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Learning curve in phacoemulsification eye surgery simulator

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Abstract

Purpose

To investigate the learning curve for phacoemulsification procedure using a virtual reality simulator.

Method

Ten medical students were recruited. Each student performed 20 simulations on the cataract surgery simulator in the sculpting and evacuation phases respectively. For each simulation in each phase 35 variables were recorded by the simulator and a performance index which indicates how well a simulation is performed was calculated.

Results

Two groups were distinguished: learners and non-learners. A minority of the participants were considered learners. The performance index as a function of simulation in the learners group increased exponentially but far from reaching the asymptote. All participants performed well in avoiding damage anatomical structures.

Conclusions

The investigated population was too small to gather conclusive results. Therefore, further investigation with larger sample size and larger number of iterations is suggested.

Populärvetenskaplig sammanfattning

Katarakt, även kallat grå starr, är den vanligaste orsaken till blindhet i världen. Sjukdomen drabbar ögats lins och gör den grumlig vilket leder till nedsatt synskärpa och utan åtgärd i förlängningen även till blindhet. Förekomsten av katarakt ökar med stigande ålder och i takt med att vår population blir äldre förväntas fallen av katarakt att öka. Sjukdomen kräver kirurgisk behandling och kataraktoperationen är redan idag den vanligaste operationen i Sverige. På grund av ögats uppbyggnad och komplexitet är felmarginalerna extremt små varför ögonkirurgi betraktas vara på gränsen till vad mänsklig motorik klarar av. Detta kräver minutiös träning för blivande ögonkirurger. Träningen går delvis ut på att oerfarna kirurger opererar på patienter vilket innebär en högre risk för komplikationer. Således är det starkt motiverat att förbättra denna upplärningsprocess. Ett sätt att effektivisera kirurgisk motorisk inlärning har visat sig vara simulatorträning. Simulatorer för kataraktkirurgi är under utveckling men ytterligare forskning krävs för att utröna hur de ska användas för att maximera inlärningen. Denna studie syftade till att undersöka inlärningskurvan för läkarstudenter. Tio läkarstudenter fick genomgå ett utbildningsprogram innehållandes introduktion till ämnet samt praktisk utbildning i simulatorn. De fick därefter genomföra 20 simuleringar bestående av två utvalda moment ur kataraktoperationen. En deltagare visade signifikant förbättrad prestation i båda momenten och ytterligare tre deltagare i endast ett av momenten. Inlärningskurvan var tydligt linjär vilket indikerar att de dock inte uppnått sin maximala potential. Med tanke på inlärningskurvans utseende och att endast en minoritet av deltagarna visade en signifikant förbättring föreslås vidare forskning på området med större antal deltagare och fler simuleringar i följd. Som framtida forskning föreslås även försök med ögonkirurger under utbildning för att utforska simulatorns kliniska potential.

Background

Anatomy of the human eye

The beams of light that penetrates the eye to make us visualize an object passes several structures. The outermost surface of the eye is the cornea. In the limbus area the cornea is continuous with the sclera that surrounds the eye bulb. The cornea forms the anterior surrounding of the anterior chamber. The posterior surrounding consists of the capsule of the lens together with the iris. The anterior chamber is continuously filled with aqueous humour. The lens consists of a surrounding capsule i.e. anterior and posterior capsule, encompassing the crystalline lens. The posterior capsule is continuous with the anterior part of the vitreous body. The vitreous body consists of vitreous humour. Lastly retina with its rods and cones absorb the light beam to convert light to electrical signals which can be transferred to the brain for interpretation. Given the narrow space with many sensitive anatomical structures, small room is left for error which makes eye surgery exceptionally challenging.

Cataract

World Health Organisation estimated in 2010 that 285 million people were visually impaired and 39 million were blind on both eyes. One of two main causes of visual impairment is cataract, accountable for 33% of the cases (1) and causing 51% of the cases of blindness (2). Cataract is defined as visual impairment caused by optical disturbance in the lens of the eye. This results in decreased visual contrast, especially in low light situations when the pupil is enlarged. If diagnosed and correctly treated, patients with cataract can avoid progressing towards blindness. The greatest risk factor for developing cataract is age and the prevalence is increasing from the age of 50. In the elder population the prevalence reaches around 80% (+85 years) (3). Our population keeps growing and steadily getting older. Consequently the number of cataract cases are anticipated to raise (4).

Surgical treatment

According to Svenska Kataraktregistret totally 133 019 cataract surgeries were performed in Sweden 2017 (5), making it the most common surgery. In other words, 1,33 surgeries per 100 citizens and approximately 440 surgeries per surgeon. Due to safer surgical technology the indication for surgery has been widened and the number of surgeries performed increases (3).

Intracapsular Cataract Extraction (ICCE)

Historically, cataract surgery during the fifth century BC (6), was a risky, painful and sometimes even lethal procedure. During the early 20th century ICCE became the predominant method (7). ICCE was a big improvement but patients needed long hospitalizations with full head immobilization and often had complications such as vitreous loss and retinal detachment. A large corneal incision was necessary to allow removal of the entire capsule (8).

Extracapsular cataract extraction (ECCE)

In the 1950s intraocular lenses and improved surgical microscopes made ECCE the predominant method. ECCE allowed extraction of the lens without removal of the posterior capsule. By leaving the innate capsule the risk for vitreous loss was reduced and it provided support for the implanted intraocular lens (IOL). Instead postoperative inflammation and dense posterior capsule opacification was the main problems until improvements of the capsulectomy techniques and automated irrigation-aspiration systems were made (8,9).

