



The Utility of Virtual Reality Simulation in Cataract Surgery Training: A Systematic Review

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Abstract

Introduction Cataract surgery is a fundamental intraocular procedure with a steep learning curve. Virtual reality simulation offers opportunity to streamline this aspect of ophthalmic education by exposing trainees to operative techniques in a controlled setting.

Materials and Methods A systematic review of the PubMed database was conducted through December 2019 for English language studies reporting on use of virtual reality simulation in cataract surgery training to assess usefulness. Studies meeting inclusion criteria were examined for pertinent data: study design, number of subjects and live cases, simulator model, training regimen, surgical skills assessed, and overall outcomes.

Results Of the 41 analyzed studies, 15 investigated the impact of virtual reality simulation-based training on performance in live surgery or wet laboratories; 20 used simulation as a device for direct assessment of operative proficiency; 6 explored simulation-based training's effect on performance in simulated surgery. Thirty-seven studies employed an iteration of the Eyesi simulator, though methodologies varied widely with a few randomized trials available. The literature endorsed validity of simulator-based assessment and benefits of structured training on live complication rates, operative times, and self- and faculty-perceived competency, particularly in novice surgeons.

Discussion The literature surrounding simulation in cataract surgery training is characterized by significant heterogeneity in design. However, most works describe advantages that may outweigh the costs of implementation into training curricula. Collaborative efforts at establishing a structured, proficiency-based cataract surgery curriculum built around virtual reality and wet laboratory simulation have the potential to improve outcomes and enhance future surgical training.

Keywords

- ▶ simulator
- ▶ simulation-based training
- ▶ virtual reality simulation
- ▶ cataract surgery
- ▶ Eyesi
- ▶ residency training
- ▶ education
- ▶ systematic review

Cataract surgery is the most frequently performed surgical procedure in the United States.¹ Likewise, it is the surgery performed most often by ophthalmology residents during their training.² The literature describes a steep and lengthy associated learning curve that can extend beyond minimum caseloads required for accreditation.³ As such, enhancing

cataract surgery training is of utmost importance to academic programs aiming to produce skilled surgeons.

Meanwhile, simulation has played a role in medical training since the advent of computers and primitive graphics hardware,⁴ with pertinent randomized controlled trials published as early as 1999.⁵ In ophthalmology, surgical simulators such

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Table 1 Database search for systematic review. Search terms were entered into PubMed search engine to identify English language studies through December 2019

Database	Search terms
PubMed	Keyword: ("cataract extraction"[MeSH Terms] OR ("cataract"[All Fields] AND "extraction"[All Fields]) OR "cataract extraction"[All Fields] OR ("cataract"[All Fields] AND "surgery"[All Fields]) OR "cataract surgery"[All Fields]) AND (simulator[All Fields] OR "virtual reality"[MeSH Terms])

as the Eyesi (VRmagic, Mannheim, Germany), MicroVisTouch (ImmersiveTouch Inc., Chicago, IL), and PhacoVision (Melerit Medical, Linköping, Sweden) are intended to develop surgical technique by using microscopes with stereoscopic imaging and haptic feedback to portray a realistic operative environment.⁶ Overall, surgical simulation is an attractive educational modality for its potential to enhance knowledge and skill acquisition and retention without risk to live patients.⁷

In 2014, a review of 10 works on simulation-based cataract surgery training detailed construct validity of simulator modules, subsequent performance in wet laboratories, and association with lower complication rates in one study utilizing a control group.⁶ Wider integration of simulation within ophthalmic surgical training has since contributed to an influx of pertinent literature. Our scope comprises over 40 studies, many of which incorporate new methodology or evaluate previously unreviewed hypotheses pertaining to variable intraoperative conditions, curricular satisfaction, or predictiveness of future live operative performance. The aim of this review is to update and more broadly evaluate the utility of virtual reality simulation (VRS) for educating residents to become proficient cataract surgeons, especially in comparison to more traditional teaching methods.

Materials and Methods

The PubMed computerized database was systematically searched to identify all literature reporting on use of VRS in cataract surgery through the year 2019. Articles were obtained using a search of Medical Subject Headings and keyword terms and their respective combinations (– **Table 1**). Full text English language studies were included in analysis, while review articles, surgical technique guides, case reports, and comments were excluded.

The literature search is outlined in – **Fig. 1**. Initial search of titles yielded a subset of possible articles that were subsequently selected for relevant abstract contents. Full text was reviewed for articles meeting criteria and appropriate studies were retained. The title, abstract, and full-text selection process with assessment of bias at the study level was performed independently by study authors with discrepancies discussed and resolved by mutual agreement.

Data Extraction and Analysis

Several metrics were obtained from each article to describe study characteristics: level of evidence per Oxford Center for Evidence-Based Medicine (OCEBM) criteria,⁸ study design, number and identity of subjects, outcome variables, and overall findings.

