· Review Article ·

Advances in the application of virtual reality technology in ophthalmic surgical skills training

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Abstract
● Conventional surgical teaching techniques face several challenges, highlighting a necessity for ongoing innovation in ophthalmology education to align with the evolving demands of clinical practice. The recent rapid advancement of computer technology has enabled the integration of virtual reality (VR) into medical training, thereby revolutionizing ophthalmic surgical education through VR-based educational methods. VR technology offers a safe, risk-free environment for trainees to practice repeatedly, enhancing surgical skills and accelerating the learning curve without compromising patient safety. This research outlines the application of VR technology in ophthalmic surgical skills training, particularly in cataract and vitreoretinal surgery. Including assessing the effectiveness of intraocular surgery training systems, evaluating skills transfer to the operating room, comparing it with wet lab cataract surgery training, and enhancing non-dominant hand training for cataract surgery, among other aspects. Additionally, this paper will identify the limitations of VR technology in ocular surgical skills training, offer improvement strategies, and detail the advantages and prospects, with the objective of guiding subsequent researchers.
● **KEYWORDS:** virtual reality; ophthalmology; ophthalmic surgical skills training; surgical simulation; cataract surgery; vitreoretinal surgery
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INTRODUCTION
The traditional method of teaching surgery, known as Halsted's model of "see one, do one, teach one"[1], along with wet lab training, has been the cornerstone for cultivating surgical skills[2]. However, this model suffers from heterogeneous proficiency and non-standardized training, prolonging the learning curve and compelling ophthalmic education to continuously innovate to meet evolving clinical demands[3]. In recent years, the rapid advancement of computer technology has spurred the integration of virtual reality (VR) technology into the medical training system[4], revolutionizing surgical education in ophthalmology through innovative instructional methods based on VR[5]. VR creates a three-dimensional (3D) artificial environment using computer technology, human-computer interfaces, graphics, and sensor technologies. It aims to replicate the physical characteristics and sensory sensations of the real world by integrating visual, aural, and tactile encounters. Furthermore, a subset of VR known as augmented reality (AR) has emerged. AR uses cameras to capture the actual surroundings and overlays photos, text, 3D models, and other virtual elements onto the real-world view, seamlessly blending virtual information with reality[6].

Currently, VR technology is being integrated into various aspects of ophthalmology, including screening, diagnosis, vision training, and skill development. In ophthalmic screening and diagnosis, VR is utilized for visual field testing in glaucoma patients[7], diagnosing strabismus[8], and assessing contrast sensitivity[9]. For vision training, it aids in repairing visual field defects in glaucoma[10], amblyopia training[11], postoperative strabismic patient training[12], myopia

Table 1 Comparison of Eyesi surgical simulator and HelpMeSee surgical simulator

Parameters	Eyesi surgical simulator	HelpMeSee surgical simulator
Research and data support	It is extensively utilized in studies, with a plethora of documented data regarding training efficacy and skill transfer	Compared with Eyesi, it has less research data but tentatively confirmed effectiveness in resource-constrained regions
Simulator design	This simulator comprises a computer connected to a microscope that produces three-dimensional images, a mannequin head equipped with a virtual eyeball, and two-foot pedals that control the microscope and the ultrasonic emulsification device	This simulator features a reclining patient connected to a microscope-shaped display for three-dimensional visuals. The configuration comprises a table, a mannequin head equipped with tactile feedback, a solitary pedal for phacoemulsification regulation, and a tactile interface featuring two ocular probes
Training design	Designed for phacoemulsification and vitreoretinal surgery	Designed for MSICS
Training methods	Supports self-directed training	Training sessions are supervised by qualified instructors.
Application scenarios	High-end specialized training	Mass-oriented, non-profit training
Target audience	As a commercial product, it is expensive and predominantly used in high-income countries	Created by a non-profit group, it is more affordable and primarily aimed at regions with limited resources in low- and middle-income countries

MSICS: Manual small incision cataract surgery.

treatment[13], color vision deficiency correction[14], and vision therapy for convergence insufficiency and accommodative dysfunction[15]. In terms of ophthalmic examination skills, VR is applied in pupil examination[16], slit lamp examination[17], direct ophthalmoscopy[18], and indirect ophthalmoscopy[19]. Furthermore, in ophthalmic surgical skill training, VR is used for procedures such as glaucoma surgery[20], corneal laceration repair[21], and corneal transplantation[22], with a particular focus on cataract and vitreoretinal surgery[23].

