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Analysis of Influencing Factors and Development of a Clinical Prediction Model for Postoperative Visual Improvement Prognosis in Patients with Age-Related Cataract

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Abstract

Purpose: To identify independent factors associated with postoperative visual improvement after phacoemulsification combined with intraocular lens (IOL) implantation in patients with age-related cataract (ARC) and to develop an interpretable individualized clinical prediction nomogram for preoperative risk stratification.

Methods: This single-center retrospective study included 1,847 eyes with ARC who underwent phacoemulsification combined with IOL implantation. Univariate and multivariate logistic regression analyses were performed to identify independent predictors associated with postoperative visual improvement. Internal validation was conducted using bootstrap resampling with 1,000 iterations. Model performance was evaluated using the receiver operating characteristic (ROC) curve, calibration curve, decision curve analysis (DCA), and Shapley Additive Explanations (SHAP) value analysis.

Results: Age, severity of preoperative visual impairment, fundus lesions, axial length, and keratometric value (K-value) were identified as independent predictors of postoperative visual improvement. The prediction model demonstrated good discriminative ability, with an area under the curve (AUC) of 0.83 (95% confidence interval [CI], 0.78–0.89) in the training cohort and 0.78 (95% CI, 0.70–0.86) in the validation cohort. Calibration analysis showed good agreement between predicted and observed outcomes, and decision curve analysis indicated favorable clinical utility. SHAP analysis revealed that age contributed most significantly to the model prediction. A visual nomogram was subsequently developed to provide individualized risk estimation.

Conclusion: The nomogram incorporating five independent predictors demonstrated good discrimination, calibration, and clinical applicability for predicting postoperative visual improvement in patients with ARC. This model may serve as a practical tool for preoperative risk assessment, individualized patient counseling, and doctor–patient communication.

Key message

What is known:

Multiple factors affect visual recovery after age-related cataract surgery, but few easy-to-use preoperative prediction tools are available for routine clinical practice.

What is new:

Age, severity of preoperative visual impairment, fundus lesions, axial length, and K-value were independently associated with postoperative visual recovery.

1 Introduction

Age-related cataract (ARC) is a common age-associated ocular disorder characterized by progressive and irreversible lens opacification, leading to visual impairment. It primarily affects individuals aged over 50 years, with prevalence increasing substantially with advancing age. ARC is the most prevalent form of cataract worldwide and remains the leading cause of blindness according to the World Health Organization, representing a major threat to visual health and quality of life among the elderly.[1, 2]

With the acceleration of global population aging, the prevalence of ARC continues to rise, creating a substantial public health burden. Epidemiological studies have predicted that the number of ARC patients in China will reach approximately 187.26 million by 2050, accounting for nearly 78% of all cataract cases. The increasing disease burden not only impairs the independence and daily functioning of older adults, increasing the risks of falls[3] and depression[4], but also places considerable pressure on healthcare resources, medical expenditure, family caregiving, and social security systems.[5] Therefore, optimizing ARC management through standardized treatment strategies, effective postoperative rehabilitation, and individualized medical decision-making has important clinical and social implications.

Currently, phacoemulsification combined with intraocular lens implantation (Phaco + IOL) is the primary surgical treatment for ARC worldwide due to its minimally invasive nature, rapid recovery, and predictable refractive outcomes. However, despite successful surgery and the absence of apparent intraoperative complications, a proportion of patients fail to achieve satisfactory postoperative best-corrected visual acuity, resulting in limited improvement in visual function and reduced quality of life.[6–8]

Postoperative visual improvement after cataract surgery were influenced by multiple interacting factors. However, considerable heterogeneity exists among previous studies regarding patient populations, evaluated variables, sample sizes, and statistical approaches. Consequently, currently available prediction models differ substantially in their predictive performance and clinical applicability, and a reliable individualized risk assessment tool for preoperative prediction remains lacking.[9, 10]

Therefore, this study aimed to identify independent predictors associated with postoperative visual improvement in ARC patients undergoing Phaco + IOL surgery and to develop an interpretable clinical prediction model based on logistic regression analysis. The model performance was comprehensively evaluated through discrimination, calibration, and clinical utility assessments. Furthermore, SHAP (Shapley Additive Explanations) analysis and nomogram visual improvement were incorporated to enhance model interpretability and facilitate individualized risk estimation. This study may provide clinicians with an objective tool for preoperative risk stratification, personalized perioperative management, and improved doctor–patient communication.