Results

Study Characteristics

This systematic review comprised 41 published works: 5 level II studies (12%), 18 level III studies (44%), 17 level IV studies (41%), and 1 level V study (2%) per OCEBM criteria.⁸ Six randomized controlled trials (1 nonblinded, 4 single-blinded, 1 double-blinded), 16 cohort studies (7 prospective, 9 retrospective), 16 cross-sectional studies, and 3 case series were included.

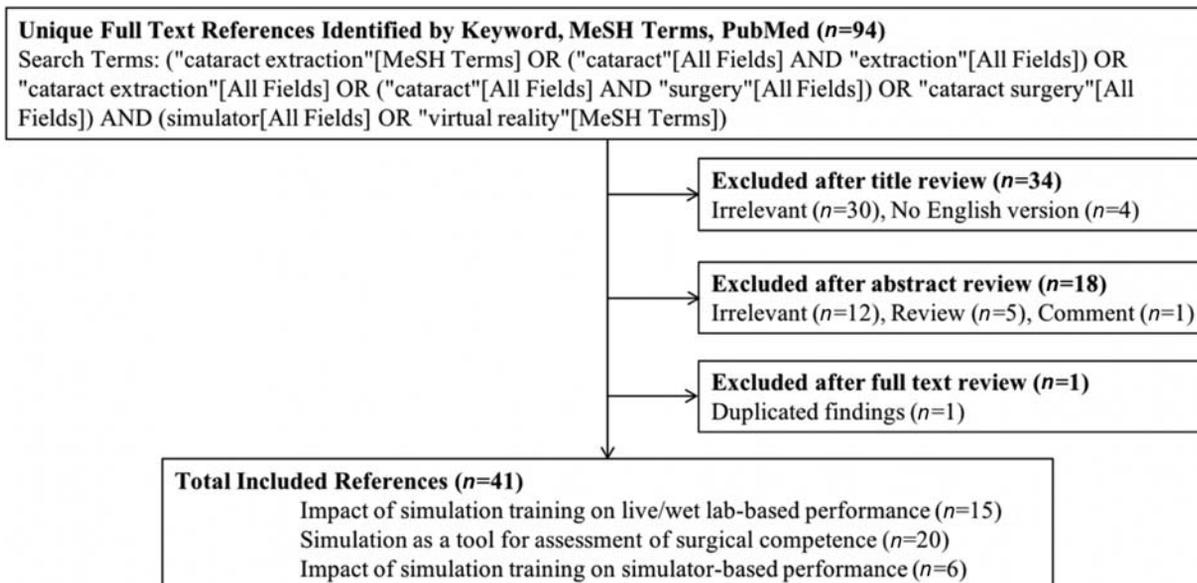


Fig. 1 Flow diagram presenting the systematic review process used in this study.

The Eyesi, MicroVisTouch, and Sensimmer Virtual Phaco Trainer systems were used in 37, 1, and 1 studies, respectively. An additional study used a computer-based simulator developed in-house, and the final study was questionnaire-based and did not specify a requisite model.

The mean number of subjects in each study was 33.6 ± 42.4 (median, 22; range, 3–265; $n = 41$), the majority of which were ophthalmic residents. However, more experienced surgeons and novice students were also involved, particularly in studies of construct validity that used level of surgical expertise as an independent variable.

Researchers often set out to answer similar questions pertaining to simulation and surgical performance, but with unique and varied approaches in terms of study design (training modules used, outcome variables tracked, etc.). Most often, studies compared real-world and/or simulated performance using differing training methods or baseline experience level. As far as real-world performance was concerned, 11 studies analyzed VRS impact on video-derived scores (Objective Structured Assessment of Cataract Surgical Skill—OSACSS⁹ or Global Rating Assessment of Skills in Intraocular Surgery—GRASIS¹⁰) or operative complications across 24,352 total cases (mean, 2,214; range, 21–17,831).

Temporal Trends

The number of articles meeting inclusion criteria published in any given year varied from 1 (2008, 2009, 2010) to 8 (2013). ► **Figure 2** depicts the count of reviewed articles published by year, stratified by category. The majority of articles was published after 2013.

Methodology

Literature meeting criteria for review examined the use of VRS training in cataract surgery primarily from one of three angles: the first, exploring association with surgical performance in the operating room or wet laboratories (► **Table 2**, $n = 15$); the second, investigating VRS as an assessment tool for surgical competency (► **Table 3**; $n = 21$); the third, evaluating effect of VRS training on VRS performance (► **Table 4**; $n = 5$). Among those approaching the first angle, some stud-

ies specifically were designed to investigate the effect of VRS versus other training methodologies (wet laboratories or no training, for example). Others were designed to track performance metrics both at baseline and after VRS training on an individual basis. The remainder provided qualitative data on participants' attitudes toward VRS and perceived contribution to operating room preparedness. Among studies approaching the second angle, many aimed to establish construct validity of simulator devices. Others assessed the effect of VRS on simulator-scored performance, used it to predict future performance or validate other means of assessment, or investigated questions pertaining to operator or other characteristics as related to simulator-scored performance. Studies approaching the third angle focused on simulator task repetition and improvement, intermodule skills transfer, or nondominant hand use that could not ethically be conducted on live patients.

