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VALIDITY AND USABILITY OF A VIRTUAL REALITY INTRAOCULAR SURGICAL SIMULATOR

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Doctoral thesis

Lund University
Faculty of Medicine

Malmö 2013

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To my family

“Experience is the name every one gives to their mistakes”

Oscar Wilde, *Lady Windermere’s Fan, Act III*
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ABSTRACT
Cataract surgery is one of the most common surgical procedures in Sweden and around 90 000 operations are made each year. An aging population with increased demands on quality of life and good visual acuity, has led to an increased rate of surgery and more surgeons needs to be trained. Training of new cataract surgeons is done on scarce wet-lab training but mainly on patients. Training is costly and complications are higher for new surgeons compared to experienced ones. In the airline industry simulators are used for training. Pilots have to prove competent before flying a new airplane. No such standards exist for new cataract surgeons.

Surgical simulators have been used in other surgical fields for training and reports have shown that training has improved performance on real operations. The purpose of this work was to validate Eyesi, a surgical simulator for cataract surgery training, and analyze learning curves. Furthermore we set out to investigate whether factors like stereoacuity and sex would be important for performance in the simulator.

Evidence for construct validity was found for cataract specific modules capsulorhexis, hydromaneuvers and phaco divide and conquer and for manipulating modules cataract navigation training, cataract forceps training and cataract cracking and chopping training. Analysis of learning curves showed significant improvement throughout training. Evidence for concurrent validity was established for the capsulorhexis module. For the hydromaneuvers and phaco modules, the innate simulator scoring could not distinguish surgical skill but discrimination was dependent on video based human scoring. Stereoacuity was found to correlate with performance on the simulator but there were large individual variations. An individual's sex had no influence on performance.

We have shown that Eyesi can differentiate cataract surgical skill and that naïve can train in the simulator and improve. Stereoacuity has an effect on performance but there were large individual variations. Simulation-based training has the potential to move the early learning curve out of the operating room.

Keywords: simulator, cataract surgery, learning, training, Eyesi
THESIS AT A GLANCE

- Does Eyesi differentiate between skilled cataract surgeons and naive (construct validity)?
  Paper I
  - YES

- Can naive train in the simulator and improve their results?
  Paper II
  - YES

- Is the innate scoring system in the simulator safe for assessment?
  Paper III
  - Not for the phaco module, here video-based scoring is more accurate

- Does stereoacuity correlate with performance?
  Paper IV
  - YES

- Does sex correlate with performance?
  Paper IV
  - NO
BACKGROUND

INCREASED DEMAND FOR INTRAOCULAR SURGERY

Intraocular surgery has experienced a tremendous technical development that has led to beneficial results for patients. From treating retinal detachment conservatively to high technology vitrectomy leading to 80-90% healing with one operation; from large incision cataract surgery without intraocular lenses to millimeter incision phacoemulsification surgery with multifocal lenses making patients spectacle independent. Cataract surgery, an operation where the lens is exchanged with an intraocular plastic lens, is one of the most common operations in Sweden today. An aging population with increased demands on quality of life and good visual acuity at all ages in life, has led to more people being operated and being operated at an earlier stage in their cataract development. The result is, an increase in rate of surgery from 4.5 to 9 per 1 000 inhabitants from 1992 to 2009, and patients being operated at a younger age. In Sweden around 90 000 cataract operations are performed each year.

HIGHER DEMANDS FOR QUALITY CONTROL

The clinical competence of surgeons is a matter of public concern. Since the beginning of the 90s, several quality registers have been established to assure quality benchmark for surgical procedures. Since 1992, the Swedish cataract register has been used to follow surgical quality parameters and complication rates associated with cataract surgery. Pressure from government regulatory bodies as well as public advocacy has focused the attention on quality of surgical procedures. Complications during and after cataract surgery are costly and harmful for patients; posterior capsular rupture during cataract surgery leads to highly increased risk for retinal detachment and deficient postoperative visual acuity.

The cataract surgical procedure

Cataract surgery is performed in local anesthesia and the operation is done under a microscope. Millimeter large incisions are made to let instruments enter the eye. Viscoelastics is injected into the eye to keep the anterior chamber stable. A microforceps or a cystotome is used to create a flap on the anterior capsule of the lens. The forceps is used to pull the flap and create a round opening in the capsule, the capsulorhexis (Fig. I). Hydrodissection is performed by injecting fluid between the lens and the
capsule to make the lens mobile and movable in the capsule (Fig. II). By using phacoemulsification energy, the lens is divided into smaller parts and consumed with the probe (Fig. III). The lens capsule is cleaned with an irrigation and aspiration device and the lens is thereafter inserted into the capsular bag. All remaining viscoelastics is removed before the incisions are hydrated and made tight sealed.

Figure I. Capsulorhexis
Figure II. Hydrodissection

Figure III. Phacoemulsification
INCREASED DEMAND FOR SAFE TRAINING OF ASPIRING INTRAOCULAR SURGEONS

More operations being performed leads to an increased need for training of new eye-surgeons. At present, an estimated number of 30 surgeons are under training for cataract surgery in Sweden today. In the aviation industry, pilots are trained in simulators before flying new airplane models. They are evaluated in several steps and have to prove proficiency before flying new airplanes. Airline simulators play an important part in this training. Such a standard does not exist for new intraocular surgeons. Training of aspiring surgeons is time consuming and the risk for complications such as posterior capsular rupture, are considerably higher for new cataract surgeons compared with experienced ones. Cataract surgeons under training also show a less efficient operative technique and use more phacoemulsification energy. Phacoemulsification energy has a negative effect on the corneal endothelium. These facts altogether makes it preferable to move the learning curve for new eye-surgeons out of the operating room.

![Figure IV. The anatomy of the eye](image)

Training of new surgeons has traditionally taken place via a master-apprentice model. The apprentice has learned by being instructed by a master and the master has been the guarantee for appropriate learning and progress being made. Disadvantages with this type of training and demands from the American Accreditation Council for Graduate Medical
Education\textsuperscript{20} has advocated a focus on competence in surgical training. In all, there is a trend and ambition to move towards a more competency based curriculum\textsuperscript{21,22} instead of the master-apprentice model.

MICROSURGERY AND STEREOCUITY

It might be considered intuitive that a good feeling of depth would be advantageous in microsurgery. Stereocuity is not the same as feeling of depth though. To sense depth, monocular depth cues such as shadows, linear perspective, gradient and texture play a role\textsuperscript{23,24}. Binocular depth cues such as accommodation and convergence can also be used to determine whether and object is close or far away\textsuperscript{24}. Stereocuity develops in early infancy and is fully developed at the age of 5-7 years\textsuperscript{23}. Stereocuity of 30-40 sec of arc is regarded normal\textsuperscript{23}. Stereopsis decreases with age and of individuals over 65 years, only a quarter have normal stereocuity\textsuperscript{25}.

Several methods exist for measuring stereocuity. Standard plates such as Titmus, Frisby and TNO are frequently used but computer-based procedures are sometimes also applied in studies\textsuperscript{26}. Random dot stimuli are regarded as “gold standard” for measuring stereocuity\textsuperscript{27}. In studies using several different stereocuity measurements, TNO usually receives the highest thresholds compared to other tests\textsuperscript{27,28}. TNO is a random dot test where red-green glasses are used to separate the images presented to each eye. It contains no contour specific information in the picture and the stereotarget is not visible by monocular visible contours. This is considered to be the explanation for TNO being more difficult compared to for example Titmus\textsuperscript{27}.

In a British cohort, the prevalence of deficient stereocuity defined as above 40 sec of arc was 14%\textsuperscript{29}. In a study by Rawlinson et al. investigating the stereocuity threshold levels among dental students, they found that 26% of students had a stereocuity threshold level above 60 seconds of arc\textsuperscript{26}. As mentioned above, stereocuity is diminished in older individuals but again this effect is most marked using TNO stereocuity test\textsuperscript{27}. It is suggested that this might be because of a failure to obtain and maintain fusion rather than a true loss of stereopsis\textsuperscript{27}.

It is known that stereocuity is of value for humans especially in near vision and where complex hand-eye coordination is involved\textsuperscript{23}. The function of vision is measured on applicants for several professions involving public safety (pilots, police officers, sea captains, fire fighters). No such visual standard exists for screening professionals in medicine but there is a positive attitude towards visual screening\textsuperscript{31}. In a survey, 80% of ophthalmologists felt that there was a need for screening of new candidates.
for residency\textsuperscript{31}. Some countries do have restrictions for their eye doctors; in the Czech Republic normal stereoacuity is mandatory for becoming an intraocular surgeon, and in the Netherlands stereoacuity is measured on all residents before entering into ophthalmology. The scientific base for such exclusions in ophthalmology is not fully investigated though. Several studies have elucidated the effect of stereoacuity on motor skills. Amblyope children have been found to perform poorer than control subjects on some fine motor skills\textsuperscript{32}. On a dexterity test, Murdoch et al. found that normal individuals performed better than those with no stereoacuity\textsuperscript{33}. Other studies have investigated the motoric skills of grasping and catching, where bad stereoacuity makes grasping objects more difficult\textsuperscript{34} and where the success of catching a ball is favorable for those with normal stereoacuity\textsuperscript{35}. In the latter study they also saw that with training, there was no improvement for those individuals with bad stereoacuity.

In surgical training studies have shown that individuals with deficient stereoacuity perform worse than normal subjects on basic laparoscopic skills training\textsuperscript{36,37} and that the difference remained also after training\textsuperscript{37}. Having found these results on fine motor tasks one would expect that working with microscope would be more difficult for individuals with deficient stereoacuity. However, Grober et al did not manage to show a correlation between the level of stereoacuity and performance on a microsurgical skills task\textsuperscript{26}.

Initial data has shown that strabismic patients with bad or no stereoacuity performed worse than normal controls on an intraocular surgical simulator\textsuperscript{38}, but if there is a correlation between level of stereoacuity and performance is not known. Also, a study by Rossi et al showed that individuals with better stereoacuity performed better on the same intraocular surgical simulator training device for the posterior segment\textsuperscript{39}. A confounding factor in their study though was that the vitreoretinal surgeons also had better stereoacuity.
INVESTIGATING VALIDITY AND USABILITY OF A VIRTUAL REALITY INTRAOCULAR SURGICAL SIMULATOR

1. INTRODUCTION TO THE STUDIES

1.1 Training of new surgeons

Training of new intraocular surgeons is costly and time consuming\(^{40}\). Learning cataract surgery demands well-developed psychomotor skills and data shows that around 10\% of aspiring surgeons have difficulties in acquiring surgical skills\(^{22}\). Development of surgical training programs in ophthalmology is still in an early phase and only a few have been published\(^{41-44}\). Validated detailed programs for follow up of improvement of post-operative results on an individual base, are rare\(^{45}\). Assessment of trainees in intraocular surgery training is still in its early stages\(^{13,46-49}\) and only few assessment tools have been thoroughly validated\(^{50-53}\). Furthermore, validation of training programs is incomplete\(^{13,54}\). Today, training takes place on scarce wet-lab training occasions\(^{42,55-58}\) but mainly the training is done in the operating room on real patients\(^{39,60}\).

Capsulorhexis (where the anterior lens capsule is opened) and phacoemulsification (where ultrasonic energy is used to fragment the opaque lens into smaller pieces and with vacuum remove the pieces out of the eye) are the two procedures in a cataract operation that most trainees find difficulties in handling\(^{61}\). For surgical training to be efficient, it has to focus training on improving difficult parts\(^{62}\). The psychologist Ericsson has studied individuals that on different areas possess a high level of expertise. What they all have in common is that they have sacrificed an enormous amount of time to deliberate practice. For training to be efficient, it also needs to be distributed in time\(^{53,64}\). Surgical simulators provide possibilities of deliberate and distributed training. They are easy to use without tedious preparations and set-up lead times. Specific parts of an operation can be trained intensely without limitations. Performance can be assessed and progress can be measured. Lack of progression can call for intervention, and performance can be compared with previously set target criteria and not with peers.

1.2 Simulators for training of intraocular surgery

Surgical simulators have been used in other surgical fields for training and reports have shown that training has improved performance on real
Simulators for intraocular surgery is still in an early phase of development even though some systems have been presented. For intraocular surgery, two commercially available virtual reality simulators have been presented: Eyesi (VRmagic, Germany) and PhacoVision (Melerit, Sweden). PhacoVision is a simulator for training of cataract surgery. Eyesi is a simulator with possibilities to train both cataract surgery and posterior segment surgery.

