Original article

Development of a virtual reality training curriculum for laparoscopic cholecystectomy

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Background: **Training within a proficiency-based virtual reality (VR) curriculum may reduce errors during real surgical procedures. This study used a scientific methodology for development of a VR training curriculum for laparoscopic cholecystectomy.**
Methods: **Inexperienced (had performed fewer than ten laparoscopic cholecystectomies), intermediate (20–50) and experienced (more than 100) surgeons were recruited. Construct validity was defined as the ability to differentiate between the three levels of experience, based on simulator-derived metrics for nine basic skills, four procedural tasks and full laparoscopic cholecystectomy on a high-fidelity VR simulator. Inexperienced subjects performed ten repetitions for learning curve analysis. Proficiency measures were based on the performance of experienced surgeons.**
Results: **Thirty inexperienced, 11 intermediate and 16 experienced operators were recruited. Eight of nine basic skills and three of four procedural tasks were found to be construct valid. The full procedure revealed significant intergroup differences for time (1541, 673 and 816 s; $P = 0{\cdot}002$), movements (1021, 595 and 638; $P = 0{\cdot}006$) and path length (2038, 1235 and 1303 cm; $P = 0{\cdot}033$). Learning curves plateaued between the second and ninth sessions.**
Conclusion: **This study shows that it is possible to define and develop a whole-procedure VR training curriculum for laparoscopic cholecystectomy using structured scientific methodology.**

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Introduction

Training in the operating theatre is often unstructured, and occurs by chance encounters dependent on patient and disease variability. A particular facet of surgical practice is the need to train inexperienced individuals to a level of competence in their chosen field. The term 'learning curve' has been used repeatedly to account for longer operating times, higher complication rates and even higher mortality rates during this period of skills acquisition[1,2]. Although training is supervised, and in accordance with informed consent of the patient, this is probably no longer an ethically or economically viable option for modern medical practice. It is thus necessary to explore, define and implement modes of surgical skills training that do not expose the patient to preventable errors[3].

Simulation in the form of virtual reality (VR) and synthetic models has been proposed for technical skills training at the early part of the learning curve[4]. A recent systematic review has substantiated the transfer of simulation-based training to the operative setting, in the fields of laparoscopy and endoscopy, through provision of a 'safe, effective and ethical way for trainees to acquire surgical skills'[5]. Nonetheless, the authors stated that the included studies were of variable quality, using a number of different strategies for training of participants. It is considered preferable for training to be structured within a standardized curriculum[6].

The aim of a training curriculum is for an individual to acquire skills to a predetermined level of proficiency before progression to more challenging cases. It is thus not solely the simulator, but also the mode of training on the simulator, that determines the degree of transference of skill to the operative setting. This constitutes knowledge-based learning, a stepwise technical skills pathway, ongoing feedback and progression toward proficiency goals, enabling transfer to the real environment[7].

The aim of this study was to develop an evidence-based and stepwise VR training curriculum for acquisition of technical skills for laparoscopic cholecystectomy (LC). Although curricula for basic and procedural tasks on VR simulators have been defined previously[8,9], this is the first time that a whole-procedure VR simulation tool has been subjected to a structured scientific method for curriculum development. The challenge was to define a hierarchical model of training that is underpinned by objective measures of proficiency, with the eventual aim of demonstrating a significant reduction in length and gradient of the learning curve during LC on real patients.

Methods

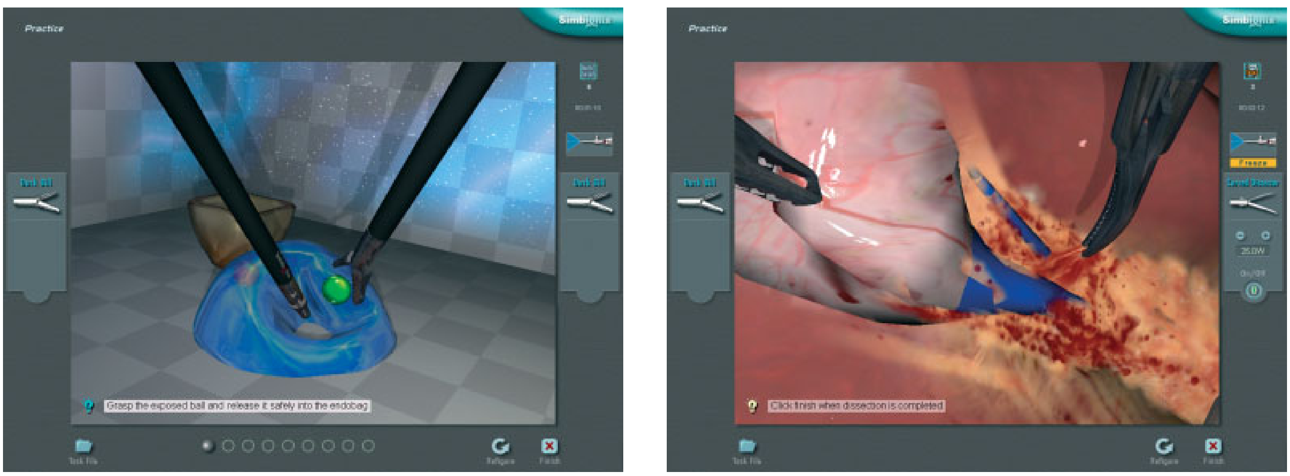
The study recruited subjects, divided into experienced (who had performed more than 100 LCs), intermediate (20–50 LCs) and inexperienced (fewer than ten LCs) operators. To be included in the inexperienced group, individuals who had not performed any LCs at all had to have been the primary assistant for a minimum of five LC procedures. Recruitment was solely through personal communication. The only exclusion criterion was previous training experience with a laparoscopic simulator of any kind, including box trainers.

