Original Article

The Learning Curve of the Deliberate Practice of Phacoemulsification in the Ophthalmic Training System

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Objective: To determine the number of surgeries needed for trainees to achieve competence in performing phacoemulsification with deliberate practice (DP).

Materials and Methods: The present study was a prospective observational study, the residents were observed as they progressed through their third year of residency. Resident and patient demographic data were recorded. Complexities of the cases and surgical steps and rate of surgical complications were recorded. Self and staff assessments as to the DP learning zone attained by the trainees were collected. Risk adjusted-cumulative summation (RA-CUSUM) was used to evaluate the competency of the trainees to achieve the acceptable posterior capsule rupture (PCR) rate of 5%. Kaplan-Meier analysis was used to determine the median number of surgeries required to attain competency.

Results: Eight of the 10 trainees achieved competence in performing phacoemulsification. A median of 28 cases and 278 days was required before competence was attained. There were no statistically significant associations between the achievement of competence and the gender of the trainees, perceived complexity of the cases, or the grade-point average of the residents during their tenure in medical school. A median of four cases were required for a shift in the trainees' DP confidence levels from "panic" to "learning" from self-assessment, while the median of ten case were required from staff assessment. The PCR was 8.53% and dropped to 6% at two years after the trainees finished residency training.

Conclusion: Trainees require at least 28 cases of non-complicated phacoemulsification surgery to achieve a minimum level of competency. The perceived skill in performing phacoemulsification differs between novice and experienced surgeons. Phacoemulsification skills can be further developed after graduating from the training program. Assisting staff should be attentive when trainees perform lens nucleus division and lens nucleus removal to avoid complications.

Keywords: Residency training; Phacoemulsification; CUSUM; Deliberate practice; Cataract

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As one of the most common surgical techniques, phacoemulsification is a professional skill acquired in ophthalmology residencies[1]. Attenuating the learning curve of phacoemulsification has focused on improving the completion and surgical complication rates[2]. In the United States, the Accreditation Council for Graduate Medical Education (ACGME) requires a resident to perform at least 80 cataract surgeries as a primary surgeon[3,4], while the Royal College of Ophthalmologist of Thailand residency training program requires at least 50 for accreditation. Although complications from phacoemulsification occur more frequently among trainees than professional surgeons[5], there are a variety of methods of preparing trainees to perform cataract surgery, including the completion of surgical steps in their routine order (sequential training), starting at the end of the case (reverse training), achieving competence in only one surgical maneuver per case before progressing onto

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the next maneuver (modular training), and having the trainees learn as much as possible within a limited set of time[6,7].

Deliberate practice (DP) is defined as the repeated and focused performance of a task with coaching and informative feedback from experts to improve competence and maintain superior surgical skills. The continuous feedback from experienced advisors and self-reflection after finishing a specific operation help trainees adjust and improve their performance and reach a desirable level of skill[8]. The application of DP to surgical and medical training were widely used[9]. In cataract surgery training, several programs have integrated DP in real-patient phacoemulsification and preoperative training consisting of wet-labs and surgical simulators[10,11].

The present study aimed to determine the number of surgeries required before trainees became competent in performing phacoemulsification through a DP paradigm. The perceived mean difficulty score and incompletion rate of each step of phacoemulsification were further analyzed according to the complexity of the surgery to explore the challenging step for cataract surgery training.

Materials and Methods

The present prospective cohort study included 377 phacoemulsification surgeries performed by 10 trainees in the department of ophthalmology between February 2017 and March 2018. The present study was part of the classroom research and learning management system developed by the Department of Ophthalmology, Faculty of Medicine, Chulalongkorn University. The present study adhered to the Declaration of Helsinki and was approved by the Institutional Review Board of the Faculty of Medicine, Chulalongkorn University (IRB No. 117/61).

Study population

The authors recruited 10 ophthalmology trainees in the academic year of 2017 who were beginning their third-year training of residency. All trainees age above 18 years old in the academic year were enrolled in to the study. Information about the study and consent were done before starting the enrollment.

Data collection

All surgeries were performed by the individual trainees across the academic year. The demographic data of the trainees, including age, gender, and accumulated grade point average during their six years in medical school (GPAX), were collected. Patient data including age, sex, and side of the treated eye were recorded for each surgical case. The DP level of the trainees, as assessed separately by the trainee and faculty member, were recorded immediately after the completion of the surgery. DP levels were categorized into three zones according to the perceived confidence while performing the operation: panic, learning, and comfort.