Cataracts, a leading cause of blindness in individuals over 50[24], are most effectively treated through surgery. Cataract surgery is the most frequently performed ocular surgical operation globally. However, it has a steep learning curve, with novices requiring 300 cases to achieve surgical proficiency[25]. Additionally, intraoperative complications like posterior capsule rupture (PCR) can significantly impact the patient's visual outcome[26], necessitating exceptional hand-eye coordination. Vitreoretinal surgery is one of the most technically demanding minimally invasive procedures, requiring precision and dexterity within a delicate environment and a lengthy learning period[27]. VR technology offers a safe, risk-free environment for trainees to practice repeatedly, enhancing surgical skills and accelerating the learning curve without compromising patient safety.

VR surgical simulators are increasingly recognized as indispensable tools in surgical education. In the field of ophthalmology, advanced virtual simulation training tools such as Eyesi and HelpMeSee are being effectively implemented and leveraged[28] (Table 1). The objective of this project is to systematically evaluate the recent advancements in the application of VR technology for training in ocular surgical skills. It will also identify the limitations of VR technology in this domain and propose potential improvements. By delineating the advantages and prospects of VR in ocular surgical skill training, this study aims to serve as a reference for scholars seeking to explore new research directions in this field.

APPLICATION OF VR TECHNOLOGY IN CATARACT SURGERY SKILLS TRAINING

Application of the Eyesi Surgical Simulator in Cataract Surgery Skills Training The Eyesi surgery simulator stands out as the leading commercially available VR simulator for intraocular surgical skills training and is the only extensively validated simulation-based teaching model in ophthalmology[29]. The cataract training module is meticulously structured, and divided into four progressively challenging stages. Furthermore, the module features complex cataract surgical cases, providing a risk-free setting for advanced ophthalmologists to refine their specialized surgical skills.

Assessment of the cataract surgery training system's effectiveness The application of a VR surgical simulator, such as the Eyesi, should be supported by empirical evidence, just like other teaching methods. Numerous studies have validated the construct validity of the Eyesi surgical simulator by assessing its ability to discern skill differences between novice and experienced surgeons. Selvander and Asman[30] confirmed the construct validity of six cataract training modules, while Thomsen *et al*[31] conducted the first study on 13 modules with the Eyesi surgical simulator, identifying validity evidence for seven modules. Colné *et al*[32] validated the construct validity of three cataract training modules. However, Forslund Jacobsen *et al*[33] in their first validation of advanced cataract surgery training modules, found that not all studied modules could differentiate between varying levels of surgical competence.

Thomsen *et al*[34] found a robust correlation between proficiency-based tests on the Eyesi surgical simulator and real-life performance, as evaluated by motion-tracking software analyzing cataract surgical videos. This finding supports the use of the simulator as an objective assessment tool in ophthalmology. When using the Eyesi surgical simulator for assessment, it is crucial to account for the warm-up effect and to employ at least two distinct methods to assess surgical competency. Further investigation by the team[35], revealed a significant association between Eyesi surgical simulator scores and the mean objective structured assessment of cataract surgical skill (OSACSS) scores across all experience levels, suggesting that the combined simulator score is a valuable assessment tool. Roohipoor *et al*[36] also identified a substantial link between Eyesi surgical simulator scores and total global rating assessment of skills in intraocular surgery (GRASIS) scores, indicating that module scores on the Eyesi surgical simulator can predict future performance in the operating room. These studies indicate that the Eyesi surgical simulator may serve as a significant instrument for assessing cataract surgical competence.

Cataract surgery skills transferred to the operating room Skill transfer refers to the ability to apply cognitive and behavioral competencies acquired in one context to a different context, with outcomes that may vary from positive to negative or neutral[37-38]. In an ideal scenario, surgical skills learned in a simulated environment should effectively transfer to the operating room, leading to enhanced surgical technique performance, increased confidence, reduced operative duration, and a lower rate of intraoperative complications.

Consistent results from two studies[39-40], show that training with the Eyesi surgical simulator improves performance for novice doctors, who have not yet performed surgery independently, and for intermediate-level surgeons with fewer than 75 independent cataract surgeries. However, experienced cataract surgeons do not gain additional benefits from simulator training in actual procedures. Ducloyer *et al*[41] found that four consecutive days of two-hour Eyesi surgical simulator sessions significantly improved the surgical competencies of novice ophthalmology residents. While additional training may improve scores, the exact number of sessions needed to reach a competence threshold is still unknown. Bozkurt Oflaz *et al*[42] demonstrated a correlation between participants' surgical experience and their scores on the capsulorhexis module, indicating that capsulorhexis scores improve with increased training repetitions. Ng *et al*[43] found that training on the Eyesi surgical simulator enhances confidence and reduces tension during surgical procedures. Lopez-Beauchamp *et al*[44] conducted a retrospective cohort study showing that early and continuous implementation of mandatory virtual simulator surgical training before intraocular surgery significantly decreases operating times for third-year residents learning phacoemulsification compared to their non-simulator trained counterparts.

