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ALGORITHM FOR PREDICTING RISKS OF CHILD PASSENGER INJURIES IN VARIOUS TRAUMA SCENARIOS INSIDE AN AUTOMOBILE

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Summary.
Road traffic accidents remain a leading cause of mortality and disability among children worldwide and represent a major public health concern. The anatomical and physiological characteristics of the paediatric body – including a relatively larger head-to-body ratio, incomplete development of the musculoskeletal system, and insufficient myelination of the central nervous system – render children particularly susceptible to mechanical injuries in autumobile collisions. This vulnerability underscores the need for effective preventive strategies and reliable risk assessment tools.

Objective: *To develop and validate a mathematical algorithm for predicting injury risks to child passengers in automobile collisions, accounting for age, anthropometric characteristics, and use of child restraint systems.*

Materials and Methods: *A retrospective analysis was performed of 218 cases of child passenger injuries involving individuals aged 29 days to 18 years during the period 2014-2024. Data collected included age, sex, anthropometric parameters, type and correctness of child restraint system use, road traffic accident characteristics, and severity of traumatic injuries. The study was conducted in accordance with basic bioethical principles. Statistical methods applied were Spearman correlation analysis, multiple regression, discriminant analysis, and receiver operating characteristic (ROC) analysis.*

Results and Discussion: *A statistical model with high predictive performance was developed ($R^2 = 0.738$, $p < 0.001$). Correct use of child restraint systems was found to reduce the risk of severe injuries by 71% ($\beta = -0.508$, $p < 0.001$). The area under the ROC curve was 0.912, with model sensitivity of 86.8%, specificity of 81.5%, and overall classification accuracy of 84.2%. The high validity metrics support recommendation of the model for practical application.*

Conclusion: *The developed algorithm enables highly accurate assessment of individual risk of injury to child passengers and can be implemented in pediatric practice and forensic medical examination.*

Keywords: *Risk Prediction; Child Trauma; Automobile Trauma; Child Restraint Systems; Multiple Regression; Discriminant Analysis; Anthropometric Parameters.*

Introduction

Road traffic accidents (RTAs) remain one of the leading causes of mortality and disability among children worldwide and represent a major challenge for contemporary pediatrics, pediatric traumatology, and forensic medicine [1,2]. According to the World Health Organization, more than 1 million children under 18 years of age die annually from road traffic injuries, while millions more sustain injuries of varying severity [3].

In European Union countries, the adoption of modern child restraint standards (ECE R129 [i-Size] and ECE R44) has been associated with a decrease in fatal outcomes among child passengers and an increase in appropriate child car seat utilization.

In Ukraine, recent regulatory changes have specified the mandatory use of child restraint systems for children up to 150 cm in height during car travel.

Nevertheless, national data on compliance with these requirements and on the incidence of severe injuries among child passengers remain limited, underscoring the need for the present study aimed at developing a risk prediction algorithm.

In Ukraine, child passengers account for 45% to 52% of all injured children in road traffic accidents [4-7]. Over the past five years, the proportion of child passengers among injured children has increased from 42% in 2018 to 52% in 2023 [8,9].

Frontal collisions, which constitute 56-62% of all RTAs involving child passengers, are associated with particularly severe outcomes [8,9]. At an impact speed of 50 km/h, a child weighing 15 kg generates an approximate impact load of 375 kg [10].

Anatomical and physiological characteristics of children render them particularly susceptible to traumatic forces in autumobile collisions. These include a disproportionately large head-to-body mass ratio (approximately 25% of total body weight in infants versus 6% in adults), underdeveloped cervical musculature, and incomplete skeletal ossification [11].

Incomplete bone tissue formation leads to specific injuries: greenstick fractures, epiphysiolysis, growth zone damage. The elasticity of ribs and cartilaginous connections determines the risk of internal organ damage even in the absence of fractures [12].

Incomplete ossification predisposes paediatric patients to distinctive injury patterns, including greenstick fractures, epiphysiolysis, and physeal injuries. Furthermore, the increased compliance of the rib cage and costal cartilages heightens the risk of intrathoracic and intra-abdominal organ injury in the absence of rib fractures [12].

