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Prognostic model of integral renal risk in infants after correction of congenital heart defects

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Renal complications and subclinical renal stress are frequent components of the early postoperative period in infants after cardiac surgical correction of congenital heart defects and require early risk stratification.

OBJECTIVE – to develop a prognostic scoring index for assessing the integral renal risk index in infants after correction of congenital heart defects in the early postoperative period.

MATERIALS AND METHODS. A retrospective single-center descriptive-analytical study was conducted (n = 101; age 1–12 months). The dependent variable was the integral renal risk index (a continuous scale of integral renal risk or stress) formed within the analysis of the early postoperative period. The following predictors were considered: disease severity, physical development as a proxy for nutritional status, class or complexity of the surgical intervention, syndromic or genetic features, creatinine level, and left ventricular ejection fraction. Multiple linear regression was constructed with diagnostics of assumptions (normality of residuals, linearity, homoscedasticity, multicollinearity assessed by the variance inflation factor, and influential observations).

RESULTS. The model was statistically significant ($F(6, 94) = 9.82$; $p < 0.001$) and explained 38.5 % of the variance in risk (adjusted $R^2 = 0.346$). The largest independent contribution was made by the operation class (surgical complexity) ($b = 0.578$; $p < 0.001$), whereas ejection fraction demonstrated an inverse association with risk ($b = –0.0167$; $p = 0.016$).

CONCLUSIONS. A scoring index, X, defined by a formula and within-cohort thresholds ($X > 1$ – high risk; $X > 1.5$ – very high risk), is proposed. This index integrates perioperative burden and perfusion reserve and may be used for early nephroprotective management.

KEYWORDS
congenital heart defects, infants, postoperative period, acute kidney injury, renal stress, scoring, regression model.

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The early postoperative period in infants after cardiac surgical correction of congenital heart defects (CHD) is accompanied by hemodynamic lability and a systemic inflammatory-stress response, which increases the risk of organ dysfunction [5, 7]. The kidneys are among the most sensitive target organs to hypoperfusion/reperfusion, fluctuations in cardiac output, hemodilution or anemia, vasoactive therapy, and nephrotoxic drugs [5, 7]. The combination of perfusion disorders, cytokine-mediated changes, microcirculatory disturbances, and fluid imbalance can lead to both clinically overt acute kidney injury (AKI) and early manifestations of renal dysfunction, which may occur before an increase in creatinine levels [5, 6].

According to contemporary summaries, AKI in pediatric cardiac surgery is associated with worse clinical outcomes (longer stay in the intensive care unit and hospital, higher complication rates, the need for renal replacement therapy, and increased mortality) [5, 8]. Prognostic significance is attributed not only to the presence of AKI but also to its severity, duration of impairment, and fluid overload; the timing of initiation of renal replacement therapy in critically ill children is also important [1].

Key predictors include age and body weight, complexity of the intervention, perioperative burden, the need for vasopressor support, and markers of reduced perfusion capacity; meta-analytic data emphasize the central role of the «operative burden + perfusion reserve» complex [8], and instrumental indicators (in particular, Doppler-derived variables of renal blood flow) may have additional prognostic value [2].

Thus, there is a practical need for a simple calculated index that combines available clinical, laboratory, and instrumental parameters and allows assessment of integral renal risk at the bedside in the first postoperative days. Such a tool should not aim to replace AKI diagnosis but rather to support early decisions: intensification of hemodynamic and diuresis monitoring, correction of infusion strategy, limitation of nephrotoxic combinations, and optimization of the perfusion regimen with regard to cardiac perfusion reserve [2, 4, 6, 8].

Objective – to develop a prognostic scoring index for assessing the integral renal risk index in infants after correction of congenital heart defects in the early postoperative period.

Materials and methods

Design: A retrospective single-center study was conducted using de-identified data of 101 infants (1–12 months) who underwent cardiac surgical CHD correction, with assessment of the early postoperative period course during the first hospitalization at the Department of Cardiovascular Surgery of the Odesa Regional Children's Clinical Hospital. The analysis covered clinical characteristics of the early postoperative period, basic laboratory parameters, and echocardiographic variables.

The endpoint was the integral renal risk index, reflecting the gradient of renal risk or stress in the early postoperative period. The use of linear regression was justified by the continuous scale of risk and the need to obtain a numerical index for bedside stratification.

Predictor selection was performed according to three interrelated criteria: data availability, pathophysiological association with mechanisms of renal hypoperfusion and stress in the early postoperative period, and minimal reliance on protocol-based descriptive variability. The most suitable instrumental parameter for inclusion in the model was left ventricular ejection fraction (EF; n = 101), as it is a standardized integral marker of pump function and perfusion reserve. From a pathogenetic perspective, EF is associated with the risk of systemic hypoperfusion and secondary target-organ injury, in particular renal injury. Among clinical and systemic predictors, preference was given to parameters (severity), physical development as a proxy for nutritional status and metabolic reserves (Physical), type or surgical intervention complexity (Operation class), presence of syndromic and genetic features (Stigmata), as well as creatinine (Creatinine) as a laboratory marker of renal stress. Such a set of variables allows combining three levels of risk in a single equation: baseline vulnerability, the intensity of surgical and perioperative impact, and early laboratory «response» of the kidneys.