To ensure statistical significance, substantial sample sizes are necessary due to the low incidence of complications in cataract surgery. A study of 1037 consecutive cataract surgeries performed over four academic years at a teaching hospital[45], found that Eyesi capsulorhexis training did not correlate with an overall reduction in vitreous loss rates. However, the rate of vitreous loss associated with non-errant continuous curvilinear capsulorhexis (CCC) was higher among those who underwent Eyesi capsulorhexis training. Staropoli *et al*[46] conducted a retrospective case series of 955 cataract cases, indicating a significant decrease in the incidence of PCR and vitreous prolapse following Eyesi training. A multicenter audit involving 265 novice surgeons and 17 831 cataract operations[47], showed a 38% decrease in the PCR rate after the introduction of the Eyesi surgical simulator for cataract surgery skills training between 2009 and 2015. A systematic review of the literature[48], suggests that the simulator reduces the incidence of PCR and erroneous CCC, but there is limited evidence regarding its effectiveness in reducing other complications.

These studies demonstrate VR technology's potential to transfer skills to the operating room, underscoring its significant potential in medical education and surgical skills training. However, a potential confounding variable in these studies is the extended total resident training duration due to simulator training. Future research should adopt an experimental design with strict control over total training time to account for this variable[49]. A Meta-analysis[50], indicated that the Eyesi surgical simulator could enhance technical skill development (evidence grade: low certainty) and reduce technical errors (evidence grade: very low certainty) in cataract surgery among trainees. Further prospective studies with standardized scoring systems for evaluating Eyesi modules are warranted.

Comparison with wet lab cataract surgery training Several studies have compared the effectiveness of Eyesi surgical simulator training with traditional wet lab training. Daly *et al*[51] assessed the operating room performance of ophthalmology residents trained through both traditional wet lab methods and surgical simulation for the CCC portion of cataract surgery. They found no significant difference in scores between the two training methods, except for time, and concluded that both methods effectively enhanced CCC skills. Hu *et al*[52] suggested that integrating both the Eyesi surgical simulator and the wet lab, each with its unique benefits, into the curriculum for new residents is beneficial. Ng *et al*[53] supported this view, arguing that combining these training modalities not only promotes skill transfer to the operating room but also offers economic advantages. A systematic review in the Cochrane Library[54] indicates that current evidence has not conclusively demonstrated VR training to be superior to wet lab or conventional methods for improving trainee performance in ophthalmic trainees. These findings are limited by small sample sizes, imprecise reporting of study protocols, and heterogeneity in interventions and outcomes. Consequently, high-quality.

Table 2 Application of the Eyesi surgical simulator in cataract surgery skills training