2 Materials and Methods

This single-center retrospective cohort study included consecutive patients with ARC who underwent cataract surgery between 2013 and 2026. Clinical data were retrospectively collected from the electronic medical record system. The inclusion criteria were: (1) ARC confirmed by slit-lamp examination and

fundus evaluation, with planned Phaco + IOL; (2) first Phaco + IOL surgery with an uneventful procedure and no intraoperative complications; (3) complete and traceable ophthalmic examination data before and after surgery; and (4) ability to cooperate with examinations and postoperative follow-up. The exclusion criteria were: (1) previous intraocular surgery or ocular trauma; (2) severe psychiatric or cognitive disorders preventing cooperation; (3) incomplete or unreliable preoperative or postoperative ophthalmic data; and (4) severe systemic diseases involving the heart, liver, or kidneys that affected surgical tolerance or follow-up.

Clinical data were extracted from the electronic medical record system and categorized into four groups: (1) Demographic characteristics: age, sex, ethnicity, occupation, number of children, and marital status; (2) Ocular parameters: laterality, severity of preoperative visual impairment, refractive status, axial length (AL), keratometric value (K value), lens nuclear hardness according to the Lens Opacities Classification System III (LOCS III), fundus lesions, and operative duration; (3) Systemic medical history: allergy history, diabetes status and treatment (insulin, insulin plus oral hypoglycemic agents, oral hypoglycemic agents alone, or no diabetes), duration of hypertension, cardiovascular disease, cardiovascular surgery, and other systemic surgery; and (4) Visual outcome: postoperative visual acuity and visual improvement.

Visual acuity was measured using a standard logarithmic visual acuity chart by the same experienced ophthalmic technician. All surgeries were performed by the same senior ophthalmic surgeon using a standardized protocol.

Preoperative visual impairment was categorized into six grades according to the World Health Organization (WHO) 2019 Classification of Visual Impairment. Good postoperative visual recovery was defined as an improvement of ≥ 2 LogMAR lines, whereas < 2 lines was considered poor recovery. Postoperative visual outcome was used as the binary outcome for subsequent risk factor analysis and prediction model development.

3 Statistical Analysis

R 4.4.0 and Zstats 1.0 software were used for statistical analyses. Continuous variables were presented as mean ± standard deviation; categorical variables as counts and percentages. Independent-sample t-test was applied for continuous variables and χ^2 test for categorical variables for inter-group comparison. Univariate logistic regression was performed for preliminary variable screening. Variables with $P < 0.05$ entered multivariate stepwise logistic regression to identify independent predictors. The dataset was randomly divided into training and validation cohorts at a 7:3 ratio. Bootstrap resampling (1000 iterations) was used for internal validation. ROC-AUC quantified discrimination; mean absolute error (MAE) from calibration curves assessed calibration performance. DCA was calculated to evaluate clinical net benefit. SHAP value analysis was applied to quantify variable contribution and interpret model outputs. A nomogram was constructed according to multivariate regression coefficients. P-value < 0.05 was considered statistically significant.

4 Results

4.1 Baseline Characteristics and Comparison Between Groups

A total of 1,847 eyes with ARC were included. Of these, 787 (42.61%) were from male patients and 1,060 (57.39%) from female patients. Age ranged from 50 to 95 years, with a mean of 72.23 ± 8.91 years. According to postoperative visual outcomes, eyes were classified into the good visual recovery group (1,719 eyes, 93.07%) and poor visual recovery group (128 eyes, 6.93%). Significant between-group differences were observed in age, occupation, number of children, operative duration, lens nuclear hardness, preoperative LogMAR visual acuity, severity of preoperative visual impairment, fundus lesions, systemic underlying diseases (except diabetes and hypertension), and cardiovascular disease history (all $P < 0.05$). No significant differences were found in AL, K-value, duration of diabetes or hypertension, sex, marital status, allergy history, myopia, laterality, history of systemic surgery (except cardiovascular surgery), or cardiovascular surgery history (all $P > 0.05$). Detailed characteristics are presented in Table 1.