Impact on Performance in Live Surgeries/Wet Laboratories (► **Table 2**)

Simulation versus Other Training Methodology: Wet Laboratory-Based, No Exposure, etc.

As early as 2009, Feudner et al found prior VRS training to be associated with improved baseline wet laboratory capsulorhexis performance by residents and students.¹¹ Within 4 years, other groups noted comparable performance between VRS and wet laboratory-trained residents at baseline¹² and improved outcomes compared with those reported in the general cataract surgery literature.¹³ Thereafter, a common study methodology involved assessing live surgical performance among resident cohorts in years prior to and after implementing VRS training. Each of the following outcomes was found to be significantly improved in some or all such studies: number of cases performed, operative score as measured by OSACSS or GRASIS, mean/adjusted phacoemulsification time and power, total operative time, trypan blue use, complication rate (posterior capsule rupture [PCR], nucleus fragment dislocation, extracapsular conversion, aphakia, errant continuous curvilinear capsulorhexis, vitreous loss, etc.).^{14–21}

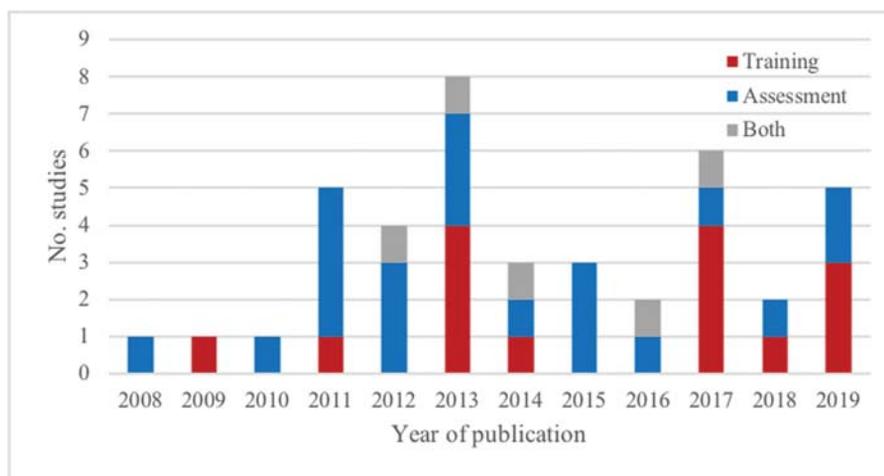


Fig. 2 Article count by year, stratified by category.

Table 2 Characteristics and findings of studies describing the impact of simulated cataract surgery module training on operative performance in live surgeries and wet laboratories (n = 15)

Author (y)	Design	Level of evidence (OCEBM)	Participants	n (live cases)	Simulator	Independent variable(s)	Outcome variable(s)	Skills/modules tested	Findings
Baxter et al (2013) ¹³	CS	4	3 residents	903	Eyesi	Sim and wet laboratory training	Case load, complications, survey	Unspecified (~50 h)	Complication rates of ~1% over first 100 live cases
Belyea et al (2011) ¹⁴	RCS	3	42 residents	592	Eyesi	Sim training (>2 h/y)	Phaco time, power, complications	CCC ± phacoemulsification	Reduced phacoemulsification time and power in VRS group
Daly et al (2013) ¹²	RCT (single-blinded)	2	21 residents	21	Eyesi	Sim versus wet laboratory training	Video grading, satisfaction questionnaire	CCC	Comparable performance; shorter CCC time and more effective orientation to instruments in wet laboratory group
Ferris et al (2019) ²¹	RCS	3	265 residents	17831	Eyesi	Sim training	PCR rate	Various	Reduced PCR rate in VRS group
Feudner et al (2009) ¹¹	RCT (single-blinded)	2	32 residents, 30 students	N/A (372 porcine)	Eyesi	Sim training	Video grading of wet laboratories, perceived usefulness	Forceps, antitermor, CCC	Improved wet laboratory capsulorhexis score in VRS group
Kloek et al (2014) ²⁴	RCS	3	23 residents, 8 faculty	N/A	Eyesi	Sim training	Resident comfort, faculty assessment, case load, % case turnover	CCC, hydrodissection, sculpting, quadrant removal	Increased case load, improved comfort with surgical steps and faculty assessment in VRS group
Lopez-Beauchamp et al (2019) ²⁰	RCS	3	29 residents	722	Eyesi	Sim training	Operative time, vitreous loss rate	CT-A, CT-B	Reduced operative time in VRS group
Lucas et al (2019) ¹⁹	RCS	3	14 residents	140	Eyesi	Sim training	Complications (post capsule rupture, aphakia, nucleus fragment dislocation, extracapsular conversion)	CT-C: CCC, divide and conquer, chopping, I/A, toric IOLs	Reduced total complications over first 10 live cases in VRS group
McCannel et al (2013) ¹⁶	RCS	3	48 residents	1037	Eyesi	Sim training	Rate of errant CCC, trypan blue use	33-module CITC: antitermor, navigation, forceps, bimanual, CCC	Reduced errant CCC rate in VRS group
McCannel (2017) ¹⁷	RCS	3	38 residents	1037	Eyesi	Sim training	Complications (vitreous loss, retained lens material, errant CCC)	33-module CITC: antitermor, navigation, forceps, bimanual, CCC	Comparable vitreous loss rates overall; increased non-errant CCC associated vitreous loss in VRS group
Pokroy et al (2013) ¹⁵	RCS	3	20 residents	1000	Eyesi	Sim training	PCR ± vitreous loss, operative time, attending survey of improved group performance	Unspecified (>6h)	Reduced % of long cases (>40 minute) among cases 10-50 in VRS group
Puri et al (2017) ²⁵	XS	5	116 residents	N/A	N/A	N/A	Self-perceived preparedness, competency	Unspecified (onsite availability)	Improved preparedness/competency among residents with supervised wet laboratory or VRS training

