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ORIGINAL RESEARCH

Analysis of Risk Factors of Postoperative Dry Eye in Cataract Patients Based on Lens Nucleus Hardness Grading

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Objective: To investigate the risk factors associated with dry eye disease (DED) development in cataract (CAT) patients following phacoemulsification surgery, with a focus on lens nucleus hardness grading, and to develop a predictive model for individualized clinical management.

Methods: This retrospective study included 150 cataract patients who underwent phacoemulsification from January 2023 to January 2025. Lens nucleus hardness was graded using the Emery system. Preoperative assessments included ocular surface status and systemic comorbidities. Logistic regression was used to identify independent risk factors, and a predictive model was developed and evaluated by receiver operating characteristic (ROC) analysis.

Results: Postoperative DED occurred in 38.7% of patients. Multivariate analysis revealed that diabetes mellitus, history of keratoconjunctivitis, conjunctivochalasis grade ≥III, lens nucleus hardness grade ≥IV, and 3.0 mm clear limbal incision were independent risk factors (all $P<0.05$). The prediction model showed good performance (AUC=0.836), with 84.5% sensitivity and 69.6% specificity.

Conclusion: Lens nucleus hardness, along with key clinical factors, independently predicts DED risk after cataract surgery. The developed model may assist in early risk identification and personalized perioperative management.

Keywords: cataract, dry eye disease, conjunctivochalasis severity, lens nucleus hardness, diabetes mellitus

Introduction

Cataract (CAT), the leading cause of blindness worldwide, has witnessed a steady increase in surgical cases driven by global population aging.[1] While phacoemulsification with intraocular lens (IOL) implantation remains the gold standard for visual rehabilitation, postoperative dry eye disease (DED) emerges as a prevalent complication, affecting 30–70% of patients and substantially compromising both visual outcomes and satisfaction metrics.[2,3] Although emerging research has identified surgical trauma, ocular surface microenvironment alterations, and perioperative medication effects as contributing factors to postoperative DED,[4,5] the potential association between lens nucleus hardness—a fundamental surgical parameter—and DED development remains systematically underexplored. While FLACS is increasingly recommended for managing dense cataracts due to its ability to reduce phacoemulsification energy, several reports suggest that the suction docking and high laser energy employed in FLACS may transiently impair the ocular surface and increase the risk of postoperative DED.[6,7] Recent advances in low-energy pulse FLACS platforms have shown improved ocular surface tolerance and may offer a safer alternative for patients with pre-existing ocular surface vulnerability.[8] This nuanced risk-benefit profile warrants careful selection of candidates for FLACS. Current evidence indicates that lens nucleus hardness serves not only as a primary determinant of phacoemulsification energy requirements and surgical duration but may also critically influence postoperative ocular surface homeostasis through multifaceted mechanisms, including intraoperative mechanical stress, inflammatory cascade activation, and corneal nerve impairment.[9]

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Nevertheless, existing studies predominantly consider nuclear hardness merely as a surrogate marker for procedural complexity,[10,11] overlooking its potential etiopathogenic role in DED development. Furthermore, the clinical translation of this parameter remains limited, with no established risk stratification models or predictive tools incorporating nucleus hardness grading. The resultant clinical dilemma impedes accurate risk prognostication and consequently, the implementation of precision medicine approaches in postoperative management.

