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Mathematical modeling and prediction of the effectiveness of surgical treatment in surgery of the spine and pelvic complex

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Abstract

Based on the study of the literature on the quality assessment of operative treatment in reconstructive surgery of the spine and pelvic complex, it can be concluded that, as a rule, multiple linear or logistic regression, a decision tree, is used to predict the quality of operative treatment. Neural networks are less commonly used.

Forecasting is performed on the basis of a comparison of the pre- and postoperative condition of the patient, assessed according to various ordinal and quantitative scales as a result of interviewing the patient.

With a relatively small number of analyzed cases of the disease (several tens or hundreds) and a small number of indicators (no more than two or three dozen), the use of neural networks seems premature for two reasons: a small amount of data allows analyzing them with classical methods of mathematical statistics, and identifying dependencies on a given stage requires constant "manual" intervention, taking into account information from the subject area.

The application of statistical analysis methods to data on the treatment of chronic injuries showed the presence of standard problems for medical

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data. This is the presentation of the initial information in nominal or ordinal scales, the subjective nature of some indicators, as well as the interdependence of the presented characteristics, which reduces the quality of research.

The search for the objective function that characterizes the quality of surgical treatment has shown the ambiguity of solving this problem even for a highly specialized situation.

The identification of objectively present relationships also revealed a large number of problems, especially related to the choice of the type of surgical treatment, which is largely determined by the experience of the surgeon.

Based on the study, it was proposed to build a model for predicting the quality of surgical treatment, based on expert assessments in the form of a forecast tree with recommended surgical treatment options and a statistical forecast based on the available experience. It is assumed that the model will be dynamic with feedback and be able to self-update.

To predict the quality of surgical treatment in reconstructive surgery of the spine and pelvic complex, it is advisable to use a forecast tree, which allows us to recommend the type of surgery for a specific case of injury or disease and calculate the predicted values of quality of life indicators.

Keywords: evaluation of the effectiveness of treatment, prognosis of treatment, decision support.

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1. Introduction. The task of predicting the results of surgical treatment is becoming increasingly relevant in the conditions of accumulating practical experience and the ever accelerating introduction of IT technologies in medicine. Prediction based on statistical data on the results of previous similar operations contributes to the informed choice of surgical reconstructive treatment. Statistical analysis allows to take into account difficultly formalizable factors describing diseases or injuries, as well as data from ordinal and nominal scales. Therefore, when developing clinical decision support system, along with planning and modeling, it is necessary to apply the prediction of treatment results based on statistical analysis.

2. Theoretical analysis. The search for criteria for the effectiveness of treatment, identifying dependencies of the quality of treatment on the type of diseases, injuries and patient characteristics has been the subject of many scientific studies. Sufficient attention is paid to building clinical decision support systems (Clinical DSS) in general, and in surgery in particular.

As a rule, Clinical DSS find effective application in diagnostics. For example, A. B. Goncharova, E. I. Sergeeva [1] described the use of the Clinical DSS model when making a diagnosis of patients based on the knowledge base of the expert

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system, presented in the form of a table of values based on the notion/absence of symptoms.

The work of A. A. Litvin, V. A. Litvin [2] presents a review of the literature on the use of DSS in surgery. Noted, in particular, that the article by P. Davuluri et al. [3] developed and applied a computer DSS for patients with pelvic injuries. An automated system for analyzing the results of examining patients using statistical tests is used for calculations.

A. A. Egorov and V. S. Mikshina [4] developed a DSS based on artificial neural networks to determine the possible outcomes and ways to complete the surgical treatment of peritonitis. Three variants of the outcome of operations are considered.

R. Mofidi et al. [5] developed a DSS for classifying the severity of acute pancreatitis and predicting the possibility of death with the use of artificial neural networks for classification. The following parameters are taken into account as significant indicators: age, hypotension, two or more signs of SIRS, PaO_2 levels, lactate dehydrogenase, glucose, urea, calcium, hematocrit, and the number of leukocytes in the blood.

B. Andersson et al. [6] conducted a study in which developed DSS on the basis of artificial neural networks for early prediction of acute pancreatitis exacerbation.

N. A. Korenevsky et al. [7] developed and used DSS using fuzzy logic to control decision-making processes in the treatment of patients with acute cholecystitis. The authors also solve the problem of forecasting with the use of expert assessments in the development of rules.