Table 2 (Continued)

Author (y)	Design	Level of evidence (OCEBM)	Participants	n (live cases)	Simulator	Independent variable(s)	Outcome variable(s)	Skills/modules tested	Findings
Roohipoor et al (2017) ²³	CS	4	30 residents	N/A	Eyesi	Sim scores	Case load, GRASIS score, need for help	Antiterror, bimanual, CCC, forceps, navigation	Correlation between VRS scores and future case load, total GRASIS score, reduced need for extra help
Staropoli et al (2018) ¹⁸	RCS	3	22 residents	955	Eyesi	Sim training	Complications (PCR, vitreous prolapse, retained lens fragment, zonular dehiscence, endophthalmitis, IOL dislocation, return to OR), qualitative survey	CT-A, CT-B	Reduced rate of total complications, PCR, vitreous prolapse in VRS group
Thomsen et al (2017) ²²	CS	4	18 surgeons, varying experience	114	Eyesi	Sim training	Video-based OSACSS score	Navigation, antiterror, forceps, bimanual, CCC, divide and conquer	Improved OSACSS score among novice/intermediate after VRS training

Abbreviations: CCC, [continuous curvilinear] capsulorhexis; CS, case series; I/A, irrigation/aspiration; IOL, intraocular lens; OSACSS, objective structured assessment of cataract surgical skill; PCR, posterior capsular rupture; PCS/RCS, prospective/retrospective cohort study; RCT, randomized controlled trial; XS, cross-sectional study.

Comparative Performance before and after Simulation Training

Thomsen et al assessed OSACSS scores before and after VRS training, finding improved performance by novice and intermediate surgeons, but not by expert colleagues.²²

Prediction of Future Live Performance

Roohipoor et al found increased simulator score during early residency to be associated with increased future case load, primary surgery volume, and third-year GRASIS scores.²³

Qualitative Assessment of Satisfaction and Preparedness

In their survey-based study, Kloek et al noted VRS-trained residents to feel more comfortable with surgical steps and rate as more well-prepared by faculty.²⁴ Daly et al reported that residents deemed VRS and wet laboratory-based curricula to be similarly helpful and realistic, but with different strengths.¹² Finally, Puri et al highlighted increased self-perceived competency among residents with access to either VRS or wet laboratory training in a large cohort spanning numerous training programs.²⁵

Simulation as an Assessment Tool (~Table 3)

Concurrent and Construct Validity: Simulator Technique and Scoring

Other studies were conducted to establish concurrent and construct validity of VRS equipment and scoring. Most compared computed module performance across first-time operators and found expert/intermediate surgeons to outperform novices.²⁶⁻³³ Banerjee et al found simulator scores to correlate with prior live surgical performance,³⁴ while others described similar associations with additional stratification by experience level.^{35,36} Meanwhile, Sikder et al endorsed improvement in capsulorhexis scores from baseline after 6 months of residency training.³⁷ Saleh et al noted significant intrasubject variability in simulator task scores during early attempts by novice surgeons.³⁸

Concurrent and Construct Validity: Other Assessment Tools

Balal et al successfully discriminated between live surgical videos of junior and senior surgeons using a motion tracking system correlated with previously validated simulator parameters.³⁹

Other Simulator-Based Assessment

Multiple groups used VRS performance as measured by the simulator itself to quantify the impact of external conditions: fatigue after a day of live operative cases, distractive arithmetic tasks, beta-blocker use, and caffeine intake.⁴⁰⁻⁴² Preference for and safety of various operative approaches such as hand- versus foot-operated forceps and nondominant hand surgery were similarly assessed.^{43,44} Lastly, VRS performance was compared in context of inherent user characteristics including stereoacuity and Kolb Inventory learning style.^{45,46}