Statistical analysis [3]: multiple linear regression was constructed with assessment of model quality (multiple correlation coefficient (R), coefficient of determination (R^2), adjusted R^2, F-statistic, p), analysis of coefficients (unstandardized coefficients (b), standard error (SE), t-statistic, p), and diagnostics of model assumptions. Homoscedasticity (homogeneity of residual variance) was assessed graphically (scatter of residuals relative to predicted values). Multicollinearity was assessed using variance inflation factors (VIFs). Influential observations were analyzed using Cook's distance. The level of statistical significance was set at $p < 0.05$. Calculations were performed using IBM SPSS Statistics and Microsoft Excel.

The study was conducted using de-identified data in compliance with ethical principles of biomedical research and the provisions of the Declaration of Helsinki. As the study was retrospective and used de-identified data, informed consent was obtained in accordance with local procedures.

Results

In infants after CHD correction, even with formally preserved systolic function, perfusion fluctuations may occur in some patients, triggering transient renal stress. Therefore, a multifactor prognostic index was constructed to assess individual risk from the combined effect of hemodynamic, clinical, and systemic factors (Fig. 1).

Fig. 1 presents the conceptual scheme for score formation: integration of predictors reflecting baseline vulnerability (severity, physical, stigmata), perioperative complexity (operation class), a laboratory signal of renal stress (Creatinine), and instrumental perfusion reserve (EF).

The constructed model included 101 observations (children under 1 year of age after CHD correction) and six predictors, which ensured an observation-to-parameter ratio sufficient for multiple regression estimation without excessive parametrization. Table 1 presents the integral indicators

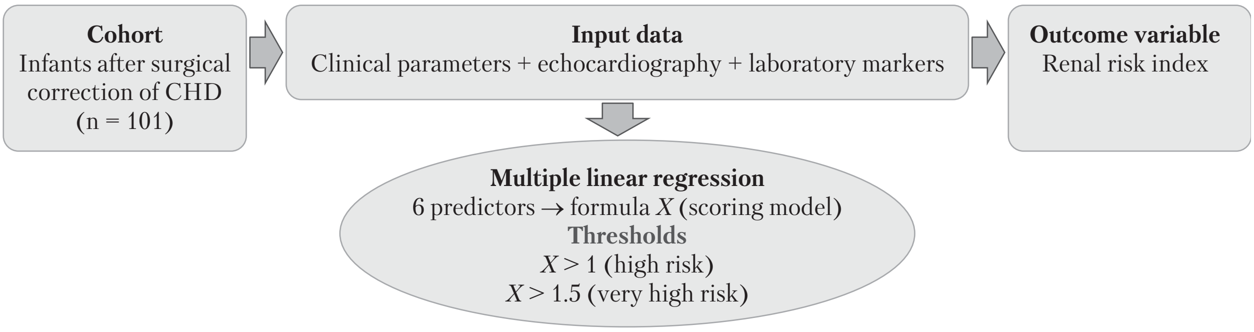

Figure 1. **Scheme of construction of the prognostic integral renal risk index**

of the quality of the linear regression model and its statistical significance for predicting the integral renal risk index (risk of renal complications) in infants after CHD correction.

As shown in Table 1, R = 0.621 indicates moderate agreement between the observed risk values and the model predictions. The coefficient of determination, $R^2 = 0.385$, indicates that the set of predictors explains 38.5 % of the variance in risk in the sample. After adjustment for the number of variables, the explanatory power is 34.6 % (adjusted $R^2 = 0.346$), which is expected for clinical data with a multifactorial endpoint. The F statistic ($F(6, 94) = 9.82$; $p < 0.001$) confirms that the model significantly improves predictive performance compared with the null model (without predictors). The obtained values indicate that the constructed regression model has practical prognostic value and establishes a basis for calculated scoring to facilitate early stratification of postoperative renal risk.

The logic of inclusion of the selected predictors corresponds to the three-component concept of renal risk: (1) patient vulnerability (severity, physical, stigmata); (2) intensity of perioperative impact (operation class); (3) early laboratory signal of renal stress (Creatinine) in combination with the instrumental marker of perfusion reserve (EF).

Before constructing the equation, data quality control was performed: verification of ranges, detection of outliers, and assessment of predictor correlations to prevent multicollinearity. For linear regression, it is important to ensure the adequacy of basic assumptions; therefore, normality of residuals, homoscedasticity, and influential observations were also evaluated (Table 2).