For a surgical simulator to be included into a training curriculum, it needs to be evaluated for how well it imitates the reality it should simulate, “construct validity”. It is usually measured by comparing performance between individuals with different surgical experience. How well a simulator scoring measures the performance is called “concurrent validity”. This is examined by comparing the simulator evaluation system with another already used method for evaluation.

For the Eyesi simulator, initial reports have shown construct validity for capsulorhexis (where the anterior lens capsule is opened), but no reports have investigated other procedural modules in the simulator. Furthermore, the learning curves for these modules have not thoroughly been investigated. No studies have addressed concurrent validity.

Individuals learn at different pace and have different innate abilities when training starts. Sex is said to be one factor that affect surgical simulator training whereas other reports have shown no such differences. As shown above, stereoacuity has also been considered as a factor to influence surgical skill. Initial data has shown that strabismic patients with bad or no stereoacuity performed worse on an intraocular simulator, but if there is a correlation between performance and level of stereoacuity is not known. Previous video-game experience and visuospatial ability are additional factors that have been reported to influence surgical performance but their role in intraocular surgical training is unknown.
2. AIM OF THE THESIS

- To investigate construct validity of Eyesi, a simulator for training of intraocular surgery
- To investigate concurrent validity of Eyesi modules
- To investigate learning curves on Eyesi for specific modules
- To investigate factors that can influence performance of intraocular surgery using an intraocular surgery simulator
3. MATERIAL AND METHODS

3.1 EYESI INTRAOCULAR VIRTUAL REALITY SURGICAL SIMULATOR

For the purpose of this study, the Eyesi simulator for intraocular surgery was used. The simulator consists of a mounted eyepiece on a mannequin head. There is one head for training for cataract surgery, and one head for training of vitreoretinal surgery. Instruments or “probes” are inserted into the eye and cameras inside the eye detect the movements of the probes. The movements are processed in a computer and a three dimensional stereoscopic image is projected on two oculars mimicking a real operations microscope. The same image is also shown on an observer screen (Fig. V).

![Image of the Eyesi surgical simulator](image)

**Figure V.** Student training in the Eyesi surgical simulator.

Several different training modules are available for each of the two simulator heads. The modules are both procedure specific modules for cataract surgery and vitreoretinal surgery, and manipulating modules for the two different types of surgery. Furthermore, each module is also available in different levels of difficulty. The modules used in this study are presented in table I and shown in fig. VII and VIII.
Table 1. Description of anterior chamber modules

<table>
<thead>
<tr>
<th>Module</th>
<th>Level</th>
<th>Description</th>
<th>Used in paper</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capsulorhexis</td>
<td>1</td>
<td>A flap is already present. The trainee has to form and complete a capsulorhexis</td>
<td>IV</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>The trainee has to inject viscoelastics into the anterior chamber and create a flap and form a capsulorhexis.</td>
<td>I, II, III</td>
</tr>
<tr>
<td>Hydromaneuvers</td>
<td>1</td>
<td>The trainee places a cannula under the rhesis edge and injects liquid solution in order to create a visible fluid wave in the cortex. Afterwards, the trainee rotates the nucleus proving that an appropriate hydrodissection has occurred.</td>
<td>I, III</td>
</tr>
<tr>
<td>Phaco divide and conquer</td>
<td>5</td>
<td>The trainee has to create groves in the nucleus, crack the nucleus into quadrants, and finally consume the quadrants with ultrasonic energy using phacoemulsification.</td>
<td>I, III</td>
</tr>
<tr>
<td>Cataract forceps training</td>
<td>3, 4</td>
<td>With forceps, the trainee has to move small triangles into a fictive basket. When put in place, the triangles turn green.</td>
<td>I, IV</td>
</tr>
<tr>
<td>Cataract navigation training</td>
<td>2, 3</td>
<td>The trainee has to hold a probe still inside of spheres until it turns green (1-2 sec). The spheres are scattered at different levels in the anterior chamber.</td>
<td>I, IV</td>
</tr>
<tr>
<td>Cataract cracking and chopping training</td>
<td>6</td>
<td>The trainee has to pull each end of a handle simultaneously thereby elongating it into a given length.</td>
<td>I</td>
</tr>
</tbody>
</table>
Validity and usability of a virtual reality intraocular surgical simulator

Figure VII. Procedure-specific modules: capsulorhexis, hydromaneuvers and phaco divide and conquer.

Figure VIII. Manipulating modules: cataract navigation training, cataract forceps training and cataract cracking and chopping training.

Video clips from procedure-specific modules can be seen on http://www.eyesifilmer.eyelearn.se.

For each task, the simulator calculates a performance score between 0 and 100 as a judgment of how well the task was performed. The score is a sum of several parameters that reflects performance of to what extent the task was accomplished, how the instruments were handled, time efficiency, tissue damage and microscope usage. Several performance based parameters can be achieved afterwards in an excel spreadsheet but how the overall score is calculated is not fully disclosed by the manufacturer.

3.2 Simulator film evaluations
Recorded of performance on modules capsulorhexis, hydromaneuvers and phaco divide and conquer were evaluated with regard to cataract surgical skill in paper I, II and III. The recorded video clips were anonymously analyzed with the Objective Assessment of Cataract Surgical
Skill (OSACSS) tool[^6] in applicable parts and modified Objective Assessment of Surgical Skill (OSATS) tool[^8]. OSACSS is a procedure specific evaluation tool where different parts of a cataract operation is evaluated and given a score of 1 to 5 based on the performance. The OSACSS has been used in real cataract operations and has been shown to differentiate different levels of cataract surgical skill[^50]. OSATS is a general video-based assessment tool that has been used in real operations, laparoscopic surgery[^67,^85] as well as in ophthalmic microsurgery[^86], and has been shown to differentiate surgical skill. OSATS involves judgments regarding precision of operative technique, tissue handling, economy and confidence of movements. Two experienced cataract surgeons who were masked regarding the subjects’ identity evaluated the procedures.

### 3.3 Participants in the Studies

The cataract surgeons in paper I and III have been recruited among practicing surgeons in the local hospital and in the region. They have all given informed consent. Their experience ranged from 15 to over 10,000 operations.

The medical students in the studies were recruited during their ophthalmology rotation on the clinic. The simulation session is part of a mandatory session but the students’ participation in the studies was voluntarily.

None of the study participants had previous experience with the Eyesi surgical simulator.

### 3.4 Stereoacuity

In paper II and III information regarding study participant’s stereoacuity was presented. Threshold stereoacuity was measured using TNO chart plates V to VII (Lameris Ootech BV).

### 3.5 Statistical Analysis

Differences in performance parameters between surgeons and medical students in paper I were tested for statistical significance using the Mann–Whitney U-test. Spearman correlation test was used to analyze correlation between the OSACSS and OSATS video scores and the overall score given by the surgical simulator. Intraclass correlation coefficient was used to determine interrater reliability for the OSACSS and OSATS scoring.

Friedman test was used to analyze learning curves in paper II. Also Wilcoxon signed ranked test was used to compare scores between first and
tenth iteration. Mann-Whitney U-test was used to compare performances between group A and B. Again Spearman correlation test was used to analyze correlation between the OSACSS and OSATS video scores and the overall score given by the surgical simulator.

In paper III ROC curves were plotted and the areas under the curves were compared using an algorithm suggested by DeLong, DeLong and Clarke-Pearson. Interrater reliability was analyzed with intraclass correlation coefficient.

Performance parameters were correlated to level of stereoacuity with Spearman correlation test. For comparisons of performance between men and women, Mann-Whitney U-test was used.

4. RESULTS AND DISCUSSION

4.1 RESULTS AND DISCUSSION PAPER I: EVIDENCE FOR CONSTRUCT VALIDITY AND CONCURRENT VALIDITY

In this paper we decided to investigate construct and concurrent validity of the Eyesi anterior segment cataract surgical simulator. Performance scores were compared between surgeons and medical students. Cataract surgeons received higher simulator scores than naïve on capsulorhexis (Fig. IX), cataract navigation training, cataract forceps training and cataract cracking and chopping training. Analysis also revealed that naïve made more tissue damage on the cornea (capsulorhexis, p = 0.048; cataract forceps training, p = 0.021) and lens (cataract cracking and chopping training p = 0.048). These findings are in accordance with previous studies demonstrating construct validity for capsulorhexis and cataract forceps training. In the latter study they also showed that surgeons made less damage to the cornea, which are findings also supported in our study. In addition we could show evidence for construct validity based on overall score for several modules not previously investigated: manipulating modules cataract navigation training and cataract cracking and chopping training.
On the hydromaneuvers and phaco divide and conquer modules, the overall score did not differ between the two groups and we could notice disappointingly low simulator scores for surgeons on the phaco divide and conquer module. (Fig. IX).

The second iteration on capsulorhexis, hydromaneuvers and phaco divide and conquer was also recorded and evaluated with OSACSS and OSATS tools. The video scores were compared between surgeons and naïve. Surgeons received significantly higher video scores compared to naïve thus showing evidence for construct validity also for the two latter modules (Fig. X).

The video scoring (OSACSS) correlated well with the computer based overall scores for capsulorhexis ($r=0.669 \ p<0.0001$) but only moderately for hydromaneuvers and phaco divide and conquer ($r=0.525 \ p=0.010$, $r=0.566 \ p=0.004$ respectively). Also the OSATS score correlated significantly with the sum of overall score for the three modules above ($r=0.657 \ p=0.001$). Because the OSACSS video evaluation tool has demonstrated construct validity for video-based evaluations of real cataract operations\textsuperscript{10}, it strengthens the concurrent validity of the scoring.
system in the simulator for the capsulorhexis module where the correlation was high. For hydromaneuvers and phaco divide and conquer, the correlation was only moderate and poses questions regarding the innate simulator scoring.

A shortcoming in our study is that it does not include residents. One could argue that residents possess surgical cognitive knowledge that medical students do not have. So, in that case, it could be possible that the differences exposed between surgeons and naive represented by medical students would at least partly constitute of cognitive knowledge differences rather than manual surgical skills. To overcome these discrepancies we recruited the students during their ophthalmology rotation. Before the training started, they received information regarding important structures of the eye and were thoroughly informed of important structures and important parts of the procedures. Before each new module was commenced, they were all shown voice-guided instructional videos where important aspects were pointed out. As a comparison Le et al.\textsuperscript{77} did show a correlation between ophthalmic experience and total score on two manipulating modules (forceps and anti-tremor modules) where they showed that medical students performed worse than the other groups including residents and staff. However, their most junior group of residents had performed 0-15 cataract surgeries and also several of them had previous experience with the Eyesi simulator making this group not representative of non-surgically experienced residents.

We did use a non-parametric approach when analyzing the data. The simulator overall scores were truncated and not normally distributed.

---

**Figure X.** Comparison between cataract surgeons (dark blue) and naive (light blue) during second iteration of capsulorhexis, hydromaneuvers and phaco divide and conquer measured by OSACSS. Median = thick horizontal line, boxes = 25 and 75% percentiles, whiskers = min and max.
regarding overall score for the naïve group in modules capsulorhexis and phaco divide and conquer and thus not appropriate for a parametric statistical analysis. For hydromaneuvers the parametric approach could have been used but we decided to treat data consistently between the different modules thus using non-parametric statistics for all analyses.

4.2 Results and Discussion Paper II: The Surgical Performance Improves with Training, Evidence for Concurrent Validity of the Capsulorhexis Procedure

The purpose of this study was to investigate learning curves on two modules, cataract navigation training and capsulorhexis. Furthermore, we wanted to investigate whether training in one module affected performance on the other, and study the concurrent validity of capsulorhexis. As a pilot study, students’ level of stereoacuity was also measured.

The modules used in this study were chosen for being one manipulating module and one procedure specific module. For the manipulating module cataract navigation training, a plateau was reached already after three iterations regarding overall score (Fig. XI) and the students reached surgeon proficiency levels (Paper I) indicating a rapid learning, something that has been found in other surgical simulators as well. For capsulorhexis, the overall score learning curve did not reach a plateau (Fig. XI) and the levels were far from the scores of surgeons (54, Paper I). Being a different simulator software version used in paper I, the results are not completely comparable, but gives a hint of what level to strive for. Capsulorhexis is considered to be one of the most difficult steps in a cataract operation for new surgeons to master so it is not surprising that more than ten iterations would be needed to capture this skill. Furthermore, ten iterations on the same level of difficulty might not be the optimal training schedule. Gradually increasing difficulty might be a better approach.

As shown in paper I, one of the differences found between naïve and skilled surgeons was that the naïve made more damage to intraocular structures such as the corneal endothelium and the lens. In laparoscopic operations it has been shown that tissue damage on real operations was less likely to occur in a VR-trained group. In our study, with training, the students learned how to handle instrument with more caution and efficiency leading to less injuries to cornea and lens. This indicates that the simulator might be part of early training of new cataract surgeons.
Training in one module did not significantly affect score in the other showing that training improves somewhat different skills.

