Original Articles

DOI 10.18019/1028-4427-2020-26-1-6-12

Prognostic value of objective examination of patients with intra-articular fractures of the calcaneus

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Introduction The scope of examination of patients with closed intraarticular fractures of the calcaneus against the background of concomitant pathology has been discussed up to date. The aim of the study was to improve the accuracy of predicting the nature of postoperative wound healing after osteosynthesis of intra-articular fractures of the calcaneus from the extended lateral approach on the background of chronic obliterating diseases of the lower limb arteries of different etiology, smoking and a combination of these factors. **Material and methods** Sixty-nine patients who were smokers and/or suffered from chronic obliterating diseases with a total of 74 closed intra-articular fractures of the heel bones were analyzed. All patients received a comprehensive clinical and instrumental examination consisting of radiography and computed tomography of the calcaneus to determine the proximal-distal gradient (PDG), ankle-brachial index (ABI) and transcutaneous oximetry (TrOc). A single-factor analysis of variance was performed, after which an expert evaluation of the features was performed, as well as testing of models with different sets of signs. **Results** The disperse analysis of variance in respect of 74 cases for the relevant group of patients allowed us to obtain two models: the first with a level of statistical significance $p_0 < 0{,}001$ (χ^2 - 82,63; df =7) and the predictive efficiency of 97.3 % in regard to possible complications after open reduction with internal fixation; the second level of statistical significance $p_0 < 0{,}001$ (χ^2 - 34,76; df = 7) and prognostic effectiveness of 93,24 % related to the risk of repeated surgical interventions. **Conclusions** The proposed method of predicting the development of complications in the immediate postoperative period after internal osteosynthesis of the calcaneus allows estimation of the risks of complications by calculating PDG, ABI and TrOc with high efficiency (97.3 %). The proposed discriminant model predicts the need for repeated surgical interventions with an efficiency of 93.24 %, and feasibility of surgical treatment with an extended lateral approach.

Keywords: intra-articular fracture of the calcaneus, transcutaneous oximetry, ankle-brachial index, immediate postoperative complications, chronic peripheral artery disease

INTRODUCTION

The calcaneal bone is the biggest foot bone. Its fractures account for 5 % of the total of skeleton fractures and for 60 % of tarsal fractures. Ninety-two percent of its fractures are intra-articular [1, 5, 6].

According to sources, chronic obliterating diseases of the lower limbs arteries (CDLLA) that cause microcirculatory disorders are encountered in 3 % of the working age population in the Russian Federation. Moreover, their preclinical condition may be four times greater in number [7–9].

Among the working age individuals, smoking habits that cause CDLLA are reported in 50.9 % males and 14.3 % of females [10]. Moreover, smoking affects wound healing [11].

To express the severity of lower limb ischemia, we used the working classification of chronic lower limb arterial insufficiency (CLLAI) developed by R. Fontaine (1954) and A.V. Pokrovsky (1979) [8].

Currently, it is known that orthopedic traumatologists use the methods to objectively determine the severity of blood flow disturbance in the lower extremities, which enable to make an informed choice of a specific treatment methodology for patients with the pathology indicated and to determine the likelihood of soft tissues complications in the region of surgical intervention [12]. However, to date, these methods have not been widely used in multidisciplinary hospitals.

Rejection to use surgical approaches that ensure open anatomical reduction and stable functional internal fixation of bone fragments in favor of minimally invasive interventions or conservative treatment due to the risks of inflammatory and infectious complications entails the early development of arthrosis of the subtalar joint and the need for its subsequent arthrodesis [6, 13].