The phacoemulsification was divided into seven steps: corneal stab incision, continuous capsulorhexis, lens nucleus division, removal of the lens nucleus, removal of the lens cortex, intraoucular lens (IOL) insertion, and wound closure. The difficulty and completion of each step were recorded by a trained research assistant.

Soon after completing the operation, every trainee had to evaluate the perceived level of difficulty of each step by filling one of three boxes with a blank star shape: the first, second, and third boxes corresponded to “easy”, “normal”, “hard” levels of difficulty, respectively.

The learning management system application was built to track case-related data after each surgery. The research assistant reminded trainees to provide the intraoperative data if it was not submitted within 24 hours of each surgery.

Phacoemulsification training program

Before starting cataract surgery in patient, the residents required intensive lecture program and a 1-day bovine cadaveric eye wet lab supervised by a member of the ophthalmology faculty at King Chulalongkorn Memorial Hospital and Chulalongkorn University. The greater detail was depicted in Supplement. After the completion of intensive pre-surgery training program, individual trainee was required to screen and evaluate each patient preoperatively whom was not too difficult for a beginner. The following inclusion criteria were employed to select patients for treatment by the trainees. The trainees were required to discuss the surgical case with a faculty member prior to begin the surgery in every case. Every trainee was paired with the same coach for a duration of approximately 1 to 2 months before changing coach. In the operating theatre, trainees assumed the role of the primary surgeon, and the coach acted as an operating assistant. The same model of a phacoemulsification machine with microtips and flare tips was used in all training programs (ALCON Infiniti system®, Texas, USA).

Post-residency training survey

The 10 trainees were asked to complete questionnaires by phone two years after they graduated. The following data were thus collected: the number of phacoemulsification surgeries performed per year, posterior capsule rupture (PCR) rate at two years after graduation, perceived levels of surgical skill (poor, fair, or good) when they were a resident and at the time of survey, and how many months they took to gain the confidence to perform the phacoemulsification perfectly.

Statistical analysis

While the cumulative summation (CUSUM) technique is primarily used in industrial quality control, it can also be used for monitoring performance because it shows how results change over time. It also can demonstrate the achievement of competence in the use of surgical techniques and show the progress of each surgeon as he or she becomes proficient in using new surgical skills[12,13] CUSUM was used to monitor the performance of the trainees in performing phacoemulsification based on the rate of complications occurred during surgeries performed by junior trainees. The lower decision limit (H_0) was indicated an acceptable rate of failure. As the standard CUSUM technique does not consider the difficulty of different cases, the authors also used the risk adjusted-CUSUM (RA-CUSUM). All related equations and variables of the standard CUSUM and RA-CUSUM calculation were shown in the Supplement. The odds ratio (OR) was calculated by using P_1 and P_0, as described previously[14]. A PCR rate of 5% was considered acceptable, while a PCR rate of 15% was considered unacceptable.

The Kruskal-Wallis and Dunn's tests were used for the comparisons of the overall patient complexity scores ranked by the 10 trainees. The RA-CUSUM was calculated with the aforementioned equation, and the resulting graph was plotted with Excel 2016. The median and 95% confidence intervals (CI) of the overall number of cases that crossed H0 with a 5% failure rate and the number of cases required before a trainee's confidence level increased were determined using the Kaplan-Meier method. Cox's regression analysis was used to evaluate the significance of the impact of covariates on the median number of cases required to achieve competence and the median number of cases required for a trainee to become more confident. The covariates included accumulated grade point average across six years of medical school (GPAX) and the gender of the trainees. Spearman's correlation coefficient was used to evaluate the association between the number of cases before the trainees' self-assessed levels of confidence improved and the number of cases required for achieving competence. The Kappa coefficient was used to determine agreement between the trainees' and staff's assessments of improved confidence. The mean perceived difficulty of each step of phacoemulsification was evaluated using a mixed-model analysis: a random effect model with an interaction between the score of perceived difficulty and the step of phacoemulsification. The final model was determined by selecting the lowest value of Akaike's information criterion (AIC). To control for type I error, Scheffe's method was used for multiple comparisons. Pearson's chi-Square was used for comparing the PCR rates between the three levels of difficulty. Off the 377 cases, two were lacked the difficulty score and were omitted from the corresponding analysis. Stata, version 15.1 (StataCorp LP, College Station, TX, USA) were used for all analyses. An alpha level of 0.05 was used to indicate statistical significance.