Phacoemulsification (PHACO)

Today, PHACO is by far the most common technique. It was developed in 1967 by Dr. Kelman (10). He developed an ultrasonic probe, inspired from deontologists. PHACO gives the ability to fragmentize and aspirate the lens with simultaneous independent liquid irrigation to maintain the anterior chamber pressure. It only needs a very small incision through the cornea that post-operatively often can be left to self-heal. The surgery is most commonly done in local anaesthesia by applying Tetracaine on the ocular surface. An optional technique is retrobulbar anaesthesia. The first incision is then made in the temporal limbus allowing access of surgical instruments into the anterior chamber. A second incision is made to give access for the PHACO probe. A window is formed in the anterior lens capsule (capsulorhexis) with an intricate technique by tearing the capsule in a round shape. The capsulorhexis is made big enough to give instrumental access but small enough to give the IOL sufficient support. The lens nucleus is mobilized by liquid dissection along the lens capsule. A plus-shaped groove is formed with the PHACO probe, deep enough to allow cracking of the lens without risking posterior capsular rupture. After cracking the lens into four quadrants evacuation of the lens is performed by emulsification along with aspiration with the PHACO probe. After evacuation of the lens nucleus, remaining cortical fibers are aspirated. Finally the artificial IOL can be implanted into the saccular capsule (11).

Cataract surgery training

Cataract surgery is highly complex. Beside coordination between both hands and foots, the required precision to avoid damage to sensitive structures in the eye is close to what human hands possibly can handle. Given the narrow margin of error several hundreds of repetitions is needed to master this art.

Although many technical improvements has been made, the success rate of a surgery highly depends on the surgeon’s skills. If used wrong or by untrained hands many of the earlier described complications can still occur, such as vitreous loss and dens posterior capsule opacification and corneal oedema, in the worst case leading to blindness.

To avoid the complications, it is highly important that residents have gathered enough knowledge but also enough surgical skills before proceeding to the cataract patients. The most common alternative training object for human eyes are enucleated pig eyes despite several differences such as dimensions, proportions and density.

Today, eye surgeons in training go through a minute training program (to learn phacoemulsification) spanning over approximately 12-24 months. The first 6 to 12 months are spent observing an experienced colleague as well as training surgical skills on enucleated pig eyes in wet lab. In the next 6-12 months small procedures on real patients are initiated. The residents progress step by step towards completing the whole procedure by supervision (12). Training on real patients comes with several challenges. The most obvious is that the patient is exposed to a higher risk for complications (4). Various complications rates amongst residents are presented, for example 5-20% of capsular ruptures during the first 200 cases (12–16). Nevertheless, higher skills before proceeding to real cases gives an advantage in reaching complication free surgeries. It takes up to 400-1000 surgeries for an experienced surgeon to reach asymptote in complication rate (17,18). Another challenge is the relatively limited operation field that makes it hard for the teacher to have quick access if complications are about to occur, despite sufficient supervision. The fact that most patients are awake during surgeries limits how freely the surgeons can discuss the current surgery, limiting thereby also the learning process of the resident (4). Also it cannot be neglected that teaching a resident result in a lower production rate when a high productive surgeon is set aside to supervise new residents. Despite the increasing total number of surgeries performed, the number of patients available for residents as teaching objects shows a negative trend (19). This further delay the resident’s development towards becoming high-productive surgeons. There is both a benefit for the patients as well as an economical advantage if the learning process is kept as effective as possible (4). It has been suggested that surgeons could be required to complete a regulated simulator training program to be licensed for surgery (20).

Simulator

One step in rationalizing the learning process for residents is to use simulators to practise a variety of procedures. High volume training can be done with focus on different difficulties such as fine motor skills or challenging steps in a specific surgery. Unlimited trials can be done and a teacher can comment freely, obviously without placing a patient at risk.

Simulators for virtual surgical training has been developed over the last decades (19) (21) (22)). Simulators have also been shown to be effective in developing surgical motoric skills

(23). As previous work has showed, the simulator used in this trial presents sufficiently authentic surgical features which are necessary for practise the chosen surgical skills – briefly, experienced eye surgeons overall performed superior to naive medical trainees during surgery on the simulator (24). Also, it is shown that unexperienced students, with minimal or no surgical knowledge, develop skills during training in this simulator (25). Variables for evaluating the performance has been established (26)(27). Further, a method for interpreting the produced data evaluating a subject's performance has been developed (27)(28). However, further research is needed to investigate in which way the simulator can be used. A previous pilot study has shown that naive medical students improve exponentially towards asymptote after approximately 20 iterations.

Purpose

In this study we therefore aim to further investigate the learning curve of naive medical students performing phacoemulsification in this particular simulator.

Method

Participants

Recruitment for this trial was based on certain inclusion criteria to fit the design of the study. The basic medical knowledge in anatomy and ophthalmological diseases but without personal ophthalmological surgical experience were desired. Ten medical students were therefore recruited by announcing in a common social network forum for medical students in Uppsala University. The participants recruited were introduced to this study and signed on a consent form and commanded to attend to complete their trial in two consecutive days. Both genders were represented between the age of 23 and 41.