To assess the risk of complications in the acute postoperative period in patients with closed intra-articular fractures of the calcaneus, it was proposed to add ultrasound Doppler scanning of the vessels of

Kulik N.G., Vashchenkov V.V., Khominets V.V., Ostapchenko A.A. Prognostic value of objective examination of patients with intra-articular fractures of the calcaneus, *Genij Ortopedii*, 2020, vol. 26, no 1, pp. 6-12. DOI 10.18019/1028-4427-2020-26-1-6-12. (In Russian)

the lower extremities to the preoperative examination including the study of medical record data, condition of the skin, computed tomography findings, bad habits and peripheral vascular diseases [14, 15]. However, ultrasonographic scanning is an "operator-dependent method" requiring special skills. Thus, comparing the ultrasound study of the lower extremities obtained by different specialists will be difficult. The volume of the running diagnostic program does not provide reliable information about the state of microcirculation, i.e. state of tissue metabolism.

E.N. Schurova et al. (2011) point to transcutaneous oximetry as a method of high diagnostic value in the examination of trauma patients, which is able to predict the development of complications in the short-term postoperative period [16].

The state of blood circulation in the area of the surgical approach in the specified patients using physical and instrumental methods was assessed [17]. However, the absence of parametric criteria that define the scope of diagnostic studies in the treatment of patients with intra-articular calcaneus fractures and affected by CLLAI, associated with the risk of complications in the immediate postoperative period, determine the feasibility of this study.

The **aim** of the study was to increase the accuracy of predicting the healing of postoperative wounds during osteosynthesis of intra-articular calcaneal fractures from an extended lateral approach in patients with chronic obliterating diseases of the lower limb arteries of various etiologies, smoking and a combination of these factors.

MATERIAL AND METHODS

The material of the study was 69 patients affected by CLLAI with closed intra-articular calcaneus fractures and smoking, as well as a combination of these factors. All patients had open reduction and internal fixation (ORIF) with bone autografting through an extended lateral approach to the calcaneus. All of them were operated on by the surgeons with a 10-year experience in surgical treatment of calcaneal fractures. Upon admission, all patients underwent a comprehensive clinical and instrumental examination aimed both at determining the nature and morphology of the calcaneal fracture with a focus on the study of the regional blood flow in the lower extremities.

The examination protocol was supplemented by several specialized instrumental techniques, including remote infrared polypositional thermometry (DIPT) with the determination of the proximal distal gradient (PDG); segmental manometry with determination of the ankle brachial index (ABI) and transcutaneous oximetry (TrOx).

When executing the TrOx, upon reaching the "plateau", the compensatory abilities of the microvasculature were determined by performing orthostatic tests (OrtT), lifting the lower limb (1st OrtT) and lowering it below the bed level (2nd OrtT). To study regional blood flow, ABI was measured with a digital tonometer AND UA-787; DIPT with an infrared thermometer "Sensitec" NF3101; TrOX with a monitoring system TSM – 4/40 "Radiometer".

Exclusion criteria were the presence of trophic ulcers, purulent diseases, excoriation of the skin, epidermal blisters that were not epithelized at the estimated time of the operation; diabetes; alcoholism, drug addiction, mental illness; age younger than 35 years or older than 60 years; CLLAI in stage III and IV according to R. Fontaine /A.V. Pokrovsky; other somatic pathology, including in the acute stage which is a contraindication to surgical intervention due to the high operational and anesthetic risk; previously performed surgical aids after a calcaneal fracture; pregnancy and lactation; continued smoking at the stages of the study; polytrauma; absence of signs of CODALL, non-smoking and a combination of these factors in the anamnesis.

To conduct the study, an approval was obtained from the independent Ethics Committee at the VMedA named after S.M. Kirov No. 163 dated 06/30/2015. The studies were conducted in accordance with the ethical standards of the Helsinki Declaration of the World Medical Association on recommendations for physicians participating in biomedical research in humans" (as amended in 2013). Written informed consent was obtained from all the individuals included in the study.

The materials of the study were formalized according to generally accepted principles and summarized in a data matrix using the table processor Microsoft Office Excel 13.0. Statistical analysis was performed with STATISTICA for Windows and IBM SPSS Statistics 22. The mathematical statistical method of step-by-step discriminant analysis was used in the statistical processing of the data in order to develop the methods for predicting the complications after osteosynthesis of the calcaneus, as well as the need for re-operation.