Although numerous studies have examined postoperative dry eye disease (DED) risk factors, the potential prognostic role of lens nucleus hardness—a key determinant of phacoemulsification energy and corneal trauma—has not been previously studied. This work, therefore, contributes novel insights by integrating nucleus hardness into a multifactorial prediction model for postoperative DED. To overcome this limitation, our study pioneers an investigation into the dynamic correlation between lens nucleus hardness grading and DED following CAT surgery. Moving beyond conventional univariate analysis approaches, we systematically integrate multidimensional variables including preoperative ocular surface characteristics, surgical parameters, and systemic metabolic indicators to establish the first predictive model for postoperative DED risk. We hypothesize that lens nucleus hardness, as a surrogate of phacoemulsification energy and corneal trauma, is an independent predictor of postoperative dry eye disease (DED). By integrating this parameter into a multifactorial predictive model, this study extends current understanding of DED risk stratification and offers a clinically applicable tool that enhances preoperative planning in cataract surgery. Our findings will elucidate both the independent contribution of lens nucleus hardness in DED pathogenesis and its synergistic interaction with surgical stress, offering novel mechanistic insights into postoperative DED development. Beyond theoretical implications, this research will drive a transformative shift in clinical practice—from empirical prophylaxis to data-driven risk stratification. Furthermore, these results are expected to inform evidence-based perioperative management strategies, ultimately reducing dry eye incidence and enhancing the overall therapeutic outcomes of CAT surgery. This work carries substantial scientific significance and immediate clinical relevance. By integrating lens nucleus hardness and other key clinical variables into a risk prediction model, this study offers a tool that may support individualized perioperative management strategies aimed at minimizing postoperative dry eye complications and enhancing patient satisfaction following cataract surgery.

Materials and Methods

Study Design

We conducted a retrospective study analyzing CAT patients who underwent treatment at our institution between January 2023 and January 2025. Sample size estimation was conducted using G-Power (version 3.1) based on logistic regression, assuming an effect size of 0.3, $\alpha = 0.05$, power $(1–\beta) = 0.95$, and 6 predictors, yielding a minimum sample size of 138. The final sample size (n=150) exceeded this requirement, Figure 1 presents the detailed participant selection flowchart.

Inclusion and Exclusion Criteria

Inclusion criteria: (1) Age ≥50 years; (2) undergoing phacoemulsification with IOL implantation (unilateral or bilateral); (3) documented lens nucleus hardness grading; (4) preoperative best-corrected visual acuity (BCVA) ≤0.5; (5) absence of clinically significant preoperative DED; (6) standardized phacoemulsification parameters and the same IOL model, with all surgeries performed by the same surgical team; (7) complete clinical records.

Exclusion criteria: (1) Significant ocular surface comorbidities (meibomian gland dysfunction, active keratoconjunctivitis, glaucoma); (2) history of refractive surgery, ocular trauma, or intraocular procedures; (3) autoimmune disorders; (4) chronic use of tear secretion-affecting medications (within 3 months preoperatively).

Ethical Considerations

The institutional review board approved this study and waived informed consent requirements due to its retrospective nature. All procedures complied with the Declaration of Helsinki principles.

