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REVIEW

Applications of Artificial Intelligence in Cataract Surgery: A Review

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Abstract: Cataract surgery is one of the most performed procedures worldwide, and cataracts are rising in prevalence in our aging population. With the increasing utilization of artificial intelligence (AI) in the medical field, we aimed to understand the extent of present AI applications in ophthalmic microsurgery, specifically cataract surgery. We conducted a literature search on PubMed and Google Scholar using keywords related to the application of AI in cataract surgery and included relevant articles published since 2010 in our review. The literature search yielded information on AI mechanisms such as machine learning (ML), deep learning (DL), and convolutional neural networks (CNN) as they are being incorporated into pre-operative, intraoperative, and post-operative stages of cataract surgery. AI is currently integrated in the pre-operative stage of cataract surgery to calculate intraocular lens (IOL) power and diagnose cataracts with slit-lamp microscopy and retinal imaging. During the intraoperative stage, AI has been applied to risk calculation, tracking surgical workflow, multimodal imaging data analysis, and instrument location via the use of "smart instruments". AI is also involved in predicting post-operative complications, such as posterior capsular opacification and intraocular lens dislocation, and organizing follow-up patient care. Challenges such as limited imaging dataset availability, unstandardized deep learning analysis metrics, and lack of generalizability to novel datasets currently present obstacles to the enhanced application of AI in cataract surgery. Upon addressing these barriers in upcoming research, AI stands to improve cataract screening accessibility, junior physician training, and identification of surgical complications through future applications of AI in cataract surgery.

Plain language summary: Although barriers remain for the generalizability and standardization of artificial intelligence in cataract surgery, there are growing applications improving efficiency, data analysis, safety, training, and patient outcomes in pre-operative, intraoperative, and post-operative stages.

Keywords: cataract surgery, artificial intelligence, deep learning, convolutional neural networks

Introduction

Cataracts are an opacification of the eye lens.[1] Cataracts are strongly associated with aging, as over 90% of those aged 80 years or older have cataracts.[2] As the worldwide population continues to age, the prevalence of cataracts is expected to increase from over 10 million in 2010 to 40 million by 2025.[2] In both middle- and low-income countries, cataracts currently represent the leading cause of blindness.[3] Therefore, access to cataract surgery will become increasingly important for preventing vision-related injuries, automobile collisions, and even risk of developing dementia.[2] Globally, cataract surgery is the most performed procedure.[4] Paralleling the expected increase in prevalence of cataracts over the upcoming decades, an increase in cataract surgery between 72 and 144% is anticipated by the year 2036.[5]

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Artificial intelligence (AI) represents the rapidly developing field combining large-scale data analysis and decision-making algorithms facilitated by evolving computer capabilities.[6] For the purpose of this review, we will consider this definition of the term AI to encompass machine learning (ML), deep learning (DL), and convolutional neural networks (CNN), as well as additional "smart" or robotic mechanisms described below. The applications of AI in medicine have now reached the operating room for other surgical specialties, with utilization in ophthalmological surgery only recently emerging.[6,7] Thus far, AI has been utilized in ophthalmologic microsurgery procedures including cataract surgery, refractive surgery, keratoplasty, oculoplastic surgery, and vitreoretinal surgery.[6] We aim to understand the contributions of AI in ophthalmology from the perspective of pre-operative, intraoperative, and post-operative stages of cataract surgery and its applications for safety, efficiency, training, and personalized patient care.

Methodology

We conducted literature searches on journal databases such as PubMed and the scholarly literature search engine Google Scholar. We accessed these databases during the time frame from March 13, 2024 to April 24, 2024. We identified articles to be included in this literature review by searching with keywords and phrases including "artificial intelligence in cataract surgery", "ophthalmology", "deep learning", "machine learning", "convolutional neural networks", and "phacoemulsification". This literature search yielded both original articles and reviews, thus both qualitative and quantitative data were included in our review of the literature. Articles published prior to 2010 were excluded from review, while articles published since 2010 were included. Inclusion criteria were as follows: relevance to the applications of artificial intelligence in cataract surgery from pre-operative, intraoperative, and post-operative stages, as well as discussion of artificial intelligence in the general field of ophthalmology and its challenges and future applications.

