Translated by E.V. Trushina

Research Article

https://doi.org/10.23934/2223-9022-2025-14-1-61-68

Method for Predicting the Outcome of Burn Injury Based on a Mathematical Model

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ABSTRACT The choice of treatment tactics for a patient with burns should be based on individual prediction of injury outcome. Known models for predicting the outcome of burn injury are inaccurate and do not allow us to determine the probability of different outcomes for a particular patient.

AIM OF THE STUDY To develop a method for individual prediction of the outcome of burn injury based on a mathematical model using the revised Frank index.

MATERIAL AND METHODS 399 patients: men 283 (71%), women 116 (29%); age — 50 (36; 66) years; total burn area — 25 (15; 40) % TBSA, I–II degree — 20 (10; 30) % TBSA, III degree — 8 (3; 20) % TBSA. In 140 (35%) patients, inhalation injury was detected.

Based on the number of revised Frank Index (RFI) scores (in increments of 10), frequency diagrams of different outcomes were constructed. The mathematical model of individual prognosis is based on a regression equation that was derived from an approximated curve of the proportions of a favorable outcome in the optimal RFI range.

RESULTS Patient survival probability (%) depending on the number of RFI points was distributed as follows: with RFI<72 — ⩾99.9%; for RFI ⩾72 ⩽189, the probability of survival is calculated using the formula obtained as a result of approximation by a 4th degree polynomial of the curve of the dependence of survival on the number of RFI points: $0.0049x^4 - 0.1027x^3 - 0.1624x^2 + 2.6794x + 96.54$; where x= (RFI -35)/10; with RFI>189 — ⩽0.1%. The probability of a lethal outcome is determined by subtracting the resulting probability of a survival from 100%.

CONCLUSION The developed method for predicting the outcomes of a burn injury based on a mathematical model allows us to determine the probability of different outcomes for a particular patient.

Keywords: Burns, Inhalation Injury, Prognosis, Mathematic Model

For citation Zhirkova EA, Spiridonova TG, Sinyakova OG, Sachkov AV, Medvedev AO, Eliseenkova EI, et al.Method for Predicting the Outcome of Burn Injury Based on a Mathematical Model. *Russian Sklifosovsky Journal of Emergency Medical Care*. 2025;14(1):61–68. https://doi.org/10.23934/2223-9022-2025-14-1-61-68 (in Russ.)

Conflict of interest Authors declare lack of the conflicts of interests

Acknowledgments, sponsorship The study has no sponsorship

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b.s. — body surface area
FET — Fisher's exact test
II — inhalation injury
M–W — Mann–Whitney test
PC — probability calculator
R — correlation coefficient
R^2 — determination coefficient
RFI — Revised Frank Index
Y — survival prognosis

INTRODUCTION

The probability of a favorable or unfavorable outcome in burn injuries is associated with the patient's age, burn area, presence of inhalation injury (II), and other factors related to predictors of an unfavorable outcome [1–5]. Domestic and foreign authors proposed models for predicting the outcome of burn injury based on specialized point indices [6–11] or mathematical formulas, including various predictors of unfavorable outcome [12–14]. In the proposed models, the authors either established the proportion of surviving patients with a certain number of index points empirically, as in the ABSI calculator, or used linear multiple or logistic regression, and as a result received only a qualitative definition of the prognosis ("favorable", "relatively favorable", "doubtful", "unfavorable"), which is not sufficient for choosing the patient's treatment tactics, including surgery. We set out to develop a method for predicting the outcome of burn injury that would assess the likelihood of a favorable or unfavorable outcome for each patient individually.

The aim of the study was to develop a method for individual prediction of the outcome of burn injury based on a mathematical model using the revised Frank index.

MATERIAL AND METHODS

The retrospective observational single-center study included 399 patients admitted to the Intensive Care Unit for Burn Patients of the N.V. Sklifosovsky Research Institute for Emergency Medicine in 2019–2022. Inclusion criteria: age over 18 years; thermal burns of the skin (flame, boiling water or contact), including those accompanied by II. All the patients were hospitalized within 24 hours of the injury.

Of the 399 patients, 283 (71%) were men and 116 (29%) were women. The mean age of the patients was

50 (36; 66) from 18 to 93 years. The total burn area was 25 (15; 40) from 3 to 95% of the body surface area (b.s.). The area of superficial burn (I–II degree according to ICD-10) was 20 (10; 30) from 0.5 to 86% of the total b.s. The area of deep burn (III degree according to ICD-10) was 8 (3;20) from 0.5 to 95% of the b.s. Of the 399 patients, 140 (35%) were diagnosed with II by bronchoscopy [15]. The Revised Frank Index (RFI) score was calculated for all the patients [16].