Table 3 Characteristics and findings of studies describing simulation technology as an assessment tool in cataract surgery training (n = 21)

Author (y)	Design	Level of evidence (OCEBM)	Participants	n (live cases)	Simulator	Independent variable(s)	Outcome variable(s)	Skills/modules tested	Findings
Balal et al (2019) ³⁹	XS	4	40 residents	120	Eyesi	Surgical experience	Eyesi-based Phaco-Tracking metrics (live surgeries)	CCC, phacoemulsification, I/A	Correlation between experience level and VRS performance (CCC, phacoemulsification, and I/A tasks: path length, number of movements, time)
Banerjee et al (2012) ³⁴	XS	4	8 residents	24	ImmersiveTouch	Live surgical scores	Sim scores	CCC	Correlation between VRS and live performance (CCC circularity, standard deviation of duration, number of forceps grabs)
Bozkurt-Ofiaz et al (2018) ³³	XS	4	16 (7 novice residents, 6 intermediate, 3 faculty)	N/A	Eyesi	Surgical experience	Sim scores	Navigation, forceps, bimanual, antitremor, CCC	Correlation between experience level and VRS performance (baseline CCC score, improvement with repetition, nondominant hand CCC, mature cataract CCC)
Jacobsen et al (2019) ³⁶	XS	4	19 surgeons, varying experience	57	Eyesi	Live surgical performance (OSACSS)	Sim scores	Navigation, antitremor, forceps, bimanual, CCC, divide and conquer	Correlation between mean OSACSS score and VRS performance (total score)
Lam et al (2016) ³²	XS	4	16 (10 attendings, 6 residents)	N/A	In-house: PC, sim software, dual haptic devices	Surgical experience	Sim scores	Corneal incision, CCC, phacoemulsification, IOL implantation	Correlation between experience level and VRS performance (total scores, operative time, antitremor, antirupture, CCC, phacoemulsification, IOL implantation)
Mahr and Hodge (2008) ²⁶	XS	4	15 (12 residents, 3 experienced surgeons)	N/A	Eyesi	Surgical experience	Sim scores	Forceps, antitremor	Correlation between experience level and VRS performance (forceps, antitremor, operative time, out-of-tolerance %)
Modi et al (2015) ⁴⁶	XS	4	30 residents	N/A	Eyesi	Learning style (Kolb Inventory)	Sim scores	Forceps	No association between particular learning style and VRS performance (total score, odometer movement, cornea injury, lens injury, operative time)

Table 3 (Continued)

Author (y)	Design	Level of evidence (OCEBM)	Participants	n (live cases)	Simulator	Independent variable(s)	Outcome variable(s)	Skills/modules tested	Findings
Park et al (2011) ⁴¹	PCS	3	21 (14 novice, 7 expert surgeons)	N/A	Eyesi	Surgical experience +/- distraction	Sim scores	Forceps	No change in VRS performance with distracting cognitive task; reduced rate of distracting cognitive task completion during VRS task
Park et al (2012) ⁴⁴	PCS	3	30 residents	N/A	Eyesi	Dominant versus non-dominant hand use	Sim scores	Forceps	Reduced VRS performance with nondominant hand use (total score, operative time, lens injury); intra-user correlation between dominant and nondominant hand VRS performance
Podbielski et al (2012) ⁴³	PCS	3	18 residents	N/A	Eyesi	Hand vs foot-activated forceps use	Sim scores, subjective preference	Dexterity, CCC	No association between hand versus foot forceps use and VRS performance; no preference for either modality
Pointdujour et al (2011) ⁴²	RCT (Double-blinded)	2	18 (3 students, 3 ophthalmologists, 6 residents, 6 experienced surgeons)	N/A	Eyesi	Placebo versus propranolol versus caffeine	Sim scores	Antitermor, forceps, CCC	Improved VRS performance with beta-blocker use among novice surgeons
Privett et al (2010) ²⁷	XS	4	23 (16 students/residents, 7 experienced surgeons)	N/A	Eyesi	Surgical experience	Sim scores	CCC	Correlation between experience level and VRS performance (total score, centering, corneal injury, spikes, loss of red reflex, roundness, operative time)
Saleh et al (2013) ³⁸	XS	4	18 residents	N/A	Eyesi	Attempt number	Sim scores (intra-subject variance)	CCC, cracking and chopping, navigation, bimanual, antitermor	Correlation between intra-novice task scores on first and second or first and third attempt
Selvander and Ásman (2011) ⁴⁵	XS	4	70 students	N/A	Eyesi	Stereoacuity level	Sim scores	Navigation, forceps, CCC	Correlation between novice stereoacuity and VRS performance (navigation, forceps)
Selvander and Ásman (2013) ²⁸	XS	4	24 (7 surgeons, 17 students)	N/A	Eyesi	Surgical experience	Sim scores, OSACSS, OSATS	CCC, hydromaneuvers, divide and conquer, navigation, forceps, cracking and chopping	Correlation between experience level and VRS performance (overall scores, OSATS, OSACSS)