RESULTS

As a natural result of studying the features of the nature of surgical wound healing after ORIF of the calcaneus from extended lateral approach in patients affected by CLLAI, we considered a mathematical multidimensional model for predicting short-term complications. We used discriminant analysis [18], which allows us to classify objects to one of the classes according to the selected set of features.

The discriminant model included a group of the most informative signs evaluated with the method of unifactorial dispersion analysis. Expert evaluation of the signs was performed and various models were tested that differed in the set of signs [19].

The values registered by our study were measured in quantitative and ordinal scale. The results of the dispersion analysis for prediction of complications after ORIF are given in Table 1.

When evaluating the results of the dispersion analysis, the following indicators were selected with the greatest contribution to the variance, as well as those that have a statistically significant relationship with the occurrence of complications in the immediate postoperative period: with the basal values of the oxygen level TrOx ($F = 24.699$; $p < 0.0001$), the oxygen level at the 1st OrtT ($F = 40,408$; $p < 0,0001$), the plateau of the oxygen level after the 1st OrtT ($F = 29,754$; $p < 0,0001$), the oxygen level at the 2nd OrtT ($F = 31,453$; $p < 0.0001$), the difference in oxygen levels between the basal value and the 2nd OrtT ($F = 15.084$; $p < 0.0001$), plateau of the oxygen level after the 2nd OrtT ($F = 28.350$; $p < 0.0001$), as well as with the age of the patient at the time of hospitalization ($F = 7.311$; $p < 0.01$), results of PDG ($F = 8.605$; $p < 0, 01$), ABI ($F = 10.434$; $p < 0.01$), the difference in oxygen levels between the basal value and the 1st OrtT ($F = 4.121$; $p < 0.05$).

According to the results of the dispersion analysis, the final model for predicting complications after ORIF included seven parameters (Table 2).

The following linear classification discriminant functions were obtained:

$$F_1 = -99.7797 + 28.8609*rtr + 93.4742*abi - 0.1600*toll - 1.0444*ponk + 1.3016*pall - 2.0030*dtrp + 1.6116*pfin,$$

$$F_2 = -94.9773 + 29.4140*rtr + 102.4331*abi - 0.4991*toll - 0.3221*ponk + 1.4669*pall - 2.2658*dtrp + 0.4620*pfin.$$

Table 1

Contribution of parameters into the probability dispersions of complications after ORIF

Parameter	Dispersion conditioned by the impact of a controlled factor	Dispersion conditioned by the impact of uncontrolled factors	F-criterion (Fisher)	Level of significance F-criterion, p
voz	333.6	3285.0	7.311	0.008547
rtr	4.9020	41.0185	8.6046	0.004495
abi	0.30896	2.13191	10.434	0.001865
torb	801.30	2336.16	24.6958	0.000004
toll	1144.658	2039.558	40.4084	0.000000
dtll	30.532	533.414	4.1212	0.046044
ponk	1418.58	3432.78	29.7537	0.000001
pall	2226.79	5097.33	31.4534	0.000000
dtrp	356.517	1701.767	15.08384	0.000226
pfin	1638.65	4161.72	28.3496	0.000001

Notes: voz – age of the patient at the time of hospitalization, full years; rtr – PDG, ºC; abi – ABI, rel. units; torb – basal values of the oxygen level at TrOx, mm Hg; toll – oxygen level at the 1st OrtT, mm Hg; dtll – difference in oxygen levels between the basal value and the 1st OrtT, mm Hg; ponk – oxygen level plateau after the 1st OrtT, mm Hg; pall – oxygen level of the 2nd OrtT, mm Hg; dtrp – the difference in oxygen levels between the basal value and the 2nd OrtT, mm Hg; pfin – plateau of the oxygen level after the 2nd OrtT, mm Hg

Table 2

Parameters included into the model for predicting complications after ORIF

Parameter	F-criterion value	Level of significance (p_0)
rtr	0.236	0.30
abi	3.481	0.29
toll	2.690	0.21
ponk	7.190	0.07
pall	0.190	0.03
dtrp	0.740	0.14
pfin	21.067	0.08

Function F_1 corresponds to the group of patients without complications after ORIF and function F_2 to patients with complications after ORIF.