Simulator

The simulator used in this trial was developed in the beginning of the 21th century by Laurell et al. in corporation with Melerit AB in Linköping, Sweden. The simulator is based on a personal computer equipped with a simulation software (M-base, Melerit AB, Linköping, Sweden) that works on top of Cosmo3D/Optimizer (Silicon Graphics Inc., Mountain View, CA). Connected to the computer is hardware for visual feedback with dual LCD-displays which allows 3D observation of the surgical field, audial feedback (built in speakers), two handpieces and two foot pedals for input (figure). The microscope was developed from a virtual reality helmet (AddVisor 100, Saab Avionics, Sweden) mounted on a commercial Carl Zeiss (Stockholm Sweden) microscope. The right handpiece function as a phacoemulsification probe connected to a software module created on top of M-base. Left handpiece function as a nucleus manipulator. Both handpieces allow four degrees of movement in three axes as well as rotation approximately 360 degrees. Left foot pedal allows adjustment for focus, zoom and movement of the field of view in x- and y-axis. The right foot pedal controls the activation of the phacoemulsification probe in three positions: irrigation, aspiration and phacoemulsification. Alongside with the virtual microscope a computer screen allows observation by a supervisor (12). The simulator creates data files in txt-format for 35 predetermined measure variables (Appendix 1) that can be extracted and further analysed.

Procedure

Each participant attended to a standardized two-day program where they completed a total of 20 registered simulations. Day one, they were introduced to the subject by a short lecture, including study design, knowledge about the anatomy of the eye as well as cataract surgery. They were also showed a short instructional film of a real-life cataract surgery. In the next step they were demonstrated the simulator, how to operate it and what the simulator registers. Two complete simulations were demonstrated by the instructor to give basic knowledge in the simulator surgery technique. The participant then completed two complete simulations as practice runs with the instructor's supervision with the possibility to ask questions followed by 3 more simulations without the instructor. 20 simulations were registered (8 simulations day one and 12 day two) without the instructor's supervision in a self-learning approach. One simulation consisted of two separate phases which were registered separately; sculpting and evacuation. In sculpting phase the participant were presented a lens with the capsulorhexis procedure completed i.e. two incisions in the limbus area also already made. The participant were supposed to prepare the lens for cracking by sculpting a cross-shaped groove in the lens with the phacoemulsification probe and then crack it into four quadrants. In the evacuation phase the participant were presented a pre-cracked lens ready to be evacuated. The participant were supposed to evacuate the four quadrants with the phacoemulsification probe. Throughout the whole procedure caution was to be taken to avoid nearby sensitive anatomical structures.

Experimental design

Altogether 10 participants performed 20 simulations in both sculpting and evacuation phases respectively. In each simulation of each phase 35 variables were recorded for further analysing the performance index.

Data analysis

Söderberg et al. (27) suggests, an overall performance index was calculated for the two separate phases in each simulation from the 35 recorded parameters for each participant. This performance index was calculated by comparing the recorded parameters to reference data found by Söderberg et al. (28). The individual variable specific performance index (IVPI) is estimated according to Eq. 1, in which P_{ij} is a specific variable measured and RP_j is the reference to this specific variable. The IVPF equals 1 if the measured value is the same as reference. The 35 measured variables are categorized into 6 different classes. The individual class specific performance index (ICPI) is the average of the IVPIs within a class of variables. The individual overall performance index (IOPI) is the average of the ICPIs for the individual.

$$IVPI_{ij} = 2 - \frac{RP_j}{P_{ij}} \qquad Eq. 1$$

A priori, it was intended to fit the individual overall performance index, IOPI, as a function of the maximum individual overall performance index, $IOPI_{Max}$, the performance index improvement, $IOPI_{Improvement}$, and training session number, N_i (i=1, 2…20), assuming an exponential model Eq. 2 as seen in Fig. 1.

$$IOPI = IOPI_{Max} - IOPI_{improvement} * exp^{-k*N_i} \; Eq.2$$

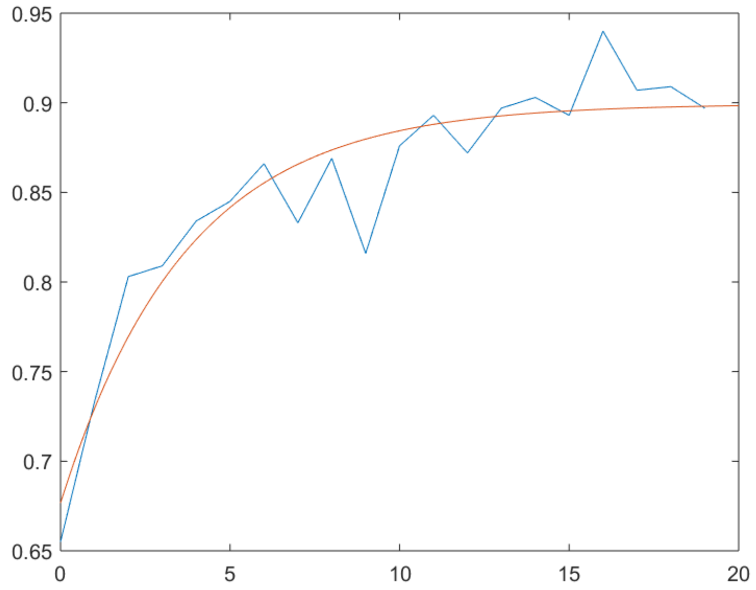


Fig. 1 Example of the learning curve (blue) and associated exponential model (Red) from a previous study.

Our primary outcome was performance index for each individual over 20 simulations (IOPI).

Results

Our result did not show improvement following an exponential curve. Instead, a preliminary analysis of each individual learning curve demonstrated two categories of trainees, learners and non-learners (Fig. 2).