International investigations have demonstrated that misuse of child restraint systems (CRS) occurs in 46-73% of cases. Predominant errors encompass selection of age-inappropriate restraints (32%), improper installation or securement (28%), premature transition to forward-facing orientation (24%), and incorrect routing or positioning of the harness or seat belt (19%) [13].

The application of multivariate statistical techniques facilitates the construction of individualized predictive

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models, which are indispensable for effective injury prevention strategies, optimization of clinical management, and enhancement of forensic medical assessments [14].

Objective: to develop and validate a mathematical algorithm for predicting the risk of injury to child passengers in automobile collisions, incorporating the utilization of passive and active restraint systems, through multivariate statistical analysis.

Materials and Methods. A retrospective analysis was conducted on 218 cases of injuries sustained by child passengers aged 29 days to 18 years during the period 2014-2024. Data were retrieved from the Communal Non-Commercial Enterprise «Ivano-Frankivsk Regional Children's Clinical Hospital» and the State Institution «Ivano-Frankivsk Regional Bureau of Forensic Medical Examination.»

Inclusion criteria comprised: age between 29 days and 18 years, documented injury as a vehicle passenger, availability of comprehensive medical documentation, and informed consent provided by parents or legal guardians. The study protocol received approval from the institutional bioethics committee (protocol No. 12, dated 15 March 2024).

Study participants were allocated to the following age-stratified groups: group 1 (29 days-1 year) – 23 children; group 2 (1-3 years) – 28 children; group 3 (4-7 years) – 29 children; group 4 (7-11 years) – 32 children; group 5 (12-18 years) – 35 children. The control group consisted of 32 individuals aged 18-59 years. The total number of child passengers analysed was 218.

Investigative methods included morphometric assessment of injuries, diagnostic imaging modalities (radiography, computed tomography, magnetic resonance imaging), Spearman correlation analysis, multiple regression, discriminant analysis, receiver operating characteristic (ROC) analysis, k-fold cross-validation (k=10). A threshold for statistical significance was established at $p < 0.05$.

The degree of injury severity was determined in accordance with the «Rules for Forensic Medical Determination of the Severity of Bodily Injuries,» as approved by Order No. 6 of the Ministry of Health of Ukraine dated 17 January 1995 [15].

Results and Discussion. The structure of the study sample is presented in Table 1.

Spearman correlation analysis identified several statistically significant associations (Table 2). The strongest inverse correlation was observed between correct use of child restraint systems and injury severity ($r = –0.71$, $p < 0.001$).

Table 1

Characteristics of Study Groups

Group	Age	n	Boys	Girls
1	29 days-1 year	23	12 (52%)	11 (48%)
2	1-3 years	28	14 (50%)	14 (50%)
3	4-7 years	29	15 (52%)	14 (48%)
4	7-11 years	32	16 (50%)	16 (50%)
5	12-18 years	35	18 (51%)	17 (49%)
Control	18-59 years	32	16 (50%)	16 (50%)
Total	–	218	115 (53%)	103 (47%)

Table 2

Results of Correlation Analysis

Parameters	r	p	Interpretation
Age – Injury severity	-0.66	<0.001	Strong inverse
Correct use – Injury	-0.71	<0.001	Strong inverse
Height – Head injuries	-0.51	<0.001	Moderate inverse
Correct use – Neck injuries	-0.57	<0.001	Moderate inverse
Age – Thoracoabdominal injuries	-0.42	0.003	Moderate inverse
Type of protection – Injury severity	-0.47	<0.001	Moderate inverse

Child age exhibited a strong inverse correlation with injury severity ($r = –0.66$, $p < 0.001$), indicating greater vulnerability among younger children. The heatmap of the correlation matrix (Fig. 1) provides a visual representation of the interrelationships among all examined variables.

A multiple linear regression equation was developed:

$$Y = 0.842-0.044\times X_1-0.0031\times X_2-0.037\times X_3-0.508\times X_4,$$

where Y represents the predicted probability of severe injury, X_1 is age (years), X_2 is height (cm), X_3 is type of restraint system (coded 0-4), X_4 is correctness of use (coded 0-1). Model fit statistics: $F = 263.18$; $p < 0.001$; $R^2 = 0.738$ (Table 3).