The selection of the objective function in the DSS is a key task. A sufficient number of studies are also devoted to the definition of target functions as an indicator of the effectiveness of surgical treatment and the identification of factors affecting its value.

A. V. Krut'ko, E. S. Baikov [8] presented a review of the current literature analyzing the criteria for predicting the results of surgical treatment of herniated intervertebral disks.

In the work of J. During et al. [9] the connection of lumbar lordosis with the pelvic geometrical parameters established by X-ray studies was revealed.

In the work of G. Duval-Beaupere et al. [10] it was revealed that a decrease in the angle of inclination of the pelvis and the sacrum correlates with a higher frequency of recurrence of hernias of the lumbar spine.

Y. J. Sur, C. G. Kong, and J. B. Park [11] found that the presence of the transitional lumbosacral vertebra correlates significantly with the frequency of hernia relapses.

In the work of M. Shen, A. Razi [12] it was revealed that the possibility of recurrence is associated with retrolisthesis, which is defined as a vertebral displacement by more than 8 %.

In the thesis, S. I. Ovcharenko [13], on the basis of the quantitative significance of clinical factors due to the intensity of pain syndrome and the number of affected vertebral motor segments, developed a technology for predicting the outcome of surgical treatment of lumbar osteochondrosis based on the use of polyfactorial correlation analysis and tabular prediction.

In the thesis, A. Antipko [14], based on discriminant analysis using data on the duration of conservative treatment, a model was developed for assessing the risk of recurrence of intervertebral hernia in the lumbosacral spine.

A. V. Krut'ko, E. S. Baikov [15] developed guidelines for "Predicting the results of surgical treatment of patients with hernias of lumbar intervertebral disks" and created a software product for prediction based on the results of MRI and X-ray of the likelihood of recurrence of intervertebral hernia after its deletion.

The thesis of A. G. Nazarenko [16] considers various types of operations and indications for their use. The creation of a vertebral register of patients is described.

J. D. Berne, A. Cook, S. A. Rowe, and S. H. Norwood in the article [17] applied logistic regression to analyze for the presence or absence of arterial damage. To identify patterns, a retrospective database was used, containing about 10,000 records for the period 2000–2009.

In articles [18] and [19], in the course of thematic cohort studies, regression models for additive-multiplicative hazards in multiple outcomes of the disease are constructed and evaluated.

Multiple linear regression was constructed in [20], according to a prospective observational study of 424 patients with severe trauma, devoted to traumatic endotheliopathy. Mortality is considered as a function of the following indicators - adrenaline, norepinephrine syndecan-1, thrombomodulin and selectin, demography, type and severity of injury, physiology, treatment.

Hae-Dong Jang et all. [21], in the article, devoted to the risk factor analysis for predicting vertebral body re-collapse after posterior instrumented fusion in thoracolumbar burst fracture, explores data for 10 years to build a logistic regression: the probability of a reoperation is analyzed.

In work [22] the problem of sagittal alignment is considered. Multiple regression is constructed, the resulting variable is the level of residual curvature. Self-learning computer programs are used for surgical planning and prediction of postoperative alignment.

In [23], logistic regression is used to determine the risk factors for cage subsidence in patients with ossification of the posterior longitudinal ligament (OPLL) after anterior cervical discectomy.

In [24], preoperative leg pain assessment is used to predict transforaminal lumbar interbody fusion. The dependence of the success of the operation on preoperative indicators such as clinical evaluations, age and body mass index is analyzed.

The analysis of the studied sources led to the following conclusions. Each study presents a solution to a particular task, usually determined by the type of disease, injury or line of research, within which a specific objective function is selected and statistical models are built. Usually it is a classification or regression. Forecasting is reduced to the classification of patients according to indicators before and after surgery. Multiple linear or logistic regression, a decision tree are applied for forecasting. More rarely it is neural networks. Statistical indicators of interrelations are used for their identification.

3. Empirical analysis. A study of empirical data obtained from one of the authors' own studies on the results of surgical treatment chronic injury with the use of multidimensional statistical analysis was conducted to build a forecast model for the clinical decision support system in surgery of spine and pelvic complex implemented under the project of Advanced Research Foundation.

Data of 80 patients, including the following indicators: gender and age, type of injury, quality of life indicators before and after surgery, type of operation were investigated. Baseline data and their designations are presented in Table 1.