Evidence for concurrent validity was found for capsulorhexis ($r = 0.704$, $p < 0.0001$).

Looking into detail at each individual’s overall score learning curve for cataract navigation, one could notice that skills at baseline vary between individuals. We could see that some individuals showed improvement
during the training, others performed good at baseline and therefore did not improve considerably. Yet others showed generally low scores with no improvement or a few scores with good results and after that no improvement or even stagnation. This might be due to pure luck with one or two iterations or maybe they were just slow learners and ten iterations might not be enough for them to excel. For a couple of individuals, exhaustion was seen at the end of the training. The training took place during one session that lasted one hour and for a non-trained individual that could be a long time to train without a pause.

Grouping of individuals based on their learning curves has been considered. Curve fitting is one statistical model to illustrate and quantify learning. In our case, using a linear curve is not appropriate since it has no limit or plateau. The same is true for a logarithmic or power curve. An inverse curve and an S-curve have plateaus and slopes. We decided to use a non-linear regression model with an inverse curve \((y=a-b/x)\) to fit with our learning curves. Thereby, it would be possible to characterize each individual’s learning curve by two figures: the asymptote (where the end training would aim at) and the slope (the rate of progression)\(^9\). In our curve “a” would represent the asymptote and “b” the slope. Applying this approach to the learning curves for overall score of cataract navigation training gave a reasonable curve fit for six of the 17 curves with \(r^2>0.35\) (Fig. XII).

Another approach to handle learning curves is to try to group individuals based on their performance throughout training. Schijven et al grouped their individuals into four categories based on their innate abilities and gain through VR training\(^9\). Using the same approach and grouping of individuals based on their learning curves on the cataract navigation training module overall score is shown in table II and fig. XIII. The four respective groups are also marked with colors in fig. XII.

For capsulorhexis, the overall scores showed a similar pattern as for cataract navigation training with a lot of individual variations. Some learning curves showed incremental improvement whereas other curves did not improve or showed inconclusive improvement. Also here was an exhaustion phenomenon seen for three individuals. Looking at the scores
throughout the iterations, a blunt scaling rendering many iterations 0 score is noticeable. As is seen in paper I, this raises questions regarding the perfection of the scoring parameter overall score in the simulator. Comparing with the videoscoring, there was decent correlation between the simulator score and the OSACSS video-based score, but as also seen in paper III, the video-based score was more accurate in detecting surgical skill for the capsulorhexis (ROC area 0.887 compared to for 0.761 simulator innate score) pointing towards an improvement potential in the scoring for the capsulorhexis module.

Trying to group individuals based on their innate abilities and gain with VR training using the overall score is difficult and not meaningful due to the nature of the scoring (blunt scaling, imperfect scoring). Comparing the learning curves to inverse and S, only 2 of the 18 curves significantly fitted to a curve. Again, this is judged to be due to an innate insufficient scoring and not due to a non-existing learning. Overall, the inverse curve gave the best fit (8 out of 18) for the group as a whole (Fig. XII).

Our study subjects all took a stereoacuity test. We could see a trend in difference between individuals with normal and subnormal stereoacuity in performance scores on the simulator working favorable for those with normal stereoacuity. These results lead to the initiation of the study presented in paper IV.

![Figure XII](image.png)
Table II. Grouping of individuals based on their performance on cataract navigation training.

<table>
<thead>
<tr>
<th>Group</th>
<th>Group description</th>
<th>Profile description</th>
<th>Participants</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(blue) High level of innate abilities, gaining little extra improvement</td>
<td>mean score &gt;70, SD&lt;13.2</td>
<td>6, 8</td>
<td>12</td>
</tr>
<tr>
<td>2</td>
<td>(green) Moderate levels of innate abilities, gaining improvement</td>
<td>mean score 60-70, SD 13.3-15</td>
<td>3, 4, 11, 15</td>
<td>24</td>
</tr>
<tr>
<td>3</td>
<td>(pink) Moderate levels of innate abilities, gaining some improvement</td>
<td>mean score 50-73, SD &gt;15, all last three iterations &gt;30</td>
<td>1, 2, 7, 10, 14</td>
<td>29</td>
</tr>
<tr>
<td>4</td>
<td>(orange) Low levels of innate abilities, improvement not demonstrated</td>
<td>mean score 0-49, SD&gt;15, one or more of last three iterations &lt;30</td>
<td>5, 9, 12, 13, 16, 17</td>
<td>35</td>
</tr>
</tbody>
</table>

SD=standard deviation
Figure XIII. Learning curves for individuals divided into four groups based on their performance. Group 1 high level of innate abilities, gaining little improvement (blue). Group 2 moderate level of innate abilities, gaining improvement (green). Group 3 moderate level of innate abilities, gaining some improvement (pink). Group 4 low level of innate abilities, improvement not demonstrated (orange).
4.3 Results Paper III: The Simulator Scoring System Needs Improvement for Hydromaneuvers and Phaco Divide and Conquer Modules

Based on the results in paper I, further analysis was made to analyze the possibility of using the simulator score for assessment for the cataract specific modules capsulorhexis, hydromaneuvers and phaco divide and conquer. ROC curves for these modules were plotted for simulator based scoring and compared with video-based scoring. The areas under the curves were compared between simulator score and video-based scoring. To our knowledge, this is the first report evaluating a simulator with regard to performance score using ROC curve analysis.

The ROC areas were higher for video scoring for all modules observed, significantly so for phaco divide and conquer (p=0.01) (Fig. XIV). In addition, the simulator scoring for the ROC area for hydromaneuvers and phaco divide and conquer, did not differ from hazard judgment and thus were not significantly different from 0.5. Thus, analysis showed that video scores were significantly better as a discriminating tool for cataract surgical skill. Possible explanations for these differences might be that the video-based scaling is smoother. The simulator score has a narrow window of success making a small mistake as vulnerable as a large, often rendering a 0 score thus making discrimination impossible. Furthermore, it seems that video examinations detect skills that are not captured by the inert simulator scoring; video assessment does not only capture surgical mistakes, but also identifies potentially hazardous situations.

This altogether points towards a need for further development of the simulator, perhaps not necessarily on the modules but on the scoring. Today, many institutions have acquired an Eyesi surgical simulator for training. Many also use the simulator for assessment. Our study indicates caution towards using the hydromaneuvers and phaco divide and conquer modules for assessment since the scoring seems to be hazardous. Meanwhile, perhaps the somewhat tedious but accurate assessment would be to analyze the video recordings from the simulator.
Figure XIV. ROC-curves for simulator score and video-based score respectively for modules capsulorhexis, hydromaneuvers and phaco divide and conquer. Videoscore better than simulator score in phaco divide and conquer module.

4.4 Results and Discussion Paper IV: Performance correlates with level of stereoacuity. No sex difference

As indicated in paper II, stereoacuity seemed to affect performance in the surgical simulator. That good stereoacuity could be advantageous in cataract surgery might seem intuitive and in some countries normal stereoacuity is mandatory for ophthalmic surgeons. We let 70 medical students train in the simulator. They performed one iteration on each of the modules cataract navigation training, cataract forceps training and capsulorhexis.
As a previous study had shown a difference between normal and strabismic patients in intraocular surgery training, our report is the first to demonstrate a correlation between the level of stereoacuity and performance and this on a group more prone to become cataract surgeons than strabismic patients. In this study, we could demonstrate a correlation between the level of stereoacuity and performance on two manipulating modules on the Eyesi surgical simulator, cataract navigation training ($r=0.377$, $p=0.001$) and cataract forceps training ($r=0.306$, $p=0.01$) but not on capsulorhexis ($r=0.18$, $p=0.136$). Summation of the overall score for each of the three procedures (cataract navigation training, cataract forceps training, capsulorhexis) also correlated to level of stereoacuity ($r=0.386$, $p=0.001$) (Fig. XV).

A detrimental effect on performance was seen such that the worse the stereoacuity, the worse the performance. Even though our results show a correlation between the level of stereoacuity and surgical performance, it did not give enough evidence for excluding individuals with deficient stereoacuity from training as is done in some countries. Firstly, our study did only involve initial training and did not investigate the effect of prolonged training. Whether these differences remain after further training needs further investigation. A study by Suleman et al., showed that a performance gap on a basic laparoscopy task remained also after simulator training for individuals with deficient stereoacuity. Whether this is applicable on ophthalmic surgery is not known, but it is known though that approximately 10% of residents have difficulties in mastering intraocular surgery. Secondly, the performance scores in the group of individuals with deficient stereoacuity varied such that even though most of them had lower scores, there were individuals that performed on the level of those with normal stereoacuity. Apparently these individuals were compensating their lack of stereopsis with other visual and nonvisual cues. A measurement of stereoacuity would perhaps be interesting though, not for exclusion from surgery, but for guidance regarding a plausible need for more or perhaps different training before reaching good levels of performance. This needs to be investigated further.

As noted, correlation between scores and level of stereoacuity was not found for capsulorhexis but was found for cataract navigation training.
Figure XV. Correlation between level of stereoacuity and sum performance score for modules cataract navigation training, cataract forceps training and capsulorhexis. Median = thick horizontal line, boxes = 25 and 75% percentiles, whiskers = min and max.

and cataract forceps training. Being a more complex procedure, compared to the two manipulating modules, capsulorhexis is dependent on other factors such as understanding of tissue behavior and ability to focus attention not only to the grasping area but also to other areas of interest when moving the forceps. Also, capsulorhexis is performed mostly in one plane and other visual cues might compensate for the lack of stereoacuity. Besides, capsulorhexis was performed on the easiest level of difficulty and perhaps that level was too easy to be able to discriminate differences based on stereoacuity.

In our study, 21 of the 70 (30%) students had a deficient stereoacuity (i.e. > 60 seconds of arc). This is in accordance with the results of Rawlinson where they found that about 24% of dental students had a deficient
Our results, even though being a little higher, still fall into the statistical variation of a prevalence of 0.24 using a p value of 0.05. Comparing with a population based report where Rahi et al. investigated a 1958 British birth cohort, they found an incidence of deficient stereoacuity of 14%\textsuperscript{29}. They tested stereoacuity with Lang II stereo card. This test is known to have low sensitivity in screening so perhaps the real figures are a little bit higher\textsuperscript{93,94}. We chose to use the TNO charts in our study because it does not possess any contour stimulus but rather captures the true disparities. Other tests such as the Titmus and Lang also give contour specific stimuli and that might be one of the explanations for giving better stereoacuity scores on screening\textsuperscript{27}. For our purposes, perhaps a stereoacuity test such at the Titmus might actually have been more relevant since it also takes into account the disparity of real contours in objects and therefore more mimics factors that are important in a real operative setting. Stereoacuity measured with Titmus might have correlated even more with performance than stereoacuity measured with TNO charts.

Exposure time plays a role in perceiving depth on tests\textsuperscript{95}. Our participants were given plenty of time and were free to move to a specially designated light source. Viewing distance was however kept at 40 cm all the time.

An additional explanation to our high threshold levels of stereoacuity among the students might have been the testing conditions. The stereoacuity was measured in the same room in which we also have placed our simulator. This room is situated in a basement with little daylight. The room is well lit and standardized light bulbs have been used in the room. If our testing conditions give higher thresholds than expected, since the TNO score parameter is an analogue measurement, the scale would in this case be shifted a little bit but one would assume that the proportions among the groups would remain unchanged and therefore the correlation with simulator scores would not be affected.

The data in this study was treated as non-Gaussian since the simulator scores were not normally distributed and included truncations. Also the grouping variable threshold level of stereoacuity, however continuous in nature, the threshold grouping of the variable turns it into an ordinal variable making it less suitable for using parametric statistical analysis.