Correctness of use has the greatest impact ($\beta_4 = –0.508$, $p < 0.001$), corresponding to a 71% reduction in the risk of severe injuries. Each additional year of age was associated with a 4.4% reduction in risk.

Correct use of child restraint systems exerted the predominant protective effect ($\beta = –0.508$, $p < 0.001$), equivalent to a 71% decrease in the risk of severe injuries.

Wilks' lambda value of 0.312 indicated indicates high classification quality (Table 4).

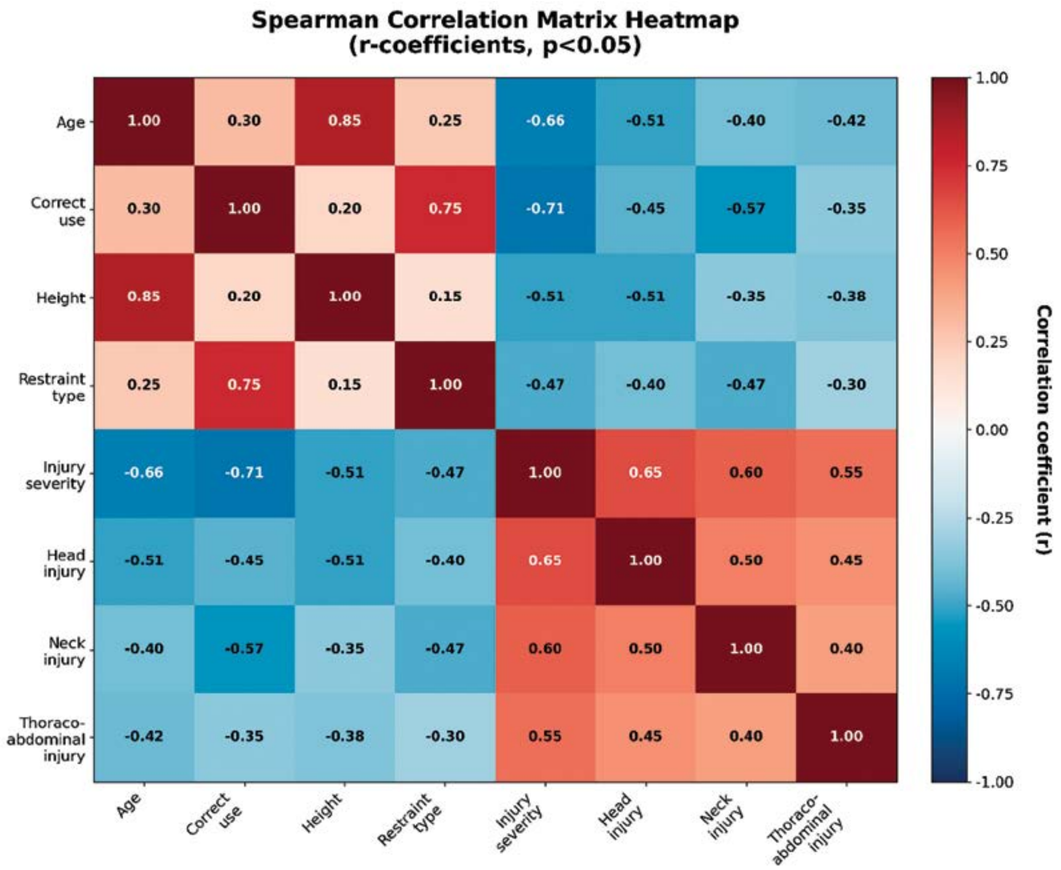

Fig. 1. Heat map of Spearman's correlation matrix. Red indicates a negative correlation, blue indicates a positive correlation. The intensity of the colour corresponds to the strength of the correlation. The strongest inverse correlation was found between the correct use of protective equipment and the severity of traumatic injuries (r= –0.71, p<0.001).