Study	Year	Participants	Surgical simulator	Main outcomes
Selvander and Asman[30]	2013	7 cataract surgeons and 17 medical students	Eyesi surgical simulator	Training module assessment score
Thomsen *et al*[31]	2015	26 ophthalmic trainees (no cataract surgery experience), 11 experienced cataract surgeons (>4000 cataract procedures) and 5 vitreoretinal surgeons	Eyesi surgical simulator	Training module assessment score
Colné *et al*[32]	2019	24 cataract surgeons with different experience levels	Eyesi surgical simulator	Training module assessment score
Forslund Jacobsen *et al*[33]	2020	10 cataract surgeons (>250 surgeries performed) and 10 ophthalmic residents	Eyesi surgical simulator	Training module assessment score
Thomsen *et al*[34]	2017	11 surgeons	Eyesi surgical simulator	Simulation-based test score and motion-tracking score
Jacobsen *et al*[35]	2019	19 cataract surgeons with different experience levels	Eyesi surgical simulator	Surgical simulator performance score; OSACSS scoring system
Roohipoor *et al*[36]	2017	30 first-year ophthalmology residents	Eyesi surgical simulator	Surgical simulator performance score; GRASIS rating scale
Thomsen *et al*[39]	2017	18 cataract surgeons with different levels of experience	Eyesi surgical simulator	OSACSS scoring system
la Cour *et al*[40]	2019	19 cataract surgeons with different experience levels	Eyesi surgical simulator	Surgical simulator performance score; OSACCS scoring system
Ducloyer *et al*[41]	2024	16 newly nominated ophthalmology residents	Eyesi surgical simulator	Surgical simulator performance score; Success rate; PCR rate
Bozkurt Oflaz *et al*[42]	2018	16 doctors	Eyesi surgical simulator	Comparison of simulator scores according to surgical experience: capsulorhexis
Ng *et al*[43]	2018	22 residents	Eyesi surgical simulator	Survey on ophthalmic residents' perceived difficulties based on ICO-OSCAR
Lopez-Beauchamp *et al*[44]	2020	29 different third-year residents	Eyesi surgical simulator	Surgical times; vitreous loss rate
McCannel *et al*[45]	2017	38 residents	Eyesi surgical simulator	Vitreous loss rate; retained lens material rate
Staropoli *et al*[46]	2018	11 simulator-trained residents and 11 simulator-naive predecessors	Eyesi surgical simulator	The complication rate
Ferris *et al*[47]	2020	265 first and second year trainee surgeons	Eyesi surgical simulator	PCR rate
Daly *et al*[51]	2013	10 residents trained in the wet lab and 11 on the simulator	Eyesi surgical simulator	Surgical simulator performance score; Wet lab performance score
Hu *et al*[52]	2021	60 ophthalmology residents (in their second year) and 3 cataract surgeons	Eyesi surgical simulator	Surgical simulator performance score; Wet lab performance score
Ng *et al*[53]	2023	22 trainees	Eyesi surgical simulator	ICO-OSCAR-phaco; ICER
Gonzalez-Gonzalez *et al*[55]	2016	3 were attending physicians and 11 were trainees	Eyesi surgical simulator	Surgical simulator performance score
Hind *et al*[56]	2022	16 trainees	Eyesi surgical simulator	Surgical simulator performance score; self-confidence scale for surgical trainees
Chung *et al*[57]	2017	33 medical students	Eyesi surgical simulator	Surgical simulator performance score
Eltanamly *et al*[58]	2022	30 ophthalmic surgeons	Eyesi surgical simulator	Surgical simulator performance score

OSACSS: Objective structured assessment of cataract surgical skill; GRASIS: Global rating assessment of skills in intraocular surgery; ICO-OSCAR: International council of ophthalmology surgical competency assessment rubric; PCR: Posterior capsule rupture; ICER: Incremental cost-effectiveness ratio.

Training of cataract surgical skills in the non-dominant hand Ophthalmic surgery requires the coordinated use of both hands, yet real-world training for the non-dominant hand is often limited by patient safety and ethical considerations. VR surgical simulators, such as the Eyesi, provide a risk-free environment for repetitive practice, thereby enhancing non-dominant hand dexterity. Gonzalez-Gonzalez *et al*[55] conducted the pioneering study evaluating the impact of structured instruction on non-dominant hand dexterity within the cataract module of the Eyesi surgical simulator. Their research indicated that the non-dominant hand showed a steeper learning curve and significant improvements in dexterity compared to the dominant hand, thus enhancing bimanual task performance, a finding supported by Hind *et al*[56]. Chung *et al*[57] proposed that daily training of the non-dominant hand might enhance navigation and bimanual skills, although these findings did not achieve statistical significance. While previous studies[39-40] have shown that experienced cataract surgeons do not exhibit significant skill improvement through Eyesi surgical simulator training, Eltanamly *et al*[58] demonstrated that these surgeons significantly increased their simulator scores after non-dominant hand training, indicating that such instruction could be a valuable addition to the residency curriculum (Table 2).

Application of the MicroVisTouch Surgical Simulator in Cataract Surgery Skills Training The MicroVisTouch simulator is an inaugural cataract surgical simulator that introduces haptic feedback, as reported in its prototype release in 2012[59]. In comparison to the Eyesi simulator, fewer studies have been conducted on the MicroVisTouch. Sikder *et al*[60] found that after six months of training with the MicroVisTouch, ophthalmology residents showed significant improvements in accuracy, fluency and overall in capsulorhexis compared to their baseline performance.

Application of the HelpMeSee Surgical Simulator in Cataract Surgery Skills Training The HelpMeSee surgical simulator is specifically developed for manual small incision cataract surgery (MSICS), covering all phases of the MSICS procedure, including capsulorrhexis, nucleus delivery, cortex aspiration, and intraocular lens implantation[61]. By integrating high-quality computer graphics with real-time haptic feedback and a physics-based model for MSICS activities, the simulator offers a realistic training experience. It can not only facilitate task execution as intended but also identify potential errors and difficulties that may arise during surgery[62].

