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REVIEW

Artificial Intelligence in Ophthalmic Surgery: Current Applications and Expectations

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Abstract: Artificial Intelligence (AI) has found rapidly growing applications in ophthalmology, achieving robust recognition and classification in most kind of ocular diseases. Ophthalmic surgery is one of the most delicate microsurgery, requiring high fineness and stability of surgeons. The massive demand of the AI assist ophthalmic surgery will constitute an important factor in boosting accelerate precision medicine. In clinical practice, it is instrumental to update and review the considerable evidence of the current AI technologies utilized in the investigation of ophthalmic surgery involved in both the progression and innovation of precision medicine. Bibliographic databases including PubMed and Google Scholar were searched using keywords such as "ophthalmic surgery", "surgical selection", "candidate screening", and "robot-assisted surgery" to find articles about AI technology published from 2018 to 2023. In addition to the Editorials and letters to the editor, all types of approaches are considered. In this paper, we will provide an up-to-date review of artificial intelligence in eye surgery, with a specific focus on its application to candidate screening, surgery selection, postoperative prediction, and real-time intraoperative guidance.

Keywords: ophthalmic surgery, AI, machine learning, surgery selection, candidate screening, robot-assisted surgery

Introduction

The widespread utilization of artificial intelligence (AI) across diverse domains, including healthcare, finance, education, and industry, has been facilitated by the proliferation of computer proficiency. It is worth noting that AI encompasses significant branches, namely machine learning (ML), deep learning (DL), and natural language processing (NPL), each characterized by distinct architectural frameworks and algorithms. The term "artificial intelligence" was originally introduced by John McCarthy in 1956 to describe Simulated Intelligence, thus marking the formal inception of this emerging field. Since then, significant progress has been made in this domain.[1] In the past decade, the utilization of AI in medicine has witnessed a notable rise, aiming to enhance patient care through improved efficiency, accuracy, and outcomes.[2] Among various medical disciplines, ophthalmology stands out as one of the most dynamic fields for the clinical application of AI.

The application of AI in the field of ophthalmology has shown considerable potential, owing to advancements in big data and image-based analysis.[3] AI has proven to be highly effective in early screening[4,5] and identification of various ocular conditions. Particularly noteworthy is its success in detecting diabetic retinopathy (DR),[6] age-related macular degeneration (ARMD),[7] retinopathy of prematurity (ROP),[8] and other ocular disorders. Concurrently, there has been a growing body of scholarly literature dedicated to investigating the implementation of AI in the field of ophthalmic surgery, encompassing various aspects such as the assessment of surgical candidates and the determination of intraocular lens power.[9] Moreover, the exploration of robot-assisted surgery and drug delivery for fundus diseases serves as a testament to the increasing interest in leveraging AI as a pivotal tool in ophthalmic surgery.[10] Undoubtedly, AI is rapidly emerging as a fundamental instrument in the realm of ophthalmic surgery.

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Ophthalmic surgery is widely recognized as a complex and delicate form of microsurgery, requiring meticulous precision within the confined intraocular environment. Consequently, there is a paramount emphasis on the imperative need for precise control. It is widely acknowledged that AI demonstrates exceptional proficiency in the acquisition and simulation of the extensive digital data generated during surgical procedures.[11] This technological advancement serves to overcome the inherent limitations faced by physicians during such procedures, ultimately enhancing both efficiency and accuracy.[12] Furthermore, the integration of corneal tomographic imaging with AI plays a crucial role in assessing the appropriateness of patients for surgical interventions, thereby facilitating informed surgical decision-making. Moreover, the field of ophthalmology is currently experiencing significant progress in the domain of robot-assisted technology, with a particular focus on advancements in retinal surgery. Robotic platforms have exhibited promising outcomes, as evidenced by encouraging human studies.[13] Lastly, AI has the potential to predict postoperative vision and adjust the surgical plan, thereby enabling personalized treatment and enhancing surgical precision.

However, there are few numbers of studies have reviewed the application of artificial intelligence in ophthalmic surgery. Mishra et al[14] made a literature review of the application of AI in the field of ophthalmic surgery, which focus mainly on cataract surgery and Vitreoretinal surgery. However, AI had also been widely used in a lot of other ophthalmic surgeries, such as refractive surgery, keratoplasty, oculoplastic surgery and so on. Therefore, we try to present review that offers comprehensive insight into current developments in the field of artificial intelligence and ophthalmic surgery.