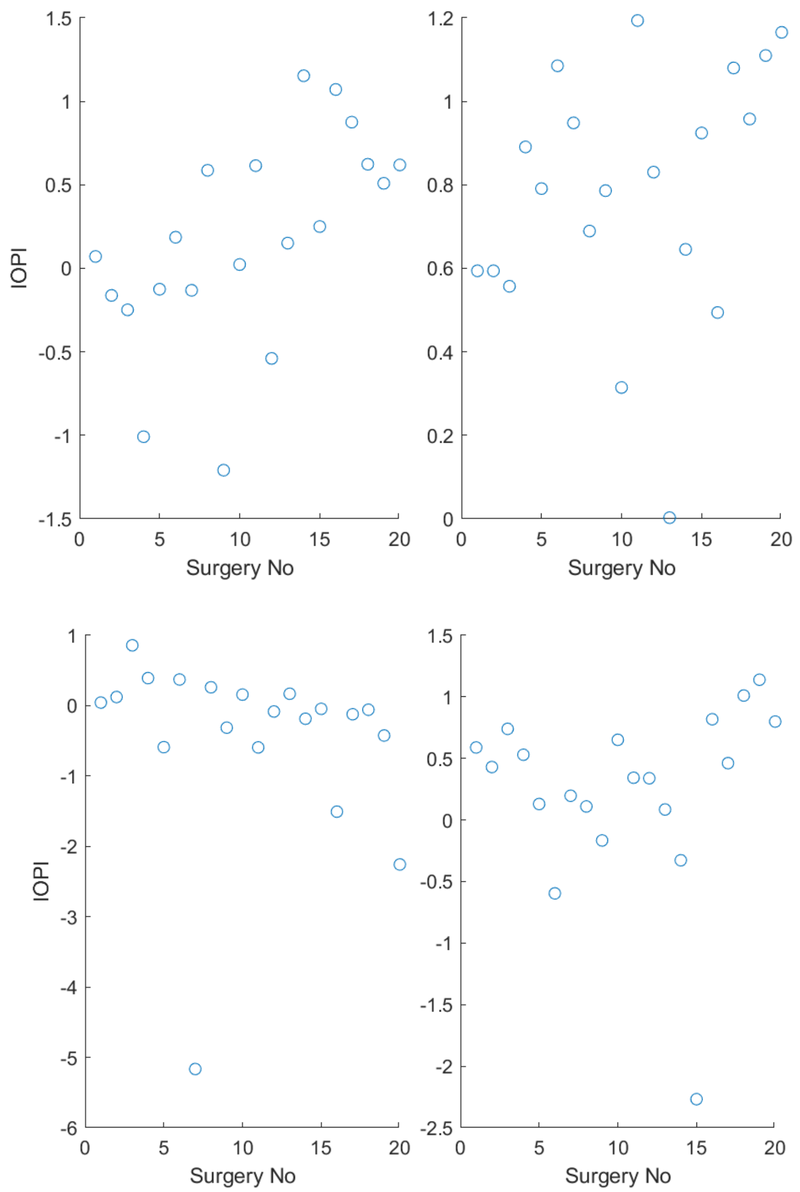


Fig. 2 Example of IOPI as a function of surgery at the sculpting (left) and evacuation phase (right). Up: learner; Lower: non-learner.

It was realized that the learners were far from reaching the asymptote (Eq. 2, $IOPI_{Max}$). Therefore, the asymptote in the model was set to 1 based on previous data. Then a linear regression (Eq. 3) can be used to estimate the improvement, $IOPI_{Improvement}$, and the learning rate, k.

$$IOPI = 1 - IOPI_{improvement} * exp^{-k*N_i}, \quad or$$

$$ln(1 - IOPI) = ln(IOPI_{improvement}) - k * N_i \quad Eq.\ 3$$

The inclination coefficient for non-learners were calculated using Eq. 4.

$$IOPI = IOPI_{Initial} + k * N_1 \quad Eq. 4$$

Estimation for learner and non-learner group in sculpting phase

In Table 1 and 2 (below), the inclination rate (k) for the estimated best fit curves for all participants in sculpting phase can be seen. For learner group (Table 1), 95% CI for k shows that the improvement was significant.

Table 1 Estimated inclination coefficients and the improvement for learner group in sculpting phase.

Subject no	95%CI for inclination coefficients, k	95%CI for improvement, IOPIImprovement	Residual standard deviation
5	0.0107±0.0071	6.4954±1.0887	0.4972
8	0.0085±0.0044	6.4044±1.0540	0.2991
10	0.0062±0.0039	5.9524±1.0484	0.2619