(Continued)

Table 3 (Continued)

Author (y)	Design	Level of evidence (OCEBM)	Participants	n (live cases)	Simulator	Independent variable(s)	Outcome variable(s)	Skills/modules tested	Findings
Selvander and Asman (2013) ³⁰	XS	4	24 (7 surgeons, 17 students)	N/A	Eyesi	Surgical experience	Sim scores, OSACSS, OSATS	CCC, hydriomanuevers, divide and conquer	OSACSS provided superior discrimination of experience level compared with VRS scoring
Sikder et al (2015) ³⁷	PCS	3	40 residents	N/A	MicroVisTouch	Interim surgical experience	Sim scores	CCC	Improved VRS performance and reduced standard deviation after interim residency training
Spiteri et al (2014) ²⁹	XS	4	30 residents, varying experience	N/A	Eyesi	Surgical experience	Sim scores	Forceps, antitempor, CCC	Correlation between experience level and VRS performance (procedural modules); ceiling effect among intermediate/experienced surgeons (abstract modules)
Thomsen et al (2015) ³¹	XS	4	42 (26 novice residents, 11 experienced cataract surgeons, 5 experienced vitreoretinal surgeons)	N/A	Eyesi	Surgical experience	Sim scores	Navigation, antitempor, forceps, bimanual, cracking and chopping, phacoemulsification, CCC, hydriodissection, divide and conquer, I/A, IOL insertion	Correlation between experience level and VRS performance; cataract surgeons did not significantly outperform vitreoretinal surgeons
Thomsen et al (2017) ³⁵	XS	4	11 surgeons, varying experience	33	Eyesi	Live surgical performance (motion-tracking score)	Sim scores	Navigation, antitempor, forceps, bimanual, CCC, divide and conquer	Correlation between VRS performance and live motion-tracking scores
Waqar et al (2011) ⁴⁰	PCS	3	7 experienced surgeons	N/A	Eyesi	Pre versus post live OR session	Sim scores	Forceps	Improved VRS performance (plateau total score, operative time) after day of live cases

Abbreviations: CCC, [continuous curvilinear] capsulorhexis; CS, case series; IOL, intraocular lens; OSACSS, objective structured assessment of cataract surgical skill; OSATS, objective structured assessment of technical surgical skills; PCS/RCS, prospective/retrospective cohort study; RCT, randomized controlled trial; XS, cross-sectional study.

Effect of Simulator-Based Training on Simulator-Based Performance

Finally, other studies described significant improvement in VRS performance of trainees after varying extents of VRS training.^{47,48} Gonzalez-Gonzalez et al stratified by experience level and dominant/nondominant hand use during VRS capsulorhexis, noting steepest improvement in the nondominant hand/novice subgroup.⁴⁹ Selvander and Åsman observed limited skill transfer between capsulorhexis and navigation modules among students,⁵⁰ whereas Thomsen et al described similar findings between prior VRS cataract surgery and vitreoretinal modules (► **Table 4**).⁵¹

Discussion

Limitations

The predominant limitations of this review include study heterogeneity and small sample size. Protocols ranged from merely providing trainees with VRS access to mandating completion of more rigorous module sequences in the accompanying Eyesi curriculum (► **Table 5**). Outcome variables of interest also varied. Studies assessing VRS as a training modality measured outcomes of live surgeries and/or wet laboratories objectively (case load, complication rates, phacoemulsification/total operative time, phacoemulsification power) and subjectively (qualitative trainer/trainee surveys, video grading, OSACCS score, need for additional help). Similarly, those assessing VRS as a proficiency assessment tool relied predominantly on simulator-based and other scoring metrics, both objective (path length, number of movements, time, circularity, number of forceps grabs) and subjective (post-training satisfaction survey, OSACCS score). Certainly, studies associating VRS training with larger operative caseload later in residency hint at a potential confounder for improved performance in virtual and live environments.

The vast majority of reviewed studies (37) used the Eyesi as opposed to other devices (ImmersiveTouch, MicroVis-Touch, or other in-house models). This reduces the generalizability of our conclusions to all simulators, which may boast different strengths. However, at present, over 70% of accredited residency programs possess at least one Eyesi; with 109 Eyesi simulators active at US accredited residency and fellowship programs, federal government-affiliated centers, and nongovernmental organizations, it is the most commonly used VRS device used by current-day prospective ophthalmologists trained in the US (Marshall Dial, e-mail communication, January 2020).