We did not find any difference in performance between men and women among the parameters analyzed. Among previous reports on surgical simulators, a few have shown gender differences but many have shown no
such differences. Previous video exposure and interest in surgical training have been reported as being confounding factors. Our material included a large study group of participants and therefore it is likely that gender effects are negligible in early anterior segment surgical training.
OVERALL DISCUSSION - SIMULATOR TRAINING CAN REPLACE SOME OF TODAYS TRAINING ON PATIENTS

STUDY RESULTS

Training of intraocular surgeons has come into focus. Our first paper describes construct validity for the cataract surgery simulator Eyesi, i.e. the simulator captures skills attributed to cataract surgeons and through our studies we have distinguished levels of proficiency for several modules. For the cataract specific modules, the discrimination between surgeons and naïve subjects based on simulator score was most pronounced for capsulorhexis. On the hydromaneuvers and phaco divide and conquer modules, the simulator scoring had difficulties in distinguishing the two groups. Further analysis in paper III revealed that the ROC curve areas for computer scoring of hydromaneuvers and phaco divide and conquer did not differ from 0.5. Also, analysis showed that video scores were significantly better as a diagnostic tool for cataract surgical skill. This altogether points towards a need for further development of the simulator, perhaps not necessarily on the modules but on the scoring. Today, many institutions have captured an Eyesi surgical simulator for training. Many use the simulator for training, which based on our results would seem reasonable. Many also use the simulator for assessment. Our findings in paper III indicates caution towards using the hydromaneuvers and phaco divide and conquer modules for assessment since the scoring seems to be hazardous. Meanwhile, perhaps the somewhat tedious but accurate assessment would be to analyze the video recording on the simulator. Videoevaluation is an already validated method for assessment.

Training of cataract surgeons is costly and complications are higher for new surgeons. Today, training of new surgeons is based on scarce wet-lab training but mainly on patients. New surgeons that have never operated before, can after training on pig eyes, under supervision perform parts of operations on humans; there has been no alternatives. We have shown that naïve individuals can train in the simulator and improve their scoring with practice (paper II). For other medical fields, such as colonoscopy and laparoscopic surgery, simulator training has shown beneficial effect on early clinical performance. Whether VR training to levels of proficiency does improve real cataract operative performance however is not known. Feudner et al. reported improved performance in wet-lab capsulorhexis for individuals trained in simulator surgery. For real operations, Belyea et al. reported less complications and improved operative performance after
introduction of Eyesi simulator training in their institution. An objection is that this was a retrospective report and several other parameters might have changed thus questioning whether the change was contributed to simulator training only. Despite these objections, most scientific results point towards a beneficial effect of training in surgical simulators, indicating that the learning curve for cataract surgery potentially could be moved out of the operating room with simulator training.

INDIVIDUALIZED TRAINING
As is noticed in our material, skills at baseline vary between individuals and we could see that some individuals with bad stereoacuity (paper II) had difficulties in improving their performance score whereas some individuals reached high levels after just a few iterations. We could also see that the level of stereoacuity correlated with performance on the simulator at initial training (paper IV). This factor may have impact in the recruitment and training of new cataract surgeons. The variations between individuals were however large, such that some individuals despite deficient stereoacuity performed on levels of those with normal stereoacuity. Other studies have shown influence of previous computer experience on performance on VR surgery simulators and some have reported no benefit at all for a group when VR trained. Visuospatial ability is another factor that has shown to affect performance on surgical simulators. Altogether this points towards an individualized training model with predefined target criteria (proficiency levels) instead of the old master-apprentice model that is still widely used for surgical training. Individuals that need more training can be identified and can be given extra possibilities for training. For these purposes, a simulator is well suited for training where difficult parts can be trained separately and intensely, it is possible to repeat exactly and measure improvement, and the deliberate practice approach is easily applicable.

THE STRUCTURE OF TRAINING – COMPETENCE BASED CURRICULUM
How simulation based training should be structured to be efficient have been discussed. It is known that distributed practice works better than massed practice. To receive feedback on progress is also important for learning. Training has to be challenging enough to be efficient. Training has to involve clear goals and it’s important that training is integrated with a curriculum.
Surgical training of new intraocular surgeons internationally is still dependent on the apprenticeship model and there is no reason to believe that the situation is different in Sweden. The cataract registry take notice of complications during cataract surgery for each registered operative unit but no specific database for follow up of surgeons under training exists. As Rogers et al show, the introduction of a structured surgical curriculum has reduced the complications associated with surgery. A national initiative needs to be taken to change the view of surgical training in Sweden. A shift from counting operating cases to measure operative performance and operative outcome has to be done; competence based curriculum has to be designed in which simulator based training together with wet-lab is a part and where surgical progress and outcome is measured and assessed with validated assessment tools such as OSACSS and OSATS.
CONCLUSIONS

• Evidence for construct validity was found for cataract specific modules capsulorhexis, hydromaneuvers and phaco divide and conquer on the Eyesi cataract intraocular surgical simulator. Construct validity was also found for manipulating modules cataract navigation training, cataract forceps training and cataract cracking and chopping training. For the hydromaneuvers and phaco divide and conquer modules, the innate simulator scoring could not distinguish surgical skill but discrimination was dependent on video-based human scoring (OSACSS). Concurrent validity was found for the capsulorhexis module (Paper I).

• Learning curves were investigated for modules capsulorhexis and cataract navigation training. Naïve individuals reached plateau levels of performance on cataract navigation training with ten iterations but not on capsulorhexis even though improvement was evident. Evidence for concurrent validity was reconfirmed for the capsulorhexis module. (Paper II).

• Innate simulator scoring was not different from hazard score for modules hydromaneuvers and phaco divide and conquer. Video-based human scoring was superior to innate simulator scoring on the phaco divide and conquer module (Paper III).

• Stereoacuity was found to correlate with performance on the simulator but there were large individual variations. (Paper IV).

• No differences in performance on the simulator were found between men and women (Paper IV).

• Simulation-based VR cataract surgical training has the potential to move the early training out of the operating room. Future studies need to focus on the correlation between simulation based training and improved operative performance. Future studies should also address the influence of factors such as previous videogame experience and visuospatial abilities on such training.
POPULÄRVTENSKAPLIG SAMMANFATTNING

BAGGRUND VALIDERING OCH ANVÄNDBARHET AV SIMULATOR FÖR TRÄNING AV ÖGONKIRURGI

ÖKAD EFTERFRÅGAN AV ÖGONOPERATIONER

Ökade efterfrågan av ögonoperationer och den tekniska utvecklingen har lett till ökade krav på kvalitet och effektivitet. Detta medför att fler operatörer behöver undervisning och utbildning. Utbildning av blivande ögonkirurger är tidsödande och det finns ett behov av att se till att operationstekniken och effektiviteten förbättras. Utvärdering av simulatorer och andra utbildningsresurser är ett viktigt element för att säkerställa effektiv undervisning och hög kvalitet.

HÖGRE KRAV PÅ KVALITETSKONTROLL

Sedan början av 90-talet har kvalitetsregister för grässtarrskirurgi följt utvecklingen vad gäller kvalitetsindikatorer och komplikationer till grässtarrskirurgi. Krav från Socialstyrelsen såväl som från allmänheten har satt kvalitet i fokus. Komplikationer under och efter kirurgi är kostsamma och skadliga för patienterna; kapselbrott vid grässtarrskirurgi leder till kraftigt ökad risk för näthinneavlossning och efterföljande dålig syn.

ÖKADE KRAV PÅ SÄKER TRÄNING AV BLIVANDE ÖGONKIRURGER


INTRODUKTION TILL STUDIERNA

TRÄNING AV BLIVANDE KIRURGER

Träning av blivande ögonkirurger är tidsödande och kostsam. Att lära sig gråstarrskirurgi kräver väl utvecklade psykomotoriska färdigheter och undersökning visar att ca 10% av blivande kirurger har svårigheter att klara de kirurgiska färdigheterna. Utvecklingen av träningsprogram för ögonkirurger och uppföljning av lärandeprocessen är fortfarande i sin linda och endast ett fåtal är publicerade. Validering är inkomplett. Idag ges möjlighet för träning punktvis i wet-lab men den huvudsakliga tråningen av blivande kirurger sker i operationssalen på verkliga patienter.


SIMULATORER FÖR TRÄNING AV ÖGONKIRURGI

Simulatorer för träning av kirurgiska färdigheter har använts inom allmänkirurgi och man har också visat att sådan träning har förbättrat utfall vid verkliga operationer. Simulatorer för träning av ögonkirurgi är i sin linda även om några system har presenterats. Två kommersiella system finns för träning av ögonkirurgi; Eyesi (VRmagic, Tyskland) och PhacoVision (Melerit, Sverige). PhacoVision är en simulator för träning av gråstarrskirurgi. Eyesi är en simulator med möjlighet att träna både gråstarrskirurgi och bakre segmentskirurgi.

Innan en kirurgisimulator inkluderas i träningsprogram bör den utvärderas för hur väl den liknar den verklighet den skall simulera, ”construct validity” eller konstruktvaliditet. Detta är ofta undersökt genom att utvärdera om utfall för olika övningar skiljer mellan individer med olika kirurgisk kompetens. Vidare undersöks om det finns samstämmighet mellan de bedömningar simulatorn leverar och annan känd mätmetod, ”concurrent validity” eller kriterievaliditet.

För Eyesi kirurgisimulator har rapporter visat konstruktvaliditet för capsulorhexis men inga studier har rapporterat validitet för de andra kirurgispecifika modulerna bl.a. hydrodissektion (då linskärnan lossas från
omgivande bark) och phaco. Vidare är inlärningskurvorna för dessa moduler inte undersökta. Inga studier har undersökt kriterievaliditet.


**ÖGONSIMULATORN EYESI**


**SYFTE**

Målsättning med avhandlingsarbetet har varit att utvärdera Eyesi kirurgisimulator och undersöka hur den kan användas för att träna intraokulärkirurgi. Mer specifikt har avsetts att:

I. undersöka hur väl det går att särskilja kirurgisk förmåga i Eyesi då man jämför kirurger med naiva ("construct validity")

II. undersöka om icke-kirurger kan träna upp sina prestationer i simulatorn

III. utvärdera hur det poängsystem som finns i Eyesi fungerar om man använder simulatorten som bedömningsverktyg för grästarrkirurgisk
IV. undersöka huruvida andra faktorer såsom kön och stereoseende påverkar prestation i Eyesi kirurgisimulator

RESULTAT: SIMULATORTRÄNING KAN FÖRBÄTTRA KIRURGISK FÖRMÅGA FÖR BLIVANDE ÖGONKIRURGER

KIRURGER PRESTERAR BÄTTRE ÄN ICKE-KIRURGER I EYESI (I)


DET GÅR ATT TRÄNA UPP DEN KIRURGISKA FÖRMÅGAN I EYESI (II)
Vi har här visat att det genom att träna i Eyesi går att förbättra resultaten både vad gäller poäng och övriga parametrar. Vävnadsskador ses ofta i tidig kirurgisk träning och man har också visat att simulatorträning inom andra kirurgiska discipliner kan minska dessa skador. I vår studie kunde vi se att med träning minska skadorna på hornhinna och lins. Simulatorn har därför en möjlighet att vara del av den initiala träningen av blivande grästarrkirurgen.

VIDEODEÖMNINGAR SÄKRARE ÄN SIMULATORNS POÄNGSYSTEM (III)


Att använda simulatorns inbyggda poäng för utvärdering av capsulorhexis går bra. För hydromaneuvers och phaco divide and conquer är simulatorpoängen inte bättre än slumpen. Videobaserad poängsättning fungerar bra och är klart bättre än den inbyggda simulatorpoängen och detta talar också för att poängsättningen i simulatorn behöver utvecklas.

PRESTATIONEN KORRELERAR MED STEREOSEENDET – JU SÄMRE STEREOSEENDE DESTO SÄMRE PRESTATION. INGEN SKILLNAD MELLAN MÄN OCH KVINNOR (IV)

Personer med defekt stereoseende kan lära sig att kompensera för sin brist på stereoseende. I capsulorhexisproceduren rör man sig också mest i ett plan, djupseendet kanske inte blir så betydelsefullt i just detta moment.


Vi undersökte också eventuella skillnader i prestation mellan män och kvinnor. Inga skillnader sågs.

**BETYDELSE:** TRÄNING I SIMULATOR KAN ERSÄTTA DAGENS TRÄNING PÅ VERKliga PATIENTER


Träning av blivande ögonkirurger är kostsam och komplikationerna är högre för nya kirurger. Idag sker utbildning av kirurer i viss mån på grasögon men framförallt på patienter. Nya ögonkirurer som aldrig opererat tidigare får efter träning på grasögon och under handledning utföra delar av operationer på människor eftersom det inte har funnits några alternativ. Med effektiv träning i simulatorm finns förhoppning att detta också leder till förbättrade resultat vid verkliga operationer och att en del av inlärmingskurvan därmed kan flyttas ut ur operationssalen.

Det har rapporterats att ca 10% av blivande ögonkirurer har bekymmer med att lära sig de kirurgiska färdigheterna. I våra studier har vi sett att olika individer presterar på olika nivåer, några presterar bättre resultat och andra sämre. Vi har bl.a. sett en korrelation mellan prestation och stereoseende.