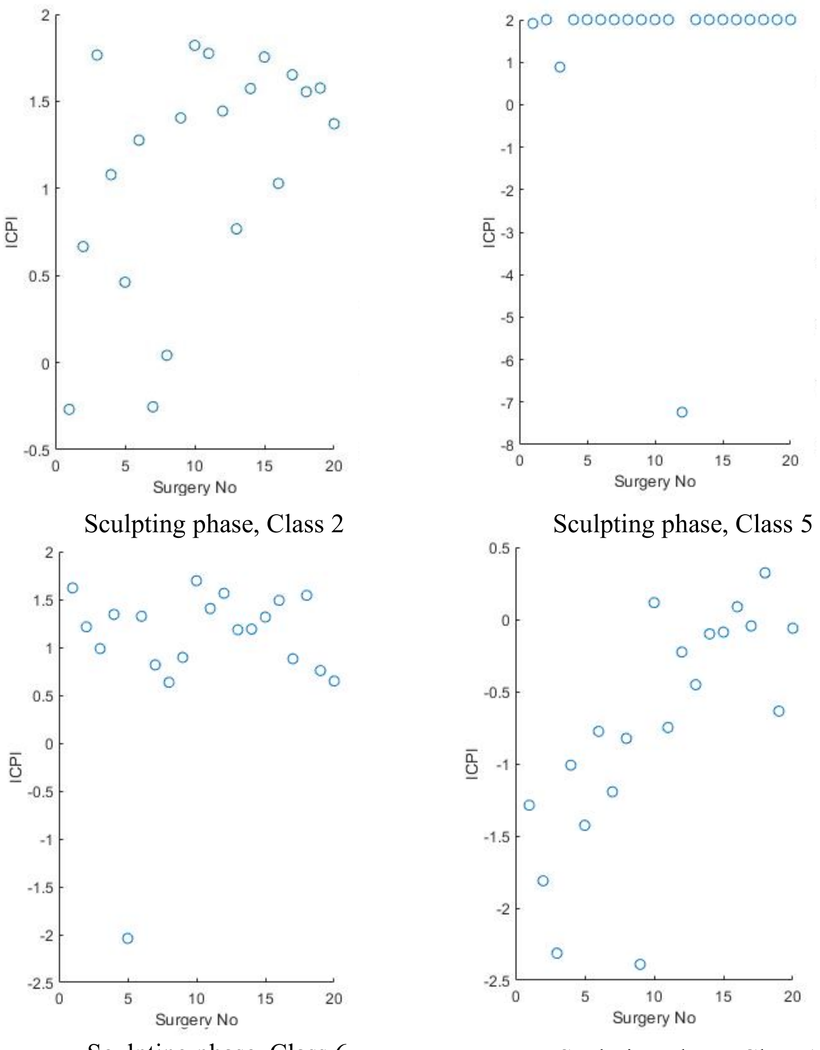
For non-learner group (Table 2), none of the inclination coefficients were significant which indicates that these trainees did not improve.

Table 2 Estimated inclination coefficients for non-learner group in sculpting phase

Subject no	95%CI for inclination coefficients k
1	0.0425±0.0565
2	0.0357±0.0864
3	0.0126±0.043
4	0.0203±0.2244
6	0.0137±0.0308
7	0.0443±0.0551
9	-0.0389±0.1069

Evaluation of performance change for classes in sculpting phase

The scatter plot showing the data in different classes (ICPI) for sculpting phase, it was seen that the students performed well in class 2, 5 and 6 (Fig. 3). In the latter two only one student's result were far from reference and did not show improvement. In class 4, seven out of ten students showed improvement but two of them did not reach the reference value (ICPI<1). In class 1 and 3 all the students performed below the reference value although 1 student in each class did show improvement (Fig. 3).



Sculpting phase, Class 2 — Sculpting phase, Class 5

Sculpting phase, Class 6 — Sculpting phase, Class 1

Fig. 3 Example of ICPI as a function of simulations for classes in the sculpting phase

Estimation for learner group and non-learner group in evacuation phase

In Table 3 and 4 (below), the inclination rate (k) for the estimated best fit curves for all participants in evacuation phase can be seen. For learner group (Table 3), 95% CI for k shows that the improvement was significant.

Table 3 Estimated inclination coefficients and the improvement for learner group in evacuation phase

Subject no	95%CI for inclination coefficients, k	95%CI for improvement, $IOPI_{Improvement}$	Residual standard deviation
7	0.0087±0.0081	6.5571±1.1016	0.5939
8	0.0075±0.0051	6.2959±1.0633	0.3633

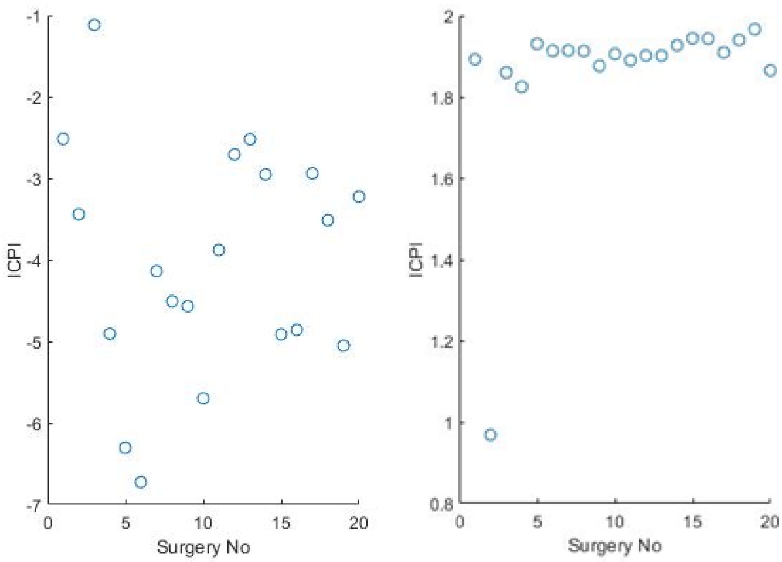
For non-learner group (Table 4), none of the inclination coefficients were significant which indicates that these trainees did not improve.

Table 4 Estimated inclination coefficients for non-learner group in evacuation phase

Subject no	95%CI for inclination coefficients k
1	0.0130±0.0324
2	-0.0103±0.0167
3	0.0027±0.0226
4	0.0146±0.0291
5	0.0142±0.0245
6	-0.0032±0.0122
9	0.0069±0.0616
10	0.0298±0.0344

Evaluation of performance change for classes in evacuation phase

The scatter plot showing the data in different classes (ICPI) for evacuation phase it was seen that the students performed well in 5 out of 6 classes. The data shows low performance index for all the students in class 2 (*Foot pedal technique*) (Fig. 4).



