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Progress in the Application of Artificial Intelligence in the Perioperative Period of Cataract

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ABSTRACT
With the advancement of artificial intelligence (AI) technology, the research and application scope and influence of methods such as deep learning in the medical field are expanding day by day. The combination of new technologies and clinical practice has also become a research hotspot in recent years. This article systematically reviews the current application status of AI in key stages of the cataract perioperative period, including preoperative biometry, intraocular lens (IOL) calculation, surgical navigation, and complication prediction. It focuses on analyzing innovative technologies such as preoperative analysis based on AI, surgical processes assisted by computer vision, and prediction models constructed for postoperative risks. AI shows quite obvious advantages in improving measurement accuracy, optimizing surgical plans, and reducing the risk of complications, but still faces challenges in data standardization and model interpretability.

KEYWORDS
Artificial intelligence; Cataract; Biometry

1 Introduction

Cataract is the main cause of visual impairment worldwide. With the deepening of population aging, the number of cataract surgeries shows a continuous upward trend. Early diagnosis and timely management of cataracts are crucial for improving patients' quality of life and reducing medical burdens. However, especially in low- and middle-income regions, the allocation and management of medical resources are still unsatisfactory [1]. In recent years, medical AI has moved from theory to practical clinical application, with advantages including reducing medical costs and improving diagnosis and treatment efficiency [2]. Currently, the application of artificial intelligence technology in the cataract perioperative period is profoundly transforming traditional diagnosis and treatment methods. In the traditional diagnosis and treatment model, there are significant limitations in surgical planning, operational accuracy, and postoperative management. Artificial intelligence, especially deep learning in the field of medical image analysis, has opened up a new technical approach for the management of the cataract perioperative period. This article analyzes the current application status and future development trends of AI technology, and discusses the main challenges currently faced.

2 Key Technological Innovations of Artificial Intelligence (AI) in Preoperative Evaluation

2.1 Deep Learning-Based Biometry and IOL Calculation

With the development of medical technology and the improvement of people's living standards, cataract patients' requirements for postoperative visual quality have evolved from "being able to see" in the past to "seeing clearly and comfortably" today. Therefore, accurate calculation of intraocular lens power is particularly important. Studies have shown [3] that current IOL power calculation formulas can already control postoperative refractive error to a low level, with approximately 95% to 98% of patients having a postoperative refractive error of less than 1.00 diopter (D). However, about 5% to 20% of patients still experience significant refractive errors, resulting in low postoperative satisfaction. Currently, AI-based IOL power calculation is based on two main principles: first, comparing the patient's ocular parameters with a database containing a large number of correctly matched ocular and IOL parameters to obtain the required IOL power for the patient. The most representative AI formulas based on this principle are the Hill-RBF and Kane formulas; second, based on multiple widely used IOL power calculation formulas, comparing the patient's ocular parameters with system data to select the most suitable one among traditional formulas for calculation. This method effectively reduces selection bias and improves calculation accuracy, and the most representative AI formula based on this principle is the Ladas Super Formula [4-5]. Currently, researchers use pipeline tracking software (Okulix10) and a new generation of AI algorithms (based on Hill-RBF, Kane formula, FullMonte IOL system, Ladas Super Formula (LSF) AI) to integrate multiple morphological data such as corneal topography, anterior chamber depth (ACD), axial length (AL), and postoperative effective lens position (ELP) to find new calculation formulas, greatly improving calculation accuracy [6]. Some researchers have trained a neural network multi-layer perceptron model to predict IOL power based on corneal K-values, axial length, and refractive error predicted by theoretical formulas [7]. IOL calculation formulas operated by neural networks have significantly lower prediction errors compared to traditional formulas, especially for special cases such as high myopia and post-corneal refractive surgery. By analyzing past surgical data, AI models can provide calculation methods more suitable for individual patient conditions [8].

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2.2 Intelligent Surgical Indication Screening System

Studies have shown [9] that medical AI mainly belongs to two technical categories. The first category analyzes structured data, such as slit-lamp anterior segment images, optical coherence tomography (OCT) scan images, and visual function-related examination data, and achieves accurate evaluation of surgical timing by combining multi-modal image fusion technology and machine learning algorithms. The second category extracts information from unstructured data, such as medical journals and clinical databases, to supplement and optimize structured clinical data. In addition, AI systems can construct prediction models for surgical necessity. When judging the surgical indications for early cataracts, using anterior segment slit-lamp images and neural networks to analyze the degree and classification of lens opacity, the accuracy is significantly better than traditional clinical evaluation methods [10]. In addition, natural language processing (NLP) technology can automatically analyze electronic medical records to identify high-risk patients with comorbid systemic diseases, thereby providing decision support for preoperative evaluation [11].