4.2 Univariate Logistic Regression Analysis for Candidate Variables

Univariate logistic regression identified occupation, lens nuclear hardness, myopia, fundus lesions, age, number of children, duration of diabetes, and severity of preoperative visual impairment as significant predictors of postoperative visual outcome (all $P < 0.05$). Fundus lesions were strongly associated with visual recovery; compared with patients without fundus lesions, those with fundus lesions had lower odds of achieving good postoperative visual recovery (OR = 0.13, 95% CI: 0.08–0.21, $P < 0.001$). Compared with level 0 preoperative visual impairment, levels 1 and 2 were associated with higher odds of achieving ≥ 2-line visual improvement (OR = 6.09, 95% CI: 3.16–11.73, $P < 0.001$; OR = 9.40, 95% CI: 2.11–41.88, $P = 0.003$, respectively). Duration of hypertension showed a borderline association (OR = 0.98, 95% CI: 0.96–0.99, $P = 0.050$), whereas AL and K-value were not significant ($P = 0.097$ and 0.069, respectively).

4.3 Multivariate Logistic Regression Analysis and Identification of Independent Predictors

Multivariate stepwise logistic regression identified age, severity of preoperative visual impairment, fundus lesions, AL, and K-value as independent predictors of postoperative visual outcome. After adjustment, fundus lesions remained strongly associated with lower odds of good postoperative visual recovery (OR = 0.11, 95% CI: 0.06–0.19, $P < 0.001$). Each 1-year increase in age was associated with a 9% reduction in the odds of good postoperative visual recovery (OR = 0.91, 95% CI: 0.89–0.94, $P < 0.001$), while each 1-mm increase in AL was associated with a 13% reduction (OR = 0.87, 95% CI: 0.77–0.99, $P = 0.029$). Compared with level 0 preoperative visual impairment, levels 1–4 were independently associated

with higher odds of achieving ≥ 2-line visual improvement, with ORs of 9.34 (95% CI: 4.51–19.34, P < 0.001), 14.28 (95% CI: 3.03–67.28, P < 0.001), 3.86 (95% CI: 1.59–9.35, P = 0.003), and 2.69 (95% CI: 1.20–6.04, P = 0.017), respectively. K-value was also independently associated with postoperative visual outcome (OR = 0.84, 95% CI: 0.72–0.99, P = 0.032). Regression coefficients and ORs are summarized in Table 2.

4.4 Model Evaluation

In the training dataset, the ROC-AUC was 0.83 (95% CI: 0.78–0.89), compared with 0.78 (95% CI: 0.70–0.86) in the validation dataset (Fig. 1a). Calibration curves showed good agreement between predicted and observed probabilities, with MAEs of 0.010 and 0.024, respectively. DCA demonstrated greater net clinical benefit than “treat-all” or “treat-none” strategies across most risk thresholds (Online Resource 1–2).

4.5 SHAP-Based Interpretation of the Prediction Model

SHAP analysis was performed to interpret individual variable contributions to the prediction of good postoperative visual recovery. Age contributed most to model output, followed by preoperative visual impairment severity and fundus lesions, whereas AL and K-value contributed less. Higher age and fundus lesions generally shifted predictions toward a lower probability of good visual recovery, whereas the contribution of preoperative visual impairment severity varied across categories. The SHAP waterfall plot further illustrated the direction and magnitude of feature contributions for individual patients (Fig. 1b-1d).

4.6 Potential Application of the Clinical Nomogram

Based on the independent predictors identified by multivariate logistic regression, an individualized nomogram was developed to estimate the probability of good postoperative visual recovery in ARC patients. The nomogram incorporated five variables: age, severity of preoperative visual impairment, fundus lesions, AL, and K-value. By assigning points to each predictor and summing the total score, clinicians can estimate an individual’s probability of good postoperative visual recovery. This tool may facilitate preoperative risk stratification, individualized patient counseling, and clinical decision-making in ARC management.

5 Discussion

Although Phaco + IOL is the standard surgical treatment for ARC, postoperative visual outcomes vary considerably among individuals.[11] In the present study, we systematically investigated factors associated with postoperative visual recovery in a large cohort of patients with ARC and developed a clinical prediction model to facilitate individualized preoperative risk assessment. The model demonstrated good discrimination and calibration, while decision curve analysis suggested potential clinical utility. SHAP analysis and nomogram visualization further improved the interpretability and clinical applicability of the model.