Table 3

Multiple Regression Coefficients

Predictor	β	SE	t	p	95% CI
Constant (β_0)	0.842	0.056	15.04	< 0.001	0.732-0.952
Age (β_1)	-0.044	0.003	-14.67	< 0.001	-0.050-0.038
Height (β_2)	-0.0031	0.0004	-7.75	< 0.001	-0.004-0.002
Type of protection (β_3)	-0.037	0.006	-6.17	< 0.001	-0.049-0.025
Correctness (β_4)	-0.508	0.026	-19.54	< 0.001	-0.559-0.457

Table 4

Results of Discriminant Analysis

Indicator	Value	95% CI
Wilks' lambda	0.312	0.289-0.335
Classification quality, %	84.2	79.8-88.6
Sensitivity, %	86.8	82.1-91.5
Specificity, %	81.5	76.8-86.2
AUC	0.912	0.883-0.941
Positive predictive value, %	85.1	80.5-89.7
Negative predictive value, %	83.6	79.1-88.1
Cross-validation (k=10), %	84.0 ± 2.5	81.5-86.5

The diagnostic performance of the prognostic model is illustrated in Fig. 2. All metrics surpassed the acceptability threshold of 80%, confirming the model's high diagnostic utility.

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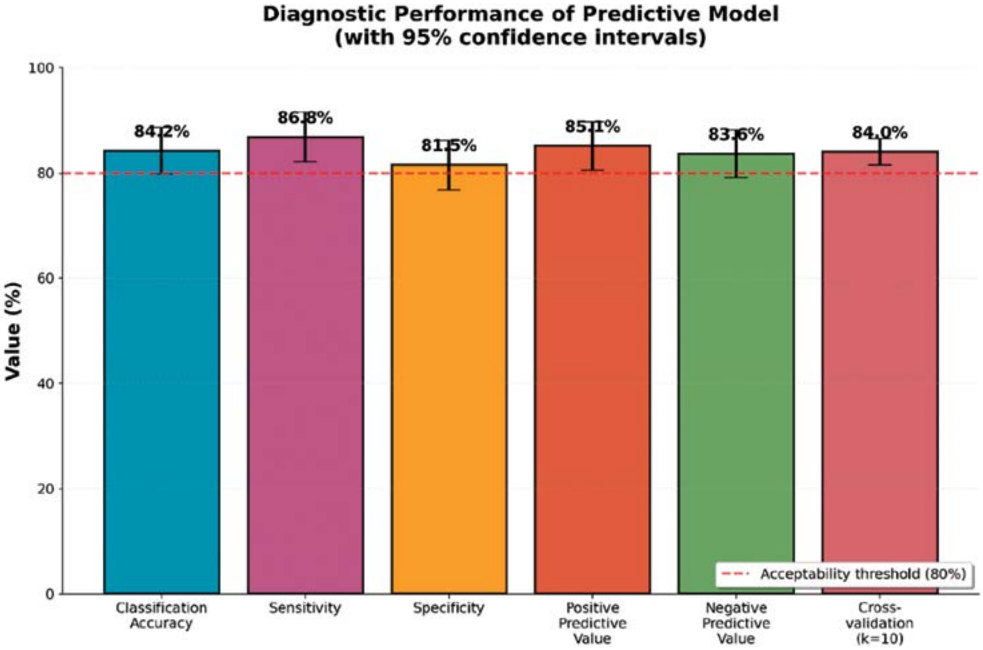

Fig. 2. **Diagnostic performance metrics of the prognostic model with 95% confidence intervals. Overall classification accuracy is 84.2% (95% CI: 79.8-88.6%). The model e a balanced relationship between sensitivity (86.8%) and specificity (81.5%). Cross-validation (k=10) verified result stability (84.0±2.5%).**

ROC analysis: AUC=0.912 (excellent predictive ability). Cross-validation confirmed model stability (84.0±2.5%). Age-stratified analysis of injury severity revealed a statistically significant inverse association with increasing child age ($r = -0.66$, $p < 0.001$), corroborating the heightened vulnerability of younger children (Fig. 3).