Results

During the 13-month period of the present study, the 10 trainees performed 377 consecutive phacoemulsification surgeries under the direct supervision of the coaching staff. Baseline demographics were shown in Table 1.

The RA-CUSUM analysis showed that eight (80%) of the 10 trainees achieved competence in performing phacoemulsification, as indicated by the line on the RA-CUSUM crossing below H_0 (Figure 1). The Kaplan-Meier analysis revealed that a median of 28 surgeries (95% CI 11 to 35), which took 278 days, were required for the trainees to achieve competence in performing phacoemulsification. There were no statistically significant associations between the achievement of competence and the gender of trainees, perceived complexity of the cases, or the GPAX score ($p=0.631$, 0.205, and 0.687, respectively). Two (20%) of the 10 trainees did not achieve competence according to the CUSUM analysis (Figure 1). The PCR rates of the two trainees who failed to achieve competence (trainee 4 and trainee 8) were 18.18% and 20.69%.

According to the self-assessment of trainees, a median of four cases (95% CI 3 to 8) were required before the level of DP confidence increased from panic to learning (Figure 2). Furthermore, the covariates of the gender of trainees, perceived complexity of

Table 1. Baseline characteristics of the patients and trainees

Factors	n=377
Patient characteristics	
Age in years; mean±SD	68.77±8.56
Male-to-female ratio	1:1.6
Right-to-left eye ratio	1:1.1
Number of operation per trainees; mean±SD	37±4
Trainee characteristics	N=10
Age in years; mean±SD	31.5±0.71
Male-to-female ratio	1:4
GPAX*; mean±SD	3.35±0.71
Mean operation time (minutes)	55.10±42.68
Average number of cases in each DP level from staff assessment	
Panic zone	34
Learning zone	271
Comfort zone	64
Number of cases in each DP level from trainee-assessment	
Panic zone	39
Learning zone	324
Comfort zone	14

DP level=deliberate practice level of trainees during operating each case; SD=standard deviation

* Grade point average across six years in the medical school ranged from 0 to 4. There were significant differences in the patient complexity scores between the 10 trainees (p<0.001).

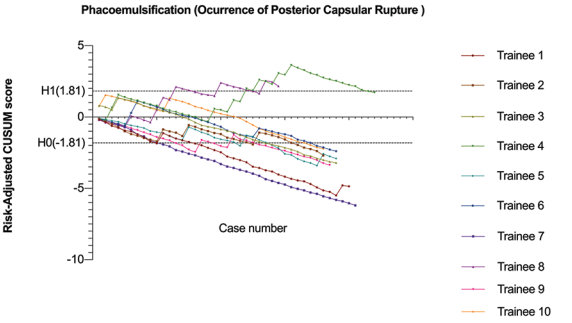

Figure 1. Risk-adjusted CUSUM chart plotting the rate of PCR complications during the phacoemulsifications consecutively performed by the 10 trainees: upward movement indicates failure of operation, while downward movement indicates successful phacoemulsification. Competency is defined when the risk-adjusted CUSUM reached the H0 line (H0: lower decision limit, and H1: upper decision limit). The performance of each trainee was represented in each different color.

the cases, and the GPAX of each trainee were not significantly related to improvements in the self-assessed confidence levels of the trainees (p=0.214, 0.508, and 0.878, respectively). By contrast, a median of 10 cases (95% CI 3 to 9) were required before the trainees' levels of confidence increased from panic to learning according to the staff's assessment (Figure 2). The Spearman's correlation coefficient between the number the self and staff assessments of the number of cases required to achieve competence was –0.519.

The overall mean perceived difficulty score of each step of phacoemulsification showed the perceived difficulty score of each step of phacoemulsification according to the complexity of each case. The easiest step was the initial corneal stab incision (step 1) (1.60±0.05). The score of step 1 was significantly lower than the ratings of every other step (p<0.001). The most difficulty step was lens nucleus division (step 3) (2.44±0.05), followed by the removal of the lens nucleus (step 4) (2.29±0.06). The mean difficulty score of step 3 was significantly higher than the scores of steps 1 (p<0.001), 2 (p<0.001), 6 (p=0.001), and 7 (p=0.014). The mean difficulty score of step 4 was significantly higher than the scores of steps 1 (p<0.001) and 2 (p=0.008). In the subgroup analysis performed according to the complexity of the cases, step 3 remained the most difficult case in the mid- and high-complexity groups. Step 3 was considered significantly more difficult than steps 1 (p<0.001) and 2 (p=0.002) in the mid-level complexity group and more difficult than steps 1 (p<0.001), 2 (p<0.001), 6 (p<0.001), and 7 (p=0.004) in the high-level complexity group. In the low-level complexity group, the mean perceived difficulty scores of steps 3 (3.08±0.30) and 4 (3.08±0.32) were highest but not significantly more than any of the other steps. The mean perceived difficulty score of step 1 was lowest in all groups of patients and was significantly lower than every other step in the mid-level (p<0.001) complexity group and significantly lower than steps 2 (p=0.008), 3 (p<0.001), 4 (p<0.001), and 5 (p<0.001) in the high-level complexity group. In the low-level complexity group, the perceived difficulty score of step 1 was not significantly lower than those of steps 2, 3, 4, 5, 6, and 7.