To determine the criterion of success of treatment (objective function), various

Table 1

Designations of patient indicators

Designation	Indicators
x_1	Gender
x_2	Age
x_3	Injury Level
x_4	Primary Injury Type
x_5	Stability
x_6	Deformation Character
x_7	Group
x_8	Surgery Type
y_1	Correction Result
x_9	Kyphosis Degree Before Surgery
y_9	Kyphosis Degree After Surgery
y_{11}	Correction Measure Percentage
y_{111}	Correction Measure In Degrees
z_1	Correction Loss Degree
x_{10}	VAS before Surgery
y_{10}	VAS after Surgery
x_{12}	ODI before Surgery
y_{12}	ODI after Surgery
r_{12}	Relative Modify ODI

methods of multivariate statistical analysis were applied to the existing empirical data.

A feature of research in medicine is the interdependence of indicators, which complicates the specification of forecast models. Correlation, factor and component analysis were used to identify relationships.

So the method of principal components showed that almost all the initial data are associated with the first principal component, which may indicate interdependencies of the initial data. This fact has been confirmed in the calculations of the pair correlations of the initial indicators. The component itself explains 53 % variation. “The type of Surgery” and “Measure of correction in degrees” correlate significantly with the second component, it explains 16 % of the variation, the third is related to “Age” and “Level of injury”, it accounts for about 7 % of the explained variation. The fourth component is due to the “Gender” of the patient. The first six main components account for more than 90 % of the variation of indicators. The results of the application of the principal component method are partially given in Table 2.

The factor analysis, after rotation of the factor axes, made it possible to single out three significant factors explaining 76% of the total variation of indicators. The identified factors have a more meaningful interpretation than the main components. The first is associated with postoperative patient characteristics, the second with preoperative characteristics. The corresponding factor loads are shown in Table 3.

Cluster and discriminant analyzes were used to group patients. The results of the use of cluster analysis are not given, since they did not allow to unambiguously interpret the resulting partitions. The use of discriminant analysis has allowed for some indicators to build effective discriminatory functions. For example, discrimination in terms of the “Correction result” (y_1) indicator made it possible to obtain a 100% separation of the initial data for the training sample. Some baselines do

Table 2

Correlations of indicators with four main components

Variables	Factor 1	Factor 2	Factor3	Factor4	...
x_1	−0.269	0.197	0.196	0.820	...
x_2	0.135	−0.139	−0.778	−0.182	...
x_3	0.019	0.258	−0.660	0.393	...
x_4	−0.888	0.161	−0.008	−0.070	...
x_5	−0.830	0.259	−0.116	0.012	...
x_6	−0.842	0.243	−0.103	−0.058	...
x_7	−0.850	0.191	−0.031	−0.031	...
x_8	−0.048	0.679	−0.180	0.081	...
y_1	−0.759	−0.587	−0.049	0.016	...
x_9	−0.819	0.402	0.058	−0.105	...
y_9	−0.862	−0.368	−0.014	0.019	...
y_{11}	0.849	0.439	0.025	−0.004	...
y_{111}	−0.356	0.842	0.088	−0.152	...
z_1	−0.798	−0.375	−0.003	0.087	...
x_{10}	−0.828	0.363	0.060	−0.176	...
y_{10}	−0.893	−0.317	−0.031	0.012	...
x_{12}	−0.865	0.279	0.071	−0.008	...
y_{12}	−0.889	−0.312	−0.038	0.074	...

Table 3

Factor loads

Variables	Factor 1	Factor 2	Factor3
x_1	0.079	0.324	0.196
x_2	0.027	−0.206	−0.774
x_3	−0.130	0.181	−0.673
x_4	0.603	0.671	0.019
x_5	0.504	0.711	−0.096
x_6	0.523	0.706	−0.082
x_7	0.556	0.671	−0.007
x_8	−0.365	0.563	−0.213
y_1	0.961	0.001	0.012
x_9	0.397	0.821	0.069
y_9	0.906	0.236	0.039
y_{11}	−0.940	−0.173	−0.031
y_{111}	−0.239	0.885	0.058
z_1	0.860	0.192	0.047
x_{10}	0.428	0.796	0.074
y_{10}	0.901	0.296	0.020
x_{12}	0.507	0.751	0.091
y_{12}	0.895	0.297	0.014
Expl.Var	7.000	5.364	1.182
Prp.Totl	0.388	0.298	0.065

not affect the outcome of discrimination. The results of the use of discriminant analysis are shown in Table 4.