The largest independent contribution to the predicted risk is made by operation class (b = 0.577951; $p < 0.001$). This means that with increasing class and complexity of the intervention, the risk index increases, reflecting a higher probability of renal stress under conditions of greater perioperative burden. The second statistically significant predictor is EF: the inverse association (b = –0.016666; p = 0.016) indicates that lower EF is associated with a higher risk, which is pathophysiologically consistent with mechanisms of reduced perfusion reserve and increased renal sensitivity to hemodynamic fluctuations. The variables severity, physical, stigmata, and Creatinine did not demonstrate independent statistical significance in this model; they should be considered risk modifiers and indicators of background vulnerability, with effects that may

Table 1. **Quality of the regression model (basis for scoring)**

Indicator	Value
N	101
R	0.621
R^2	0.385
Adjusted R^2	0.346
F (6, 94)	9.82
p (overall model)	< 0.001
Dependent variable	risk

Table 2. **Regression coefficients for the construction of index X**

Predictor	b	SE(b)	t	p
Intercept	0.817678	0.710820	1.15033	0.253
Severity	0.141593	0.142791	0.99161	0.324
Physical	0.097574	0.412245	0.23669	0.813
Operation class	0.577951	0.082910	6.97086	< 0.001
Stigmata	0.020198	0.019659	1.02743	0.307
Creatinine	0.000398	0.003856	0.10328	0.918
EF	–0.016666	0.006805	–2.44899	0.016

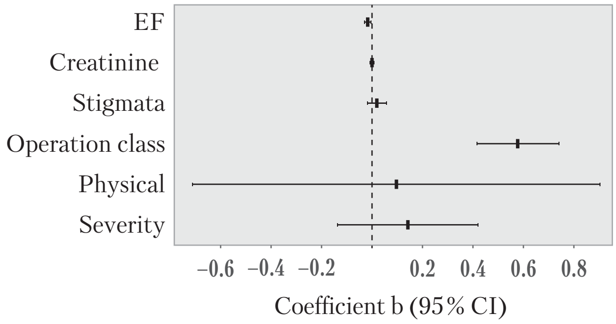

Figure 2. **Model coefficients with 95 % confidence intervals (linear regression)**

become apparent with a larger sample, a different endpoint definition, or in nonlinear models.

Fig. 2 graphically illustrates the magnitude and direction of the associations between each predictor and risk: the most pronounced positive contribution is observed for operation class, whereas EF has a negative coefficient.

The multiple linear regression equation (unstandardized coefficients) was transformed into a practical, calculated index, *X*, for individual assessment of integral renal risk in the first postoperative days. This presentation allows the model to be used as a bedside tool for risk stratification and planning the intensity of monitoring and nephroprotective interventions. The formula for index *X* is given below:

$$X = 0.817678 + 0.141593 \cdot \text{Severity} + 0.097574 \cdot \text{Physical} + 0.577951 \cdot \text{Operation class} + 0.020198 \cdot \text{Stigmata} + 0.000398 \cdot \text{Creatinine} - 0.016666 \cdot \text{EF}.$$

For practical interpretation of the index within the studied cohort, intra-empirical thresholds were used: $X > 1$ – high risk; $X > 1.5$ – very high risk. These thresholds should be regarded as indicative until external validation is obtained.

The *X* score is intended for rapid stratification of infants by renal risk level immediately after surgery and during the first postoperative days. The most unfavorable profile in the model is the combination of a higher intervention-complexity class and lower EF. For such patients, the following are advisable:

- intensified perfusion monitoring (arterial pressure trends, urine output, laboratory parameters);
- nephroprotective strategy (optimization of hemodynamics, avoidance of nephrotoxic combinations, early correction of hypovolemia/overload);
- more frequent monitoring of creatinine/urea during the first 24–48 hours;
- closer control of fluid balance and adjustment of infusion strategy.

The advantage of the index lies in its simplicity: it is based on parameters that are usually available in routine practice (surgical characteristics, EF, and basic clinical and laboratory variables) and can be used as an auxiliary decision-support tool for determining the intensity of monitoring.

Discussion

The proposed model represents an attempt to transform the descriptive postoperative profile of infants after CHD correction into an applied tool for predicting renal risk. The key methodological idea was to combine within a single index two «core» mechanisms: (1) the intensity of operative and perioperative burden and (2) the perfusion reserve of the cardiovascular system. In our sample, these components – the operation class and EF – were statistically significant independent predictors of risk, supporting the pathophysiological concept of renal stress as a derivative of perfusion stability in the context of intervention complexity.