The highest incompletion rate was found for lens nucleus division (36.65%), followed by the removal of the lens nucleus and of the lens cortex. The subgroup analysis performed according to surgical complexity, lens nucleus division was associated with the highest incompletion rate in the low- (50%), mid- (19.10%), and high-level (40.86%) complexity groups.

The reported complications included PCR (8.53%), Descemet's membrane detachment (1%), lens drop (0.53%), and remaining aphakic (0.53%) and zonular tears (0.27%). The PCR was the most frequently observed complication in the low- (8.33%),

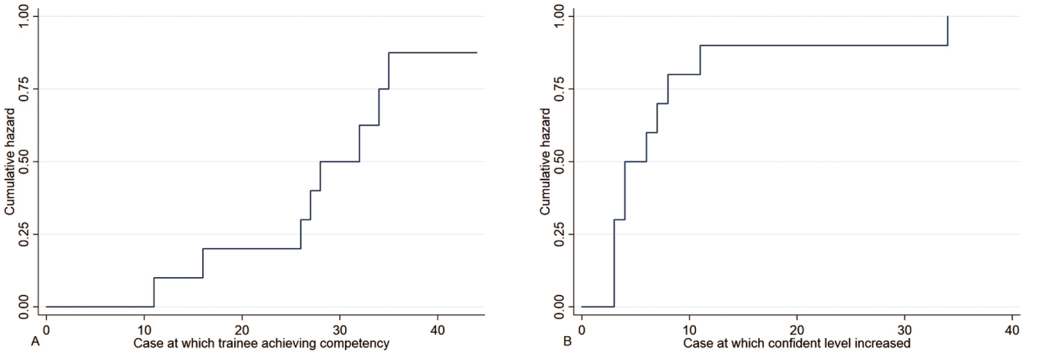

Figure 2. Cumulative hazard curve between the achievement of competency by trainees and the increase in their DP level: (A) Phacoemulsification cumulative hazard curve indicating the number of cases before the lower decision limit was crossed with a 5% acceptable posterior capsular rupture rate. (B) Assessment hazard curve indicating the number of cases required before the self-assessed confidence level of the trainees increased.

Table 2. Self-assessed level of surgical skill and PCR rate during training and at 2 years after the completion of the residency training program

Trainee	PCR rate		Perceived level of surgical skill		Average number of phacoemulsification operations per year after graduation
	Residency	2 years after	Residency	2 years after	
1	5%	4%	Fair	Fair	312
2	8.33%	10%	Fair	Poor	35
3	5.26%	7%	Good	Good	130
4	18.18%	25%	Poor	Fair	208
5	7.89%	0%	Fair	Good	130
6	7.89%	2.50%	Fair	Fair	338
7	0%	3.30%	Fair	Good	1040
8	20.69%	1.33%	Fair	Good	260
9	5.41%	2%	Good	Good	78
10	8.33%	4%	Fair	Good	104

PCR=posterior capsular rupture; NI=still felt not confident enough to operate perfectly

The skill after graduation was self-assessed by the trainees according to whether it was sufficient for further subspecialty training or operating alone. Level of surgical skill was rated fair, poor, or good by trainees' evaluation.

mid- (7.41%) and high-level (11.83%) complexity groups. The PCR rates did not differ significantly between the three complexity groups (p=0.421).

All trainees practiced as ophthalmologists in different hospitals within two years of finishing residency training. They performed an average of 264 phacoemulsification surgeries per year (range 35 to 1,040 surgeries/year). The average PCR rate was 6% (range 0% to 25%). The PCR rates of each trainee during their residency and at 2 years after graduation were shown in Table 2.