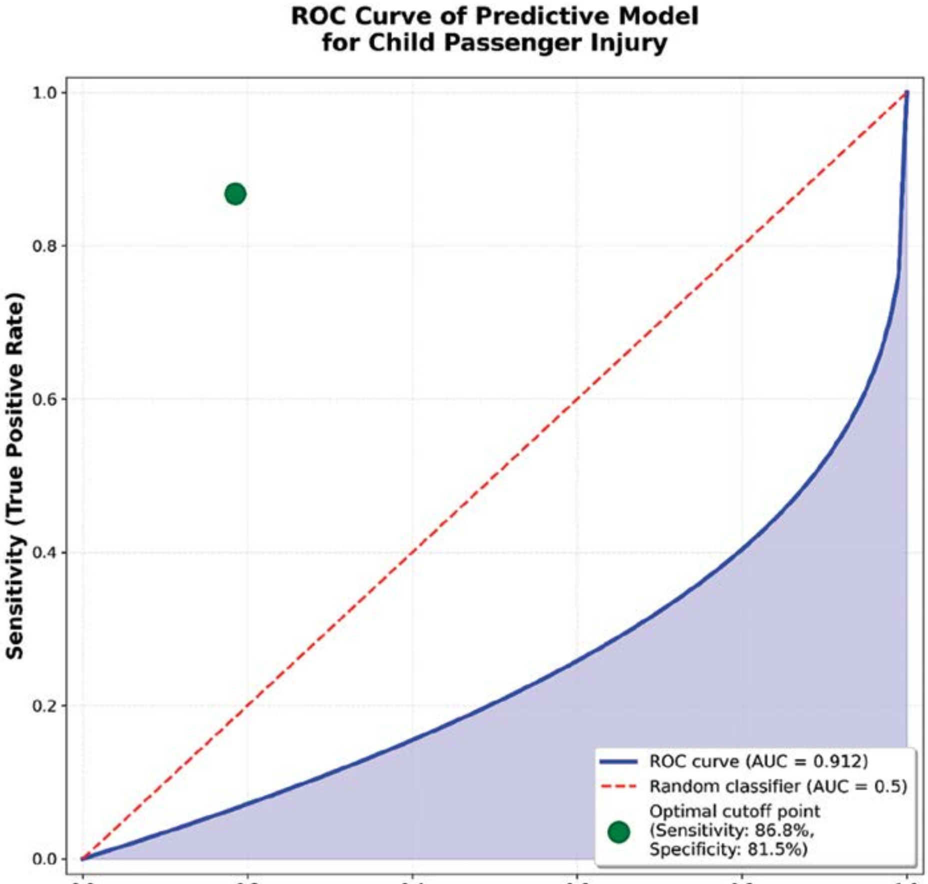

Fig. 3. **Receiver operating characteristic (ROC) curve of the predictive model for child passenger injuries. The area under the curve (AUC) is 0.912 (95% CI: 0.883-0.941), which indicative of excellent classification quality. The optimal cutoff point (marked in green) corresponds to sensitivity of 86.8% and specificity of 81.5%.**

A comprehensive algorithm for predicting the severity of traumatic injuries in child passengers of vehicles was developed on the basis of a retrospective analysis of 218 documented road traffic accident cases involving child passengers. Statistical validation of the developed model demonstrated high predictive performance, with a coefficient of determination R^2=0.738 at a statistical significance level of $p < 0.001$, indicating that approximately 74% of the variability in injury severity can be accounted for by the included predictors. The diagnostic value of the algorithm is confirmed by the area under the ROC curve (AUC=0.912), reflecting model excellent classification performance and its capacity to discriminate between different levels of injury severity.

Discriminant analysis applied to evaluate the classification properties of the algorithm revealed high discriminatory quality across severity groups, as evidenced by a Wilks' lambda value of 0.312, which indicates substantial between-group differences.

Overall classification accuracy reached 84.2%, with sensitivity of 86.8% (demonstrating the model's strong ability to correctly identify cases of severe injury) and specificity of 81.5% (confirming reliable detection of less severe cases). These performance metrics reflect a well-balanced model suitable for implementation in routine clinical and forensic settings.

A central finding of the study was the substantial protective effect associated with correct use of child restraint systems and seat belts. Multiple regression analysis indicated that proper application of passive restraint devices was associated with a 71% reduction in the risk of severe traumatic injuries (standardized coefficient $\beta = -0.508$, $p < 0.001$). This result carries significant implications for the development of targeted prevention strategies and underscores the necessity of strict adherence to child passenger safety regulations. The finding highlights the critical importance of educational initiatives directed at parents and caregivers to promote both the mandatory and correct use of age-appropriate restraint systems across all paediatric age groups.