Method

In this study, we compiled, categorized, and presented a comprehensive and up-to-date survey of artificial intelligence in ophthalmic surgery. A literature search was conducted using the PubMed database and Google Scholar. Only English-language documents published between 2018 to 2023 were considered. Our search keywords lied at the intersection of two key clusters: artificial intelligence and ophthalmic surgery. We also included Medical Subject Headings (MeSH) for relevant keywords to ensure our search was as inclusive as possible. The search terms encompassed the following: "ophthalmic surgery", "surgical selection", "candidate screening", "robot-assisted surgery", "artificial intelligence", "machine learning", "deep learning", "refractive surgery", "vitreoretinal surgery", and "keratoplasty". When linking the keywords, AND and OR were used according to the needs of the selected terms and keywords. In addition to the Editorials and letters to the editor, all types of publication were considered. Finally, we thoroughly explored the bibliography of the review articles, in order to find relevant articles main focus of this study.

State-of-The-Art of the Ophthalmic Operative Application of AI

As with numerous surgical procedures, the success of ophthalmic surgery heavily relies on the surgeon's discernment and expertise. Situational awareness, decision-making, technical proficiency, and various cognitive and procedural factors all play a pivotal role in achieving favorable outcomes. Fortunately, AI not only addresses the shortage of surgeons but also mitigates financial constraints, complications, and high-quality surgical interventions. Particularly noteworthy is the role of AI in eliminating geographic barriers and contagion hazards, which have become even more pertinent during the COVID-19 pandemic. In this section, we shall provide an overview of the remarkable advancements in AI technology that have been applied to various ophthalmic surgical procedures.

Refractive Surgery

Refractive surgery serves as a safe and effective means of correcting refractive errors, providing patients with an alternative solution to glasses or contact lenses. Notably, refractive surgery has already demonstrated remarkable visual outcomes.[15] However, given the diverse array of refractive surgery techniques and the potential for complications, the subsequent challenge for clinicians lies in optimizing surgical outcomes and minimizing adverse effects by selecting the most suitable method for each patient. In contemporary times, the incorporation of AI in the assessment of individuals suitable for refractive surgery and the anticipation of complications after the operation has facilitated the exploitation of data obtained from corneal topography and biometry to enhance refractive surgery approaches and attain the most favorable outcomes.

Screening Candidates of Refractive Surgery

Candidates who possess normal corneas in both eyes may be eligible for refractive surgery, provided that the remaining corneal thickness meets the established safety criteria. Conversely, patients who exhibit suspected corneal abnormalities in one or both eyes are at an increased risk when considering laser vision correction. For instance, keratoconus represents a contraindication to refractive surgery. However, presently, the identification of patients with early-stage keratoconus (KC) poses significant challenges. In light of this context, Yoo et al[16] introduced a model aimed at automating the screening process for potential candidates of corneal refractive surgery. Their model employed machine learning algorithms to analyze a substantial cohort's clinical and optical data, enabling the identification of discernible patterns. The results suggest that the machine learning model exhibited similar performance to a particular subset of high-risk professionals who possess distinct characteristics. This model integrates the knowledge of seasoned professionals with abundant patient data obtained from various instruments, leading to a thorough and reliable screening methodology. Furthermore, Xie et al[17] devised a classification system centered around the Pentacam InceptionResNetV2Screening system (PIRSS), an artificial intelligence model employed for the identification of suitable candidates for refractive surgery. In order to develop this system, the authors collected tomographic corneal imaging data from 1385 patients undergoing assessment for refractive surgery at a single center in China. Subsequently, they trained the PIRSS system using 6465 images extracted from these scans and evaluated its performance on an external dataset comprising 100 scans. The validation dataset demonstrated an impressive overall detection accuracy of 94.7% (95% CI, 93.3%-95.8%) for the model. This study represents a significant milestone in the advancement of semi-automated screening methods for refractive surgery candidates. Moreover, Yoo et al[18] conducted a study where they created a ML model that could select expert-level laser surgery options in a way that was easy to understand. Notably, this study represents a pioneering endeavor in utilizing AI to expertly select the most suitable corneal refractive surgery option. The interpretability frameworks introduced in this research provide a more comprehensible decision-making system applicable to a wide range of medical concerns. The integration of explainable machine learning is anticipated to enhance the practicality of AI in ophthalmology clinics. Collectively, these studies underscore the pivotal role of AI in screening refractive surgery candidates based on diverse characteristics, ultimately enhancing the precision of surgical decision-making.

Predicting Postoperative Implantable Collamer Lens (ICL) Vault

The EVO Visian implantable intraocular lens (ICL hole; STAAR Surgical, Monrovia, California, USA) is widely recognized as an effective long-term method of correcting moderate to severe myopia.[19] In a clinical context, achieving the optimal size of ICL is of paramount importance to ensure a secure postoperative ICL vault, which refers to the space between the ICL and the lens.[20] Notably, a taller and off-centered ICL hole following ICL implantation represents a risk factor for anterior subcapsular cataract, particularly in patients with angle-closure glaucoma, abnormally large pupils, and a lower vault.[21] However, there is promising potential in harnessing AI algorithms to investigate potential remedies for these challenges.