Kirurgisk träning för blivande ögonkirurger internationellt förlitar sig fortfarande mycket på lärlingsmodellen och det finns ingen anledning att tro att situationen är annorlunda i Sverige. Gråstarrregistret registrerar komplikationer vid gråstarrskirurgi för varje enhet men ingen särskild databas för uppföljning av resultat för kirurger under träning finns. Man har i en studie visat att införandet av ett strukturerat curriculum för träning, minskat komplikationer vid gråstarrskirurgi. Ett nationellt initiativ kan komma att behöva tas för att förändra synen på kirurgisk träning i Sverige. Ett skifte från att räkna antal operationer till att mäta operationsutfall och kirurgisk förmåga måste ske; kompetensbaserade curriculum måste utformas i vilken simulatortränning tillsammans med wet-lab ingår och där kirurgisk utveckling mäts med validerade bedömningsverktyg.
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Cataract surgeons outperform medical students in Eyesi virtual reality cataract surgery: evidence for construct validity

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ABSTRACT.

Purpose: To investigate construct validity for modules hydromaneuvers and phaco on the Eyesi surgical simulator.

Methods: Seven cataract surgeons and 17 medical students performed capsulorhexis, hydromaneuvers, phaco, navigation, forceps, cracking and chopping modules in a standardized manner. Three trials were performed on each module (two on phaco) in the above order. Performance parameters as calculated by the simulator for each trial were saved. Video recordings of the second trial of the modules capsulorhexis, hydromaneuvers and phaco were evaluated with the modified Objective Structured Assessment of Surgical Skill (OSATS) and Objective Structured Assessment of Cataract Surgical Skill (OSACSS) tools.

Results: Cataract surgeons outperformed medical students with regard to overall score on capsulorhexis (p < 0.001, p = 0.035, p = 0.010 for the three iterations, respectively), navigation (p = 0.024, p = 0.307, p = 0.007), forceps (p = 0.017, p = 0.03, p = 0.028). Less obvious differences in overall score were found for modules cracking and chopping (p = 0.266, p = 0.022, p = 0.324) and phaco (p = 0.011, p = 0.081 for the two iterations, respectively). No differences in overall score were found on hydromaneuvers (p = 0.588, p = 0.503, p = 0.773), but surgeons received better scores from the evaluations of the modified OSATS (p = 0.001) and OSACSS (capsulorhexis, p = 0.003; hydromaneuvers, p = 0.017; phaco, p = 0.001).

Conclusions: Construct validity was found on several modules previously not investigated (phaco, hydromaneuvers, cracking and chopping, navigation), and our results confirm previously demonstrated construct validity for capsulorhexis and forceps modules. Interestingly, validation of the hydromaneuvers module required OSACSS video evaluation tool. A further development of the scoring system in the simulator for the hydromaneuvers module would be advantageous and make training and evaluation of progress more accessible and immediate.

Key words: cataract surgery – construct validity – simulator – virtual reality

Introduction

Learning cataract surgery is a timely assignment. Besides requiring resource intense training, inexperienced cataract surgeons also have more complications than more experienced ones (Randleman et al. 2007). Capsulorhexis and phacoemulsification are considered to be the most difficult steps for a new cataract surgeon to handle (Dooley & O’Brien 2006). It would be preferable if the initial learning of these steps could take place in a safe and standardized simulated environment instead of in the operation theatre where standardization is difficult if not impossible, and patient safety is compromised. For some time, surgical simulators have been used to train and assess surgical skills (Thijssen & Schijven 2010). For cataract surgery, a few simulators have been presented (Laurell et al. 2004; Mahr & Hodge 2008; Choi et al. 2009), and the Eyesi surgical simulator (VR Magic AG, Mannheim, Germany) has been partly evaluated for validity (Mahr & Hodge 2008; Privett et al. 2010; Selvander & Åsman 2010; Le et al. 2011).

In a retrospective study, Belyea et al. (2011) recently found better phacoemulsification usage in real operations associated with training in a virtual reality eye surgery simulator. It has been shown that, for the capsulorhexis procedure, experienced cataract surgeons perform better than
residents on the Eyesi surgical simulator (Privett et al. 2010). So far though, no studies have reported the validity and training effects specifically for the hydromaneuvers and phaco divide and conquer modules. The aim of this study was to investigate the construct validity for these modules.

Material and Methods

Seven cataract surgeons and seventeen medical students participated in the study. The group of surgeons were recruited on a voluntarily basis and they were practicing at the Skåne University Hospital or at a local hospital in the region. Five of them had performed 800–10 000 cataract operations, one had performed over 150 cataract operations, and one had done 18 cataract operations. The group of students were attending their 9th semester and were recruited during their 6-week ophthalmology rotation.

The students were given a brief orientation on important anterior chamber structures before the simulator training started. Both the students and the surgeons were instructed in a standardized manner on the function of the simulator. None of the students had previous experience with this or any other intraocular surgical simulator. One of the cataract surgeons had several years before been exposed to an intraocular surgical simulator for demonstration purposes only. The other six surgeons had not trained in an intraocular surgical simulator before.

Surgical simulator

To evaluate the study participants’ cataract surgical skills, the intraocular surgical simulator, Eyesi, was used. This simulator has previously been described (Selvander & Asman 2010), and for this study, the cataract head with a model eye for cataract surgery was used. Probes are inserted into a model eye and a virtual binocular image is created. The image is shown through two oculars giving an image of the anterior segment. Software version 2.5 was used.

Three cataract modules and three manipulating modules were used. The level for each module was chosen based on a pilot study so that tasks would be difficult enough to enable discrimination based on surgical skill and be as close as possible to reality. Cataract modules: the capsulorhexis module (level four of ten) where the trainee has to inject viscoelastics into the anterior chamber, create a flap with a cystotome and pull the flap and perform a capsulorhexis with a forceps (Fig. 1A); the hydromaneuvers module (level one of four) where the trainee has to make a hydrodissection of the lens and move the nucleus around to prove that a dissection has been obtained (Fig 1B); the phaco divide and conquer module (level five of six) where the trainee has to divide a nucleus into four quadrants and thereafter remove and emulsify each quadrant with the phaco probe (Fig. 1C). Manipulation modules: the cataract navigation training module (level two of three) where the trainee has to hold an instrument tip steady in mobile spheres scattered at different levels in the anterior chamber (Fig. 2A); the cataract forceps training module (level four of four) where the trainee has to make triangles lying on top of the lens into a fictive basket sitting in the middle of the anterior chamber (Fig. 2B); the cataract cracking and chopping module (level six of eight) where the trainee has to pull each end of a handle simultaneously thereby elongating it into a given length (Fig. 2C).

The tasks were performed at a single 60 min session in the above given order three times each except for the phaco divide and conquer module in which two iterations were performed. Several different performance parameters were calculated in the simulator scoring system. A summary parameter (overall score) was obtained for all iterations. For the second iteration, additional parameters were also obtained (Table 1).

The sessions on the simulator were video recorded as seen on the observer screen (Fig. 3). The video recordings from the second iteration of the capsulorhexis, hydromaneuvers and phaco divide and conquer modules were saved for later evaluation. Because of a technical error, the module hydromaneuvers was not recorded for one of the students. For all the other participants, the appropriate modules were recorded.

Video evaluation

The recorded video clips were analyzed with regard to surgical skills with the Objective Structured Assessment of Cataract Surgical Skills (OSACSS) (Saleh et al. 2007) in applicable parts and a modified Objective Assessment of Surgical Skill (OSATS) (Ezra et al. 2009). Two experienced cataract surgeons, who were masked regarding the subjects’ identity, evaluated the procedures. The OSACSS video anal-

Fig. 1. Three cataract modules were used. (A) Capsulorhexis module: a capsulorhexis is performed, (B) hydromaneuvers module: hydrodissection is created and tested, (C) phaco divide and conquer module: phacoemulsification of the nucleus.
The analysis of real cataract operations has construct validity for cataract surgical skill (Saleh et al. 2007). It has also been used to evaluate capsulorhexis procedures on the Eyesi system (Selvander & Asman 2010). The modified OSATS has been used for the evaluation of surgical skills in other surgical areas (Grantcharov et al. 2004) as well as in ophthalmic surgery (Ezra et al. 2009) and has also been used to score capsulorhexis procedures on the Eyesi system (Selvander & Asman 2010).

### Statistical analysis

Differences in performance parameters between groups were tested for statistical significance using the Mann–Whitney U-test. Spearman correlation test was used to analyse correlation between the OSACSS and OSATS scores and the overall score given by the surgical simulator. Intraclass correlation coefficient was used to determine interrater reliability for the OSACSS and OSATS scoring.

### Results

Cataract surgeons outperformed medical students with regard to overall score on the modules capsulorhexis (p < 0.001, p = 0.035, p = 0.010 for the tree iterations, respectively), cataract navigation training (p = 0.024, p = 0.307, p = 0.007), cataract forceps training (p = 0.017, p = 0.03, p = 0.028). Less obvious differences in overall score were found for modules cataract cracking and chopping training (p = 0.266, p = 0.022, p = 0.324) and phaco divide and conquer (p = 0.011, p = 0.081 for the two

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**Table 1.** Comparison of performance parameters between cataract surgeons and medical students' second iteration (median, range).

<table>
<thead>
<tr>
<th>Module: Capsulorhexis</th>
<th>Cataract surgeons</th>
<th>Medical students</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall score (of 100)</td>
<td>54 (0–75)</td>
<td>0 (0–78)</td>
<td>0.035*</td>
</tr>
<tr>
<td>Average radius of capsulorhexis value</td>
<td>2.27 (2.09–3.21)</td>
<td>2.43 (1.58–3.02)</td>
<td>0.589</td>
</tr>
<tr>
<td>Centering (distance rhexis centre to eye centre)</td>
<td>0.39 (0.04–0.49)</td>
<td>0.56 (0.27–2.19)</td>
<td>0.065</td>
</tr>
<tr>
<td>Deviation of rhexis radius from 2.5 mm</td>
<td>0.26 (0.08–0.71)</td>
<td>0.28 (0.01–0.92)</td>
<td>0.949</td>
</tr>
<tr>
<td>Injured cornea area value</td>
<td>0 (0–0.67)</td>
<td>0.56 (0–16.3)</td>
<td>0.048*</td>
</tr>
<tr>
<td>Maximum radial extension of capsulorhexis value</td>
<td>2.66 (2.57–3.73)</td>
<td>3.59 (2.5–4.62)</td>
<td>0.098</td>
</tr>
<tr>
<td>Roundness of capsulorhexis value</td>
<td>0.553 (0.01–0.71)</td>
<td>0 (0–0.95)</td>
<td>0.099</td>
</tr>
<tr>
<td>Time (with instruments inserted) duration (second)</td>
<td>118 (73–425)</td>
<td>170 (93–373)</td>
<td>0.153</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Module: Hydromaneuvers</th>
<th>Cataract surgeons</th>
<th>Medical students</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall score (of 100)</td>
<td>86 (54–90)</td>
<td>81 (44–90)</td>
<td>0.503</td>
</tr>
<tr>
<td>Injured cornea area value</td>
<td>0 (0–0.722)</td>
<td>0 (0–0.57)</td>
<td>–**</td>
</tr>
<tr>
<td>Time (with instruments inserted) duration</td>
<td>21 (17–37)</td>
<td>25 (9–104)</td>
<td>0.408</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Module: Phaco divide and conquer</th>
<th>Cataract surgeons</th>
<th>Medical students</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall score (of 100)</td>
<td>0 (0–95)</td>
<td>0 (0–76)</td>
<td>0.081</td>
</tr>
<tr>
<td>Injured cornea area value</td>
<td>0 (0–0.722)</td>
<td>0 (0–0.57)</td>
<td>–**</td>
</tr>
<tr>
<td>Time (with instruments inserted) duration</td>
<td>373 (263–480)</td>
<td>399 (207–590)</td>
<td>0.092</td>
</tr>
<tr>
<td>Ultrasonic energy value</td>
<td>444 (341–743)</td>
<td>536 (117–883)</td>
<td>0.874</td>
</tr>
<tr>
<td>Ultrasonic leakage value</td>
<td>372 (238–608)</td>
<td>414 (105–994)</td>
<td>0.874</td>
</tr>
<tr>
<td>Emulsification near capsule no events</td>
<td>3 (0–6)</td>
<td>6 (0–22)</td>
<td>0.051</td>
</tr>
<tr>
<td>Posterior capsule torn no events</td>
<td>1 (0–5)</td>
<td>4 (0–10)</td>
<td>0.063</td>
</tr>
<tr>
<td>Successful cracking attempts value</td>
<td>2 (1–3)</td>
<td>0 (0–3)</td>
<td>0.014*</td>
</tr>
</tbody>
</table>

**Table 2.** Statistical significance.

---

*Statistical significance.