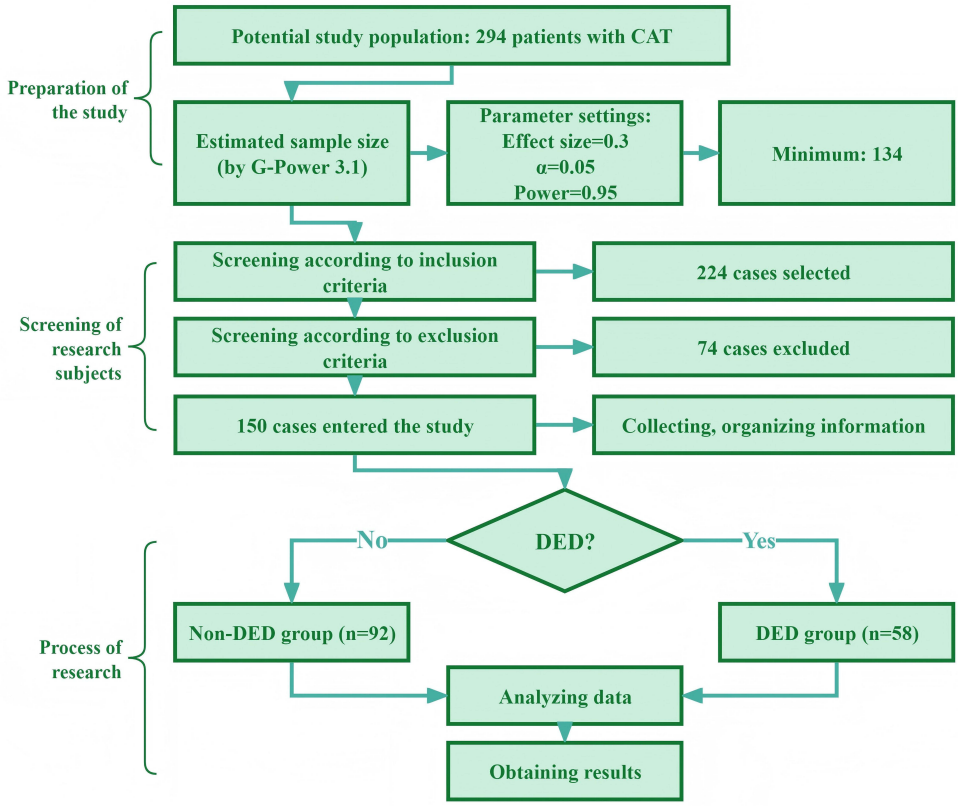

Figure 1 The main flow of this study.

Diagnostic Criteria for DED

The diagnosis of DED is established based on the diagnostic guidelines,[12] requiring the presence of characteristic symptoms (eg, ocular dryness, foreign body sensation, and visual fatigue) in conjunction with at least one of the following objective signs: tear film breakup time (BUT) ≤10 seconds, corneal fluorescein staining (CFS) ≥5 spots (Oxford grade ≥I), or positive conjunctival lissamine green staining. Patients were followed for 30 days postoperatively, a period during which early-onset postoperative dry eye symptoms are most frequently observed.

Grading of Lens Nucleus Hardness

Lens nucleus hardness is classified into five distinct grades according to the Emery-Little system:[13] Grade I: Transparent lens with no discernible nucleus, exhibiting a soft consistency; Grade II: Yellow-white to yellow nucleus with maintained softness; Grade III: Dark yellow nucleus demonstrating moderate hardness; Grade IV: Brown or amber-colored nucleus with pronounced hardness; Grade V: Brownish-black to black nucleus, indicating extreme hardness.

Clinical Data Collection

Baseline clinical characteristics, including age, gender, disease duration, and body mass index (BMI), were recorded. Comorbidities such as diabetes mellitus (DM), hypertension, and hyperlipidemia were also documented. Additionally, the conjunctivochalasis severity (Grade I: Asymptomatic or no obvious symptoms; Grade II: Mild symptoms, including epiphora, foreign body sensation, and ocular dryness; Grade III: Moderate symptoms significantly impacting daily life, with persistent epiphora, foreign body sensation, and dryness; Grade IV: Severe symptoms, including marked epiphora, foreign body sensation, dryness, and additional discomfort such as stinging and burning sensations) of patients was documented. All patients received a standardized postoperative regimen of topical levofloxacin 0.5% and prednisolone acetate 1% (four times daily for one week, then tapered). Preservative-free artificial tears were permitted as needed.

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Statistical Analysis

All statistical analyses were conducted using SPSS 25.0. Categorical variables are presented as [n (%)] and were analyzed using Pearson's chi-square tests. The normality of continuous variables was assessed using the Shapiro–Wilk test. Normally distributed variables are expressed as () and were compared using independent samples *t*-tests. Non-normally distributed variables are reported as median (interquartile range) and were analyzed using the Mann–Whitney *U*-test. To identify potential associated factors, we performed multivariate logistic regression analysis. Diagnostic performance was evaluated through receiver operating characteristic (ROC) curve analysis, with the area under the curve (AUC) serving as an indicator of diagnostic accuracy; an AUC value approaching 1.0 denotes optimal diagnostic performance. A P-value < 0.05 was considered statistically significant for all analyses.