Statistical analysis was performed using Microsoft Excel and Statistica™ TIBCO®Software Inc. version 13.3. Since most of the data had a distribution different from normal, nonparametric methods were used. Descriptive statistics are presented as medians (Me), interquartile ranges (Q1;Q3), minimum and maximum values, absolute (n) and relative (%) values. Comparison of groups was performed using the Mann–Whitney (M–W) criteria for continuous numerical data, Fisher's exact test (FET) for discrete indicators, and the probability calculator (PC) for proportions [17]. The level of statistical significance was set at $p<0.05$. The sample was formed using a continuous method.

To obtain a formula predicting the outcome of the injury, graphs of incidence of favorable and unfavorable outcomes were constructed depending on the number of RFI points. The curve of the proportion of surviving patients was approximated to obtain a regression equation, based on which the probability of a favorable outcome was determined. The quality of approximation in different RFI ranges was assessed using the following coefficients: determination (R^2) and correlation (R), the average deviation of the calculated values from the original ones. High accuracy of approximation was characterized by R^2 greater than 0.95 [18]. The probability of a favorable or unfavorable outcome was expressed as a percentage.

RESULTS

Of the 399 patients, 297 (74%) survived and 102 (26%) died. Comparative characteristics of surviving and deceased patients are presented in Table 1.

Table 1

Comparative characteristics of 399 surviving and deceased patients

Indicators		Outcome	Results				p, FET, M–W, PC
			n	%	*Me* (Q_1; Q_3)	*min–max*	
Gender	Male	Survived	225	80	–	–	<0,0011
		Died	58	20	–	–	
	Female	Survived	72	62	–	–	
		Died	44	38	–	–	
Age, years		Survived	297	74	46 (34; 59)	18–93	<0,0012
		Died	102	26	64 (51; 80)	18–91	
Total burn area, % of b.s.		Survived	297	74	22 (15; 31)	3–88	<0,0012
		Died	102	26	40 (25; 65)	3–95	
Surface burn area, % of b.s.		Survived	296	76	20 (10; 30)	1–86	0,0492
		Died	95	24	15 (7; 25)	1–75	
Deep burn area, % of b.s.		Survived	140	60	4 (2; 10)	0,5–40	<0,0012
		Died	95	40	25 (12; 39)	2–95	
II		Survived	81	58	–	–	0,0073
		Died	59	42	–	–	

Notes: [1] — FET — Fisher's exact test; [2] — M–W — Mann–Whitney test; [3] — PC — probability calculator; II — inhalation injury; b.s. — body surface area

As can be seen from the table, deceased patients were statistically significantly older (p<0.001), had a larger burn area: total (p<0.001), superficial (p = 0.049), and deep (p<0.001), and more often had concomitant II (p<0.007).

In 399 patients, the RFI took values in the range of 37–372 points: among 297 surviving patients, the RFI score was — 85 (68; 102) from 37 to 175; among 102 deceased patients, the RFI score was — 169 (131; 207) from 78 to 372, and was statistically significantly higher than in survivors (p<0.001; M–W). To determine the incidence of fatal outcomes at different RFI scores ranging from 37 to 372 points, we constructed diagrams of the absolute number (Fig. 1) and proportions (Fig. 2) of favorable and unfavorable outcomes depending on the number of RFI points in increments of 10 (from 31 to 380 points).

The diagrams of the absolute number and proportions of surviving and deceased patients demonstrate the stratification of patients into groups of favorable and unfavorable outcomes depending on the number of RFI points. The lower the RFI score, the higher the proportion of surviving patients (Fig. 2A); the higher the RFI score, the higher the proportion of deceased patients (Fig. 2Б).

To obtain a regression equation for calculating the probability of burn injury outcomes, diagrams were constructed in the form of functional curves, which were subjected to approximation. The argument on the abscissa axis (x) was the midpoint of the intervals, and the function on the ordinate axis (y) was the proportion of surviving and deceased patients in percent. When approximating the outcome curves with the construction of a trend line among five types of approximation (linear, exponential, logarithmic, polynomial, and power), the best quality of the model (R^2>0.97) was obtained when choosing a 4th order polynomial (Fig. 3).