The model of predicting complications after ORIF is statistically significant (criterion F (7.66) = 22.07; $p_0 < 0.00001$).

In the obtained discriminant model, the most informative for predicting the variant of complications after ORIF were indicators of the plateau of the oxygen level after the 1st OrtT TrOx ($p_0 < 0.07$) and the oxygen level of the second OrtT TrOx ($p_0 < 0.03$).

In order to predict complications after ORIF, PDG was calculated after DIPT. Next, segmental manometry was performed and ABI and TrOx were defined. According to TrOx results, the oxygen level at the 1st OrtT, the plateau of the oxygen level after the 1st OrtT, the oxygen level of the 2nd OrtT, the difference in oxygen levels between the basal value and the 2nd OrtT, the oxygen level plateau after the 2nd OrtT were measured. Then, using the obtained values, linear classification discriminant functions were calculated according to the above formulas.

At the next stage, the values of two discriminant functions revealed were compared. The patient's group without complications or with complications after ORIF of the calcaneal fracture on the background of CALLI is indicated by the function which value is greater.

The quality of the discriminant model was evaluated using the "folding knife" method of discriminant analysis (Table 3).

Table3

Quality assessments of the discriminant model

Parameter	Value, %
Sensitivity	95.83
Specificity	98.00
Efficiency	97.30
Level of false negative response	4.17
Level of false positive response	2.00

The efficiency of the obtained model of 97.3 % proves a high probability of predicting complications after ORIF in calcaneal fractures.

The canonical analysis enabled to obtain a canonical linear discriminant function (CLDF) with a level of statistical significance $p_0 < 0.001$ (criterion χ^2 – 82.63; df = 7). Factor loading CLDF (Table 4) was estimated.

CLDF is calculated according to the formula:

*CLDF = -0.69566 - 0.17158*rtr - 2.77896*abi + 0.10517*toll - 0.22406*ponk - 0.05126*pall + 0.08155*dtrp + 0.35659*pfin.*

Table 4

Factor loading of canonic function

Parameter	Canonic function
rtr	-0.228036
abi	0.176761
toll	0.608104
ponk	0.514241
pall	0.711757
dtrp	0.550586
pfin	0.726307

This canonical function may be interpreted as a factor of the oxygen level plateau after the 2nd OrtT, since it has the closest correlation with the above canonical function ($r_{xy} = 0.73$).

The analysis of the coordinates of the group centroids, the matrix of the factor loading of the classification variables and the coefficients of the canonical linear discriminant function revealed a number of factors indicating a high likelihood of complications after ORIF, such as a high value of PDG, a plateau of the oxygen level after the 1st OrtT, oxygen level of the 2nd OrtT as well as low oxygen levels at the 1st OrtT, differences in oxygen levels between the basal value and the 2nd OrtT, plateau of the oxygen level after the 2nd OrtT.

To assess the risk of complications after ORIF, the CLDF value calculated is compared with the critical CLDF values. CLDF less than 1.05 indicates a high risk of complications after ORIF; a relative risk (RR), calculated after the analysis of the observation matrix, was at a value of 29.8. If the CLDF ranges from -1.05 to 2.18, the risk of complications after ORIF is moderate (RR = 20.9). Minimum risk (RR = 0.03) is with CLDF values of more than 0.42.

To predict the development of purulent complications after osteosynthesis of the calcaneus from an extended lateral approach against the background of chronic arterial insufficiency of the lower extremities and repeated surgical intervention (RSI), a discriminant model for predicting the need of RSI was developed.

Then, the informative value of each feature was evaluated by the method of uni-factor analysis of variance for selection into the group of the most informative ones that would be included in the discriminant model. In addition, an expert assessment of the signs was performed, and various models with different sets of signs were tested.

The indicators collected in this study were measured in both quantitative and ordinal scales. Based on the dispersion analysis, the contribution of indicators to predicting the occurrence of complications after calcaneus ORIF was determined (Table 5).