3 Innovative Applications of AI During and After Surgery

3.1 Computer Vision-Assisted Precision Surgical Operation

The traditional cataract surgery model is being reshaped by the application of computer vision technology in cataract surgery. Neural networks can improve surgical efficiency through deep learning [12], process microscope video streams in real time, accurately identify key anatomical structures such as the boundary of the anterior capsule and the position of the lens nucleus, and then provide submillimeter-level precision spatial positioning references for surgeons [13]. Some researchers have developed an automatic video analysis system that automatically extracts surgical phases (such as the continuous curvilinear capsulorhexis (CCC) phase) from surgical videos, identifies the diameter and center position of the capsulorhexis, and superimposes virtual guide rings through augmented reality technology, thereby greatly improving the standardization and centration of capsulorhexis operations [14]. In addition, surgical process models can predict anatomical variations that may be encountered in different surgical steps, such as evaluating zonular relaxation, providing surgeons with proactive decision support and reducing complications. These technological innovations not only improve surgical safety but also shorten the learning curve by standardizing operational processes [15].

3.2 Intelligent Parameter Optimization and Adaptive Control

Artificial intelligence has also shown significant breakthroughs in the field of dynamic optimization of surgical parameters. Some researchers have developed an intraoperative tracking and quantification system that can continuously analyze dozens of real-time parameters such as nuclear hardness and anterior chamber stability to construct a multi-variable control model and evaluate the operating range of intraoperative instruments [16]. This system uses reinforcement learning algorithms to automatically adjust key parameters such as ultrasonic energy, negative pressure, and irrigation flow according to different stages of surgical progress, ensuring high surgical efficiency while effectively minimizing the risk of tissue damage. The personalized parameter recommendation system for special cases integrates preoperative biometric data, image features, and the surgeon's daily operating habits to generate the optimal parameter combination strategy [17]. These intelligent optimization strategies not only improve surgical controllability but also significantly reduce the workload of surgeons. After surgery, the data analysis module can automatically generate surgical reports and record detailed change curves of parameters at each stage, thereby providing data support for the improvement of surgical quality and teaching research activities.

3.3 Postoperative Visual Acuity Prediction and Risk Management

In the field of postoperative management, artificial intelligence has built a comprehensive intelligent monitoring system. A computer vision-based automatic follow-up system can quantitatively analyze indicators such as corneal transparency and anterior chamber inflammation using anterior segment photos collected by slit lamps, thereby achieving remote accurate monitoring. Due to the interference of preoperative cataract opacity and complex fundus conditions such as high myopia, researchers[18] have developed a deep learning algorithm based on optical coherence tomography (OCT) to predict patients' postoperative visual acuity. This algorithm uses five different deep convolutional neural networks (DCNNs) to test different datasets to verify the model's performance, and the mean absolute error (MAE) of internal and external datasets is 0.1524 and 0.1602 logMAR, respectively, proving the model's stability and accuracy. Researchers such as Liu used natural language processing (NLP) to identify cases of intraoperative posterior capsule rupture and intracameral injection of antibacterial drugs in surgical records for the analysis and monitoring of postoperative complications [19]. In addition, for cataract postoperative complications such as cystoid macular edema (ME), some scholars have developed a machine learning-based paired classification algorithm that uses different spectral domain OCT images for ME classification, which can distinguish between diabetic ME, pseudophakic ME, and mixed ME [20]. The multi-center data integration platform collects various postoperative complication cases, and based on individual patient characteristics, can predict the occurrence probability of complications such as macular edema and endophthalmitis, and provide recommendations for preventive intervention measures.

Artificial intelligence and neural networks have also been applied in cataract postoperative follow-up and care, such as the identification of early corneal endothelial cell loss patterns. Compared with traditional clinical examinations, they can detect potential risks earlier and strengthen postoperative follow-up. To explore the feasibility of applying AI to improve care quality, Long [21] et al. created CC-Guardian for the follow-up management of congenital cataracts. CC-Guardian consists of three modules: a prediction module for identifying high-risk congenital cataract patients who may develop postoperative complications; a scheduling module for arranging personalized follow-up; and a telemedicine module for making intervention decisions based on examination results in subsequent rechecks. In multi-center validation, the area under the receiver operating characteristic (ROC) curve (AUC) of the first module for predicting visual axis opacification (VAO) was 94.4%, and the AUC for predicting high intraocular pressure (IOP) was 96.1%. The sensitivity and specificity of the third module for providing intervention decisions were 95.9% and 94.5%, respectively, and the results were comparable to those of internal validation. This management system can identify potential cataract patients, improve patient consultation efficiency and doctor decision-making efficiency, and provide a basis for the development of home-based telemedicine platforms.

4 Conclusion

Artificial intelligence is gradually reshaping the diagnosis and treatment model during the cataract perioperative period. It improves preoperative evaluation accuracy, enhances surgical safety, and optimizes postoperative management efficiency, showing extremely broad application prospects. In the future, efforts should be made to build a standardized multi-center database, develop more interpretable AI models, and verify clinical effects through rigorous randomized controlled trials. With the continuous maturity of technology and the further advancement of clinical validation, AI is likely to become an important intelligent auxiliary tool in the cataract diagnosis and treatment system.

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