**Too many zeros allow for meaningful statistical analysis.
iterations, respectively). No differences in overall score were found on the hydromaneuvers module ($p = 0.588$, $p = 0.503$, $p = 0.773$) (Fig. 4).

Analysing the second iteration in detail, it could be noted that naïve trainees made more damage to the cornea (capsulorhexis, $p = 0.048$; cataract forceps training, $p = 0.021$) and lens (cataract cracking and chopping training $p = 0.048$) during training (Table 1). For the cataract forceps module, naïve trainees had higher odometer and time duration value than the surgeons had ($p = 0.008$; $p = 0.024$) and during the phaco procedure, their cracking attempts were less successful ($p = 0.014$) (Table 1).

The difference between surgeons and students was also evident on the video evaluations of the capsulorhexis, hydromaneuvers and phaco procedures where surgeons received significantly higher and thus better scores from the evaluations of the modified OSATS ($p = 0.001$) and OSACSS (capsulorhexis, $p = 0.003$; hydromaneuvers, $p = 0.017$; phaco divide and conquer, $p = 0.001$) (Table 2).

Statistical analysis revealed significant correlations between the overall score given by the simulator and the video performance scores (OSACS) for capsulorhexis, hydromaneuvers and phaco ($r = 0.669$, $p < 0.0001$; $r = 0.525$, $p = 0.010$; $r = 0.566$, $p = 0.004$, respectively). Also, the modified OSATS score correlated significantly with the sum of overall score for the three modules above ($r = 0.657$, $p = 0.001$). Interrater reliability was high for OSACSS capsulorhexis ($r = 0.788$), phaco divide and conquer ($r = 0.726$) and OSATS ($r = 0.764$) and moderate for OSACSS hydrosedsection ($r = 0.598$).

Fig. 3. A medical student training in the Eyesi intraocular virtual reality surgery simulator.
### Table 2. Evaluation of recorded video clips from the second iteration of the modules capsulorhexis, hydromaneuvers and phaco divide and conquer (median, range). Scores based on the video evaluation tool OSACSS and OSATS. Maximum possible score in parenthesis.

<table>
<thead>
<tr>
<th>Cataract surgeons</th>
<th>Medical students</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>OSACSS Caps (15)</td>
<td>13.5 (8–14)</td>
<td>8 (5.5–13.5)</td>
</tr>
<tr>
<td>OSACSS Hydro (5)</td>
<td>4 (3.5–5)</td>
<td>3 (1–5)</td>
</tr>
<tr>
<td>OSACSS Phaco (25)</td>
<td>20.5 (15–23)</td>
<td>8.5 (5–22.5)</td>
</tr>
<tr>
<td>OSATS (20)</td>
<td>17 (9.5–19.5)</td>
<td>5.5 (4–18)</td>
</tr>
</tbody>
</table>

OSACSS = Objective Structured Assessment of Cataract Surgical Skill; OSATS = Objective Structured Assessment of Surgical Skill.

*Statistical significance.

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### Discussion

Not surprisingly, differences in performance scores were found between medical students and cataract surgeons in this study. The Eyesi intraocular surgical simulator has previously been validated as a scoring tool for some cataract surgical skills (Privett et al. 2010; Le et al. 2011). We showed that cataract surgeons outperform naïve subjects on the capsulorhexis module. These results are in accordance with the study from Privett et al. where they showed that surgeons had not only better scores but they also had less damage to the cornea, which are findings also supported in our study. Given the differences between cataract surgeons and naïve subjects, a level of proficiency for overall score and injured cornea area can be determined for the capsulorhexis procedure (Table 1).

We could also demonstrate construct validity for the phaco module, and to the best of our knowledge, this is the first report showing construct validity also for this specific module. There were significant differences for successful cracking attempts between surgeons and students. However, the overall score for experienced cataract surgeons was disappointingly low (median 4 and 0 of 100 for the first and second iterations, respectively), and only the first iteration was significantly better than the students’. Two reasons may account for this: (i) inherent shortcomings in the scoring system or (ii) the low number of participants and the heterogeneity in experience among surgeons. Excluding the two junior cataract surgeons would make the surgeon group more homogeneous but did not change the overall score median values. Interestingly, comparing the video recordings of the phaco procedures between cataract surgeons and naïve subjects, there were no difficulties in distinguishing surgical skills. These facts indicate that the scoring system in the simulator may be more important of these two explanations pointing at a need for scoring refinement to better distinguish phaco skills. In that sense, the evaluation tools OSACSS and even OSATS are currently more accurate tools to evaluate surgical skill on the phaco module.

For the hydromaneuvers module, the surgeons could not score significantly better than the naïve subjects on the simulator. The material is considerably small and the group of surgeons is heterogeneous. The hydromaneuver was also performed on the lowest and easiest level and perhaps could not be challenging enough to allow separation between the two groups. These are factors that influence the results. However, the video evaluation easily distinguished the surgeons among the participants. Also, the correlation between the video evaluation scores and the simulator overall score was weak for this module. This suggests that the simulator scoring system needs further development also for this module to better distinguish cataract surgical skills.

Belyea et al. (2011) showed that training has an effect on surgical outcome even though their training curriculum was flexible and less controlled allowing for training both in anterior and posterior segment modules. Having found construct validity for three important modules (capsulorhexis, hydromaneuvers and phaco) for cataract surgery calls for the implementation of a structured simulator training programme. For this purpose, it is important to be able to assess the trainee and to measure progress in skills’ training as well as to provide appropriate feedback (Kluger & DeNisi 1996; Mahmood & Darzi 2004). With this study, we can define levels of proficiency for the modules capsulorhexis and phaco based on the metrics from the simulator. Based on the scoring of the video recorded training, we can also set a level of proficiency for the hydromaneuvers procedure as well as the capsulorhexis and phaco procedure and for the three cataract procedures together. It is feasible because, after completion of a trial, the trainee can record the performance, and the video can subsequently be evaluated. While being a time-consuming procedure, it would be preferable to get this process automated via an improved scoring system in the simulator.

A limitation to our study is that it does not include residents. Le et al. (2011) showed a correlation between ophthalmic experience and total score in two manipulation modules (the forceps and antitremor modules). One might assume that similar correlations would exist also for other modules. However, Le et al. grouped their participants (medical students, residents and ophthalmic surgeons) based on level of general competence rather than surgical experience, thus causing overlap in surgical experience between groups. Their study participants also had shorter session times (20 min versus 60 min), and their participants were given only a brief orientation of the simulator. Our medical students were recruited during their ophthalmology rotation. They were thoroughly informed of important structures and important parts of the procedures. All study participants were shown voice-guided instructional videos pointing out important aspects before each new module was commenced. In this way, our naïve group is likely to be more similar to a group of residents without surgical experience.

Surgical simulation allows for training and testing in a safe and uniform manner. In this study, we have shown construct validity on several modules previously not investigated (phaco divide and conquer, hydromaneuvers, cataract cracking and chopping, cataract navigation training) on the Eyesi intraocular surgical simulator and confirmed previously demonstrated...
construct validity for the capsulorrhexis and cataract forceps training modules (Privett et al. 2010; Le et al. 2011). Interestingly, validation of the hydromaneuvers module required the somewhat tedious OSACSS video evaluation tool. Thus, a further development of the scoring system in the simulator for the hydromaneuvers module would be advantageous and make training and evaluation of progress more accessible and immediate.

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Virtual reality cataract surgery training: learning curves and concurrent validity

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2Centre for Medical Simulation, Skåne University Hospital, Malmö, Sweden

ABSTRACT.
Purpose: To investigate initial learning curves on a virtual reality (VR) eye surgery simulator and whether achieved skills are transferable between tasks.
Methods: Thirty-five medical students were randomized to complete ten iterations on either the VR Capsulorhexis module (group A) or the Cataract navigation training module (group B) and then two iterations on the other module. Learning curves were compared between groups. The second Capsulorhexis video was saved and evaluated with the performance rating tool Objective Structured Assessment of Cataract Surgical Skill (OSACSS). The students’ stereoacuity was examined.
Results: Both groups demonstrated significant improvements in performance over the 10 iterations; group A for all parameters analysed including score (p < 0.0001), time (p < 0.0001) and corneal damage (p = 0.0003), group B for time (p < 0.0001), corneal damage (p < 0.0001) but not for score (p = 0.752). Training on one module did not improve performance on the other. Capsulorhexis score correlated significantly with evaluation of the videos using the OSACSS performance rating tool. For stereoacuity < and ≥120 seconds of arc, sum of both modules’ second iteration score was 73.5 and 41.0, respectively (p = 0.062).
Conclusion: An initial rapid improvement in performance on a simulator with repeated practice was shown. For capsulorhexis, 10 iterations with only simulator feedback are not enough to reach a plateau for overall score. Skills transfer between modules was not found suggesting benefits from training on both modules. Stereoacuity may be of importance in the recruitment and training of new cataract surgeons. Additional studies are needed to investigate this further. Concurrent validity was found for Capsulorhexis module.

Key words: cataract surgery – simulator – skills training – virtual reality

Introduction
Learning cataract surgery is technically challenging and demands well-developed psychomotor skills (Binenbaum & Volpe 2006). Teaching cataract surgery is costly and time-consuming. The rate of complications is higher for surgeons under training compared to more experienced ones (Randleman et al. 2007).
Capsulorhexis is one of the most difficult skills for new cataract surgeons to master (Dooley & O’Brien 2006). Besides scarce wet-lab training, most new surgeons train in the operating room on real patients (Henderson & Ali 2007; Lee et al. 2007). It is desirable to move the initial increased risk training from the operating room.
Surgical simulators have long been used for training and assessment in other surgical disciplines and can improve operating skills (Seymour et al. 2002; Grantcharov et al. 2004; Ahlberg et al. 2007; Kundhal & Grantcharov 2009; Schijven et al. 2010). The EYESi simulator (VR Magic, Mannheim, Germany) is a commercially available virtual reality (VR) eye surgery simulator for training in both anterior and posterior segment intraocular surgery. The VR simulator provides metrics and scoring at the end of each performed task. These scores correlate with the experience of intraocular surgery indicating construct validity (Rossi et al. 2004; Mahr & Hodge 2008; Solverson et al. 2009) and VR training can improve capsulorhexis wet-laboratory performance (Feudner et al. 2009).
Posterior segment VR training has been investigated but little is known regarding the learning curves associated with training on the simulator’s anterior segment modules as well as the validity of the simulator’s scoring system.

Virtual reality cataract surgery training: learning curves and concurrent validity

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Posterior segment VR training has been investigated but little is known regarding the learning curves associated with training on the simulator’s anterior segment modules as well as the validity of the simulator’s scoring system.
The aim of this study was to examine learning curves on the EYESi simulator anterior segment modules and whether achieved skills are transferable between tasks. Furthermore, we wanted to compare the performance score of the Capsulorhexis task on the simulator to a video-based scoring system of the same procedure.

Material and Methods

Thirty-five medical students at Skåne University hospital participated in the study (Table 1). They were attending the ophthalmology rotation at the 9th semester. All of them underwent simulator training. They received standard oral instructions by one test leader who also supervised all tasks. The students were shown a short instructional film incorporated in the simulator system, before performing each task on the simulator. Before commencing the simulator tasks, the students were screened for previous experience with eye surgery simulators as an exclusion criterion. Age was recorded for each student. After the simulator training, stereoeacuity was measured using the TNO (Laméris Ootech BV, Nieuwegen, the Netherlands) charts plate V–VII. Informed consent was acquired from each student.

### EYESi simulator

The EYESi surgical simulator (software version 2.4) was used in the study. The simulator has software for training in both cataract and vitreoretinal surgery. It is provided with a virtual operating microscope, a model eye and handheld probes (forceps, cannula/cystotome, and pin) that are inserted into the model eye. It generates a virtual stereoscopic image through the oculars. The simulator comes with several different modules for cataract surgery, including both cataract-specific tasks such as capsulorhexis and phacoemulsification, as well as manipulation exercises. For each module, there are several levels with progressive difficulty. The simulator calculates a performance score between 0 and 100 for each iteration and gives metrics providing feedback on microscope handling, tissue treatment, target achievement, efficiency and instrument handling. Written or oral momentary simulator feedback is available if wanted. At task completion, the entire task sequence can be saved on a USB-stick for later use.

