. One possible explanation can be the biological effects of ischemia-reperfusion injury (IRI). Severe IRI has been reported to trigger sustained pro-inflammatory signaling, such as increases in Interleukin-6 (IL-6) and Vascular Endothelial Growth Factor (VEGF) levels, along with prolonged activation of myofibroblast [27,28]. Consequently, these processes may contribute to ongoing microvascular activity and fibrosis, which manifest clinically as persistent subclinical hyperemia and hypertrophic scar formation even after the acute postoperative phase has resolved [29]. VISIA assessments at 6 months were available for 163 patients. Cases that experienced complete flap failure were not included in the aesthetic analysis because scar evaluation was not applicable in these individuals, which may limit the generalizability of these findings to salvaged and successfully healed flaps. In addition, the 6-month follow-up represents an early stage of scar remodeling, whereas final scar maturation typically occurs between 12 and 24 months. Hence, the present VISIA results should be interpreted as exploratory observations rather than definitive predictors of long-term scar quality.

This study has several limitations that should be considered while interpreting these findings. First, the retrospective nature introduces inherent selection bias that cannot be avoided. Although distributing the dataset into the training and validation cohorts helps mitigate the risk of model overfitting, retrospective data collection may still affect the representativeness of the study population. Second, while internal validation demonstrated acceptable to good model performance, the model was not tested using cross-validation or assessed in independent external cohorts, which may limit the generalizability of the proposed nomogram. Multicenter studies are required to confirm the model's reliability across different clinical settings and patient populations. Third, the CTA-based scoring system used in this study reflects morphological vascular features. Although this strategy offers promising anatomical information, it does not directly capture vascular flow dynamics. Future studies utilizing emerging imaging approaches, such as 4D-CTA, may allow a more accurate assessment of perfusion and flow characteristics [30]. A fourth and significant limitation is the lack of standardized functional outcome measures. Metrics such as the Lower Extremity Functional Scale (LEFS) were not systematically available in this retrospective cohort, which restricted a comprehensive evaluation of functional recovery. Since the ultimate goal of limb salvage is functional recovery, future investigations should incorporate validated functional evaluations. Finally, the VISIA analysis was conducted at a single time point, six months after surgery. Since scar maturation continues over a longer period, longitudinal follow-up would offer a clearer understanding of how scar characteristics evolve and how early flap events affect long-term outcomes.

Conclusions

In this retrospective cohort study, we developed and internally validated a prognostic model that integrates anatomical features with perioperative physiological indicators to assess acute flap outcomes. The model demonstrated acceptable to good discriminatory performance. Multivariable analysis identified three indicators associated with adverse outcomes, which are the CTA run-off score, preoperative lactate level, and the distance between the injury zone and the vascular anastomosis. Although several other variables showed substantial associations in univariable analyses, they were not retained after adjustment in the multivariable model. These findings should be considered exploratory. Further confirmation through prospective studies and external validation in independent cohorts is warranted to explore the broader clinical utility of the proposed model.

Availability of Data and Materials

The data that support the findings of this study are available from the corresponding authors upon reasonable request.

Author Contributions

JJZ, CYL and XZD designed the research study. ZXL and RXW performed the research. SY, RXW and JJZ analyzed the data. SY, CYL and JJZ drafted this article. All authors contributed to the critical revision of the manuscript for important intellectual content. All authors read and approved the final manuscript. All authors have participated sufficiently in the work and agreed to be accountable for all aspects of the work.

Ethics Approval and Consent to Participate

The study was approved by the Ethics Committee of Affiliated Hospital of Jiangnan University (approval number: LS2026052), and all procedures followed the principles of the Declaration of Helsinki. Given the retrospective design of the analysis involving anonymized patient data, the requirement for informed consent was waived.

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Conflict of Interest

The authors declare no conflict of interest.

Supplementary Material

Supplementary material associated with this article can be found, in the online version, at https://doi.org/10.62713/aic.4486.

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