Age was identified as one of the most important predictors of postoperative visual recovery, consistent with previous studies[5, 12]. In the present study, patients in the poor visual recovery group were significantly older than those in the good postoperative visual recovery group (77.63 ± 8.35 vs. 71.83 ± 8.82 years). Multivariable logistic regression analysis showed that increasing age was independently associated with a lower likelihood of achieving good postoperative visual recovery, with each additional year of age associated with an approximately 9% reduction in the odds of good recovery (OR = 0.91, 95% CI: 0.89–0.94, P < 0.001). This association may reflect age-related deterioration of the retinal, optic nerve, and other visual pathways. Although cataract extraction can remove the optical obstruction caused by lens opacity, age-related changes in retinal function and neural visual processing may limit the extent of postoperative visual improvement.[13] In addition, older patients are more likely to have systemic comorbidities and reduced physiological reserve, which may adversely affect postoperative recovery.[14]

The severity of preoperative visual impairment was also independently associated with postoperative visual recovery.[15] Notably, in our model, more severe preoperative visual impairment was associated with higher odds of achieving good postoperative visual recovery, rather than a higher risk of poor recovery. This finding should be interpreted in the context of the study endpoint, which was defined as an improvement of at least two lines of visual acuity rather than the achievement of a specific level of postoperative visual acuity. Patients with more severe preoperative visual impairment have greater potential for measurable visual improvement after removal of the cataractous lens. Therefore, a greater baseline visual deficit may increase the likelihood of meeting the predefined threshold for visual improvement. This finding also underscores the importance of distinguishing between the magnitude of visual improvement and the absolute level of postoperative visual acuity when evaluating cataract surgery outcomes. Nevertheless, the relationship between baseline visual impairment and postoperative visual recovery may be influenced by cataract severity, retinal function, and other systemic factors and should therefore be interpreted cautiously.[16–18]

Fundus diseases showed the strongest association with postoperative visual recovery in the present study. Compared with patients without fundus diseases, those with fundus diseases had substantially lower odds of achieving good postoperative visual recovery (OR = 0.11, 95% CI: 0.06–0.19, P < 0.001). Furthermore, the prevalence of fundus diseases was markedly higher in the poor recovery group than in the good recovery group (43.75% vs. 10.70%). This finding is clinically plausible because cataract surgery primarily addresses visual impairment caused by lens opacity, whereas concomitant retinal or macular abnormalities may impose an independent limitation on visual function.[19] Therefore, careful preoperative fundus evaluation is particularly important in patients with ARC. When fundus abnormalities are suspected, additional examinations, such as optical coherence tomography (OCT), may help identify macular or retinal pathology and improve preoperative assessment of visual potential.[20]

Axial length (AL) was another independent predictor in the multivariable model. Each 1-mm increase in AL was associated with a lower likelihood of achieving good postoperative visual recovery (OR = 0.87, 95% CI: 0.77–0.99, P = 0.029). This association may partly reflect the increased prevalence of myopia-

related retinal and choroidal abnormalities in eyes with longer axial lengths.[21] In addition, accurate ocular biometry is essential for achieving predictable refractive outcomes after cataract surgery. AL and corneal curvature are important parameters in intraocular lens power calculation, and measurement errors in either parameter may contribute to postoperative refractive error.[22, 23] Therefore, particular attention should be paid to biometric measurements in eyes with extreme axial lengths or abnormal corneal parameters[24, 25]. Optimization of preoperative biometry and appropriate selection of IOL calculation formulas may further improve refractive predictability and postoperative visual outcomes.[26, 27]

The prediction model developed in this study demonstrated good overall discrimination, with an AUC of 0.83 (95% CI: 0.78–0.89) in the training cohort and 0.78 (95% CI: 0.70–0.86) in the validation cohort. Calibration analysis showed good agreement between predicted and observed probabilities, while DCA indicated a favorable net benefit across a clinically relevant range of threshold probabilities. These findings suggest that the model may have potential value for individualized preoperative assessment[28]. However, the decrease in AUC from the training cohort to the validation cohort suggests some degree of model optimism or overfitting. In addition, the relatively low specificity and negative predictive value observed at the selected cutoff indicate that the model may have limited ability to identify individual patients who will fail to achieve good visual recovery. These findings should be considered when interpreting its potential clinical application. SHAP analysis further provided an interpretable assessment of the relative contribution of individual predictors, with age showing the greatest contribution to model predictions. The nomogram translated the multivariable model into a readily visualized tool that may facilitate individualized risk estimation and doctor–patient communication.