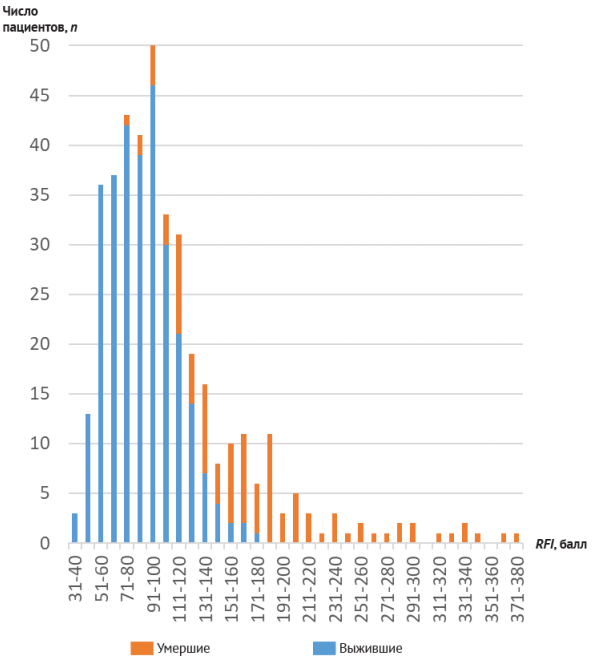

Fig. 1. The number of surviving and deceased patients depending on the number of points of the revised Frank index (RFI)

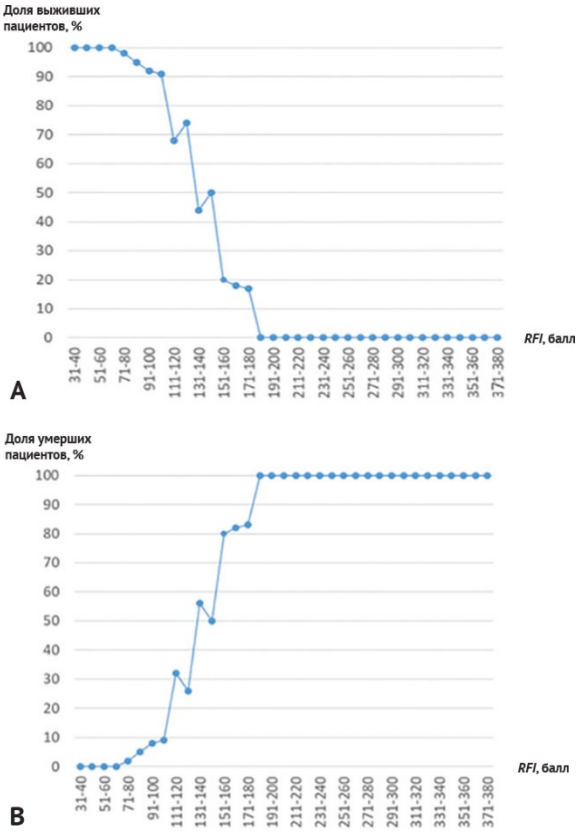

Fig. 2. Proportions of surviving (A) and deceased (B) patients depending on the number of points of the revised Frank index (RFI)

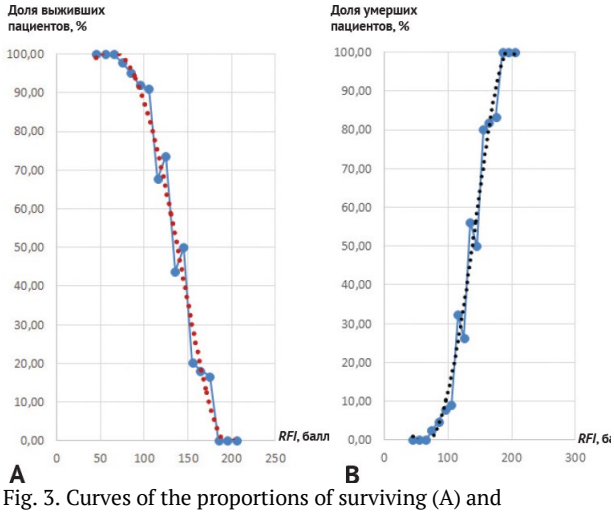

Fig. 3. Curves of the proportions of surviving (A) and deceased (B) patients with a 4th order polynomial trend line

In order to determine the optimal regression equation for calculating the probability of a favorable outcome, polynomial approximation was performed on different ranges of RFI intervals: 65–185; 55–195; 45–205; 35–215; 25–225. A comparison of the results showed that the highest value of the correlation coefficient (R) and the lowest average deviation of the calculated values from the original ones with a sufficiently high coefficient of determination (R^2) were obtained with an approximation in the range of 45–205 points (Table 2).