Results

Incidence of DED

Among the 150 patients included in the study, 58 developed DED, yielding an incidence rate of 38.67%, which aligns with previously reported rates in the literature.[14]

Univariate Analysis of Factors Influencing DED

Comparative analysis between DED and non-DED patients revealed no statistically significant differences in gender, affected eye, disease duration, or other baseline characteristics (P > 0.05), suggesting that these variables are not associated with DED development. However, patients in the DED group exhibited a significantly higher prevalence of DM, a history of keratoconjunctival disorders (KD), advanced age, larger clear limbal incision, higher grades of conjunctivochalasis, and greater lens nucleus hardness (P < 0.05). These results indicate that these factors may serve as potential risk factors for DED onset (Table 1).

Multivariate Analysis of Risk Factors for DED

The statistically significant single-factor indicators identified previously were assigned according to the values presented in Table 2 and incorporated as covariates. Employing logistic regression analysis with DED as the dependent variable and using the "Enter" method, we found that age showed no significant association with DED occurrence (P > 0.05). In

Table 1 Univariate Analysis Affecting DED

Factors	Non-DED Patients (n=92)	DED Patients (n=58)	Statistical Values (t or χ^2)	P
Age (years old)	62.13±4.70	63.97±5.99	2.091	0.038
Gender, male (%)	50 (54.35%)	36 (62.07%)	0.867	0.352
Diseased eye, left eye (%)	42 (45.65%)	32 (55.17%)	1.290	0.256
Duration of CAT (months)	7.27±2.55	7.33±2.24	0.137	0.891
Smoking, yes (%)	35 (38.04%)	26 (44.83%)	0.679	0.410
Drinking, yes (%)	24 (26.09%)	17 (29.31%)	0.186	0.666
Combined with DM, yes (%)	29 (31.52%)	32 (55.17%)	8.247	0.004
Combined hypertension, yes (%)	34 (36.96%)	19 (32.76%)	0.274	0.600
History of KD, yes (%)	9 (9.78%)	18 (31.03%)	10.893	0.001
Conjunctivochalasis severity, I–II (%)	74 (80.43%)	34 (58.62%)	8.397	0.004
Lens nucleus hardness, I–II (%)	68 (73.91%)	24 (41.38%)	15.882	<0.001
Clear limbal incision (2.2 mm vs 3.0 mm) (%)	64 (69.57%)	24 (41.38%)	11.651	<0.001
Perioperative use of drugs, 1~3 types (%)	71 (77.17%)	41 (70.69%)	0.791	0.374

Note: Data are presented as mean ± standard deviation (SD) or number (percentage).
Abbreviations: CAT, cataract; DM, diabetes mellitus; KD, keratoconjunctivitis.

Table 2 Assignment of Univariate

Factors	Assignment of Value
DED	Non-DED=1, DED=2
Age (years old)	Analysis was performed using raw data
Combined with DM	no=1, yes=2
History of KD	no=1, yes=2
Conjunctivochalasis severity	I–II=1, III–V=2
Lens nucleus hardness	I–II=1, III–IV=2
Clear limbal incision (mm)	2.2=1, 3.0=2

Note: Age entered into analysis as a continuous raw variable; Dichotomous and ordinal variables were coded numerically for entry into logistic regression; Conjunctivochalasis classified per Liu's grading: Grades I–II = mild, Grades III–V = moderate-to-severe; Lens nucleus hardness graded using the Emery system: Grades I–II = low hardness, Grades III–IV = high hardness.
Abbreviations: DED, dry eye disease; DM, diabetes mellitus; KD, keratoconjunctivitis.