Several limitations should also be acknowledged. First, this was a single-center retrospective study, and selection bias and residual confounding cannot be completely excluded. The generalizability of the model to other populations and healthcare settings therefore requires further validation. Second, postoperative factors, including follow-up duration, postoperative complications, and subsequent retinal or macular treatment, were not incorporated into the model and may have influenced visual outcomes. Third, only internal validation was performed, and external validation in independent cohorts was not available.[29] Finally, the relatively small proportion of eyes with poor visual recovery may have resulted in class imbalance and limited the precision of some performance measures.

Future research should focus on external validation in independent populations and prospective multicenter cohorts. Incorporating additional clinically relevant variables, such as detailed retinal imaging findings, macular characteristics, postoperative complications, and longitudinal visual outcomes, may further improve predictive performance. In addition, integration of the prediction model into a clinical decision-support system could facilitate automated preoperative risk assessment and individualized patient counseling.

Conclusion

In this study, older age, greater severity of preoperative visual impairment, the presence of fundus diseases, longer axial length, and K value were independently associated with postoperative visual recovery after Phaco + IOL surgery in patients with ARC. The prediction model demonstrated good discrimination, calibration, and potential clinical utility. The nomogram and SHAP-based interpretation may provide clinicians with an accessible approach to individualized preoperative assessment and patient counseling. Further external validation is required before routine clinical implementation.

Declarations

Clinical implication:

A logistic regression-based nomogram showed good discrimination, calibration, and clinical utility and provided an interpretable tool for individualized preoperative risk assessment.

Author Contributions:

Conceptualization: Liu Zhengwei, Dai Jinhui; Methodology: Liu Zhengwei; Formal analysis: Liu Zhengwei; Investigation: Dou Xinyan, Qin Yan, Sheng jing, Zhang Wei; Writing-original draft: Liu Zhengwei; Writing-review & editing: Dai Jinhui; Supervision: Dai Jinhui. All authors read and approved the final submitted manuscript.

Competing interests

The authors declare no relevant financial or non-financial competing interests.

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Ethics approval

This retrospective observational study was conducted in accordance with the principles of the Declaration of Helsinki and was approved by the Ethics Committee of Wusong Hospital, Zhongshan Hospital, Fudan University.

Consent to participate

The requirement for written informed consent was waived by the Ethics Committee because of the retrospective design and the use of de-identified clinical data.

Trial registration

Not applicable. This was a retrospective observational study and did not involve a clinical trial or prospective interventional study.

Data availability

The datasets generated and/or analyzed during the current study are not publicly available because they contain patient-related information but are available from the corresponding author on reasonable request and with appropriate ethical approval.

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Tables

Tables 1 and 2 are available in the Supplementary Files section.

Figures

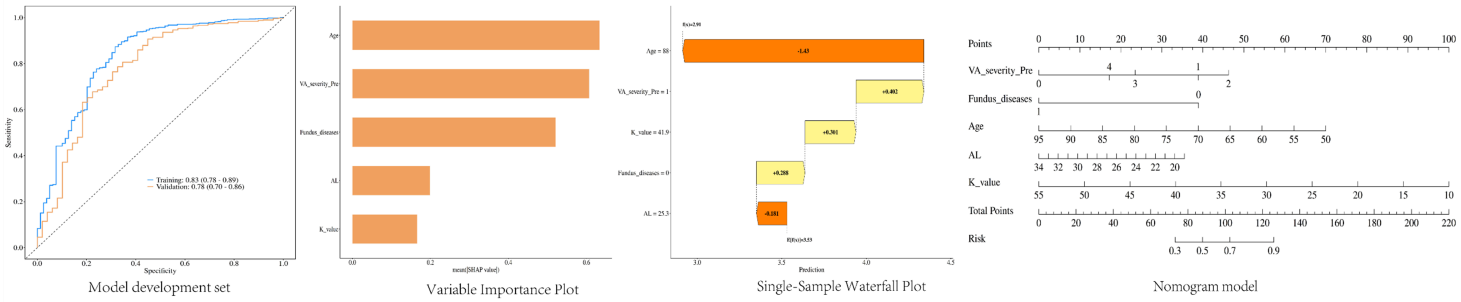


Figure 1

(a): ROC curves of prediction model in training- and validation datasets.

(b): variable importance plot

(c): Single-Sample waterfall plot

(d): nomogram model

Supplementary Files

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