Correlation analysis identified several statistically significant associations among key injury-related variables. A strong inverse correlation was observed between child age and injury severity ($r = -0.66$, $p < 0.001$), corroborating the increased vulnerability of younger children owing to their anatomical and physiological characteristics, including lower body mass, disproportionately large head size, immature musculoskeletal development, and incomplete myelination of the central nervous system. An even stronger inverse correlation was found between correct use of restraint devices and injury severity ($r = -0.71$, $p < 0.001$), further reinforcing the pivotal role of appropriate passive safety measures in preventing the most severe consequences of road traffic accidents involving child passengers.

The results demonstrate high predictive performance of the proposed algorithm for severe injury risk assessment in child passengers ($R^2 = 0.738$; AUC = 0.912; overall classification accuracy 84.2%; sensitivity 86.8%; specificity 81.5%). Correct application of child restraint systems exerts the predominant protective effect ($\beta = -0.508$; approximate risk reduction 71%). These findings align with international data indicating that proper child car seat use reduces fatal outcome risk by approximately 71% in infants and 54% in children aged 1-4 years. The association confirms the causal role of correct restraint application in preventing severe injuries, particularly in frontal collisions, the predominant injury mechanism in the paediatric population [16]. The present study extends conventional regulatory frameworks (ECE R44/04; ECE R129 i-Size) by providing a quantitative, individualized risk assessment that integrates age, anthropometric parameters, type and correctness of child restraint system use. The approach yields a clinically and forensically applicable tool [17].

The discriminatory performance of the developed model is comparable to or exceeds that reported for contemporary machine-learning approaches in related fields of paediatric trauma and neurology, where AUC typically ranges from 0.84 to 0.87 when predicting adverse outcomes (seizures in paediatric intensive care units, mortality, or functional scales in paediatric traumatic brain injury) [18].

Analysis confirmed an age-related gradient in injury risk, with a strong inverse correlation between age and injury severity. This finding is biomechanically consistent with the established vulnerability of younger children, which results from a disproportionately large head-to-body mass ratio, relative head size, immaturity of cervical musculature, and incomplete skeletal ossification. These characteristics increase the likelihood of craniocervical and thoracoabdominal injuries under equivalent collision forces. The predominant influence of correct child restraint system use corresponds to the high documented prevalence of misuse (incorrect selection, installation, or harness positioning), especially in transitional age groups. The data highlight the need for targeted educational interventions and technical advancements, including ISOFIX systems and anti-misuse designs, to minimize installation errors.

From a regulatory perspective, the findings provide empirical support for full the implementation and enforcement of UNECE Regulation R129 (i-Size), specifically mandatory rear-facing restraint until at least 15 months of age and ISOFIX anchorage requirements. Both provisions reduce misuse rates and enhance real-world effectiveness of child restraint systems. Combined with sustained national campaigns to promote child passenger safety – analogous to effective seat belt compliance programmes for adults – such measures can substantially decrease the incidence and severity of paediatric road traffic injuries.

The retrospective cohort design imposes certain limitations. Detailed collision kinematics (vehicle speed, impact direction, relative vehicle mass), subtypes of impact forces, and precise real-world misuse scenarios (incorrect restraint angles, insufficient belt tension, premature transition to booster seats) were not incorporated. These factors may exert substantial modifying effects on injury risk profiles. Prospective, multicentre studies with standardized collection of road traffic accident kinematic data, implementation of photodocumentation and telemetry protocols, and external validation on independent samples are required to enhance model transportability and to facilitate the development of practical nomograms or risk calculators suitable for clinical and forensic medical applications.

The presented model, derived from the analysis of 218 documented cases and providing quantitative confirmation of the protective effect of correctly applied child restraint systems, establishes a foundation for the integration of risk-stratified protocols into pediatric care and forensic medical examination. Such integration may span early triage, retrospective reconstruction of road traffic accident circumstances, and elucidation of causal relationships between the use or non-use of protective systems and outcomes affecting the child's life and health.

Conclusion

The developed prognostic algorithm demonstrates considerable potential for implementation in healthcare facilities at various levels and may be incorporated into clinical decision support systems during the provision of emergency medical care to children injured in road traffic accidents. Application of the algorithm in pediatric practice would optimize prehospital triage, enable more rational allocation of resources, enhance the accuracy of initial diagnosis, and support timely decisions regarding patient routing to specialized trauma centres. Concurrently, the algorithm holds substantial value for forensic medical examination by enabling objective evaluation of the correspondence between the nature and severity of traumatic injuries and the circumstances of the road traffic accident, determination of causal links between the use or non-use of restraint devices and adverse outcomes, and provision of a scientifically substantiated basis for expert conclusions in cases involving violations of child passenger safety regulations.