The participants in the study were tested on the Cataract navigation training module on level three of three (Fig. 1). Here, the trainee has to hold an instrument steady in spheres spread in the anterior chamber. The challenge is to be able to efficiently manoeuvre the instrument in the anterior chamber and hold it still in each sphere. We also used the Capsulorhexis module level four (of 10), where the trainee has to inject viscoelastics through a cannula, with a cystotome make a commencement of a capsulorhexis flap, and finally with a forceps form and complete a circular capsulorhexis (Fig. 1). Metric data collected in this study were parameters that were mutual for the two modules: overall score, procedure time with instrument inserted, injured cornea area value, injured lens area value, iris contact score, incision stress value and for the Capsulorhexis module also the parameters centring and roundness.

The students were randomly divided into two groups, A and B (Fig. 2). Each student in group A performed on microscope handling, tissue treatment, target achievement, efficiency and instrument handling. Written or oral momentary simulator feedback is available if wanted. At task completion, the entire task sequence can be saved on a USB-stick for later use.

The participants in the study were tested on the Cataract navigation training module on level three of three (Fig. 1). Here, the trainee has to hold an instrument steady in spheres spread in the anterior chamber. The challenge is to be able to efficiently manoeuvre the instrument in the anterior chamber and hold it still in each sphere. We also used the Capsulorhexis module level four (of 10), where the trainee has to inject viscoelastics through a cannula, with a cystotome make a commencement of a capsulorhexis flap, and finally with a forceps form and complete a circular capsulorhexis (Fig. 1). Metric data collected in this study were parameters that were mutual for the two modules: overall score, procedure time with instrument inserted, injured cornea area value, injured lens area value, iris contact score, incision stress value and for the Capsulorhexis module also the parameters centring and roundness.

The students were randomly divided into two groups, A and B (Fig. 2). Each student in group A performed
10 iterations on the Cataract navigation training module and thereafter two iterations on the Capsulorhexis module. The students in group B started with ten iterations on the Capsulorhexis module and then two iterations on the Cataract navigation training module. The second iteration on the Capsulorhexis for each student was recorded, and the video was saved for later evaluation. Five videos were not recorded (two from group A and three from group B); a corrupt USB memory card made three videos non-viewable and the tenth instead of the second video was recorded for two individuals.

Simulator film evaluation

The saved videos from the second Capsulorhexis were evaluated by a cataract surgeon according to the cataract performance rating tool Objective Structured Assessment of Cataract Surgical Skill (OSACSS) in applicable parts (Saleh et al. 2007). The simulator videos were also evaluated using the video-based modified Objective Structured Assessment of Technical Surgical Skills (OSATS) scoring system (Martin et al. 1997; Grantcharov et al. 2004) that has shown an ability to distinguish different levels of technical surgical skill in other ophthalmology areas (Ezra et al. 2009). The evaluator was masked regarding the simulator score, student and study group. The evaluation scores were correlated with the simulator performance score on the Capsulorhexis module. Correlation between the evaluation scores and the simulator performance score on the Capsulorhexis module were analysed.

Statistical analysis

The Friedman test was used for analyzing the learning curves. Multiple comparisons were made to identify when plateau of learning had occurred. Spearman correlation test was used to analyse the correlation between the visual evaluation of the capsulorhexis simulator videos and the simulator performance score. For the comparisons between groups A and B, the second iteration of Cataract navigation training and Capsulorhexis was analysed.
The simulator overall score on the Capsulorhexis module had a significant positive correlation with the modified OSATS score ($r^2 = 0.59$, $p < 0.0001$) and with the OSACSS score ($r^2 = 0.704$, $p < 0.0001$).

There was no significant difference in performance between groups A and B when comparing the second iteration of Cataract navigation training module (Table 2). Likewise, we could not detect any significant difference for the Capsulorhexis module between the groups. Comparing the evaluations of the simulator video recordings, there was no significant difference in evaluation score between the specific capsulorhexis parameters centring and roundness ($p = 0.091$ and $p = 0.873$). For the parameters incision stress value and iris contact value, there were too few nonzero events on both the Capsulorhexis module and the Cataract navigation training module to allow for meaningful statistical analyses related to improvement.

The simulator overall score on the Capsulorhexis module had a significant positive correlation with the modified OSATS score ($r^2 = 0.59$, $p < 0.0001$) and with the OSACSS score ($r^2 = 0.704$, $p < 0.0001$).

Table 2. Comparison between groups A and B, iteration #2 (median, range).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Group A</th>
<th>Group B</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cataract navigation training module</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overall score (points)</td>
<td>51 (0–78)</td>
<td>46 (0–78)</td>
<td>0.364</td>
</tr>
<tr>
<td>Time with instruments inserted (seconds)</td>
<td>202 (78–448)</td>
<td>272 (84–639)</td>
<td>0.291</td>
</tr>
<tr>
<td>Incision stress value</td>
<td>0.0 (0.0–8.0)</td>
<td>0.0 (0.0–136.0)</td>
<td>0.106</td>
</tr>
<tr>
<td>Injured cornea area value</td>
<td>0.0 (0.0–0.4)</td>
<td>0.0 (0.0–1.8)</td>
<td>0.296</td>
</tr>
<tr>
<td>Injured lens area value</td>
<td>0.0 (0.0–0.0)</td>
<td>0.0 (0.0–0.73)</td>
<td>0.163</td>
</tr>
<tr>
<td>Iris contact value</td>
<td>0.0 (0.0–1.4)</td>
<td>0.0 (0.0)</td>
<td>0.303</td>
</tr>
<tr>
<td>Capsulorhexis module</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overall score (points)</td>
<td>0 (0–93)</td>
<td>7.5 (0–56)</td>
<td>0.773</td>
</tr>
<tr>
<td>Time with instruments inserted (seconds)</td>
<td>114 (67–275)</td>
<td>141 (73–435)</td>
<td>0.151</td>
</tr>
<tr>
<td>Incision stress value</td>
<td>0.0 (0.0–5.7)</td>
<td>0.0 (0.0–2.26)</td>
<td>0.119</td>
</tr>
<tr>
<td>Injured cornea area value</td>
<td>0.1 (0.0–4.4)</td>
<td>0.2 (0.0–9.5)</td>
<td>0.763</td>
</tr>
<tr>
<td>Injured lens area value</td>
<td>1.5 (0.0–12.7)</td>
<td>2.2 (0.0–18.1)</td>
<td>0.817</td>
</tr>
<tr>
<td>Iris contact value</td>
<td>0.0 (0.0–0.9)</td>
<td>0.0 (0.0–0.2)</td>
<td>0.080</td>
</tr>
</tbody>
</table>

Score | | | |
| Evaluation of video-recorded Capsulorhexis | | | |
| Evaluation OSACSS (points) | 8 (6–11) | 8 (5–10) | 0.64 |
| Evaluation modified OSATS (points) | 7 (4–13) | 10 (4–13) | 0.52 |

OSACSS, objective structured assessment of cataract surgical skill; OSATS, objective structured assessment of technical surgical skills.

Discussion

Our study has demonstrated the initial learning curves for two different modules on the EYESI ophthalmic intraocular surgery simulator. A plateau for overall score as well as for time occurred after very few iterations on the Cataract navigation training module. Similar results have been reported for individuals more experienced in ophthalmology such as residents and experienced surgeons (Mahr & Hodge 2008). Rapid learning is common for other surgical simulator tasks as well (Park et al. 2007). Simulator training has shown to be beneficial in early clinical performance in other medical fields such as colonoscopy (Park et al. 2007) and laparoscopic surgery (Seymour et al. 2002). Seymour et al. (2002) showed that tissue damage such as injury and burns were five times more likely to occur in the non-trained group compared to the VR-trained group. On both our studied modules, the students learned how to more efficiently and cautiously handle instrument inside the model eye. The simulator therefore has the potential to be part of the initial training of new cataract surgeons.
The capsulorhexis procedure is considered to be one of the most difficult steps in a cataract operation (Dooley & O’Brien 2006). The trainee has to focus attention on both the instrument and on the rhexis formation. It is thus likely that considerably more training than 10 iterations is needed to reach a level of proficiency. In our study, the trainees reached a plateau regarding time but not regarding overall score. The overall score parameter includes quality parameters of the final rhexis and is a better representative of capsulorhexis skill acquisition than time. In the report by Feudner et al. (2009) designed to improve capsulorhexis wet-laboratory performance, all students (30 persons) and 29 of 32 residents were able to reach a score level of 90 of 100 after two training sessions. Each session included two rounds of nine different tasks, and four of them were capsulorhexis simulation tasks. They also showed that this training improved the performance of capsulorhexis wet-laboratory procedure. However, considering that experienced surgeons reached only a disappointing 155 of possible 300 score in a report from Le et al. (2008) where they also included the Capsulorhexis procedure, a lower performance goal might well be enough and time efficient to strive for. (In that report, experienced surgeons performed the Capsulorhexis task in conjunction with two manipulating tasks, significantly better compared to novices at initial practice.) More studies are needed to establish a true level of proficiency for experienced cataract surgeons and how many iterations in general a novice would need to reach that level. As a comparison, on a laparoscopy simulator participants receptive to training needed an average of 25 iterations to reach proficiency (Schijven & Jakimowicz 2004).

The set-up of training is important. Ten iterations on the same level is probably not the most efficient learning. Instead, gradually increasing difficulty, termed ‘shaping’ in the behavioural literature, has been suggested as one methodology of training (Gallagher et al. 2005). On the other hand, the increments have to be sufficiently large to be enough challenging to give an efficient training (Ali et al. 2002). As is noticed in our material, skills at baseline vary between individuals and we could see that some individuals with bad stereoacuity had difficulties in improving their performance score. Others have shown that previous computer experience and visuo-spatial skills affect performance on VR surgery simulators (Hassan et al. 2007; Rosser et al. 2007). Schijven & Jakimowicz (2004) found in their study one group that did not benefit from training despite their low initial scores and in ophthalmology, it has been reported that around 10% of residents have difficulties in learning surgical skills (Binenbaum & Volpe 2006). Considering these facts, individualized training towards a level of proficiency is desired. This is supported by research regarding learning of motor skills where self-controlled practice leads to more effective training (Wulf et al. 2010). To the best of our knowledge, no previous studies on the EYESi anterior segment modules have included more than five iterations of the same module on the same level. More studies are therefore needed to further investigate the capsulorhexis learning curve and training conditions.

Simulator overall score correlated with the OSACSS evaluation score. Because this evaluation tool has demonstrated construct validity for video-based evaluations of real cataract operations (Saleh et al. 2007), it strengthens the validity of the scoring system in the simulator. In a similar manner, we found a correlation also for the video-based modified OSATS scoring system. To our knowledge, this scoring system has not been used before to evaluate intraocular operations, but has shown an ability to distinguish technical surgical skill in ophthalmic microsurgery (Ezra et al. 2009). The OSATS scoring system is also widely used in video-based assessment in other surgical areas (Kundhal & Grantcharov 2009; Schijven et al. 2010).

Our study subjects all took a stereotypes test. The estimated statistical power after grouping stereocuity in <120 seconds of arc and ≥120 seconds of arc was, however, too low (<80%) to make any definite conclusions regarding effects on performance. Rossi et al. (2004) demonstrated that stereotypes correlated with performance in vitreoretinal simulation. A confounding factor in their study was however that those subjects with vitreoretinal experience had a better stereocuity. We believe, however, that good stereocuity would probably be an advantage in cataract surgery. Noteworthy, two of the three students with TNO > 480 (one from group A and one from group B) scored zero points on seven and eight of their first 10 attempts on the simulator. This study was not designed to investigate the different performances depending on stereoscopic vision but it gives an indication on its importance in intraocular surgery. This factor may have large impact in the recruitment and training of new cataract surgeons. Additional studies are needed, however, to investigate this further.

In conclusion, when training on the EYESi simulator, the trainees quickly learned how to more efficiently and cautiously handle instruments inside the model eye. The simulator therefore has the potential to be part of the initial training of new cataract surgeons and it would be beneficial to train on both modules. However, the structure of training, especially for more complex tasks like capsulorhexis, demands for an individualization of training. Our experience with individuals with poor stereocuity supports this strategy and might be of large impact in the recruitment and training of new cataract surgeons. Further studies are needed to optimize training programs and make them time efficient.

Acknowledgments

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References


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Paper IV
Stereoacuity and intraocular surgical skill: Effect of stereoacuity level on virtual reality intraocular surgical performance

Madeleine Selvander, MD, Peter Åsman, PhD

PURPOSE: To evaluate the effect of stereoacuity on various intraocular surgical skills in inexperienced medical students using a virtual reality intraocular surgical simulator.

SETTING: Department of Clinical Sciences, Malmö: Ophthalmology, Skåne University Hospital, Malmö, Sweden.