Assessment of the cataract surgery training system's effectiveness Nair *et al*[63] assembled a panel of 35 ophthalmology specialists to evaluate the simulator's effectiveness in a sclero-corneal tunnel construction course, thereby establishing its face and content validity. The panel concluded that 74.3% (26/35) of participants found the simulator's visual representation of the eye and surgical equipment to be realistic, while a unanimous 94.3% (33/35) believed the simulator would be beneficial for enhancing hand-eye coordination. Hutter *et al*[64] developed and established validity evidence for a test designed to assess MSICS skills within a VR simulator, aimed at guiding future proficiency-based training and evidence-based evaluation of training interventions. In another significant study, Yaïci *et al*[65] conducted the inaugural assessment of the extrinsic and intrinsic construct validity of the Phaco modules of the HelpMeSee surgical simulator, leveraging the established validity of the Eyesi surgical simulator.

Cataract surgery skills transferred to the operating room A randomized controlled trial[66] indicated that preoperative simulation training with the HelpMeSee surgical simulator significantly reduced the error rate among trainees during their initial 20 tunnel constructions in the operating room. However, this trial was a pilot study and required validation through a larger-scale randomized controlled trial. Regarding skill transfer from phacoemulsification to MSICS, findings from two studies are inconsistent. Hutter *et al*[64] concluded that there is no positive inter-procedural transfer of skills between phacoemulsification and MSICS. In contrast, Le *et al*[67] demonstrated that phacoemulsification skills can enhance MSICS performance in simulations, suggesting that prior experience with phacoemulsification is beneficial for MSICS training in residency (Table 3).

APPLICATION OF VR TECHNOLOGY IN VITREORETINAL SURGERY SKILLS TRAINING

Application of the Eyesi Surgical Simulator in Vitreoretinal Surgery Skills Training The Eyesi surgical simulator is not limited to cataract phacoemulsification surgery; it also extends its training capabilities to vitreoretinal surgery skills. The curriculum is structured in a tiered approach, with beginner, intermediate, and advanced levels. These levels focus on fundamental surgical skills, step-by-step surgical specialty training, and multi-step comprehensive surgical training, respectively.

Assessment of the vitreoretinal surgery training system's effectiveness A number of studies[68-69] have validated the construct validity of the vitreoretinal surgery skill training modules within the Eyesi surgical simulator, thus preliminarily establishing it as an effective tool for evaluating vitreoretinal surgical competencies. Building on this, Jaud *et al*[70] developed a performance test based on Messick's framework for use with the Eyesi surgical simulator. This test is designed to assess vitreoretinal surgical competencies and to establish a benchmark criterion. It lays the groundwork for proficiency-based training, ensuring that trainees are sufficiently qualified to perform actual procedures.

Vitreoretinal surgery skills transferred to the operating room Although a systematic review[71] could not conclusively confirm the transferability of skills from the Eyesi surgical simulator to actual vitreoretinal surgery settings, the reliability of its findings was limited by a small sample size and potential bias risks. Deuchler *et al*[72] found that warmup training with the simulator significantly improved average performance metrics across all surgeon levels, surprisingly showing that even the most experienced surgeons benefit from such warmup. For the surgeries that were preceded by the warmup procedure, a notable correlation was identified between simulator performance and operating room performance.

A multicenter research study[73] revealed that trainee respondents were confident in the transferability of simulator-based skills to the operating room and advocated for the integration of such training into the curriculum. In the development of a virtual vitreoretinal surgery skills training program, Mellum *et al*[74] suggested incorporating stress factors like auditory distractions, fasting, sleep disruption, and sleep deprivation to enhance trainees' adaptability and performance under realistic preoperative stress conditions. Petersen *et al*[75] found no positive skill transfer from basic skills training to procedure-specific modules in terms of time, starting score, or amplitude of plateau. They advise prospective vitreoretinal surgeons to focus simulation-based training on specific procedures rather than spending considerable time on fundamental skills development.

Thomsen *et al*[76] initially explored the inter-procedural transfer of surgical skills, defined as the application of skills learned in one procedure to another, and found no significant transfer of skills from cataract surgery to vitreoretinal procedures within a virtual-reality training context. This finding is supported by additional studies[40] (Table 4).