Evacuation phase, Class 2

Evacuation phase, Class 6

Fig. 4 Example of ICPI as a function of simulations for classes in the evacuation phase

Also it is seen that one subject was considered as learner in both phases.

Discussion

The purpose of this study was to further examine the learning curve of phacoemulsification for naive subjects on the Melerit PhacoVision® Simulator. Previous studies showed that medical students, naive to eye surgery, improved phacoemulsification during training by increased number of simulations following a linear curve in both sculpting and evacuation phase (25). In a previous pilot study, the results followed an exponential curve, reaching an asymptote after approximately 20 iterations, which we based our hypothesis on. In the current study no participant did reach the asymptote after 20 simulations.

It was found that the participants in this study could be categorized as two groups, learners and non-learners. Three out of ten individuals were learners in sculpting phase and two out of ten were learners in the evacuation phase. One student was identified as learner in both phases. In previous studies this distinction between groups has not been mentioned. The reason why some participants did improve and not others may be due to individual variance in experience, aptitude, ability to pay attention, contemplate information, and develop new motoric skills.

The fact that no participant did reach the asymptote and only few participants showed improvement over 20 simulations, indicates that 20 simulations were not enough to gain sufficient phacoemulsification skill.

The study design, including introduction, followed the same program as previous studies except that previously, the instructor was an experienced eye surgeon. In this study the instructor was a medical student with limited experience in eye surgery. The fact that the instructor was not an experienced surgeon can also have had a contribution. The instructor was although trained in the simulator by an experienced eye surgeon but indeed also had an individual learning curve in teaching. Therefore, the learners identifited, were all amongst the later five participants.

The scatter plots for separate classes (ICPI) during the evacuation phase indicated good performance in 5 out of 6 classes. The majority of the registrations were far above the reference value, even in the beginning of the trial although no significant improvement (Fig. 4). In sculpting phase, the ICPI scatter plots showed a more diverse result but overall good in class 2, 5 and 6. The data for both phases showed good performance in class 5 (*Damage to ocular structures*) and class 6 (*Damage to the capsule*) (Fig. 3). These classes include parameters measuring damage to cornea, iris, posterior capsule and zonulae stretch. Good results without significant improvement in these classes imply that the students payed good attention from the beginning in avoiding damaging these sensitive structures. During the introduction this was highly emphasized because of many complications associated with surrounding structural damage.

In class 2 (*Foot pedal technique*), all the students performed far below the reference value in the evacuation phase but interestingly overall good in the sculpting phase. Foot pedal technique (as seen in Appendix 1) consists of “Off Defocus Time, Irrigation Defocus Time, Aspiration Irrigation Defocus Time, Sculpting Defocus Time, Evacuation Defocus Time and Decentration Surgical Field”. As described earlier in Method the students were introduced to the simulator as well as to the parameters the simulator registers, including *Foot Pedal Technique*. Although these particular parameters can be explained and understood in the theory it was clearly seen that the students were unable to perform according to what was desired, especially in evacuation phase. During the introduction of the simulator the navigation of the operation field in both x and y axis as well as the focus and zoom of the simulator’s microscope were demonstrated. Operating this foot pedal was proportionally easy, but on other hand was the uncertainty in interpreting the visual feedback of the desired focus point in the simulator. It seems that centration of the surgical field or best available focus in the operating area may not have been perfect according to the simulators reference data. Beside these visual interpretation difficulties, it was noticed that some students over time were getting lazy with this particular foot pedal, learning that they managed to complete the surgery without perfecting the focus point or correcting the surgical field position. Among the participants it was uttered that the evacuation phase was easier than the sculpting phase. The complexity of the sculpting phase may have contributed to a higher level of focus and awareness of where the instrument’s tip is located than in the easier and less time-consuming evacuation phase.

For class 3, (*Phacoemulsification technique*) i.e. phacoemulsification probe and manipulator tip travel distance, the participants showed results far below reference in sculpting phase. The same was seen for class 1 (overall procedure) i.e. measurements for time. A more cautious approach may lead to that more time were spent carefully sculpting grooves in the lens, in small steps, approaching the desired depth for cracking at the expense of time-effectiveness. It again reflects that 20 simulations are not sufficient to fully handle phacoemulsification technique.

The scatter plots of performance index in classes showed that many of the students, including non-learners, performed overall well. The results showed scattered high performances even in the beginning of the trial and many of them even better than the reference data. As mentioned earlier one category stood out on the negative side which may have contributed to the low overall performance in evacuation phase. However, it can not be neglected that some personal surgical motoric skills or at least some experience has been developed through the trial.

Strengths and limitations

One limitation is that, according to protocol the instructor were not supposed to give any further feedback after the end of the introduction. It was noticed that the introduction was quite intense with much information to be learned before the participant got to try the simulator. The participants were given the opportunity to ask questions during demonstration and their first two test runs but after the demonstration, on the other hand, the instructor was no longer supposed to demonstrate, only give verbal feedback. Despite this feedback, many questions did occur later on during recording, which the instructor then was not allowed to answer. It is natural for a beginner to get such questions first when a given issue actually appear and although the introduction and demonstration did aim to cover this, motoric skills are naturally hard to learn without doing. This way, the participants were supposed to self-learn by doing. The instructor was only available to solve any technical issues that would occur despite the desired need for additional instructions. It was noticed an individual variance, amongst the participants, in ingenuity to tackle those upcoming obstacles. Some were able to develop methods not learned by the instructor, some of them, bad habits which were not compatible with real-case scenario. For instance, resting a finger further in on the handpiece where there is no corresponding real-life anatomical structure. The result could have been different if the learning protocol allowed individual-based instructions. On other hand there is a strength in that the instructor protocol was standardized. Obviously, the small study population limited the possibility to gather strong conclusions from the results. If possible, larger sample size would be preferred in future studies.