Artificial Intelligence in Cataract Surgery

Pre-Operative Stage

AI has been applied during pre-operative patient care to calculate intraocular lens (IOL) power and make diagnoses before cataract surgery (Table 1). IOL power is calculated prior to cataract surgery to identify the power necessary to improve a patient's refractive accuracy.[8] Vergence formulas are a type of formula used to estimate IOL power with variables such as lens thickness and anterior chamber depth.[8] Traditional vergence formulas do not use AI for IOL power calculation; however, Ladas et al (2021) are currently supplementing these traditional formulas with deep learning (DL) techniques.[9] By using DL in tandem with established IOL formulas including SRK, Holladay I, and LSF, the researchers improved the percentage of eyes within 0.5 diopters of the predicted refractive outcome after cataract surgery when compared to using these traditional IOL formulas alone.[9] Additionally, Zhou et al (2023) compared AI-based IOL formulas such as XGBoost, Hill-RBF, and Kane to traditional IOL formulas.[10] AI-based IOL formulas exhibited lower

Table 1 Applications of AI in Cataract Surgery

Cataract Surgery		
Pre-Operative Stage	**Intraoperative Stage**	**Post-Operative Stage**
Supplementing traditional IOL power calculation formulas with DL[9] Calculating IOL power using ML[8–11] DL model for diagnosing nuclear cataracts[12–14]	Facilitating a smart operating theater[15] Real-time multimodal imaging analysis[15,16] DL to recognize surgical phase and estimate workflow, ex. DeepPhase, Touch Surgery Enterprise, CaDIS[17–19] "Smart" instruments[18,20,21] ML for surgical training, ex. PhacoTracking[22]	"Smart" scheduling systems[15] Artificial neural networks to detect posterior capsule opacification[23–25] CNN to assess risk of intraocular lens dislocation[26,27] Predict post-surgical complications, ex. TempSeq-Net[24] AI assistants to evaluate recovery process, ex. Dora[28] CNN for tracking pupil size and assessing intensity of pupillary reactions[29]

mean absolute errors, which is the difference between predicted refractive outcome and actual postoperative refractive outcome.[10] Gonzalez and Bautista (2021) recently developed a DL model, Karmona, which incorporates additional variables compared to other formulas, such as the curvature of the posterior corneal surface.[11] Karmona predicted IOL power more accurately than traditional formulas such as Holladay or even emerging AI-based formulas such as Hill-RBF.[11] Modern mathematical vergence formulas have revolutionized vision improvement after cataract surgery.[8] AI-based IOL power formulas will build on these accomplishments by allowing for IOL power calculations to be tailored to unique characteristics found in each patient's eye to increase post-operative visual outcomes.[9]

Machine learning (ML) algorithms are being paired with video-recordings of slit-lamp microscopy to aid in the diagnosis of nuclear cataracts.[12] Shimizu et al (2023) created an AI algorithm with the ability to both diagnose nuclear cataracts and gauge nuclear cataract severity with overall performance similar to that of ophthalmologists.[12] Tham et al (2022) developed a DL algorithm using retinal fundus images for detection of visually significant cataracts.[13] This algorithm, when provided with solely retinal images, retained a comparable sensitivity and specificity to ophthalmologists provided with retinal images and concurrent slit-lamp photographs, thus offering a relatively simple modality to allow for healthcare providers to refer patients for cataract surgery.[13] Ueno et al (2024) developed a DL model that can triage corneal diseases, including cataracts, with only a smart phone.[14] Again, this DL model provided a similar accuracy to cornea specialists, expanding frontiers for visual healthcare access across the globe.[14]