Application of the RetinaVR in Vitreoretinal Surgery Skills Training Antaki *et al*[77] have developed and validated RetinaVR, a VR application created in the Unity 3D game engine and deployed on the Meta Quest 2 VR headset. Compared to the significant acquisition cost for the Eyesi

Table 3 Application of the HelpMeSee surgical simulator in cataract surgery skills training

Study	Year	Participants	Surgical simulator	Main outcomes
Nair *et al*[63]	2022	35 ophthalmology experts	HelpMeSee surgical simulator	Questionnaire assessing face and content validity
Hutter *et al*[64]	2023	Novice group: 15 surgeons; experienced group: 10 surgeons	HelpMeSee surgical simulator	Surgical simulator performance score
Yaïci *et al*[65]	2024	Expert-level group: 10 surgeons; intermediate-level group: 10 surgeons	HelpMeSee surgical simulator; Eyesi surgical simulator	The comparison of total and modules scores of HelpMeSee between both groups; the correlation of the HelpMeSee total score with the score previously validated for Eyesi
Nair *et al*[66]	2021	24 trainees	HelpMeSee surgical simulator	The total number of incident errors during the first 20 procedures performed tunnel construction
Le *et al*[67]	2024	29 residents or specialist in ophthalmology with no prior MSICS experience	HelpMeSee surgical simulator; Eyesi surgical simulator	Surgical simulator performance score

MSICS: Manual small incision cataract surgery.

Table 4 Application of the Eyesi surgical simulator in vitreoretinal surgery skills training

Study	Year	Participants	Surgical simulator	Main outcomes
Vergmann *et al*[68]	2017	20 medical students; 10 residents of ophthalmology; 5 trained vitreoretinal surgeons	Eyesi surgical simulator	Training module assessment score
Cissé *et al*[69]	2019	15 residents with no vitreoretinal experience and 6 trained vitreoretinal surgeons	Eyesi surgical simulator	Training module assessment score
Jaud *et al*[70]	2021	10 junior residents without any surgical experience; 8 senior residents with prior experience in cataract surgery; 5 vitreoretinal surgeons	Eyesi surgical simulator	Surgical simulator performance score
Deuchler *et al*[72]	2016	4 vitreoretinal surgeons	Eyesi surgical simulator	Surgical simulator performance score; GRASIS categorization of the parameters as used by the video analysis
Mondal *et al*[73]	2023	37 respondents	Eyesi surgical simulator	Questionnaire scores on the distribution of responses related to training aspects, simulator practice patterns, training perception and preferences
Mellum *et al*[74]	2020	19 novice surgeons	Eyesi surgical simulator	Surgical simulator performance score
Petersen *et al*[75]	2022	68 medical students	Eyesi surgical simulator	Surgical simulator performance score
Thomsen *et al*[76]	2017	12 ophthalmology residents without previous experience	Eyesi surgical simulator	Surgical simulator performance score

GRASIS: Global rating assessment of skills in intraocular surgery.

surgical simulator and its substantial annual operational expenses, the Meta Quest 2 VR headset is priced economically, making it a more cost-effective option. RetinaVR exemplifies a new concept in vitreoretinal surgery training simulation platforms, with the potential to significantly expand surgical simulation capabilities. While RetinaVR, an economical and portable tool for vitreoretinal surgery training, shows promise, it is still under development. Although its construct validity has been partially established, further verification is needed, particularly regarding the effective transfer of skills from the simulated environment to the operating room.

Application of the Microsoft HoloLens in Vitreoretinal Surgery Skills Training Microsoft's HoloLens is considered an optimal AR head-mounted display (HMD) display for surgical training[78]. It provides surgeons with the ability to view AR images from a single perspective. A significant advantage of the HoloLens is its dual role as both a display system and a standalone computer, integrated with a camera and sensors. This design eliminates the need for additional hardware and reduces the risk of contamination in the operating room[79]. Under the leadership of Menozzi *et al*[80] and Ropelato *et al*[81], a research team employed Microsoft HoloLens to simulate surgical environments in AR. Their work demonstrated the potential for training in vitreoretinal surgical skills and highlighted that integration with an intelligent tutoring system can enhance the effectiveness of such training.