DESIGN: Comparative case series.

METHODS: Ninth-semester medical students performed 1 iteration on each of the following 3 cataract training modules: navigation, forceps, and capsulorhexis. Before the simulator training, the trainees received standardized instructions and were allowed to perform 1 training round on the cataract navigation training module. After completion of the training, the level of stereoacuity was measured using TNO charts. Surgical performance for each task was measured, and performance parameter scores were recorded.

RESULTS: The study included 70 students. The simulator performance score correlated with the level of stereoacuity for the navigation training module (Spearman $r = 0.377$, $P = .001$) and forceps training module (Spearman $r = 0.306$, $P = .01$), showing a gradual increase in surgical performance with increasing stereoacuity. No such relationship was found for the capsulorhexis module (Spearman $r = 0.18$, $P = .136$).

CONCLUSIONS: A gradual detrimental effect on initial intraocular surgical skill with decreasing stereoacuity was shown. This calls for studies of the impact of deficient stereopsis on long-term training effects.

Financial Disclosure: Neither author has a financial or proprietary interest in any material or method mentioned.

a correlation between the level of stereoacuity and performance. Finally, we wanted to evaluate whether there were differences in performance on the simulator between men and women.

SUBJECTS AND METHODS

This study enrolled medical students in their ninth semester who were on ophthalmology rotation. Before the simulator training, the students were given a standardized orientation on important anterior chamber structures and on the function of the simulator. Informed consent was acquired before the study started.

Surgical Simulator

The Eyesi intraocular surgical simulator for cataract surgery (VRmagic Holding AG) and the simulator’s cataract head were used. As previously described, this simulator consists of a model eye into which probes are inserted. A virtual binocular image is created and shown through 2 oculars, giving a stereoscopic virtual image of the anterior segment.

In this study, 3 training modules were used. The first was the cataract navigation training module on level 3, on which the trainee must insert and keep an instrument tip steady in small spheres of varying sizes scattered randomly in the anterior chamber (Figure 1, A). The second was the cataract forceps training module on level 3, on which the trainee must grasp small triangles laying on the top of the lens and move them to a fictive basket (Figure 1, B). The third was the capsulorhexis module on level 1, on which the trainee must create a capsulorhexis from a preformed flap (Figure 1, C). For each module, the simulator provides summary scores for different parameters. In this study, the parameters’ overall score, time with instruments inserted, injured cornea area value, and injured lens area value were recorded for all 3 modules. For the cataract navigation training, the completed-objects parameter was also recorded.

Each student performed 1 initial iteration on the cataract navigation training module to become familiarized with the simulator. The student thereafter performed 1 iteration of the cataract navigation training, cataract forceps training, and capsulorhexis modules in that order. Before each new module, the student was shown an instructional video. After the simulator training, the student’s stereoacuity was measured using TNO chart plates V to VII (Laméris Ootech BV).

Statistical Analysis

The Spearman correlation test (r value) was used to analyze the correlation between stereoacuity and performance parameters and between age and performance parameters. The Mann-Whitney U test was used to test for differences between male students and female students.

RESULTS

Seventy medical students were enrolled in the study. Table 1 shows the students’ age and stereoacuity results by sex.

Surgical performance was affected by stereoacuity level (Figure 2), with a decrease appearing with minor stereoacuity defects. The effect became more pronounced as stereoacuity worsened. The overall simulator score correlated with the TNO value for the cataract navigation training module (r = 0.377, P = .001) and cataract forceps training module (r = 0.306, P = .01) but not for the capsulorhexis module (r = 0.18, P = .136) (Table 2). The number of completed objects correlated with the TNO value (r = 0.401, P = .001, Table 2). Time with instruments inserted, injured cornea area value, and injured lens area value did not correlate with the TNO value for any of the modules (Table 2).

There was no statistically significant difference in the performance of men and women on any parameter (Table 3). Age did not correlate with TNO values (r = 0.070, P = .565).

DISCUSSION

The intraocular surgical simulator used in this study has been validated as a scoring tool for cataract surgical skills and initial learning curves have been determined. It has been shown that the level of stereoacuity affects fine motor skills in children. Barry et al. found that for strabismic patients, performance on a laparoscopic training device was related to the level of stereoview. This finding is consistent with a report by Rossi et al., who found better performance on an intraocular surgical simulator for the posterior segment by individuals with better stereoacuity. A confounding factor in their study was that the experienced surgeons also had better stereoacuity. Sachdeva and Traboulsi report better initial performance scores for individuals with normal stereoacuity than for those who have deficient stereoacuity. Their study used the same intraocular surgical simulator in a group of patients with varying age and stereoacuity; however, they did not find correlations between the level of stereoacuity and performance beyond a crude dichotomous scoring of stereoacuity. Our results confirm their findings and also show a gradual effect in which surgical difficulty increased with decreasing stereoacuity. An important difference between our study and that of Sachdeva
and Traboulsi is that we studied medical students instead of ophthalmic patients. Thus, our population was more homogenous in age and more likely than patients in an ophthalmology clinic to become surgeons. It would be expected that the motivation to participate in a study and to perform surgical tasks was different between the 2 cohorts as well.

We found a correlation on the 2 manipulating modules of cataract navigation training and cataract forceps training, but not on the capsulorhexis module. Capsulorhexis was performed on the easiest level, whereas the other 2 modules were performed on the highest level of difficulty. Perhaps the capsulorhexis level was too easy to be able to discriminate differences based on different stereoacuity. It could also be that the capsulorhexis procedure is complex and that other factors (eg, understanding of tissue behavior, 2-dimensional visual clues) compensate and give enough support for handling the task despite compromised stereoacuity, especially on the easiest first level.

Studies of the effects of a person’s sex on surgical simulator skills are so far inconclusive. Shane et al. report a difference in performance between men and women on a laparoscopic surgical simulator. Others

### Table 1. Student stereoacuity and age by sex.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Men (n = 36)</th>
<th>Women (n = 34)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TNO plate (arcsec)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>7</td>
<td>8</td>
</tr>
<tr>
<td>60</td>
<td>15</td>
<td>19</td>
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<tr>
<td>120</td>
<td>4</td>
<td>5</td>
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<tr>
<td>240</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>480</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>&gt; 480</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>Age (y)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Median</td>
<td>27</td>
<td>26</td>
</tr>
<tr>
<td>Range</td>
<td>22, 52</td>
<td>22, 36</td>
</tr>
</tbody>
</table>

Figure 1. A: Cataract navigation training. The trainee must insert and keep an instrument tip steady in small spheres of varying sizes scattered randomly in the anterior chamber. Spheres turned green at success. B: Cataract forceps training. The trainee must grasp small triangles lying on the top of the lens and move them to a fictive basket. C: Capsulorhexis. The trainee must form a capsulorhexis from a preformed flap.
found no differences on surgical simulators between the sexes. In our considerably larger study group, we did not find differences in any parameter between the 2 sexes, implying that sex effects are negligible in early anterior surgical segment training.

Patient safety issues during the training of cataract surgeons have become an increasing concern. In the cataract community, there is an ongoing discussion of the relevance of stereoacuity. Of the countries that are members of the Organisation for Economic Co-operation and Development, only the Czech Republic requires binocular vision to perform ophthalmic surgery and The Netherlands is the only country that tests aspiring ophthalmology residents for stereopsis. Such bold regulations must be carefully supported by scientific data. It is therefore important to emphasize that neither our data nor, to our knowledge, previously published studies provide valid support in surgeon-selection decisions based on stereoacuity because they relate only to basic initial training. We do not know whether these initial effects are diluted with training or remain relevant.

Suleman et al. found that medical students with a depth-perception defect performed worse on a basic laparoscopic task. Initial learning occurred with 20 minutes of training; however, the performance gap remained constant between these students and those with normal depth perception. Mazyn et al. found that a group with a significant lack of stereopsis did not improve with training during a catching task. However, catching a ball is not comparable to performing cataract surgery, and stereoacuity is only 1 factor that determines surgical skills. Furthermore, there is great variation within the group of

<table>
<thead>
<tr>
<th>Module/Parameter</th>
<th>r Value</th>
<th>P Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cataract navigation training</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overall score</td>
<td>0.377</td>
<td>.001*</td>
</tr>
<tr>
<td>Time with instrument inserted</td>
<td>−0.162</td>
<td>.182</td>
</tr>
<tr>
<td>Injured cornea area value</td>
<td>−0.113</td>
<td>.351</td>
</tr>
<tr>
<td>Injured lens area value</td>
<td>−0.169</td>
<td>.44</td>
</tr>
<tr>
<td>Completed objects</td>
<td>0.401</td>
<td>.001*</td>
</tr>
<tr>
<td><strong>Cataract forceps training</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overall score</td>
<td>0.306</td>
<td>.01*</td>
</tr>
<tr>
<td>Time with instrument inserted</td>
<td>−0.075</td>
<td>.538</td>
</tr>
<tr>
<td>Injured cornea area value</td>
<td>−0.183</td>
<td>.13</td>
</tr>
<tr>
<td>Injured lens area value</td>
<td>−0.076</td>
<td>.604</td>
</tr>
<tr>
<td><strong>Capsulorhexis</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overall score</td>
<td>0.18</td>
<td>.136</td>
</tr>
<tr>
<td>Time with instrument inserted</td>
<td>−0.028</td>
<td>.819</td>
</tr>
<tr>
<td>Injured cornea area value</td>
<td>−0.146</td>
<td>.226</td>
</tr>
<tr>
<td>Injured lens area value</td>
<td>−1†</td>
<td>−1†</td>
</tr>
</tbody>
</table>

*Statistically significant  †Too many zero events to allow statistical comparison

Figure 2. Overall score for various levels of stereoacuity.
individuals with deficient stereoacuity, and some of them can perform on the same level as those with normal stereoacuity. Further studies are therefore needed to evaluate the longitudinal effects of stereoacuity on microsurgical skills learning.

REFERENCES


Table 3. Comparison of performance parameters in men and women.

<table>
<thead>
<tr>
<th>Module/Parameter</th>
<th>Median</th>
<th>Range</th>
<th>Median</th>
<th>Range</th>
<th>P Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cataract navigation training</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overall score (out of 100)</td>
<td>9.5</td>
<td>0, 76</td>
<td>12</td>
<td>0, 57</td>
<td>.947</td>
</tr>
<tr>
<td>Time with instruments inserted (s)</td>
<td>336.5</td>
<td>118, 621</td>
<td>415.5</td>
<td>99, 623</td>
<td>.456</td>
</tr>
<tr>
<td>Injured cornea area value</td>
<td>0.52775</td>
<td>0, 3.17</td>
<td>0.5185</td>
<td>0, 5.59</td>
<td>.467</td>
</tr>
<tr>
<td>Injured lens area value</td>
<td>0.564</td>
<td>0.0179, 2.49</td>
<td>0.251</td>
<td>0.0179, 2.71</td>
<td>.138</td>
</tr>
<tr>
<td>Completed objects (out of 12)</td>
<td>11</td>
<td>1, 12</td>
<td>11</td>
<td>8, 12</td>
<td>.541</td>
</tr>
<tr>
<td>Cataract forceps training</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overall score (out of 100)</td>
<td>57</td>
<td>0, 80</td>
<td>53.5</td>
<td>0, 94</td>
<td>.347</td>
</tr>
<tr>
<td>Time with instruments inserted (s)</td>
<td>79</td>
<td>43, 312</td>
<td>78</td>
<td>39, 118</td>
<td>.365</td>
</tr>
<tr>
<td>Injured cornea area value</td>
<td>0</td>
<td>0, 8.09</td>
<td>0.02775</td>
<td>0, 8.11</td>
<td>.277</td>
</tr>
<tr>
<td>Injured lens area value</td>
<td>0.627</td>
<td>0.0179, 9.41</td>
<td>0.7795</td>
<td>0.0179, 7.53</td>
<td>.749</td>
</tr>
<tr>
<td>Capsulorhexis</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overall score (out of 100)</td>
<td>29</td>
<td>0, 86</td>
<td>3.5</td>
<td>0, 89</td>
<td>.101</td>
</tr>
<tr>
<td>Time with instruments inserted (s)</td>
<td>107</td>
<td>40, 297</td>
<td>119.5</td>
<td>53, 254</td>
<td>.384</td>
</tr>
<tr>
<td>Injured cornea area value</td>
<td>1.525</td>
<td>0, 12.3</td>
<td>1.0385</td>
<td>0, 6.61</td>
<td>.384</td>
</tr>
<tr>
<td>Injured lens area value*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Too many zero events to allow statistical analysis

OTHER CITED MATERIAL

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