Kamiya et al[22] utilized ML techniques to analyze the ICL vaults in a cohort of 1745 patients who received ICL implantation. This analysis is based on the application of preoperative anterior segment optical coherence tomography (AS-OCT) parameters. Subsequently, they conducted a quantitative evaluation of the actual vault one-month post-surgery and compared it with the predicted vault. In comparison to conventional manufacturers, Random Forest Regression (RFR) yielded fewer Mean Absolute Errors (MAEs) and a higher percentage of eyes falling within the 50–200 μm range of the target ICL vault. Additionally, Kang et al[23] have developed a web-based ML application that utilizes clinical measurements to predict postoperative ICL vault and select the optimal ICL size. This application combines eXtreme Gradient Boosting (XGBoost) and light gradient boosting machine (lightGBM) to achieve superior results. The predictive model that effectively alleviates the likelihood of complications following ICL implantation. Through its consideration of patients' long-term visual needs and its efforts to minimize complications, this approach offers a promising solution. The model demonstrates significant potential for the progression of refractive surgery.

Based on these achievements, Sun et al[24] have developed a fully automatic method using DL to monitor the position of the ICL and detect subtle changes in the anterior chamber for patients undergoing ICL surgery. This study involved 798 AS-OCT images of 203 patients undergoing ICL implantation at an eye center. The system was then used to quantify important clinical parameters in the AS-OCT images, including central corneal thickness, anterior chamber depth, and lens vault. Interestingly, the DL system was able to accurately isolate the corneoscleral, ICL, and lens. In summary, the findings of this study suggest that the employment of the DL method offers a dependable approach for the identification and measurement of AS-OCT scans in the context of postoperative ICL implantation. This has the potential to significantly streamline and enhance the administration of clinical outcomes associated with ICL implantations.

Predicting Postoperative Complications

The screening process for laser vision correction (LVC) is of significant importance due to the progressive development of eye ectasia and subsequent decline in visual acuity observed in patients after undergoing the surgical procedure. Consequently, the prediction of ectasia or myopic regression following refractive surgery is a crucial consideration.[25] In this particular scenario, AI techniques were demonstrated to possess the capability of predicting the risk of dilatation by effectively differentiating between susceptible cases, early or subclinical disease, clinical keratoconus, and stable eyes. Lopes et al[26] generated the AI model using corneal topography parameters and evaluated parameter data from patients from five different clinics in South America, the United States, and Europe. The model was then used to separate the preoperative data into three groups: patients with stable laser-assisted intraepithelial keratotomy (LASIK), patients with eversion tendency, and patients with clinical KC. Finally, the results of show that PRFI (Pentacam Random Forest Index) has excellent accuracy in detecting KC and post-LASIK ectasia in independent tests. Kim et al[27] have devised a robust approach to identify patients who are highly susceptible to myopia regression before undergoing refractive surgery. In their investigation involving individuals who underwent corneal refractive surgery, the researchers introduced a machine learning model that integrated various variables and fundus photography. The model employed ResNet50 for image analysis and XGBoost for integration. And after a 4-year follow-up, they identified the five most critical input characteristics: fundus photography, preoperative anterior chamber depth, planned ablation thickness, age, and preoperative central corneal thickness. For instance, a notable association exists between anterior chamber depth values and the recurrence of postoperative myopia. When physicians detect abnormal parameter values, reassessing the surgical approach can improve the patient's prognosis. Postoperative myopia regression represents a persistent complication of refractive surgery. However, the available literature on myopia regression is scarce. Substantial further research is required to enhance the prediction of long-term prognosis using AI, which holds the potential to enhance the medical experience for patients.

Keratoplasty

Keratoplasty also referred to as corneal transplantation, keratoplasty has witnessed substantial progress over the past two decades.[28] For over six decades, penetrating keratoplasty, a comprehensive corneal replacement procedure, has served as the primary treatment for corneal blindness, yielding favorable outcomes in the majority of cases. However, in the past decade, specialized surgeons have increasingly embraced novel forms of lamellar transplantation surgery. These innovative procedures selectively target and replace solely the affected layers of the cornea, leading to a transformative shift in the field. Deep anterior lamellar keratoplasty has emerged as a substitute for penetrating keratoplasty in cases involving disorders impacting the corneal stromal layers, effectively mitigating the risk of endothelial rejection. Additionally, endothelial keratoplasty, a distinct transplantation technique, focuses on replacing the corneal endothelium in patients afflicted with endothelial disease. This procedure presents numerous benefits, including expedited recovery and predictable visual outcomes. Despite notable progress in transplantation techniques, such as Descemet's membrane endothelial keratoplasty, there remain several unresolved concerns in the realm of corneal transplantation that demand attention. Persisting issues include technical challenges during surgery, suboptimal graft survival rates, cellular loss, and a scarcity of available donor corneas. However, the emergence of AI, encompassing predictive algorithms and robotic techniques, has ushered in a new era for the field of corneal transplantation.