Prospects for further research. Prospects for further research include the development of mechanisms for implementing the proposed prognostic algorithm in the activities of practical healthcare institutions to improve the effectiveness of medical care for paediatric patients in road traffic accidents, as well as for use in conducting relevant forensic medical examinations.

Author Contributions: Yu. Kotsyubynska – conceptualization of the study, methodology development, formulation of aims and objectives, scientific supervision, writing and editing of the original manuscript, overall responsibility for the integrity of the research; N. Kozan – scientific consultation and supervision, validation of methodological approaches, critical review and editing of the manuscript, verification of results in accordance with forensic medicine practice standards; V. Chadiuk – collection and formation of the primary database (218 clinical cases), processing of medical documentation, formal statistical analysis (Spearman correlation analysis, multiple regression, discriminant analysis, ROC analysis), preparation of tables and figures, writing of the «Materials and Methods» and «Results» sections; M.Yurak – clinical interpretation of results from the perspective of internal medicine and paediatrics, data collection from the Municipal Non-Profit Enterprise «Ivano-Frankivsk Regional Children's Clinical Hospital», participation in critical review and editing of the manuscript.

Conflict of interest: The authors declare that they have no conflicts of interest.

Use of Artificial Intelligence. In the preparation of this article, artificial intelligence tools were used solely for machine translation of selected portions of the text from Ukrainian into English.

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АЛГОРИТМ ПРОГНОЗУВАННЯ РИЗИКІВ ТРАВМУВАННЯ ДИТИНИ-ПАСАЖИРА ПРИ РІЗНИХ ВАРІАНТАХ ТРАВМИ В СЕРЕДИНІ АВТОМОБІЛЯ

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Резюме.

Дорожньо-транспортні пригоди залишаються провідною причиною дитячої смертності та інвалідизації у всьому світі, становлячи серйозну проблему громадського здоров’я. Анатомо-фізіологічні особливості дитячого організму, включаючи відносно більші розміри голови, незавершеність формування скелетно-м’язової системи та недостатню мієлінізацію центральної нервової системи, роблять дітей особливо вразливими до механічних ушкоджень під час автомобільних зіткнень, що обумовлює необхідність розробки ефективних превентивних стратегій та інструментів оцінки ризиків.

Мета дослідження – розробити та валідувати математичний алгоритм прогнозування ризиків травмування дітей-пасажирів при автомобільних зіткненнях з урахуванням віку, антропометричних характеристик та використання засобів пасивного захисту.

Матеріали і методи. Проведено ретроспективний аналіз 218 випадків травмування дітей-пасажирів віком від 29 днів до 18 років за період 2014-2024 роки. Аналізувалися дані щодо віку, статі, антропометричних параметрів, типу та правильності використання дитячих утримуючих пристроїв, характеристик дорожньо-транспортної пригоди та тяжкості отриманих травматичних ушкоджень. При виконанні досліджень збережені основні принципи біоетики. Використовувалися методи кореляційного аналізу Спірмена, множинної регресії, дискримінантного аналізу та ROC-аналізу.

Результати та обговорення. Розроблено статистичну модель з високою прогностичною спроможністю (R^2=0,738, p<0,001). Встановлено, що правильне використання дитячих утримуючих пристроїв знижує ризик тяжких травм на 71% (β= –0,508, p<0,001). Площа під ROC-кривою становила 0,912, чутливість моделі – 86,8%, специфічність – 81,5%, загальна точність класифікації – 84,2%. Високі показники валідності дозволяють рекомендувати модель для практичного застосування.

Висновок. Розроблений алгоритм дозволяє з високою точністю оцінити індивідуальні ризики травмування дітей-пасажирів та може бути впроваджений у педіатричну практику і судово-медичну експертизу.

Ключові слова: прогнозування ризиків; дитячий травматизм; автомобільна травма; захисні системи; множинна регресія; дискримінантний аналіз; антропометричні параметри.

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