Table 4

The results of the analysis of the discriminant function

Variables	Wilks' Lambda	Partial Lambda	F-remove (2,62)	p-level	Toler.	1-Toler. (R-Sqr.)
x_1	0.056	0.995	0.292	0.590	0.832	0.167
x_2	0.057	0.979	1.309	0.256	0.788	0.211
x_3	0.057	0.982	1.150	0.287	0.835	0.164
x_4	0.059	0.952	3.129	0.081	0.116	0.883
x_5	0.060	0.938	4.146	0.045	0.094	0.905
x_6	0.059	0.954	3.036	0.086	0.136	0.863
x_7	0.063	0.896	7.286	0.008	0.094	0.905
x_8	0.057	0.976	1.530	0.220	0.528	0.471
y_1	0.058	0.967	2.117	0.150	0.012	0.987
x_9	0.059	0.953	3.098	0.083	0.167	0.832
y_9	0.060	0.932	4.542	0.036	0.016	0.983
y_{11}	0.056	0.996	0.194	0.660	0.554	0.445
y_{111}	0.056	0.999	0.015	0.900	0.160	0.839
z_1	0.056	0.999	0.039	0.842	0.213	0.786
x_{10}	0.056	0.994	0.336	0.563	0.194	0.805
y_{10}	0.066	0.850	11.075	0.001	0.222	0.777

In other cases, discrimination seemed less successful, and for a number of indicators it was not possible.

To predict the results of treatment, linear regression models were constructed and investigated. At the same time, various postoperative characteristics were selected as the resulting function characterizing the quality of treatment.

Regression analysis allowed us to build several models with varying degrees of compliance with the initial data. Below are some of the results. All indicators in the models are statistically significant at less than 5 %.

$$y_{111} = 4.1 - 2.3x_4 + 1.7x_8 + 0.73y_9, \quad R^2 = 0.71.$$

Here the dependent variable is "Measure of correction in degrees." The model adequately describes the results of treatment, but the indicator "Degree of kyphosis after surgery" (y_9) is not a preoperative characteristic and its participation in the model is very doubtful.

In the next model, the dependent variable is "The degree of correction loss"; the value of the coefficient of determination shows a good adequacy to the initial data model. It is obvious that the loss of correction is influenced by both preoperative and postoperative indicators.

$$z_1 = 6.94 + 1.03x_5 - 0.06y_{11} - 0.4x_{10} + 0.95y_{10}, \quad R^2 = 0.76.$$

In the third model, the dependent variable is "ODI after Surgery". The large value of the coefficient of determination may be due to the mutual influence of ODI before and after the surgery. Interpreting the coefficients at the "Correction result" causes some difficulties. This may be due to the interdependencies between the regressors, as previously identified.

$$y_{12} = -30.78 + 1.74x_8 + 20.89y_1 - 4.68z_1 + 0.64x_{12}, \quad R^2 = 0.88.$$

In the fourth model, the calculated characteristic, "Relative ODI change after surgery", obtained as the ratio of the ODI difference before and after the surgery to the corresponding ODI value before the surgery, was used as the dependent variable. This index can serve as an indicator of the effectiveness of surgical treatment—the higher the value of this indicator, the more effective the result of surgical treatment can be considered.

$$r_{12} = 0.94 - 0.14y_1 - 0.059x_8 + 0.035x_{10} - 0.099y_{10}, \quad R^2 = 0.89.$$

4. Discussion. The results of the analysis of empirical data show that even when solving the problem of predicting the effectiveness of treatment of chronic injury, it is impossible to unambiguously choose the objective function of the quality of surgical treatment. The exceptions are the last two models, where the dependent variable is the indicator of quality of life, and the value of the coefficient of determination is 90% or close.

In this case, the problem remains the representation of the characteristics of patients in an ordinal scale, the gradations in which are subjective in nature as patients and physicians. Perhaps this is the reason for the impossibility to build a model and determine significant factors to substantiate the choice of the type of operation.

The question of choosing one or another type of surgical treatment is more a result of the surgeon's experience than objective dependencies on trauma characteristics and patient data. Algorithmization of this experience is not yet possible due to the mixing of the experience of different specialists and the lack of scientifically proven methods of formalizing medical experience. Discussions regarding the type of surgical treatment in one case or another are an integral part of scientific publications and conferences. It also indicates that the choice of treatment is largely due to the set of practices of a particular doctor. Multiple surgical treatments can pursue specific, private results that cannot be predicted as a single statistical model. The complexity of building models is exacerbated by the lack of prerequisites for their use (independence of indicators, normal distribution of characteristics, etc.), as well as the need to use different statistically significant indicators in each case, the search for which represents a separate task.