Conclusion

In this study we were not able to verify that all users of the simulator increase their performance over 20 iterations. Although some did improve, the study population is too small to draw strong conclusions. Therefore, further investigation with larger sample size and larger number of iterations is suggested.

References

1. Global Data On Visual Impairments. WHO; 2010.
2. Pascolini D, Mariotti SP. Global estimates of visual impairment: 2010. British Journal of Ophthalmology. 01 maj 2012;96(5):614–8.
3. Läkartidningen - Katarakt – ett optiskt problem i ögats lins [Internet]. [citerad 21 augusti 2019]. Tillgänglig vid: https://www.lakartidningen.se/Klinik-och-vetenskap/Klinisk-oversikt/2016/09/Katarakt--ett-optiskt-problem-i-ogats-lins/
4. Söderberg P, Laurell C-G, Artzen D, Nordh L, Skarman E, Nordqvist P, m.fl. Computer-simulated phacoemulsification improvements. Proceedings of SPIE - The International Society for Optical Engineering. 01 januari 2002;
5. Behndig A, Lundström M, Serring I, Montan P, Kugelberg M, Nilsson I, m.fl. Antalet kataraktoperationer i Sverige 1980 - 2017. :81.
6. Davis G. The Evolution of Cataract Surgery. Mo Med. 2016;113(1):58–62.
7. Olson RJ, Mamalis N, Werner L, Apple DJ. Cataract treatment in the beginning of the 21st century. Am J Ophthalmol. juli 2003;136(1):146–54.
8. Linebarger EJ, Hardten DR, Shah GK, Lindstrom RL. Phacoemulsification and Modern Cataract Surgery. Survey of Ophthalmology. 01 september 1999;44(2):123–47.
9. Roper-Hall MJ. Microsurgery in ophthalmology. Br J Ophthalmol. juni 1967;51(6):408–14.
10. The History and Development of Phacoemulsification | Ovid [Internet]. [citerad 21 augusti 2019]. Tillgänglig vid: https://oce-ovid-com.ezproxy.its.uu.se/article/00004397-199403420-00002/HTML
11. Lam CK, Sundaraj K, Sulaiman MN. A systematic review of phacoemulsification cataract surgery in virtual reality simulators. Medicina (Kaunas). 2013;49(1):1–8.
12. Laurell C-G, Söderberg P, Nordh L, Skarman E, Nordqvist P. Computer-simulated phacoemulsification1 1L. Nordh, E. Skarman, and P. Nordqvist are employed by Melerit AB. Ophthalmology. 01 april 2004;111(4):693–8.
13. Cruz OA, Wallace GW, Gay CA, Matoba AY, Koch DD. Visual results and complications of phacoemulsification with intraocular lens implantation performed by ophthalmology residents. Ophthalmology. mars 1992;99(3):448–52.
14. Tarbet KJ, Mamalis N, Theurer J, Jones BD, Olson RJ. Complications and results of phacoemulsification performed by residents. J Cataract Refract Surg. november 1995;21(6):661–5.
15. Yang YC, Kirwan JF, Foster PJ, Pereira AM. Cataract surgery by junior ophthalmologists. Eye (Lond). 1995;9 (Pt 6 Su):22–5.
16. Robin AL, Smith SD, Natchiar G, Ramakrishnan R, Srinivasan M, Raheem R, m.fl. The initial complication rate of phacoemulsification in India. Invest Ophthalmol Vis Sci. oktober 1997;38(11):2331–7.
17. Ng DT, Rowe NA, Francis IC, Kappagoda MB, Haylen MJ, Schumacher RS, m.fl. Intraoperative complications of 1000 phacoemulsification procedures: A prospective study. Journal of Cataract & Refractive Surgery. 01 oktober 1998;24(10):1390–5.
18. Martin KRG, Burton RL. The phacoemulsification learning curve: Per-operative complications in the first 3000 cases of an experienced surgeon. Eye. mars 2000;14(2):190–5.
19. Henderson BA, Neaman A, Kim BH, Loewenstein J. Virtual training tool. Ophthalmology. juni 2006;113(6):1058–9.

20. Kilby J. Surgeons for the millennium: lessons from aviation? J R Soc Med. augusti 1998;91(8):438.
21. Sagar MA, Bullivant D, Mallinson GD, Hunter PJ. A Virtual Environment and Model of the Eye for Surgical Simulation. I: Proceedings of the 21st Annual Conference on Computer Graphics and Interactive Techniques [Internet]. New York, NY, USA: ACM; 1994 [citerad 21 augusti 2019]. s. 205–212. (SIGGRAPH '94). Tillgänglig vid: http://doi.acm.org/10.1145/192161.192200
22. Felländer-Tsai L, Wredmark T. Image-guided surgical simulation—a proven improvement. Acta Orthopaedica Scandinavica. januari 2004;75(5):511–5.
23. Jordan JA, Gallagher AG, McGuigan J, McClure N. Virtual reality training leads to faster adaptation to the novel psychomotor restrictions encountered by laparoscopic surgeons. Surg Endosc. oktober 2001;15(10):1080–4.
24. Söderberg P, Laurell C, Simawi W. Virtual reality phacoemulsification: A comparison between skilled surgeons and students naive to cataract surgery. Ophthalmic Technologies XV. 01 januari 2005;3:1–6.
25. Söderberg P, Erngrund M, Skarman E, Nordh L, Laurell C-G. VR-simulation cataract surgery in non-experienced trainees: Evolution of surgical skill. Progress in Biomedical Optics and Imaging - Proceedings of SPIE. 01 februari 2011;7885.
26. Söderberg P, Laurell C-G, Simawi W, Skarman E, Nordqvist P, Nordh L. Performance index for virtual reality phacoemulsification surgery - art. no. 64261B. Progress in Biomedical Optics and Imaging - Proceedings of SPIE. 01 februari 2007;6426.
27. Söderberg P, Laurell C-G, Simawi W, Skarman E, Nordh L, Nordqvist P. Measuring performance in virtual reality phacoemulsification surgery. Proc SPIE. 01 mars 2008;6844.
28. Söderberg P. Calculation performance index. 2009;5.