Intraoperative Stage

During cataract surgery, AI applications have become increasingly useful in calculating risk during operation, tracking progress through surgical phases, analyzing data, and performing surgical instrument control (Table 1). Furthermore, AI is pivotal in facilitating the development and functionality of an optimized "smart operating theater".[26] AI would be used to perform multimodal data analysis via integration of various data streams such as intraoperative surgical sensors and recordings, speech recognition, virtual reality, robotic assistants, patient health records, and remote communication.[26]

Intraoperative swept-source optical coherence tomography devices, such as ANTERION, CASIA2, and IOLMaster 700, generate imaging data during cataract surgery such as anterior and total keratometry, central corneal thickness, anterior chamber depth, lens thickness, and axial length.[27] AI can be applied to analyze this multimodal imaging data during cataract surgery for calculation of IOL power and precise ocular biometric measures.[26]

"Smart" instruments may also be used to enhance safety and minimize risk of complications during cataract surgery.[15] The "smart" instruments are equipped with sensors using auditory force feedback (AFF) substitution.[15,16] AFF sensors alert the surgeon to increases in generated force during ophthalmic membrane peeling procedures, allowing for reduced generated force and increased peeling performance.[15,16] These "smart" instruments are being implemented to improve safety measures during and outcomes after cataract surgery. The Johns Hopkins steady-hand eye robot utilizes similar force sensing mechanisms through its XYZ system and rolling and tilt mechanisms.[15] The robot utilizes three degrees of freedom force sensing based on fiber Bragg grating sensors to calculate high resolution for axial forces and transverse forces.[17] While not currently in use for cataract surgery, the application of the force-sensing steady-hand-eye robot in vitreoretinal surgery shows promise for further application in ophthalmic microsurgery, including cataract surgery.[17]

DeepPhase is a computer-assisted interventional system which estimates workflow based on surgical instrument recognition and analysis of corresponding phase of cataract surgery by applying a DL mechanism to cataract videos.[18] The DL paradigm utilizes residual and recurrent neural networks to detect tools and classify phases by sequence of tool features and phase annotations from the CATARACTS dataset.[18] Similarly, Touch Surgery Enterprise, developed by Medtronic, is a commercial AI system which allows real-time surgical phase recognition and workflow analysis for cataract surgery.[15] Furthermore, Grammatikopoulou et al (2021) describe the cataract dataset for surgical RGB-image segmentation (CaDIS), a semantic segmentation dataset developed using DL techniques.[19] The applications of AI in surgical stage recognition and workflow analysis could be particularly useful in the progression towards a more efficient smart operating theater.

AI is also beneficial for surgical training and operating room efficiency. ML-mediated analysis of surgical movements during cataract surgery, called PhacoTracking, utilizes data such as total instrument path length, number of movements, and time of operation to generate valuable data for surgical training.[20] A preliminary study of PhacoTracking found that junior surgeons exhibited longer total path length, greater variation in total path length, longer time of procedure, and greater number of movements compared to senior surgeons.[20] The analysis provides valuable data for training and improvement of surgical technique in cataract surgery.[20] AI has also been applied to identify risk indicators and evaluate surgical technique in real time during continuous curvilinear capsulorhexis and phacoemulsification.[21] Furthermore, the real-time surgical phase tracking ability points to the utility of AI in operating room workflow and surgical training.[26] Reliable identification of instruments and surgical stage at which they are being used would allow for the surgical team and trainees to observe and prepare for subsequent surgical stages.[26] AI-generated data would also be available for further analysis and integration into electronic medical records and educational platforms to inform training procedures and expected clinical outcomes.[26]

Post-Operative Stage

AI also assists in organizing post-operative care and predicting complications following cataract surgery (Table 1).[26] Automated AI systems are being used to schedule post-op and follow-up appointments for optimized use of time and resources.[26] The smart scheduling systems use data from past cataract surgeries such as procedure duration, surgeon experience, and anesthesia type to predict the time commitment necessary for a given procedure based on the individual patient's case.[26]