Table 3 Multivariate Analysis of Factors Affecting DED

Factors	β	S.E.	Wals	P	OR	95% CI (Lower-Upper)
Age (years old)	0.040	0.039	1.011	0.315	1.041	(0.963–1.124)
Combined with DM	1.123	0.423	7.031	0.008	3.074	(1.340–7.049)
History of KD	1.244	0.536	5.391	0.020	3.468	(1.214–9.911)
Conjunctivochalasis severity	1.423	0.467	9.282	0.002	4.150	(1.661–10.367
Lens nucleus hardness	1.770	0.437	16.385	<0.001	5.871	(2.492–13.834)
Clear limbal incision	1.513	0.438	11.962	0.001	4.543	(1.927–10.710)
Constant	−5.542	2.527	4.810	0.028	0.004	-

Notes: Variable coding is presented in Table X; Lens nucleus hardness and conjunctivochalasis grading systems were based on the Emery and Liu criteria, respectively.
Abbreviations: 95% CI, 95% Confidence Interval; β, regression coefficient; S.E, standard error; OR, odds ratio; CI, confidence interval; DED, dry eye disease; DM, diabetes mellitus; KD, keratoconjunctivitis.

contrast, DM (OR=3.074, 95% CI=1.340–7.049), history of KD (OR=3.468, 95% CI=1.214–9.911), clear limbal incision (OR=4.543, 95% CI=1.927–10.710), conjunctivochalasis grade (OR=4.150, 95% CI=1.661–10.367), and lens nucleus hardness grade (OR=5.871, 95% CI=2.492–13.834) as independent risk factors for DED development (all $P < 0.05$) (Table 3). In the predictive model, the relative contribution (weight) of each variable corresponds to its logistic regression coefficient (β). Lens nucleus hardness (β=1.770) demonstrated the highest explanatory weight, followed by clear limbal incision size (β=1.513), conjunctivochalasis grade (β=1.423), history of keratoconjunctivitis (β=1.244), and diabetes mellitus (β=1.123). These values indicate the magnitude of influence each factor exerts on the likelihood of post-operative DED.

Construction and Validation of the DED Risk Model

Based on the comprehensive analysis, we developed a predictive model for DED risk as follows: $Y_{\text{predicted value}} = -5.542 + 1.123 \times \text{DM} + 1.224 \times \text{History of KD} + 1.423 \times \text{conjunctivochalasis severity} + 1.770 \times \text{Lens nucleus hardness} + 1.513 \times \text{clear limbal incision}$. ROC curve analysis demonstrated that the model had a maximum Youden index of 54.05 and an outstanding AUC of 0.836 for DED prediction, with high sensitivity (84.48%) and specificity (69.57%) ($P < 0.05$), indicating its significant clinical value as a reliable predictive tool (Figure 2).

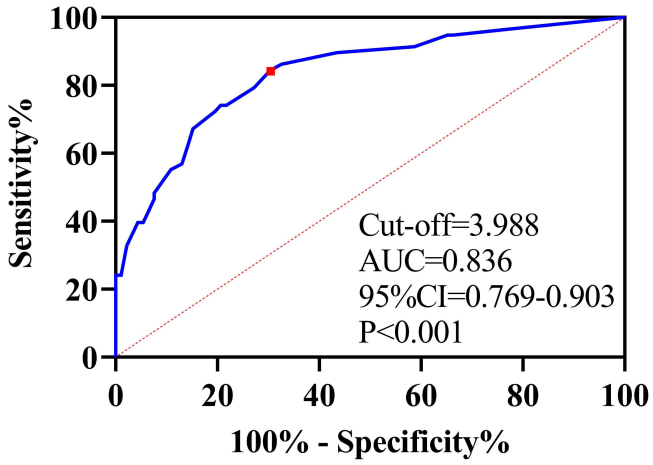

Figure 2 ROC curves for the DED risk model to diagnose the occurrence of DED.

Discussion

This study comprehensively evaluated the clinical data of 150 post-CAT surgery patients to investigate the risk factors for postoperative DED and establish a predictive risk model. The findings offer novel insights and evidence-based guidance for clinical strategies aimed at preventing DED development following CAT surgery.