Table 2

Comparison of coefficients when approximating in different ranges of RFI change

RFI range, points	Values of coefficients		Average deviation of calculated values from the original ones
	R^2	R	
65–185	0.968	0.983	0.22
55–195	0.975	0.988	0.30
45–205	0.980	0.990	0.24
35–215	0.982	0.980	1.03
25–225	0.983	0.983	0.48

Notes: R — correlation coefficient; R^2 — coefficient of determination; RFI — revised Frank index

For this RFI interval, a regression equation was obtained in the form of a 4th order polynomial with a trend line plotted:

$$y(x) = 0.0049x^4 - 0.1027x^3 - 0.1624x^2 + 2.6794x + 96.54;$$

where y is the predicted probability of a favorable outcome in %, x = (RFI – 35)/10 is the argument of the function, depending on the number of RFI points. The coefficient of determination of the obtained regression equation (R^2) is 0.9802, R is 0.9901 ($p<0.01$; FET) (Fig. 4).

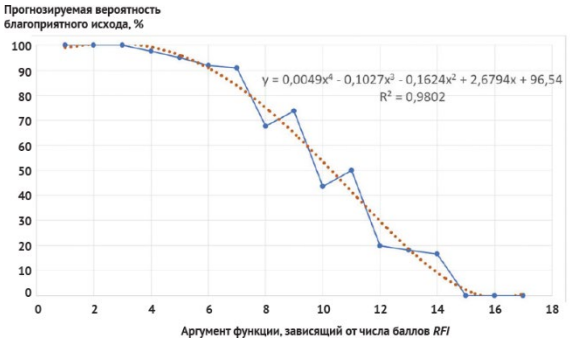

Fig. 4. Curve and equation of probability of favorable outcome regression

When calculating the regression equation depending on the RFI score, the probability of a favorable outcome (%) in patients with burns is distributed as follows:

1) if the RFI value is less than 72 points, the probability of a favorable outcome is not less than 99.9%;

2) if the RFI value is not less than 72, but not more than 189 points, the probability of a favorable outcome is calculated using the formula obtained by approximating the curve of the dependence of a favorable outcome on the number of RFI points with a 4th order polynomial: $0.0049x^4 - 0.1027x^3 - 0.1624x^2 + 2.6794x + 96.54$; where x= (RFI – 35)/10;

3) if the RFI value is more than 189 points, the probability of a favorable outcome is no more than 0.1%. The probability of an unfavorable outcome is determined by subtracting the probability value of a favorable outcome from 100%.

DISCUSSION

Known prognostic models help estimate the probability of survival of patients with burn injury, in most cases determining the prognosis of the injury outcome qualitatively, but not quantitatively. The method of predicting the outcome of a burn injury using the Frank index was first described in 1960 [6]. Currently, the number of points of the Frank index determines the prognosis of the injury outcome as

follows: no more than 30 points - favorable, 31-60 - relatively favorable, 60-90 - doubtful, at least 91 - unfavorable [19]. The revised Baux score [7] takes into account age, II, and the total burn area, but does not take into account the presence of deep burns. The prognosis of the injury outcome is determined by the number of points: no more than 60 points - favorable, 61-80 - relatively favorable, 81-100 - questionable, no less than 101 - unfavorable [19]. However, both of these methods allow predicting the outcome of the injury only at a qualitative level: “favorable”, “relatively favorable”, “doubtful”, “unfavorable”, which is not sufficient for choosing the patient’s treatment tactics.

A.V. Matveenko et al. proposed a mathematical prognostic model based on probit analysis. The predictors for constructing the coordinate grid are age and the total burn area. The probability of a fatal outcome is determined using the coordination grid (in probits from 0.01 to 1.0). At probit values of "0" the prognosis is favorable, 0.1-0.3 - relatively favorable, 0.4-0.6 - questionable, 0.7-0.9 - unfavorable, 1.0 - absolutely unfavorable. However, this method does not provide an accurate prognosis of the outcome of burn injury for a patient in the probit range from 1 to 0.1, as indicated by the authors themselves. Another disadvantage of this model is the low prognostic accuracy (77.8%) among patients with the prospect of a favorable outcome [20].