VRS training and evaluation in the analyzed studies placed greater emphasis on intraocular maneuvers as opposed to periocular manipulation at the conjunctiva, sclera, and cornea. By our literature search, these specific skills were not practiced or assessed in training modules, but are emphasized in newer virtual environments like the HelpMeSee simulator, which is used for manual small incision cataract surgery (MSICS) training. Translation of skills required for MSICS remains unstudied with respect to resident performance in other ophthalmic procedures.⁵²

Lastly, our search was limited to literature for which English full text was available in the PubMed database. Few studies were qualified as randomized controlled trials with a high level of evidence as per OCEBM criteria. Unpublished literature was not included, therefore eliciting concern for influence of a publication bias.

Validity and Implications

The concept of validity is particularly important in the medical education literature. Gallagher et al defined various subtypes important in the context of surgical education and performance evaluation.⁵³ Concurrent validity is based on whether the test produces similar results to another purporting to measure the same, whereas construct validity is in part based on whether a test will measure what is intended based on ability to differentiate experts from novices.

We found strong evidence for the concurrent and construct validity of Eyesi-based cataract surgery proficiency assessment. Simulator scores were correlated with OSACCS and other systems used during live cases, and VRS-naïve experienced surgeons universally outperformed VRS-naïve junior trainee counterparts. Novice surgeon status and nondominant hand use were associated with more dramatic early increases in module scores. This intuitively makes sense as initial scores were generally lower under these conditions and thus allowed “more room for improvement” before a ceiling effect was observed. We presume that VRS training may be more beneficial to skill development if undertaken earlier in one’s career.

Negative Findings

Nonetheless, even studies providing compelling evidence for VRS training yielded varying degrees of improvement across discrete surgical maneuvers and outcomes. For example, Daly et al reported shorter capsulorhexis time after wet laboratory training.¹² Selvander and Åsman discussed that OSACCS scoring more effectively discriminated between surgical novices and experts in simulated phacoemulsification tasks.³⁰ Puri et al did not deem VRS availability to be beneficial to residents’ perceived preparedness for live hydrodissection and sculpting, nor did surveyed residents endorse significantly reduced perceived difficulty of surgical steps after simulator use. Rather, they found the element of faculty supervision, discussion, and feedback to be most integral to development of proper techniques and comfort level.²⁵

Practical Application: Cost Consideration and Alternatives

Arguably, the most instructive quality of this review is in informing whether training programs should invest in VRS technology to reap its potential benefits, both in a vacuum and in comparison with other training modalities.

A common counter-argument is based on required expense: of the simulator device and its maintenance, of a physical training space, of faculty instruction time and diversion from other educational activities in a residency curriculum.^{35,54} However, Spiteri et al noted that reductions in the live operative learning curve may actually reduce the cost of training each

Table 4 Characteristics and findings of studies describing the impact of simulated cataract surgery module training on operative performance as assessed by simulation technology (n = 5)

Author (y)	Design	Level of evidence (OCEBM)	Participants	n (live cases)	Simulator	Independent variable(s)	Outcome variable(s)	Skills/modules tested	Findings
Bergqvist et al (2014) ⁴⁸	RCT (nonblinded)	2	20 students, 2 surgeons	N/A	Eyesi	Sim training (varying)	Sim scores	CCC, hydromaneuver, divide and conquer	Correlation between extent of VRS training and VRS performance (overall score, capsule rupture/damage)
Gonzalez-Gonzalez et al (2016) ⁴⁹	PCS	3	14 (3 attendings, 11 residents)	N/A	Eyesi	Sim training (pre versus post), dominant versus non-dominant hand usage, surgical experience	Sim scores, satisfaction questionnaire	CCC	Improved VRS performance (overall score, average radius, maximum radial extension, odometer, operative time) from baseline with dominant/nondominant hand use; reduced VRS performance with non-dominant hand use at baseline with steeper rate of subsequent improvement; no significant differences noted between trainees and attendings on satisfaction questionnaire
Saleh et al (2013) ⁴⁷	PCS	3	16 residents	N/A	Eyesi	Sim training (pre versus post)	Sim scores	Navigation, antitear, CCC, cracking and chopping	Improved VRS performance (total scores) from baseline after completion of VRS training
Selvaner and Asman (2012) ⁵⁰	RCT (single-blinded)	2	35 students	N/A	Eyesi	Sim training (capsulorhexis versus navigation-centric), user stereoacuity	Sim scores, OSACSS, OSATS	Navigation, CCC	Improved VRS performance and plateau with repetition (navigation score, CCC score, operative time, corneal damage); correlation between VRS performance (CCC score) and OSACSS; no significant skill transfer between navigation and CCC modules
Thomsen et al (2017) ⁵¹	RCT (single-blinded)	2	12 residents, 3 attendings	N/A	Eyesi	Sim training (cataract)	Sim scores (vitreoretinal)	Navigation, forceps, vitreoractor, antitear, bimanual, bimanual scissors, laser coagulation, posterior hyaloid, epiretinal membrane, internal limiting membrane peel, retinal detachment	Correlation between experience level and VRS performance on vitreoretinal modules; no association between VRS cataract pre-training and VRS performance on vitreoretinal modules

Abbreviations: CCC, [continuous curvilinear] capsulorhexis; CS, case series; OSACSS, objective structured assessment of cataract surgical skill; OSATS, objective structured assessment of technical surgical skills; PCS/RCS, prospective/retrospective cohort study; RCT, randomized controlled trial; XS, cross-sectional study.