APPLICATION OF VR TECHNOLOGY IN OTHER OPHTHALMIC SURGICAL SKILLS TRAINING

Ophthalmic surgical skills training encompasses a range of procedures, including glaucoma surgery, corneal laceration repair, and corneal transplantation. Ramesh *et al*[20] introduced an AR application named "Eye MG AR", which utilizes real-time, high-resolution TrueColor confocal images for 3D anatomy education and surgical consultation in AR. This application allows users to select from various customizable perspectives to display different anatomical and pathological features of the eyeball relevant to glaucoma, thus enhancing learning and clinical counseling for the condition. Feldman *et al*[21] demonstrated that medical students who trained on the Eyesi surgical simulator showed improved performance in repairing porcine corneal lacerations compared to those who did not use the simulator. In the field of corneal transplantation, Pan *et al*[22] proposed a deep learning framework for AR-based surgical navigation to guide suturing in deep anterior lamellar keratoplasty. Their findings suggest that this method can accurately detect and track corneal contours in real-time surgical environments, even in the presence of complex disturbances.

ADVANTAGES OF VR TRAINING IN OPHTHALMIC SURGICAL SKILLS

Improves and Enriches the Curriculum of Ophthalmic Surgical Skills Training Programs Four studies have established the construct validity of the Eyesi cataract training module[30-33], and two additional studies have confirmed the construct validity of the Eyesi vitreoretinal training module[68-69]. These affirmations support the refinement of corresponding training programs and suggest their potential for inclusion in the standard ophthalmology curriculum.

Simulated surgical training provides a safe and risk-free environment compared to traditional wet lab training[51], with each method offering unique benefits; their combined use can be effectively integrated into residency training programs[52]. Several studies[55-58] have shown that repetitive training of the non-dominant hand in a virtual environment enhances dexterity and is a valuable supplement to residency training programs. It is recommended to include distractors in the vitreoretinal surgery skills training program on the Eyesi surgical simulator to better prepare physicians for actual surgery[74]. Furthermore, trainees should engage directly in simulation-based training for specific procedures to maximize training efficiency, rather than focusing extensively on basic skills module training[75].

Multiple studies have investigated the inter-procedural transfer of surgical skills[40,64,67,76]. Given the inconsistencies in current research findings, it is advisable to develop customized, specific training strategies for each subspecialty within ophthalmology.

Become an Objective Assessment Tool for Ophthalmic Surgical Capabilities VR surgical simulators provide a standardized testing environment, minimizing the human errors inherent in traditional assessment methods. Research has established a significant correlation between performance scores on surgical simulators and motion-tracking scores from cataract surgery videos, the OSACSS scoring system, and the GRASIS rating scale[34-36]. These findings suggest that the Eyesi surgical simulator is an effective tool for evaluating proficiency in cataract surgery. It is recommended to use at least two assessment tools to measure surgical competence[34-35], and the impact of the simulator's warm-up impact must also be considered[34].

In addition to cataract surgery, several studies have explored the effectiveness of the Eyesi surgical simulator in assessing the skills required for vitreoretinal surgery[68-69]. Further study has developed and validated an evidence-based performance test, offering robust evidence for evaluating vitreoretinal surgical competencies using the Eyesi surgical simulator and establishing a benchmark criterion for the future implementation of proficiency-based training for novices[70].

Enhance Ophthalmic Surgical Skill Performance in the Operating Room Multiple studies have shown that VR surgical simulator training enhances operating room performance, particularly for novice and intermediate-level surgeons[39-40]. Increased training frequency leads to higher scores and improved capsulorhexis skills[42,60], and using simulators for pre-surgical warm-up can further boost actual surgical performance[72]. A survey indicated that proficiency-based Eyesi simulation training significantly increased ophthalmic residents' confidence in performing complex phacoemulsification tasks[43]. Additionally, training with the non-dominant hand on the simulator improved the bimanual skills necessary for intraocular surgery, which in turn increased the confidence of the trainees[56]. VR surgical simulator training not only reduces the duration of phacoemulsification cataract surgery but also increases surgical efficiency and safety among senior resident surgeons[44], and it reduces the incidence of intraoperative complications[45-48]. Furthermore, novice surgeons trained with a simulation-based curriculum committed fewer errors in their initial 20 tunnel construction attempts compared to those trained traditionally in MSICS[66].

LIMITATIONS AND IMPROVEMENT STRATEGIES OF VR TRAINING FOR OPHTHALMIC SURGICAL SKILLS

VR technology offers distinct advantages in ophthalmic surgical skills training, yet it encounters several challenges:

1) High equipment costs: The initial outlay for VR equipment is significant, and many educational institutions lack the necessary funds to acquire enough technology to meet their instructional needs. Additionally, ongoing expenses such as software licensing, training, staffing, maintenance, and program updates must be considered. While research suggests that recovering the purchase costs of equipment within a few years can be challenging in even busy institutions[82]; other studies argue that the relatively low recurring costs of VR simulators make them more cost-effective despite the high initial investment[53]. However, the time and funding required to maintain such programs are not consistently allocated[83].