AI is also being utilized to detect post-operative complications such as posterior capsular opacification after cataract surgery.[22] Artificial intelligence models have been able to detect posterior capsule opacification with up to 92.2% accuracy, showing promise for the application of artificial neural networks to evaluate and predict potential complications from cataract surgery.[22,30] These artificial neural networks consider individual patient risk factors and abundant imaging data to quantify the presence and progression of posterior capsule opacification.[23] For example, Jiang et al (2018) developed an end-to-end temporal sequence network, called TempSeq-Net, which utilizes long short-term memory methods and CNNs to assess consecutive slit-lamp images and predict the progression of ophthalmic complications following cataract surgery.[30] The risk stratification capabilities of AI would benefit post-op patient care by allowing the surgical team to monitor and prepare for potential complications during recovery.

DL methods have also been used to predict intraocular lens dislocation following cataract surgery.[24] Intraocular lens dislocation is a rare complication of cataract surgery which can contribute to decreased visual acuity, vitreous hemorrhage, retinal detachment, retinal tears, and ultimately follow-up surgery for treatment.[24,25] Ghamsarian et al (2024) developed convolutional neural networks (CNN) trained with data including lens unfolding time and unfolded-lens rotation to assess a patient's risk for post-operative intraocular lens dislocation.[24] These DL techniques were able to correctly isolate brands of intraocular lenses which have been previously associated with higher risk for post-operative intraocular lens dislocation.[24] The success of these CNNs could allow surgeons to better predict patient outcomes to cataract surgery and identify appropriate intraocular lenses based on both lens statistics and individual patient characteristics.[24]

AI can also be used to analyze cataract surgery recordings post-operatively for the presence of intraoperative pupillary changes, such as miosis.[28] These intraoperative pupillary changes could be associated with impaired post-operative success and are labor-intensive to track manually.[28] Sokolova et al (2021) proposed an approach using a CNN for automatically tracking the size of the pupil from surgical recordings.[28] This AI-based approach was able to accurately detect moderate and strong intensity pupillary reactions, and similar methods will likely be used in the future to elucidate more associations between intraoperative variables and their effects on visual outcomes in cataract surgery.[28]

Furthermore, AI can be applied in post-operative care through the use of automated phone calls to evaluate patient recovery.[29] Hatamnejad et al (2024) recently studied the efficacy of an AI assistant called Dora which is routinely used in the United Kingdom and being studied for application in Canada.[29] This study is currently underway and aims to evaluate the safety, cost-effectiveness, environmental impact, and usability of the Dora AI assistant.[29] Dora serves as a remote alternative to in-person post-operative visits, offering an unprecedented degree of convenience, especially for patients with transportation barriers.[29] The Dora AI assistant gathers information from the patient via follow-up questions, accepts questions from the patient, and discusses subsequent steps in recovery.[29] Once the automated call is complete, the audio and transcript are available for review by the clinician.[29] The current study is assessing the degree of agreement between the Dora AI assistant and the clinician's assessment of the follow-up phone call transcript and physical examination.[29] The implementation of automated assistants in post-op care would facilitate communication between patients and their healthcare team and make it easier to address patient concerns and questions.

Challenges to AI Application in Cataract Surgery

Despite the promise of AI utilization in cataract surgery, the shift toward a more automated operating theater poses distinct challenges. One main challenge facing the development of AI algorithms is the lack of publicly available datasets, as only two public cataract surgery data sets are available to researchers today.[4] Furthermore, both publicly available data sets only include phacoemulsification data, thus limiting the development of additional algorithms for other cataract procedures, such as manual small-incision cataract surgery (MSICS), which is primarily used in low- and middle-income countries.[4] It is vital for the progression of AI in cataract surgery that these limitations are overcome by increased availability of public cataract surgery data sets as well as greater representation of MSICS imaging in these data sets. Once more imaging data for cataract surgery is available to the research community, it will be possible to further refine AI algorithms for application in both phacoemulsification and MSICS.