Discussion

During residency training, phacoemulsification is taught and evaluated with many tools, including the wet lab, surgical simulators, and by performing phacoemulsification with real patients. Apart from the learning tools used outside the operating room, the performance of real-life surgical drills are considered to be important for trainees[2,15]. Salowi et al, Vedana et al, and Chan et al confirmed the efficacy of CUSUM in the evaluation of learning to execute phacoemulsification because it fulfills CUSUM criteria, including how frequently the operation is performed, whether it was successful, or whether the operation involved any complications[16-18]. PCR has been reported by many studies as the most common intra-operative complication during cataract surgery, and thus features prominent use as the benchmark for determining the quality of an operation. PCR

reportedly occurs at a rate of approximately 5% in operations performed by novice trainees[19]. Observed at a rate of 8.5%, PCR was found to be the most common complication in the present study, followed respectively by Descemet's membrane detachment, lens drop, and remaining aphakic and zonular tear. At present, CUSUM and RA-CUSUM evaluations are widely applied to monitor the performance of trainees in surgery and medical skill training[14,16,17,20-24]. These evaluations are sensitive to unacceptable performance and remain effective[23]. Furthermore, as the evaluation is dynamic and its results change over time, it can document the progress of the trainee[12,16]. After reaching a satisfactory point, trainees are considered to be competent in the performance of an operation without guidance from experts and capable of operating at a steady and acceptable failure rate.

The rate of PCR in residency training ranges between 2.8% and 10%[25-27]. According to the authors' observations, a median of 28 cases is needed for junior trainees to perform phacoemulsification with an acceptable PCR rate of 5% to 15%. The authors further found that eight of the 10 trainees learned to perform phacoemulsification with an acceptable rate of PCR; the remaining two (trainee 4 and trainee 8) achieved PCR rates of 18.18% and 21.43% over the course of the academic year. The difficulty of the cases given to the two trainees for training did not differ significantly from the others used for training. However, as the trainees operated on more eyes, the risk of PCR diminished with time (Figure 1). The complexity of the cases treated by the 10 trainees differed significantly, and Cox's regression analysis revealed that the perceived complexity score was found to affect the results. The covariates of the sex of the trainees, perceived complexity score, and GPAX were found not having significantly affected the attainment of competence or changes in the trainees' confidence levels across a median number of cases. The number of complications resulting from surgeries performed in early and late residency differed significantly[1]. Chan et al reported that a median of 55 cases and a minimum of 41 were needed for trainees to reach competence, and 16 of 20 trainees (80%) achieved competency after a median of more than 83 cases[18]. The RA-CUSUM graphs of the two trainees who did not reach competence featured a down-sloping trend towards the H1 line at the end of follow up. Hence, the trainees could be expected to achieve competency with more cases.

By integrating DP into the training program, trainees had to evaluate their level of confidence after performing each operation. Supervisors also provided feedback concerning the trainees' levels confidence after the procedure was finished. Ericsson's concept of DP was applied to a modular training paradigm: phacoemulsification was divided into seven steps, allowing the patients to evaluate the perceived difficulty of each step[8]. A median number of four (CI 3 to 8) and 10 cases (CI 9 to 30) were required to change the self and staff assessed confidence levels of the trainees, respectively; the Kappa coefficient between trainees' and supervisors' assessments was 0.335, indicating fair agreement. These results suggested that trainees felt themselves confident enough to operate earlier than did the staff. Previous studies have reported different minimum numbers of cases needed for attaining competence in performing phacoemulsification, including 55, 75, and 80 cases[1,18,28]. These studies concentrated on the method of repetitive practice to gain proficiency. The authors found no correlation between the trainees' self-assessment of the number of cases required for their changing confidence levels and the number of cases required for them to reach competence. The median of 28 cases required for the trainees in the present study to achieve competence was less than that reported in aforementioned studies[1,18,28].

The present study is the first to record the perceived difficulty score of every step of phacoemulsification and PCR rates according to the complexity of the surgery. PCR was found to occur at similar rates in every group of patients. Lens nucleus division was perceived as the most difficult step overall, and in the mid- and high-level complexity groups. Moreover, the rate of incompletion was highest for this step overall and in every complexity group. By contrast, corneal stab incision was considered the easiest overall and in every complexity group, and was associated with the lowest rate of incompletion. The overall perceived difficulty score and incompletion rate were highest in the low-level complexity group, followed respectively by the mid- and high-level complexity groups. The findings in the low-level complexity group, including the rating of the lens nucleus division step as the most difficult, but not significantly more difficult than the other steps, were unpredicted. The authors attribute these findings to the notably low number of cases (n=12). In the low-level complex group, lens nucleus division was perceived as the most critical step in phacoemulsification, while corneal stab incision was considered the easiest. Badoza et al reported that the nuclear fracture technique was frequently used in the first 35 cases of residency training

and that the chopping technique was increasingly used with experience[27]. Asking 36 residents to report the perceived difficulty of performing phacoemulsification, Prakash et al found loading a foldable IOL to be the most difficult step among second-year residents and nuclear emulsification to the most difficult among the third-year residents[29].