Prediction the Likelihood of Future Keratoplasty

Less invasive treatment modalities, such as corneal collagen cross-linking (CXL), have demonstrated efficacy in stabilizing the cornea without necessitating transplantation, rendering them particularly effective in milder cases.

However, the optimal timing for the implementation of CXL versus transplant surgery remains uncertain. In a study conducted by Yousefi et al,[29] unsupervised ML analysis was employed on OCT images and corneal parameters to determine the likelihood of future corneal transplant intervention. The study's findings reveal that eyes exhibiting early-phase anterior Ectasia Screening Index (ESI) values are more likely to necessitate endothelial surgery (68.7%). By utilizing corneal information, this model can assist surgeons in making more informed decisions regarding invasive interventions like CXL. It is important to note that the ML model does not require annotation data, such as clinical diagnosis, for training. This greatly reduces the demand for human and material resources, making the prediction of future keratoplasty more efficient and cost-effective.

Ang et al[30] analyzed high-dimensional factors associated with 10-year graft survival of Descemet stripping automated endothelial keratoplasty (DSAEK) and penetrating keratoplasty (PK). The study combined Random Survival Forest (RSF)and Cox regression models to analyze high-dimensional factors in many Asian eyes. The results found overall 10-year survival for DSAEK was superior to PK. And the top 30 variables and interactions for predicting graft failure using the RSF machine learning algorithm. Shows that diagnosis, surgical procedure, and gender are essential influencing factors. The study predicted the survival rate of grafts and analyzed the factors of graft failure. The combination of prediction and analysis has tremendous significance for surgeons to make better decisions about corneal transplantation. However, a limitation of this study is that the dataset is only Asian eyes, and external validation with other populations is required.

Robotic Surgery in Keratoplasty

Ophthalmic microsurgery presents a notable technical hurdle owing to the miniature scale of surgical instruments necessitated for ocular procedures. Surgeons must grapple with challenges pertaining to visual acuity, sensory perception, and manual dexterity. Although intraoperative micron-resolution OCT imaging can assist in monitoring and offer improved real-time visualization, surgeons still encounter physical limitations when maneuvering instruments within the eye. Nevertheless, robotic techniques hold promise in mitigating the complexities associated with corneal needle insertion.[31] In a study conducted by Keller et al[32] the feasibility of using an industrial robot for OCT-guided corneal needle insertion was demonstrated in an in vitro anterior lamellar keratoplasty (DALK) surgery model. By employing both demonstration learning and reinforcement learning, the robotic surgery allowed for precise proximal needle depth, reduced needle movement in the cornea, and improved surgical safety and prognosis in keratoplasty. Moreover, by learning from demonstrations, robots can acquire the ability to perform tasks without the need for explicit programming of each action or movement by an expert. This approach is particularly useful for complex tasks that require the expertise of a human, but where it may be difficult to explain the process in detail for quick reproduction. Additionally, Savastano et al[33] demonstrate the feasibility and potential benefits of using the Symani Surgical System, a novel microsurgical telerobotic technology for suturing in corneal transplantation. The study found that the distance of suture placement and the regularity of the corneal surface were comparable between manual and robotic treatments. However, the automated system was found to operate at a slower pace than human surgeons. Therefore, future research should explore ways to improve the efficiency of robot-assisted surgery.

Cataract Surgery

According to the World Health Organization (WHO), the prevalence of cataract blindness is projected to reach 40 million by 2025, owing to improvements in life expectancy.[34] Presently, the primary approach for treating cataracts involves surgical extraction and the subsequent implantation of an intraocular lens. AI plays a pivotal role in optimizing postoperative visual outcomes, guiding the surgeon's actions, and assessing the procedure's effectiveness. The amount of data generated during the operation contributes to the indispensability of AI as a tool for enhancing patient outcomes.

Intraocular Lens Power Calculation

Accurately determining the optimal Intraocular Lens (IOL) power through preoperative ocular biometry calculations stands as a pivotal determinant in optimizing both patient and visual outcomes. The evolution of IOL power calculation formulas has progressed through various generations, starting from the initial theoretical recipes (SRK and Hoffer) to the subsequent second and third generations of regression formulas (SRKII, SRKT, Holladay, Haigis, and Hoffer Q). The fourth generation introduced formulas such as the Olsen formula and Barrett Universal II (BUII), while the fifth generation witnessed the development of formulas by Barrett, Olsen, and others.[35] The evolution of the IOL diopter calculation formula signifies a continuous improvement in the accuracy of IOL calculations. Nevertheless, the precision of these calculations still falls short in certain exceptional cases, such as cataract patients with extremely short or long axial length, as well as those who have undergone refractive surgery. Fortunately, AI-based IOL formulas have demonstrated enhanced accuracy, exemplified by novel IOL calculation formulas or methodologies like the Clarke neural network, Ladas, Hill-RBF, Kane, Karmona, and others.[36,37] As ophthalmologists, we must learn to determine the best IOL selection method and update the knowledge base in real-time. A summary of AI-based IOL formulas is given in Table 1.[38–43]