2) Unpleasant user experiences: Extended use of VR headsets can result in muscle fatigue, visual strain, and VR sickness, which are influenced by individual, hardware, and software factors[84]. Comparative studies on these influencing factors in ophthalmic skills training remain scarce.

3) Lack of fidelity: Given the high-risk and precision demands of ophthalmic surgery, the realism and accuracy of

VR technology are crucial. Studies have shown that haptic feedback significantly enhances the realism of VR surgical simulators[85-86]. However, challenges remain in achieving realistic haptic feedback and fluid dynamics in VR simulators[87].

4) Limited focus on cataract and vitreoretinal surgery skills training: VR technology in ophthalmic education has predominantly focused on training, assessment, and guidance in cataract and vitreoretinal surgery[88]. The majority of ophthalmic surgical skills trained using the Eyesi simulator are cataract surgeries, followed by vitreoretinal procedures[23], with fewer studies exploring VR technology for other ophthalmic surgical skills.

VR technology in ophthalmic education is undergoing continuous improvement and optimization to address current limitations.

1) Cost-effectiveness is being explored through strategies such as cost-sharing across regional hospitals and establishing local training centers to facilitate trainee sharing[89]. Additionally, near-peer teaching methods are being considered for their accessibility and cost-effectiveness[90]. As an alternative, integrating teleconferencing software with the Eyesi surgical simulator facilitates remote oversight, thus eliminating travel expenses[91]. Moreover, studies suggest that grape-based training models are comparable to VR simulators and silicon suture pads, perhaps offering benefits in terms of reduced economic cost and greater accessibility[92]. Regrettably, none of the reviewed studies evaluated the costs and profitability of training programs or the return on investment in trainee development. Future research should consider incorporating assessments of training program profitability, particularly with trainees' formation and reductions in complication rates[93].

2) Technological advancements have brought significant enhancements, including the introduction of the Beyeonics One microscope, a novel digital microscope with multiple advantages such as digital image processing, improved depth perception through a 3D HMD platform, and hands-free image control *via* head gestures. The hands-free feature not only improves ergonomics and reduces physical strain during prolonged surgeries but also alleviates surgical fatigue. HMD technology provides trainees with a surgeon's viewpoint, enabling them to experience the same surgical perspective regardless of their location, facilitating remote surgical training and live surgeries. Instructors can also enhance the learning experience by offering help to trainees through on-screen pointing and drawing[94-95]. However, the Beyeonics™ Clarity headset has its limitations, such as being non-wireless and heavy (1.6 lbs./730 g). In contrast, the ORlenz™ AR headset offers a wireless, lightweight design with superior resolution at 60 pixels per degree[96]. Consequently, it can be anticipated that the issue of bulky headsets may not be a long-term concern[88]. The profiles of VR sickness can be influenced by content, visual stimulation, locomotion, and exposure times[97], and studies suggest that individuals may acquire resistance or acclimate to VR sickness over time[98]. To alleviate VR-induced symptoms and effects, it is recommended to limit immersion times to between 20 to 30min[84].

3) The integration of artificial intelligence in ophthalmology has emerged as a cutting-edge research field, achieving notable successes and showing great promise. Enhancements in artificial intelligence models are expected to increase VR fidelity, providing a more effective and authentic platform for simulated education and training[87].

4) Future research can expand the application of VR technology to other areas of ophthalmic surgical skill training, such as glaucoma surgery, corneal laceration repair, and corneal transplantation.

CONCLUSION

VR training enriches ophthalmic surgical curricula, enhances operative performance, and provides objective assessment tools that quantify surgical competence while reducing human error inherent in conventional evaluations.

While VR technologies show promise in ophthalmic surgical skills training, existing research, and applications have limitations that necessitate further enhancement. Many studies have small sample sizes and lack multi-centered designs, with inconsistencies in variables such as simulator usage duration and the total number of attempts. To address these issues, future studies should aim for large-sample, multi-centered, high-quality trials with clear protocols. They should also assess key surgical outcomes, like intraoperative complications, to further validate the effectiveness of VR training. To realize its full potential, research must overcome current challenges and confirm the long-term impacts of VR through clinical practice. Challenges in the application of VR technology in ophthalmic surgical skills training include high equipment costs, user discomfort, and fidelity issues. However, continuous technical innovation and improvements in educational models are expected to increase the significance of VR technology in ophthalmic education and clinical practice, thereby enhancing the surgical competencies of ophthalmologists.

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