PCR occurred at every stage of the operation and at similar rates in every complexity group; however, greater proficiency in lens nucleus division would significantly help to reduce rates of PCR and accelerate the attainment of competency[30]. Risk factors associated with PCR include dense nuclear sclerosis, white cataract, and the renting of the capsular tear[31,32]. Cruz et al reported that of all PCR reported during trainee operations, 72% occurred during cortical removal and 22% during nuclear emulsifications[33]. Careful attention is required by the assisting staff in this stage of phacoemulsification, as the lack of supervision by the attending physician is a significant risk factor associated with vitreous loss[32].

Responses to the post-graduation survey revealed that the rate of PCR in the surgeries performed by one of the two trainees who did not achieve competency dropped from 20.69% during training to 1.33% at 2 years after graduation, at which time he performed an average 260 surgeries per year. Perceived surgical skill also improved from "fair" during training to "good" at 2 years after graduation. However, the high rate of PCR of the other trainee did not improve: it was 18.18% during training and 25% at 2 years after graduation. Table 2 showed that most of the trainees reduced their rates of PCR across the 2 years following graduation. With the exception of trainees 2, 3, and 4, all others achieved PCR rates of less than 5% within the 2 years following graduation. While the rate of PCR is one of the most frequent outcome measures of competence in phacoemulsification, it might not correlate with a surgeon's perceived skill. Trainees who had not achieved competency during training can gain more experience and improve their surgical skills after graduation. Simulations provide unlimited opportunities for surgeons to improve their hand coordination and allow them to practice performing each step of phacoemulsification before performing surgery on real patient eyes[34]. However, for some trainees, surgical skill might not improve after treating numerous surgical cases (e.g., trainee 4). In such cases, counselling is recommended to help guide the careers of trainees with low competence in performing surgery and the benefit of potential patients. Furthermore, the present study indicates that individual training programs should include the evaluation of at least 28 cases and make provisions of special training for trainees with low performance to accelerate the accumulation of necessary skills and enhance the achievement of competency.

The present study is subject to several limitations. First, the sample of 10 trainees might not represent residents in general. Moreover, the training might be different among countries. As a result, there was a little limitation to generalizing the present study results to others. In addition, since the study focuses solely on PCR as a benchmark for surgical competence, operation time, best corrected visual acuity (BCVA), and vitreous loss may warrant consideration as alternative metrics. The present study is also limited by the significantly different populations of the complexity groups. Considering the limited duration of the present observation period and cases available for each trainee to gain practice, future research on DP should collect more cases for each trainee and extend the observation period. Finally, the present study did not compare the outcomes of different training techniques. As the training paradigm may influence the attainment of competence, future research should consider comparing training methods.

In conclusion, trainees require a median of 28 cases to achieve competence in performing phacoemulsification, i.e., a PCR rate of less than 5%. A median of four cases were required for trainees to change their perceived level of confidence in performing surgery. Apart from repetitive performing according to focusing solely on number of cases, several factors, especially the trainee basic skills, are significant to the attainment of surgical skill. Moreover, lens nucleus division was perceived to be the hardest step of the procedure, both in terms of highest perceived difficulty and associated rate of incompletion, and significantly limited the success of the trainees. As a result, this step should receive significant concentration in residency training.

What is already known on this topic?

As one of the most common surgical techniques, phacoemulsification is a professional skill acquired in ophthalmology residencies. In the United States, the ACGME requires a resident to perform at least 80 cataract surgeries as a primary surgeon, while the Royal College of Ophthalmologist of Thailand residency training program requires at least 50 for accreditation.

What this study adds?

Trainees require a median of 28 cases to achieve competence in performing phacoemulsification. A median of four cases were required for trainees to change their perceived level of confidence in performing surgery. Lens nucleus division was the hardest step for trainees and should receive significant concentration from both staffs and trainees.

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Conflicts of interest

There are no conflicts of interest among the authors.

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