Another primary limitation to the application of AI in cataract surgery is the lack of standardized DL metrics.[4,7] Muller et al (2024) identified the challenge in comparing cataract surgery algorithms due to an absence in parallels between reported analysis metrics.[4] To address this obstacle in future studies, the researchers suggest a standardization of metrics including receiver operator characteristic curve, precision, recall, accuracy, sensitivity, and specificity for classification tasks such as phase recognition and instrument detection, whereas metrics such as mean average precision, intersection over union, and Dice Similarity Coefficient should be reported for tracking or segmentation algorithms.[4] By incorporating standardized metrics into subsequent research, it will be possible to compare algorithms and facilitate the editing of existing DL frameworks for greater accuracy.

Lack of standardized DL metrics also presents a concern for generalizability of AI mechanisms, as evidenced by the difficulty researchers encountered in applying an established algorithm to a novel data set.[7] Sokolova et al (2020) described surprisingly low generalizability for DL models that were trained on one dataset but tested on a new data set of lower visual quality.[31] It will be necessary to create more generalizable AI mechanisms in future studies in order to expand clinical applications of AI in ophthalmology.

Future Directions

With AI being consistently implemented in other surgical specialties, increased applications in cataract surgery are on the horizon. Cataracts are the leading form of treatable blindness, and the burden of cataracts is only expected to increase.[23] Low-income countries often struggle with reduced accessibility to slit-lamp examinations and ophthalmologists for the diagnosis of cataracts, contributing to higher rates of cataract-caused visual impairment in these nations.[23] Therefore, the use of AI to screen for cataracts on a large scale with slit-lamp and fundus photographs will become increasingly important, particularly in low-income countries with reduced access to tertiary care.[23] Similarly, rural populations with a lack of local ophthalmologists in countries of any income will benefit from the implementation of AI-based screening for cataract diagnosis.[23]

AI has been used to detect phases of cataract surgery.[15] Eventually, AI will likely allow for the assessment of surgical techniques in individual phases, providing live feedback for intraoperative decision-making.[23] The use of AI in surgical training has already shown potential in objectively measuring surgical performance and providing feedback tailored to an individual's strengths and weaknesses.[32] AI could be used to help junior physicians improve specific surgical techniques in simulation-based training before reaching the actual operating room.[32]

The implementation of AI could decrease complications associated with cataract surgery such as posterior capsule opacification or intraocular lens dislocation.[22,24] AI is currently being used to analyze surgical recordings frame by frame to detect changes which may be associated with decreased post-cataract surgery success.[28] For example, Sokolova et al (2021) described the AI analysis of 650,000 frames generated in just 30 cataract surgery recordings, a task which would be incredibly laborious if performed manually.[28] While the researchers in the previous study focused on pupillary reactions, they already plan to correlate blunt iris trauma, detected by AI analysis of surgical recordings, to pseudophakic cystoid macular edema.[28]

Therefore, by circumventing the use of manual labor to analyze enormous samples of surgical data, AI can establish improved correlations between surgical abnormalities and subsequent surgical outcomes in the future.

Conclusion

Our review highlights the applications of AI across pre-operative, intraoperative, and post-operative stages. Prior to cataract surgery, AI is being utilized to supplement traditional vergence formulas, calculate IOL power, and diagnose nuclear cataracts using slit-lamp images. During cataract surgery, AI facilitates a smart operating theater by analyzing real-time multimodal imaging data, estimating workflow and surgical phase progression, enhancing safety and efficiency, and contributing to surgical training. After cataract surgery, AI is increasing the ease of post-op appointment scheduling and communication and detecting potential post-surgical complications such as posterior capsule opacification and intraocular lens dislocation. Despite the robust integration of AI into other surgical fields, the utilization of AI in cataract surgery specifically is still in its infancy.

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Author Contributions

All listed authors made a significant contribution to this work in multiple areas including conception, study design, execution, data acquisition, analysis, interpretation, drafting, and/or critical review. All authors gave final approval of the version to be published, agreed on the journal of submission, and agreed to be accountable for all aspects of the work.

Disclosure

The authors report no conflicts of interest in this work.

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