5. Conclusions. Based on the results of the analysis of theoretical material and empirical data, it was considered appropriate to build a forecast model for each patient taking into account the following provisions.

The model is based on expert assessments that take into account the diverse experience of surgical treatment.

The implementation of the model supposes the possibility of choosing from several options according to the types of operations based on the existing practices in the use of surgical treatment techniques.

The forecast model for the type of surgery and quality of treatment is implemented in the form of a tree, the branch points of which are determined by the type of injury (disease) and the patient's anthropometric properties. Leaves characterize the quality of treatment for the appropriate type of disease and treatment method.

To characterize the quality of surgical treatment, use an indicator (index) calculated as a relative change in ODI after surgery and VAS after surgery. The relative change in ODI is calculated as the difference between the ODI values before and after the surgery divided by the ODI value after the surgery.

The quality of the whole treatment is characterized by the absolute ODI value immediately after the surgery, as well as 3, 6 and 12 months after the surgery.

All forecasts are presented in the form of probabilistic (interval) characteristics.

The model has feedback and improved, accumulating new treatment experience.

The step-by-step algorithm for constructing a forecast tree for the examined empirical data on the treatment of chronic injury can be represented by the following branch points:

1. Disease: acute injury, chronic injury, degenerative changes.
2. The level of injury: chest, lumbar, pelvis, hip joint.
3. Type of primary injury: A, B or C.
4. Stability: stable or unstable.
5. The nature of the deformation: single-plane or multi-plane.
6. Treatment options—the choice of implants and structures, type of operation: ventral surgery, dorsal surgery, one-time two-stage intervention, etc.
7. Results of treatment: a prognosis is given on the likelihood of a patient falling into one or another range by ODI levels.

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Математическое моделирование и прогнозирование эффективности оперативного лечения в хирургии позвоночно-тазового комплекса

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Аннотация

На основе изучения литературы, посвященной оценке качества оперативного лечения в реконструктивной хирургии позвоночно-тазового комплекса можно сделать вывод, что для прогнозирования качества оперативного лечения, как правило, применяется множественная линейная или логистическая регрессия, дерево решений. Реже применяются нейронные сети.

Прогнозирование выполняется на основе сравнения до- и послеоперационного состояния больного, оцениваемого по различным порядковым и количественным шкалам в результате опроса пациента.

При сравнительно небольшом количестве анализируемых случаев заболевания (несколько десятков или сотен) и незначительном количестве показателей (не более двух-трех десятков) применение нейронных сетей представляется преждевременным по двум причинам: небольшое количество данных позволяет анализировать их классическими методами математической статистики, и выявление зависимостей на данном этапе требует постоянного «ручного» вмешательства с учетом оценок и взаимосвязей из предметной области.

Применение методов статистического анализа к данным о лечении застарелой травмы показало наличие стандартных проблем для медицинских данных. Это представление исходной информации в номинальной или порядковой шкалах, субъективный характер некоторых показа-

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телей, а также взаимозависимость представленных характеристик, что снижает качество исследования.

Поиск целевой функции, характеризующей качество оперативного лечения, показал неоднозначность решения этой задачи даже для узкоспециализированной ситуации.

Объективно присутствующие взаимосвязи также выявило обусловили количество проблем, особенно связанных с выбором типа оперативного лечения, которое в большей степени определяется опытом хирурга.

На основе проведенного исследования было предложено строить модель прогноза качества оперативного лечения с учетом экспертных оценок в виде прогнозного дерева с рекомендуемыми вариантами хирургического лечения и статистическом прогнозе, основанном на имеющемся опыте. Предполагается, что модель будет динамической с обратной связью и иметь возможность самообновления.

Для прогнозирования качества оперативного лечения в реконструктивной хирургии позвоночно-тазового комплекса целесообразно применять дерево прогноза, позволяющее рекомендовать тип операции для конкретного случая повреждения или заболевания и рассчитывающего прогнозные значения показателей качества жизни.

Ключевые слова: оценка эффективности лечения, прогнозирование лечения, поддержка принятия решений.

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