Our results identified lens nuclear hardness grading as an independent risk factor for postoperative DED. The underlying pathophysiological mechanisms may involve the following aspects: (1) Increased phacoemulsification energy exposure: Higher nuclear hardness (grades IV–V) necessitates greater cumulative dissipated energy (CDE), resulting in prolonged phacoemulsification time during surgery. Previous studies have demonstrated a 15% increase in corneal epithelial cell apoptosis rate per unit elevation in CDE.[15] The resultant thermal effects activate corneal matrix metalloproteinases, compromising epithelial basement membrane integrity and exacerbating ocular surface desiccation.[7] (2) Inflammatory cascade activation: The heightened mechanical and thermal stress from phacoemulsification triggers the release of pro-inflammatory cytokines, which suppress mucin secretion by conjunctival goblet cells, leading to the destabilization of the tear film's lipid-mucin layer equilibrium.[16] Supporting evidence from Han Y et al's experimental study revealed that excessive inflammatory mediators could reduce tear production by over 30% in animal models.[17] (3) Corneal neurosensory impairment: Phacoemulsification energy directly damages corneal trigeminal nerve terminals, diminishing corneal reflex frequency and thereby affecting the uniform distribution of tears. This study represents the first quantitative demonstration of the association between Emery nuclear hardness grading and postoperative DED risk, establishing nuclear hardness not merely as a surgical complexity indicator but as a significant prognostic factor for ocular surface outcomes. Our findings corroborate those of Rao A et al,[18] who observed a 40% reduction in postoperative tear BUT values in patients with grade IV or higher nuclear hardness compared to controls. We further identified DM, history of KD, clear limbal incision, and conjunctivochalasis severity as independent risk factors for DED development. The pathophysiological impact of DM on DED involves multiple interrelated mechanisms. For example, chronic hyperglycemia facilitates advanced glycation end product (AGE) accumulation in both the lacrimal gland and the corneal epithelium, downregulating critical tear secretion-related genes.[19] Meanwhile, diabetic retinopathy patients demonstrate 20–30% reduced lacrimal gland perfusion,[20] potentially compromising tear production capacity. As highlighted by Kangilbaeva G et al,[21] hyperglycemia-induced damage to corneal nerve fiber density diminishes corneal sensitivity, exacerbating tear film evaporation through impaired neurotrophic regulation. In patients with preexisting KD, goblet cell depletion[22] leads to deficient mucin secretion,[23] impairing the anchoring function of the tear film to a certain extent. Furthermore, conjunctivochalasis creates pathological "folds" that mechanically disrupt tear dynamics through dual mechanisms: obstructing tear flow from the lacrimal lake to the lacrimal drainage system while simultaneously causing microtrauma to the corneal epithelium through friction, thereby accelerating tear film destabilization.[24]

Based on the identified risk factors, we developed a predictive model for DED risk, which demonstrated outstanding discriminative performance (AUC=0.836), highlighting its significant clinical utility. Based on these findings, we propose the following clinical recommendations: (1) For patients with grade IV–V nuclear CATs, femtosecond laser-assisted CAT surgery should be prioritized to minimize ultrasound energy exposure. (2) Diabetic patients should achieve preoperative HbA1c levels <7% and receive adjunctive tear-stimulating therapy to mitigate DED risk. (3) Surgical techniques should favor micro-incisions (2.2 mm) and low-flow perfusion settings to reduce corneal endothelial cell loss. (4) Preservative-free viscoelastic agents (eg, sodium hyaluronate) are recommended to prevent goblet cell toxicity. Postoperatively, this risk model enables early identification of high-risk patients, facilitating timely intervention and optimized management of DED following CAT surgery.