The Clarke formula[38] and the Fullmonte formula[41] are prediction IOL formulas based on neural networks. The calculated MAE is relatively large, and the error of the predicted diopter within ±0.50 accounts for a small proportion, so they are rarely used now. The Ladas super formula[39] based on deep learning uses five formulas. Including Hoffer Q, Holladay 1, Koch adjusted Holladay 1, Haigis, and SRK/T to build a multi-formula three-dimensional surface, then analyzes the three-dimensional surface of each formula, and finally combines them to form a super formula. The Ladas Super Formula predicts 69.8% of the refractive errors to be within ±0.50 D. The Kane formula[40] combined the theoretical optics formula with the regression formula to calculate the IOL diopter and predicted that the proportion of refractive error within ±0.50 D was 91%. The Kane formula has good predictive accuracy for cataract patients with standard axial length and higher calculation accuracy for short and long-cataract patients. Karmona formula[42] and Hill-RBF 3.0 formula[43] predict diopter errors within ±0.50 D are 98.38% and 93%, respectively. Hill-RBF 3.0 has optimized the data and expanded the domain boundary value, making the formula applicable to more situations. Furthermore, Tsessler et al[44] found that Hill-RBF 3.0 is more accurate than Hill-RBF 2.0 and older-generation formulas and comparable to the fifth-generation formula in predictive accuracy.

In the future, for more special cases and higher accuracy and repeatability, these AI learning-based formulas need further research.

Robot-Assisted Surgery in Cataract

In cataract surgery, the advent of femtosecond lasers, automatic systems, and other new technological advances has made various possible surgeries—for instance, keratotomy to capsulorhexis and phalacrosis to fully automated cataract surgery.

Bourcier et al[45] successfully simulated every step of cataract surgery using the Da Vinci Xi Surgical System combined with a robot-assisted phacoemulsification system on 25 lens nuclei, including corneal incisions, capsulorhexis, grooving, cracking, quadrant removal, and irrigation/aspiration of ophthalmic viscosurgical devices (OVD). The robotic

Table 1 A Summary of AI-Based IOL Formulas

Formula	Basis of AI	Input Parameters	Post Operative Diopter Ratio (±0.50%)	Year	First Author
Clarke[38]	Neural network	AL, K, ACD, LT	Less proportion	1997	Clark GP
Ladas super formula[39]	DL based in five formular	AL, K, ACD,	69.80%	2015	Ladas
Kane formular[40]	Theoretical optics/regression	AL, K, ACD, LT, CCT, Gender	91%	2019	Kane
Fullmonte[41]	Neural network	AL, K, ACD, LT, CCT	Less proportion	2020	Clarke GP
Hill-RBF formular 3.0[43]	Regression/ neural network	AL, K, ACD, LT, CCT, WTW, Gender	93%	2020	Hill
Karmona[42]	SVM/ MARS	Sim-K, AL, ACD, LT, WTW, IOL type	90.38%	2020	Gormona

Abbreviations: AL, Axial Length; K, Curvature; ACD, Anterior Chamber Depth; LT, Lens Thickness; CCT, Corneal Central Thickness; WTW, White to White Distance; IOL, Intraocular Lens.

surgical system provides the intraocular dexterity and visualization of the surgical field needed for phacoemulsification. However, manual injection of OVD, balanced salt solution, and intraocular lens still requires the intervention of a second surgeon.

Wilson et al[46] study propose a robotic surgical system that performs a complete multi-step procedure from start to finish in cataract surgery. The Interventional Artificial Eye Surgery System (IRISS) is designed, manufactured, and evaluated for various intraocular processes. IRISS has a tooltip position accuracy of 0.027 ± 0.002 mm, which is considered sufficient for cataract extraction and finer retinal vein cannulation with visual feedback. Several surgical procedures required for cataract and retinal surgery have been tested in clinical settings. Meanwhile, the IRISS was the first robotic system to successfully perform a complete curvilinear capsulorhexis and an entire cataract surgery from start to finish.[46] However, the system must further determine clinical statistics such as operation completion time and success rate in future studies.

Real-Time Intraoperative Guidance

During cataract surgery, variables such as instrument positioning, distance from tissues such as the posterior lens capsule, and visualization of intraocular structures can affect surgical outcomes and safety.[47] Therefore, the researchers have devised an intraoperative surgical guidance platform, drawing upon prior research, which furnishes the operator with instantaneous information or feedback. Morita et al[47] developed a real-time video phase segmentation model. They identified essential steps of cataract surgery using convolutional neural networks. The results showed that the correct response rate of CCC was 90.7%, nuclear enucleation was 94.5%, and other stages were 97.9%, with an average correct response rate of 96.5%. In other words, these surgical stages' start and end times, with an average error of about 5 seconds. Meanwhile, these results lay the foundation for intraoperative surgical guidance.