When analyzing the results of the dispersion analysis, the following indicators with the greatest contribution to the variance were selected, as well as those that have a statistically significant relationship with the need of RSI. The closest relationship was found with basal oxygen levels at TrOx ($F = 41.254$; $p < 0.0001$), oxygen levels at the 1st OrtT ($F = 62.323$; $p < 0.0001$), the oxygen level plateau after the 1st OrtT ($F = 44.569$; $p < 0.0001$), oxygen level at the 2nd OrtT ($F = 85.380$; $p < 0.0001$), difference in oxygen levels between the basal value and the 2nd OrtT ($F = 51.091$; $p < 0.0001$), the plateau of the oxygen level after the 2nd OrtT ($F = 88.907$; $p < 0.0001$). Indicators such as PDG ($F = 8.764$; $p < 0.01$) and ABI ($F = 5.266$; $p < 0.05$) are somewhat less significant.

Based on the results of the discriminant analysis, the final model for predicting the occurrence of complications after ORIF included 7 indicators (Table 6).

The following linear classification discriminant functions were found:

$$F_1 = -97.8556 + 29.7001*rtr + 101.6612*abi - 0.0459*toll - 0.1662*ponk + 1.0880*pall - 1.8754*dtrp + 0.5974*pfin.$$

$$F_2 = -94.5315 + 29.2303*rtr + 100.7026*abi - 0.5313*toll - 0.5118*ponk + 1.5190*pall - 2.2998*dtrp + 0.6757*pfin.$$

Function F_1 corresponds to the group of patients who do not need RSI; function F_2 to the patients requiring RSI.

The obtained model for predicting the need of RSI is statistically significant (criterion F (7.66) = 6.232; $p_0 < 0.00001$).

In the discriminant model obtained, the oxygen level of the first orthopedic test ($p0 < 0.01$) turned out to be the most informative indicator of predicting the need of RSI. This indicator has the largest relationship of intra-group and inter-group variances.

In order to predict the occurrence of complications after ORIF, patient's PDG after DIPT is calculated. Next, a segment manometry for ABI and TrOx is conducted. After determining the basal level of oxygen, OrtT is performed, measuring and registering the oxygen level at the stages of the 1st OrtT, the plateau of the oxygen level after the 1st OrtT, the oxygen level of the 2nd OrtT, the difference in oxygen levels between the basal value and the 2nd OrtT, plateau of oxygen level after the 2nd OrtTr. Next, using the values obtained from the results of the analysis, classification linear discriminant functions (CLDF) are calculated according to the formulas above indicated.

Then, the calculated values of two discriminant functions are compared. The function, the value of which is greater, indicates that the patient belongs to the corresponding group of patients who do not need or need RSI after ORIF of the calcaneus fracture against the background of chronic circulatory disorders of the lower extremities (RF Patent for the invention No. 2657945).

To assess the quality of the discriminant model calculated, the "folding knife" method of discriminant analysis was used (Table 7).

Table 5

Contribution of indicators to dispersion of RSI probability

Parameter	Dispersion conditioned by the impact of a controlled factor	Dispersion conditioned by the impact of uncontrolled factors	F-criterion (Fisher)	Level of significance F-criterion, p
rtr	4.9830	40.9375	8.7640	0.004158
abi	0.16635	2.27451	5.266	0.024665
torb	1142.85	1994.60	41.254	0.000000
toll	1477.41	1706.81	62.3232	0.000000
ponk	1854.86	2996.50	44.569	0.000000
pall	3973.41	3350.71	85.380	0.000000
dtrp	854.325	1203.958	51.09100	0.000000
pfin	3204.92	2595.46	88.907	0.000000

Table 6

Parameters included into the model for predicting the need of RSI

Parameter	Value of F-criterion	Level of significance (p_0)
rtr	0.264	0.61
abi	0.062	0.80
toll	8.574	0.005
ponk	2.560	0.11
pall	1.983	0.16
dtrp	3.003	0.09
pfin	0.152	0.70

Table 7

Quality of the discriminant model calculated

Parameter	Value, %
Sensitivity	93.24
Specificity	87.50
Efficiency	94.83
Level of false negative response	12.5
Level of false positive response	5.17

The efficiency of the obtained model was 93.24 %, which proves its high degree of probability in predicting the need of RSI after ORIF of the calcaneus. The result of the canonical analysis was CLDF with the level of statistical significance $p_0 < 0.001$ (criterion χ^2 – 34,76; df = 7) (Table 8).