Appendix 1

Parameter name	Description	Reference value in sculpting phase	Reference value in Evacuation phase
Class 1 Overall Procedure			
Total Procedure Time	Total Time (s)	228.38	236.04
Sculpting Time	Time with phaco mode sculpting on (s)	90.45	
Evacuation Time	Time with phaco mode evacuation on (s)		52.75
Phaco Energy Used	Time integrated phacoemulsification power (mJ)	1.88	0.25
Class 2 Foot Pedal Technique			
Off Defocus Time	Time of phacoemulsification foot pedal in position 0 (no irrigation, no aspiration, no phacoemulsification) and simultaneous phaco tip outside focus (s)	7.49	10.39
Irr Defocus Time	Time of phacoemulsification foot pedal in position 1 (irrigation mode) and simultaneous phaco tip outside focus (s)	2.04	2.50
AspIrr Defocus Time	Time of phacoemulsification foot pedal in position 2 (irrigation and aspiration) and simultaneous phaco tip outside focus (s)	2.73	2.50
Sculpting Defocus Time	Time of phacoemulsification foot pedal in position 3 (irrigation, aspiration and phacoemulsification), phacoemulsification in sculpting mode and simultaneous phaco tip outside focus (s)	16.52	
Evacuation Defocus Time	Time of phacoemulsification foot pedal in position 3 (irrigation, aspiration and phacoemulsification), phacoemulsification in evacuation mode and simultaneous phaco tip outside focus (s)		0.87
Decentration Surgical Field	Time worked outside the optimal working field (s)	17.52	41.89
Class 3 Phacoemulsification Technique			
Phaco Path Total	Total path traversed with the phacoemulsification handpiece tip (mm)	296.21	307.91
Phaco Path X	Path traversed with the phacoemulsification handpiece tip in X direction (mm)	157.74	168.66
Phaco Path Y	Path traversed with the phacoemulsification handpiece tip in Y direction (mm)	183.76	190.54
Phaco Path Z	Path traversed with the phacoemulsification handpiece tip in Z direction (mm)	117.88	111.13
Manipulator Path Total	Total path traversed with the nucleus manipulator tip (mm)	133.62	171.97
Manipulator Path X	Path traversed with the nucleus manipulator tip in X direction (mm)	94.96	123.46
Manipulator Path Y	Path traversed with the nucleus manipulator tip in Y direction (mm)	49.54	64.05
Manipulator Path Z	Path traversed with the nucleus manipulator tip in Z direction (mm)	55.99	64.20
Class 4 Erroneous Manipulation			
Bubble Occlusion Time	Time that more than 3 adjacent bubbles are present (s)	31.50	67.86
No Irrigation Time	Procedure Time with the phacoemulsification foot pedal left in position 0 (no irrigation, no aspiration, no phacoemulsification) (s)	25.36	41.46
Manipulator Behind Iris Time	Time with the phacoemulsification foot pedal in position > 1 (irrigation, aspiration and or phacoemulsification) and the manipulator tip in position hidden by iris (s)	0.04	0.27

Phaco Behind Iris Time	Time with the phacoemulsification foot pedal in position > 1 (irrigation, aspiration and or phacoemulsification) and the handpiece tip in position hidden by iris (s)	0.54	0.04
Class 5 Damage to Ocular Structures			
Piece Cornea Push Time	Time when lens fragment is in contact with cornea and the phacoemulsification tip simultaneously (s)	0.00	0.28
Phaco Cornea Hit Time	Time when phacoemulsification handpiece tip is in contact with corneal endothelium in any phacoemulsification foot pedal position (s)	0.45	0.36
Phaco Cornea Hit Energy On Time	Time that the phacoemulsification tip is in touch with the cornea and ultrasound energy is on (s)	0.00	0.00
Iris Damage Time	Time when phacoemulsification handpiece tip is in contact with iris with phacoemulsification foot pedal in position > 1 (irrigation, aspiration and or phacoemulsification) (s)	0.07	0.16
Class 6 Damage to the Capsule			
Phaco Rhexis Damage Time	Time of phacoemulsification handpiece tip in contact with rhexis border during operation with phacoemulsification foot pedal in position > 1 (irrigation, aspiration and or phacoemulsification) (s)	6.91	1.76
Phaco Beyond Posterior Capsule Time	Time with the phacoemulsification tip behind the posterior capsule (s)	0.11	0.06
Manipulator Beyond Posterior Capsule Time	Time with the nucleus manipulator tip behind the posterior capsule (s)	0.04	0.08
Zonulae Stretch	Stretching of the zonulae (mm)	11.75	35.74