Garcia Nespolo et al[48] developed surgical guidance tools depending on the stage of cataract surgery. The findings combine a personalized surgical guidance tool built using computer vision technology with a deep learning neural network and an ophthalmic surgical microscope to provide surgeons with real-time audiovisual feedback during cataract surgery. This intraoperative surgical guidance platform improves capsulorhexis' symmetry and enhances anatomy visualization. Of note, intraoperative guidance dramatically improves the safety and efficiency of operations and facilitates clinical teaching.

In recent years, there has been a growing body of research focused on improving the accuracy of cataract surgery navigation. One such study, conducted by Ni et al[49] proposed a surgical image segmentation method called SRBNet. This approach utilizes spatial extrusion reasoning and low-rank bilinear feature fusion to overcome the challenge of distinguishing between tissues and instruments that may have local similarities during intraoperative guidance. By enhancing the distinction between features, this method has the potential to significantly improve the accuracy of cataract surgery navigation. The implementation of this method has a substantial impact on enhancing the precision of the intraoperative surgical guidance system. In addition, Wang et al[50] trained DeepSurgery, a deep learning algorithm that uses cataract surgery (CS) videos to assess and monitor cataract extraction for IOL implantation via phacoemulsification. DeepSurgery's evaluation performance was compared to a real-time test involving a panel of experts and assistants using CS. The results of this study indicate that DeepSurgery step recognition performance was robust (ACC of 90.30%). Meanwhile, DeepSurgery also identifies the chronological order of surgical steps and alerts surgeons to any incorrect steps. In addition, it is worth noting that wrong-site surgeries can occur due to the absence of an appropriate surgical time-out. To improve the conditions in surgical time-outs, Yoo et al[51] introduce a deep learning-based smart speaker to confirm the surgical information prior to cataract surgeries. The utilization of this device in the smart operation room system holds the potential to make a substantial impact on minimizing human errors and enhancing patient safety. Additionally, this framework can be expanded to include validation of intraocular lens placement in cataract surgery and determination of ablation depth in corneal refractive surgery. Taken together, the development of these models offers automated guidance and supervision for cataract surgery, while also introducing new objectives to enhance the accuracy of the models.

Vitreoretinal Surgery

Vitreoretinal surgery refers to surgical procedures that are performed at the posterior part of the eye, specifically involving the retina, macula, and vitreous. Like macular disease, a macular hole (MH) is a full-thickness defect of the neurosensory tissue of the foveal retina. MH is one of the causes of decreased central vision.[52] Vitrectomy and internal limiting membrane peeling (VILMP) has been commonly used to treat MH. A standard VILMP surgery includes vitrectomy, internal limiting membrane (ILM) peeling with or without staining, and air tamponade. However, in some patients the MH still remains open after initial surgery. Therefore, it is clinically important to determine the association between MH after standard VILMP and the risk of surgical failure. Moreover, higher medical costs and vision loss can be avoided with the second surgery compared to the first closed surgery. Based on OCT images of four ocular centers, Hu et al[53] developed a DL model to predict the status of idiopathic MH after VILMP. In external validation, the overall accuracy of predicting MH status after VILMP was 84.7% with an AUC of 89.32%. This result demonstrates the feasibility of automatically predicting MH status after routine retinal surgery. More recently, in another study, Xiao et al[54] trained a multimodal deep fusion network model (MDFN) that reliably predicts MH status (closed or open) one month after VILMP. Preoperative macular OCT images and clinical data (including age, gender, duration of symptoms, minimal diameter of MH, base diameter of MH, height of hole, macular hole index, diameter hole index, hole form factor, and tractional hole index) of MH/IMH eyes were used as the input data. Finally, the AUC of the postoperative idiopathic MH status prediction model were 0.947. The most surprising aspect of the multimodal presented here is the high accurate prediction of postoperative MH/IMH status. In addition, a fully automated 3D OCT image analysis of DL model has been developed for accurate measurement of MH parameters.[55] In the future, it may be useful to automate the MH measurements of the above models.

During the surgical procedure, the surgeon makes incisions in a safe area of the eye known as the pars plana. These incisions serve as access points for the insertion of instruments that are used to reach the back of the eye. Trocars, which are placed in these locations, act as both strain relief and pivoting points for the inserted instruments. Misalignment of these points can create harmful lateral forces and potentially cause irreversible damage to the eye. Birch et al[56] developed a system that can be integrated with a vitreoretinal robot that can accurately estimate and match two points of interest and provide feedback to the control system.