Postoperative medication regimen may also influence the incidence of DED. Frequent use of topical antibiotics and corticosteroids, especially formulations containing preservatives such as benzalkonium chloride (BAK), has been shown to disrupt tear film stability and induce goblet cell toxicity. In our study, although the type and duration of postoperative drops were standardized, patients with prolonged exposure may have experienced transient ocular surface irritation. This interaction underscores the need for preservative-free alternatives and optimized dosing schedules, particularly among patients at high risk as identified by our prediction model.

Compared to conventional DED assessment methods, this model relies solely on routine preoperative examination indicators and eliminates the need for complex testing equipment, making it particularly suitable for implementation in primary care settings. However, the exclusion of surgical parameters and biomarkers may lead to an underestimation of the indirect effects of nuclear hardness. Furthermore, the single-center retrospective design introduces potential selection bias, highlighting the need for multicenter prospective studies to validate the model's generalizability. The model's complexity should also be optimized through cross-validation or external cohort testing. Another primary limitation of this study is the short-term follow-up that focused on the immediate postoperative period. Since dry eye disease may evolve or recover over months, future prospective studies with longer follow-up durations are necessary to capture the chronic progression and resolution trends. The retrospective study design precludes establishing causal relationships between identified risk factors and postoperative DED. Future prospective or randomized studies are needed to validate our findings. The absence of symptom-based DED severity scales such as OSDI or DEQ represents a limitation of this retrospective analysis. Future prospective studies should incorporate validated questionnaires to capture subjective symptom burden alongside objective signs. Future studies should address these limitations through more comprehensive and in-depth investigations. Although the predictive model demonstrated favorable discriminative performance (AUC=0.836), its application should be considered preliminary until validated in larger, external, and preferably prospective cohorts. Multicenter studies with more heterogeneous populations are recommended to enhance its generalizability.

Conclusion

The present study demonstrates that higher grades of lens nucleus hardness significantly increase the risk of postoperative dry eye disease (DED), likely through mechanisms involving cumulative surgical energy exposure, inflammation, and corneal neural injury. By incorporating lens hardness alongside other clinical variables, we developed a multifactorial prediction model that showed promising discriminative performance for identifying patients at elevated DED risk following cataract surgery. However, it is important to emphasize that DED is a multifactorial condition influenced by diverse systemic, ocular surface, and surgical factors. Thus, while lens nucleus hardness emerged as an independent predictor in our model, its interpretation should be integrated within a broader clinical context. The model may assist in early risk stratification and personalized perioperative planning, but its use in routine practice should await further validation in larger, prospective, multi-center cohorts to confirm its robustness and generalizability. A comprehensive, patient-centered strategy—combining preoperative risk assessment, intraoperative energy optimization, and postoperative ocular surface monitoring—may help mitigate DED occurrence and improve visual rehabilitation outcomes in cataract patients.

Data Sharing Statement

The data that support the findings of this study are not publicly available due to institutional policy and ethical restrictions regarding patient confidentiality. The datasets generated and/or analyzed during the current study are anonymized and stored on secure hospital servers, and additional access is not permitted. No further data will be shared.

Human Ethics and Consent to Participate Declarations

This study was approved by the Human Ethics Committee of Nanjing Aier Eye Hospital (Ethics Approval Number: 176533467567), with a waiver of individual informed consent due to the use of de-identified patient data and the minimal risk nature of the research. All methods adhered to the ethical standards of the institutional and/or national research committee and complied with the Declaration of Helsinki and its later amendments. Patient information was anonymized prior to analysis to protect privacy and confidentiality.

Consent to Publish Declaration

All participants agreed to publish.

Author Contributions

All authors made a significant contribution to the work reported, whether that is in the conception, study design, execution, acquisition of data, analysis and interpretation, or in all these areas; took part in drafting, revising or critically reviewing the article; gave final approval of the version to be published; have agreed on the journal to which the article has been submitted; and agree to be accountable for all aspects of the work.

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Disclosure

The authors declare no conflict of interest, financial or otherwise.

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