O. O. Zavorotniy et al. developed a model for predicting a fatal outcome using a formula that includes 18 parameters assessed on days 1–3 after injury. The model includes victim’s age, deep burn area, results of clinical and biochemical analyses, gas and acid-base composition of arterial blood, venous blood lactate, coagulogram, clinical urine analysis results, body temperature, volume of infusion therapy on day 3, volume of water drunk on days 1 and 3, diuresis in the first three days of intensive care. The probability of a fatal outcome is determined by a formula obtained by the logistic regression method. The method requires measuring a large number of parameters, and does not allow predicting a fatal outcome up to 4 days, which does not provide a timely and accurate prognosis on the first day of admission to the hospital to select treatment tactics. Moreover, the probability of a fatal outcome has only a qualitative assessment - “minimal” or “high” [13].

I.V. Shlyk et al. proposed a prognostic model based on the assessment of the area of superficial and deep burns, the age of the victim, the severity of II, and the level of base deficiency/excess in arterial blood. The survival prognosis (Y) is calculated using the formula where if Y is greater than 0.5, the prognosis for life is considered favorable, if Y is from –0.5 to +0.5, it is questionable, and if Y is less than –0.5, it is unfavorable. The disadvantage of the method is a qualitative only determination of the prognosis ("favorable", "unfavorable", "doubtful"). In addition, this method requires arterial blood gas analysis to determine the level of base deficiency/excess, which is carried out only in the intensive care unit by qualified specialists, which means that the method is not suitable for patients who are not hospitalized in the intensive care unit. Since the level of base deficiency/excess is a dynamic value and changes with adequate drug treatment, tending to normalize, this method is suitable only for assessing the prognosis in the first hours after injury, in fact, for the period before the start of treatment. The method is not applicable for dynamic assessment of the patient's condition and prediction of the probability of a favorable/unfavorable outcome, as well as determining the timing of surgical treatment. At the same time, the normal level of acid-base balance of arterial blood at the time of its measurement does not exclude an unfavorable outcome caused by a burn injury [14].

The ABSI predicts the outcome of a burn injury by determining points for the patient's age and gender, II, total area, and the presence of deep burns, without taking into account their area. ABSI stratifies patients into six groups based on the number of index points: 2–3, 4–5, 6–7, 8–9, 10–11, and at least 12 points. For each group, the proportions of surviving patients were determined; but between 2–3 and 4–5 point groups, they were practically the same – 99% and 98%, respectively; and in 8–9 and 10–11 point groups, they had a spread of 20% – 50–70% and 20–40%, respectively, which cannot be considered an accurate prognosis [21].

The prognosis of the injury outcome based on the model we developed is calculated based on the RFI of each individual patient, and may change depending on the course of the wound process, for example, during epithelialization of superficial burns. For dynamic assessment, the prognosis of the injury outcome should be recalculated after each dressing or operation.

CONCLUSION

The injury outcome prediction model we developed based on the RFI index allows us to determine the probability of favorable and unfavorable (in percent) outcomes for each patient individually. The high accuracy of the prognosis of our model will allow developing algorithms for routing, diagnosis, selecting tactics of surgical treatment, its volume and start timing. A patent was received for the proposed model for assessing the outcome of injury, "A method for predicting a favorable outcome in patients with thermal injury to select treatment tactics (options)" (RU2825062C1); and a computer program was developed called "RFI Calculator and Thermal Injury Outcome Prediction for Patients Over 18 Years of Age" (RU2023685743) which automatically calculates the RFI score, and the probability of a favorable and unfavorable outcome based on the entered values of the patient's age, total burn area, deep burn area, and the presence or absence of inhalation injury. This program can be freely used on the website of the N.V. Sklifosovsky Research Institute for Emergency Medicine: *https://sklif.mos.ru/departments/acute-thermal-injuries/calculator/?selectedCalculator=RFICalculator&inhalationTrauma=true&age=52&mass=68&allSquare=60&firstDegreeSquare=10&thirdDegreeSquare=10&volumeOfInfusionTherapy=0*

FINDINGS

1. For RFI values less than 72 points, the probability of a favorable outcome is at least 99.9%.
2. For RFI values from at least 72 to at most 189 points, the probability of a favorable outcome is calculated using the regression equation formula with the coefficient of determination (R^2) — 0.9802, R — 0.9901 ($p<0.01$; Fisher's exact test): $0.0049x^4 - 0.1027x^3 - 0.1624x^2 + 2.6794x + 96.54$; where $x = (RFI - 35)/10$.
3. For RFI values greater than 189 points, the probability of a favorable outcome is no more than 0.1%.
4. The developed method for predicting the outcome of a burn injury based on the RFI value allows us to determine the probability of favorable and unfavorable outcomes, expressed as a percentage, for each patient individually.

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Received on 01/03/2024
Review completed on 13/05/2024
Accepted on 24/12/2024