Subretinal injections are a complex and hazardous surgical procedure that has been proposed as a potential application for robot-assisted surgery. In fact, Edwards et al[57] were the first to use a robotic surgical system (Preceyes) for retinal surgery on a human eye. This system utilized remote z-axis control to guide a thin cannula through the retina and into the subretinal space, enabling precise drug delivery. The study involved the use of robotic subretinal injections of recombinant tissue plasminogen activator (rt-PA) in three patients who had subretinal hemorrhage as a result of age-related macular degeneration. Two of the procedures were successfully completed, while one patient experienced aggravated cataract during the operation, which resulted in an unclear surgical field of vision. This model holds great promise for future retinal stem cell or gene therapy. In addition, Gijbels et al conducted a comparison between robotic and artificial retinal surgery techniques for the removal of the epiretinal membrane (ERM) or ILM.[58] The findings indicated that the control group required an average of 12 seconds for surgical safety preparation and contact with the membrane, while the robotic group took 2 minutes and 26 seconds to complete the same task. A result was considered statistically significant at the $p<0.05$ level. Moreover, the robot successfully eliminated the regenerative membrane, which had a thickness of 0.01 mm, from the patient's retina surface.

Retinal vein occlusion (RVO) is a disease that causes visual impairment in the central retinal vein or its branch veins. At present, treatments for RVO focus on managing complications associated with venous occlusion and addressing the underlying causes of the occlusion. In recent years, there has been a growing interest in robot-assisted retinal endovascular surgery (REVS), specifically retinal vein cannulation (RVC), which aims to reduce complications and achieve greater surgical precision. Animal and human eye models have been used to explore this technology. Gijbels et al[58] have developed a high-precision robotic assistance device that can address the technical difficulties and risks associated with REVS. The success rate was as high as 97.5% and 100% before human experiments, and the final technology was realized in vitro and in vivo pig experiments, respectively. In the future, this device could also enhance the quality of current virtual reality experiences and be utilized to explore other innovative applications for robots. These promising results formed the foundation for the approval of the first in-human study on robot-assisted REVS. At the time of this writing, four CRVO patients have received a robot-assisted REVS treatment with the developed technology. In all four cases, the surgeon was able to safely perform REVS with the aid of the developed technology, making this first in-human study a technical success. In a study by Patel et al[59] the chicken chorioallantoic vein was cannulated using a force-sensing microneedle tool, with a comparison between manual and robot-assisted methods. The results indicated that the average puncture force was higher in the manual injection group compared to the robot-assisted approach. In other words, the use of robotic retinal vein cannulation resulted in improved stability during infusion when compared to manual cannulation.

This indicates a significant advantage of mechanical assistance in maintaining the spatial position of the needle in small vessels. It is important to note that the development of robotic-assisted systems can lead to improved patient safety, enhanced surgeon performance, and expanded surgical capabilities, ultimately aiming to enhance patient care.

For a future outlook on robot-assisted retinal surgery, we can enhance the capabilities of robots by integrating camera image information with other data sources, such as intraoperative OCT images and mechanical force sensing devices. This will enable robots to better assist or even perform selected tasks during surgery.

Oculoplastic and Reconstructive Surgery

The eyes are a highly expressive feature that can greatly impact a person's overall appearance. Therefore, ophthalmic plastic surgery is widespread in medical aesthetic procedures, including double eyelid surgery,[60] ptosis correction,[61] and pouch surgery.[62]

The main objective of ophthalmic plastic surgery is to achieve the desired aesthetic outcomes. However, evaluating the expected aesthetic effect can be challenging due to subjective factors.[63] Consequently, artificial intelligence technology assumes a pivotal role in assisting oculoplastic surgeons in devising rational surgical strategies. Qu et al[64] proposed a multi-channel convolutional neural network (CNN) algorithm to create a three-dimensional image of the patient's eye structure and help with a pouch surgical plan. The study found that the efficiency of the multi-channel CNN reconstruction algorithm (3.41s) was comparable to that of the conventional CNN algorithm (4.02 s). Additionally, the reconstruction similarity was significantly higher (98.78%) than that achieved by the traditional algorithm. The post-operative rates of lacrimal sac, ptosis, skin brightness, and aesthetic evaluation exhibited more significant improvement in the observation group compared to the control group. This suggests that modeling and simulating workflows can be effective in enhancing the efficacy of action plans. However, the study is not without limitations. It did not include a targeted comparative analysis of specific surgical methods, and therefore lacks a certain degree of comprehensiveness.