The scientific novelty of the approach consists in (1) formalization of renal risk as a continuous gradient (risk) rather than a binary «presence/absence of AKI», which allows more sensitive identification of the «grey zone» of subclinical renal stress; (2) development of a within-cohort scoring index *X* with a simple formula based on routinely available parameters; and (3) demonstration of the priority role of the combination «operative burden + perfusion reserve» in shaping the predicted risk compared with a number of traditionally plausible but, in this sample, statistically non-dominant modifiers (baseline severity, physical development, stigmata, and baseline creatinine).

In practical terms, index *X* may be applied within the first 24–48 hours after surgery to intensify nephroprotective management in the higher-risk group: intensified perfusion monitoring, adjustment of infusion strategy to maintain fluid balance, limitation of nephrotoxic drug combinations, and more frequent laboratory monitoring (creatinine/urea).

Conclusions

The constructed multiple linear regression model for predicting the integral renal risk index in infants after CHD correction is statistically significant and has practical prognostic value ($R = 0.621$; $R^2 = 0.385$; adjusted $R^2 = 0.346$; $F(6, 94) = 9.82$; $p < 0.001$), which allows its use as the basis for a calculated clinical index.

The largest independent contribution to the increase in the predicted risk in the sample is made by the class or complexity of the surgical intervention (operation class) ($b = 0.578$; $p < 0.001$), reflecting the priority role of perioperative burden in the development of renal stress in the early postoperative period.

Left ventricular ejection fraction demonstrates an inverse association with risk ($b = -0.0167$; $p = 0.016$): lower EF is associated with higher predicted renal risk, which is pathophysiologically consistent with reduced perfusion reserve and greater renal sensitivity to hemodynamic fluctuations.

A calculated scoring index X (based on unstandardized regression coefficients) is proposed along with within-cohort stratification thresholds ($X > 1$ – high risk; $X > 1.5$ – very high risk). These tools help facilitate early identification of a higher renal risk group and selection of monitoring intensity during the first 24–48 hours after surgery.

Clinical application of index X is appropriate as a decision-support tool for nephroprotection (intensification of perfusion and diuresis monitoring, optimization of infusion strategy, minimization of nephrotoxic combinations, and more frequent laboratory monitoring). At the same time, the thresholds and coefficients require external validation in an independent sample (prospectively/multicenter) to refine calibration and generalizability.

Declaration of interests

The authors declare no conflicts of interest.

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Ethics approval and written informed consent statements

The study was conducted in accordance with the ethical principles of biomedical research and the provisions of the Declaration of Helsinki and was approved by the Ethics Committee of Odesa National Medical University (Protocol No. 1a dated January 14, 2026). Written informed consent was obtained from the parents or legal guardians of all patients.

Authors contributions

M. H. Melnychenko: study concept and design, critical revision of the manuscript, scientific supervision; V. P. Buzovskyi: clinical procedures, patient follow-up, data analysis, manuscript preparation, and editing; L. B. Elii: data collection, literature review, manuscript preparation.

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Прогностична модель інтегрального ренального ризику в немовлят після корекції вроджених вад серця

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Ренальні ускладнення та субклінічний ренальний стрес є частими компонентами раннього післяопераційного періоду в немовлят після кардіохірургічної корекції вроджених вад серця та потребують ранньої стратифікації ризику.

Мета — розробити прогностичний скоринговий індекс для оцінки інтегрального показника ренального ризику (risk) у немовлят після корекції вроджених вад серця в ранній післяопераційний період.

Матеріали та методи. Проведено ретроспективне одноцентрове описово-аналітичне дослідження (n = 101; 1—12 міс). Залежною змінною був інтегральний показник risk (безперервна шкала інтегрального ренального ризику або стресу), сформований у межах аналізу раннього післяопераційного періоду. Як предиктори розглядали: тяжкість стану, фізичний розвиток як проксі нутритивного статусу, клас або складність оперативного втручання, синдромальні або генетичні стигми, креатинін і фракцію викиду лівого шлуночка. Побудовано множинну лінійну регресію з діагностикою припущень (нормальність залишків, лінійність, гомоскедастичність, мультиколінеарність за VIF (the variance inflation factor), впливові спостереження).

Результати. Модель була статистично значущою ($F (6, 94) = 9{,}82$; $p < 0{,}001$) і пояснювала 38,5 % варіації risk (Adjusted $R2 = 0{,}346$). Найбільший незалежний внесок мав operation_class ($b = 0{,}578$; $p < 0{,}001$), тоді як фракція викиду демонструвала негативний зв'язок із risk ($b = –0{,}0167$; $p = 0{,}016$).

Висновки. Запропоновано скоринговий індекс X із формулою та внутрішньокогортними порогами ($X > 1$ — високий, $X > 1{,}5$ — дуже високий ризик), який інтегрує періопераційне навантаження та перфузійний резерв і може застосовуватися для раннього нефропротективного ведення.

Ключові слова: вроджені вади серця, немовлята, післяопераційний період, гостре ураження нирок, ренальний стрес, скоринг, регресійна модель.

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