Table 8

Factor loading of canonical function

Parameter	Canonical function
rtr	-0.425224
abi	0.468259
toll	0.921488
ponk	0.790722
pall	0.812994
dtrp	0.563001
pfin	0.771839

This canonical function can be interpreted as the factor of the oxygen level at the 1st OrtT, since it has the closest correlation with the above canonical function (r_{xy} = 0.92).

CLDF is calculated according to the following formula:

*CLDF = -2.92032 + 0.24117*rtr + 0.49211*abi + 0.24917*toll + 0.17745*ponk - 0.22125*pall + 0.21787*dtrp - 0.04021*pfin.*

An analysis of the coordinates of the group centroids, the matrix of the factor loading of the classification variables and the coefficients of the canonical linear discriminant function revealed that the high probability of the need for RSI is indicated by the high oxygen levels of the 2nd OrtT and the plateau of the oxygen level after the 2nd OrtT, as well as low PDG, ABI, oxygen level at the 1st OrtT, plateau of the oxygen level after the 1st OrtT and the difference in oxygen levels between the basal value and the 2nd OrtT.

To assess the risk of RSI after ORIF of the calcaneus, the CLDF value calculated is compared with the critical CLDF values. With a CLDF value of less than -1.53, the risk of the need in RSI is high. Based on the results of the assessment of the available observation matrix, the RR was 25.8. The minimum risk of RSI is with CLDF values of more than 0.42 (RR = 0.03). With CLDF values ranging from -1.53 to 0.42, the risk is moderate (RR = 4.8).

DISCUSSION

Despite the widespread introduction of the methods for objective examination of peripheral circulation, a number of authors [14] continue to recommend mnemonic scales for choosing treatment tactics in calcaneal fractures and prognosis of complications based on physical examination and anthropological data.

Dissatisfaction with this approach prompted a number of researchers to develop criteria for treatment tactics with discriminant analysis and the creation of a prognostic model [15]. However, these authors chose ESR, hemoglobin, ultrasound interpretation, systolic blood pressure and other characteristics as signs of a discriminant model that are very far from the objective assessment of peripheral blood flow, and the observations were not differentiated by the nature of the injury and subsequent intervention.

Researchers [12], who showed the efficiency of transcutaneous oximetry, were closest to the development of parametric criteria. The prognostic efficacy of transcutaneous oximetry was studied sufficiently, but has not been investigated specifically for closed intra-articular calcaneal fractures and loses in prognostic efficacy to the models that include other parameters.

The study that used transcutaneous oximetry, distant infrared polypositional thermometry and segmental manometry enabled to conduct a variance analysis of 69 patients with 74 closed intra-articular calcaneal fractures who underwent internal osteosynthesis, and obtained two models: the first with a level of statistical significance $p0 < 0.001$ (χ^2 – 82.63; df = 7) and a prognostic efficiency of 97.3 % which allows predicting inflammatory and purulent complications in the immediate postoperative period; the second one with the level of statistical significance $p0 < 0.001$ (χ^2 – 34.76; df = 7) and a prognostic efficiency of 93.24 % which enables to determine a probability of complications in the short-term postoperative period that would require repeated surgical interventions.

CONCLUSIONS

The method proposed for predicting complications in the immediate postoperative period after internal osteosynthesis of the calcaneus allows efficient estimation of the risks of complications by calculating PDG, ABI and TrOx (97.3 %). The proposed discriminant model predicts the need for repeated surgical interventions with an efficiency of 93.24 %, and shows feasibility of surgical treatment with an extended lateral approach.

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Received: 10.10.2019

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