Ptosis, a commonly encountered eyelid disorder, can lead to significant visual impairment in severe instances as the drooping of the eyelids extends beyond the pupil. Diagnosis typically involves evaluating the morphological characteristics of the eyelid and identifying distinctive clinical symptoms. Surgical intervention represents the primary approach for managing eyelid ptosis, with precise measurement of eyelid morphological parameters being essential for formulating an individualized surgical plan. However, manual measurements of eyelid morphology parameters can prove challenging to replicate due to subjective errors arising from head movements and variations in facial expressions. To tackle this concern, Song et al[65] devised a gradient-based decision tree (GBDT) aimed at selecting an optimal surgical approach for ptosis. The GBDT model was trained on images and scan-generated 3D models of ptosis patients' eyes, acquired through a structured light camera. The AI model is employed to assess extraocular photographs and 3D models, enabling the determination of surgical necessity and the identification of the most suitable surgical strategy. In a study by Lou et al,[66] the outcome of ptosis surgery was evaluated by comparing pre- and postoperative values of eyelid morphology parameters, such as margin reflex distance 1 and 2 (MRD1 and MRD2), which are automatically measured by UNet using images of the patient's eye appearance.

Orbital decompression surgery is an effective treatment for reducing exophthalmos and restoring appearance in patients with thyroid-associated ophthalmopathy (TAO). In a study conducted by Yoo et al[67] a generative adversarial network-based (GAN) deep learning technique was trained to synthesize a realistic postoperative appearance of orbital decompression surgery. This data-driven approach transforms preoperative facial input images into predicted postoperative photos that closely resemble the actual outcome after surgery. It has been suggested that GANs could potentially serve as a novel means of predicting the results of oculoplastic and reconstructive surgery. However, the current research model's postoperative image quality is lacking and requires improvement. In terms of preoperative evaluation, measuring eyelid parameters precisely is critical. Shao et al[68] present a system that automatically measures parameters of the TAO eyelid and compares the results with those of a control eye. The results showed that: TAO eyes had obvious eyelid contracture. And the eye detection model achieved 0.9960 accuracy on the celebrity facial attributes dataset and 0.985 accuracy on the 148-participant dataset, showing the high repeatability of the automatic system. Furthermore, their research has potential applications in the field of digital health for OAT patients. Primary eyelid changes in these patients are a dynamic process and these changes need to be recorded to assess the TAO condition. Thereby, real-time measurement of the TAO eyelid is required to determine the operation or choose botulinum toxin therapy as conservative treatment. Last but not least, the deep learning-based system presents comprehensive and quantitative results in just 3 seconds. Its high efficiency and stable performance guarantee longitudinal clinical evaluation. In addition, Wang et al[69] uses AI to segment orbital CT/MRI image structure, support endoscopic and 3D printing surgery, and lay the foundation for robotic surgery. In the future, it is important to further explore the potential application of artificial intelligence in TAO surgery.

Future Applications for AI in Ophthalmic Surgery

Despite the aforementioned promising outcomes, certain deficiencies persist within the realm of ophthalmic surgery, particularly in the context of personalized therapy's increasing significance. Personalized treatment has gained substantial importance in ophthalmic surgery, particularly for patients afflicted with myopia, cataracts, and presbyopia. This emerging direction is gaining momentum and holds immense potential for significantly enhancing patient outcomes, making it a fertile area for further exploration. First of all, the integrative development of AI and surgical robots is anticipated to yield a highly precise, minimally invasive, real-time, and intelligent operation control system. The system will seamlessly integrate the rigidity and flexibility. AI will play a pivotal role in transcending the conventional master-slave control paradigm towards a more collaborative approach that incorporates neural network control. With the development of 5G networks, remote surgery or education will moving ahead fast. It is also important to note that although robots may replace humans to perform complex surgeries in the future, the current technology cannot completely replace the clinical experience and surgical skills of doctors. With the continuous development of AI technology, its role in the field of surgery may become more significant in the future, especially in surgical planning, navigation, and support.

Moreover, recent advancements in ChatGPT have made the field of ophthalmic surgery full of opportunities and challenges. ChatGPT is best used for low-risk writing, such as summarizing clinically critical information in patient-friendly language, for pre- and post-operative patient conversations.[70] This not only saves the time of the ophthalmologist, but also contributes to the improvement of the patient's medical compliance, thus improving the outcome after surgery. If debugged and trained with a large amount of medical data, combined with the rapid development of AI technology, ChatGPT is likely to become a powerful medical assistant for humans in the near future.

Conclusion

This review article extensively explores the utilization of AI in ophthalmic surgery, thoroughly examining the existing literature studies. Evidently, the clinical implementation of AI in this domain is progressively gaining prominence and is poised to further expand in the future. Research conducted in this interconnected field holds immense potential to propel advancements in the ophthalmology medical discipline, effectively addressing the requirements of numerous patients afflicted with ocular diseases. Moreover, it has the capacity to generate substantial value for the medical economy and provide technical solutions aimed at augmenting the success rate of eye disease treatment while minimizing the recurrence rate during the rehabilitation process.

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