Table 5 Eyesi cataract curriculum

CAT-A introductory courses
Anterior chamber navigation
Intracapsular navigation
Bimanual navigation
Instruments
CAT-B beginners's courses
Navigation and instruments
Capsulorhexis
Intracapsular tissue
Stop and chop
IOL insertion
CAT-C intermediate courses
Capsulorhexis
Divide and conquer
Chopping
Irrigation/aspiration
Toric IOLs
CAT-D advanced courses
Capsulorhexis errant tear
Weak structures
White cataracts
Capsular plaques
Varying cases
Anterior vitrectomy

Abbreviation: IOL, intraocular lens.

Note: Module performance is calculated using pertinent scoring criteria: target achievement, efficiency, instrument handling, tissue treatment, etc. A "cataract challenge" is presented every 60 minutes of training time in the beginners' intermediate, and advanced courses.

resident.²⁹ Lowry et al modeled operating room savings associated with Eyesi use based on presumed shortened surgical times alone. Cost savings ranged widely but were closely associated with resident program size and duration of Eyesi use, in some cases offsetting a significant portion of the estimated \$150,000 simulator purchase price.⁵⁵ Theoretical savings attributed to reduction in complication rates or need for human mentoring were not considered in this model but would likely offer additional benefit.⁵⁶

More recently, Ferris et al's large study describing PCR rates of early career surgeons with and without Eyesi access also modeled savings based on reduced costs incurred by PCR and other complications, in addition to cost of medical negligence claims. The group estimated a 280-case reduction in total resident PCR complications per year across all sites with Eyesi training implementation, corresponding to £560,000 in savings to the United Kingdom National Health Service annually and recoupment of aggregated simulator sticker price within 4 years. Therefore, VRS training was found to be beneficial in terms of both quality optimization and cost limitation.²¹

Furthermore, the only randomized controlled trial comparing resident performance after VRS versus wet laboratory training highlighted equally realistic training environments as rated by study participants. The Eyesi was deemed a safe alternative that could also effectively predict future operating performance, thus calling attention to trainees who may require extra assistance early. Though the wet laboratory seems to offer more effective orientation to the surgical microscope and instruments, increased need for in-person mentorship and expense of machinery maintenance, instrumentation, and the eyes themselves present obstacles to training programs.¹² Meanwhile, VRS offers consistent, repeatable intraocular scenarios and immediate feedback without equal need for human supervision or recurrent material costs.

Overall

Multiple studies met inclusion criteria in each year since 2010, indicating a steady release of publications throughout the decade. Works investigated the utility of VRS in capacities related to training, assessment, or both—at times in the context of inherent operator characteristics or under varying conditions. The majority reported reduced operative time and complication rates, or improved self-perceived competency and peer evaluations with structured simulation-based training. From this review of the current literature, we posit that the ideal VRS-based cataract surgery curriculum would adhere to the following core principles:

- Commence early with novice surgeons in the first year of residency training.^{29,49,56}
- Adopt a proficiency-based rather than time-based learning approach, by which the trainee practices under increasingly difficult conditions until performance exceeds pre-defined pass/fail levels.^{16,17,29,48,50,56}
- Utilize spaced repetition and global score targets in a curriculum of diverse abstract and procedural tasks of increasing difficulty (antitremor, forceps manipulation, etc.)
- Emphasize deliberate practice of targeted capsulorhexis and phacoemulsification tasks—deemed the most difficult by novice surgeons.⁵⁷
- Complement a concurrent, supervised wet laboratory curriculum providing additional experience with tissue manipulation and orientation to the live operating environment.^{11,12}
- Provide ongoing reinforcement throughout residency training via immediate simulator-based feedback, self-assessment questionnaire,²⁴ and routine faculty evaluation.

Finally, given overall heterogeneity of design and small size of prior studies, the creation of a large educational network for VRS-based cataract surgery training may offer additional value. A movement toward evidence-based standardization and evaluation of surgical curricula in multicenter trials utilizing VRS module scores, total simulation hours, self-assessment results, and other metrics could be networked to the American Academy of Ophthalmology as the basis for prospective studies. While VRS has seemingly asserted itself as a valuable component of the modern cataract surgery education program, broader collaboration

has the potential to further optimize training by improving patient outcomes and enhancing cost-effectiveness.

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Conflict of Interest

None declared.

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