Virtual reality simulation tool

The LAP Mentor™ VR laparoscopic surgical simulator (Simbionix Corporation, Cleveland, Ohio, USA) is divided into laparoscopic basic skills, procedural tasks and full cholecystectomy procedures. There are nine basic skills (such as two-handed manoeuvres; *Fig. 1a*), four procedural tasks (for example Calot's triangle dissection; *Fig. 1b*) and 18 full LC procedures. The full LC procedures vary in terms of biliary anatomy and degree of inflammation. For the purposes of this study, which aimed to develop a curriculum to train inexperienced laparoscopic surgeons, only the first LC was used with a patient history of biliary colic with standard anatomy. The subject interacts with the simulated tissues with two generic laparoscopic instruments through a haptic feedback device. Instrument type (grasper, scissors, clip applier, diathermy hook, etc.) may be selected through an on-screen menu-driven process. A detailed description of the simulator tasks is provided in *Table 1*.

Tasks performed

Each of the nine basic skills, four procedural tasks and one full procedure were performed for two sessions by experienced and intermediate subjects, and for ten sessions by inexperienced subjects. Before commencing the tasks, each subject was provided with a one-on-one simulator familiarization session, by an experienced operator. Before each task was performed, a full demonstration was provided by the experienced operator, with an opportunity for the subject to ask questions. The familiarization period lasted for approximately 30 min. No assistance was provided during hands-on training. All sessions were completed at least 1 h apart, and those in the inexperienced group completed no more than two sessions per day.



a Two-handed manoeuvres **b** Calot's triangle dissection

Fig. 1 Screen shots of **a** two-handed manoeuvres basic skill and **b** Calot's triangle dissection procedural task

Table 1 Description of the modules on the LAP Mentor™ virtual reality simulator

Skill or task	Description
Basic skills	
Camera manipulation 0°	Using a 0° camera, locate and snap photographs of ten balls, in an abstract environment
Camera manipulation 30°	Using a 30° angled camera, locate and snap photographs of ten balls, in an abstract environment
Eye–hand coordination	Locate each flashing ball and touch with the tool of the appropriate colour
Clip application	Clip leaking ducts within a specified segment, before the pool fills
Clipping and grasping	Safely grasp and clip leaking ducts within a specified segment, before the pool fills
Two-handed manoeuvres	Use two graspers to locate the balls within the jelly mass and then place them in the endobag
Cutting	Safely cut and separate a circular form using one tool to retract and the scissors to cut accurately
Electrocautery	Use a hook to burn the highlighted band, while retracting other bands with an accessory instrument
Translocation of objects	Manipulate object with two graspers and, with a minimum number of translocations, place the object into the orientation of the matching transparent object
Procedural tasks	
Clipping and cutting—retracted gallbladder	Gallbladder already exposed with Hartmann's pouch retracted by a static tool. Clip the cystic artery and duct within a specified area and then cut safely between the clips
Clipping and cutting—two hands	With the gallbladder already exposed use a blunt grasper to retract Hartmann's pouch. Once correct retraction is achieved, clip the cystic artery and duct within a specified area and then cut safely between the clips
Calot's triangle dissection	Grasp the infundibulum of the gallbladder, retract away from the liver, and dissect the peritoneal coverings to expose the cystic duct and artery
Gallbladder separation	Separate the gallbladder from the liver bed with appropriate retraction and dissection of the peritoneal adhesions to the liver bed. Continue dissection until the gallbladder is free from the liver
Full procedure	Virtual complete cholecystectomy procedures, based on anatomies created from CT/MRI real patient data. Practise a complete cholecystectomy procedure, with a range of appropriate instruments

CT, computed tomography; MRI, magnetic resonance imaging.

Performance evaluation

Data for each of the performed tasks were measured instantly and objectively by the VR simulator. This comprised metrics ranging from time taken and economy of movement to accuracy, cautery time and error scores. The data were stored by the simulator software in a Microsoft® Excel™ spreadsheet (Microsoft Corporation, Redmond, Washington, USA).

Construct validity is a test of whether a model can differentiate between different levels of experience, and thus be used to assess performance[7]. Comparison of median performance at the first two sessions between the three groups of surgeons was used to assess whether each simulated task was construct valid and substantiated the use of the defined settings of the simulator to assess laparoscopic technical skill. Statistical analysis of the learning curves for novice laparoscopic surgeons was used to clarify whether repeated practice improved performance toward that of the experienced group. The definition of benchmark criteria to be achieved before progression to the next stage of the curriculum was by calculation of the median score for each parameter during the second session for all experienced surgeons. Assessment of the experienced surgeons' second repetition was assumed to reduce the effect of their familiarization with the simulator during the first session.

The way novices advanced through these clearly defined steps through comparative measurement of simulator-derived metrics, that is construct validation, learning curve analysis and benchmark definition, enabled the assembly of a curriculum for procedural training, based on data rather than supposition. This provided an evidence- and proficiency-based pathway for novice surgeons to follow.

Statistical analysis

The choice of at least ten subjects per group was based on a two-tailed test, with $\alpha = 0{\cdot}05$ and power $(1 - \beta) = 0{\cdot}80$, and an intended reduction of 30 per cent in time taken to complete tasks for experienced *versus* inexperienced operators, based on data from previous studies of VR simulation[8,9]. This yielded a value of eight subjects per group, which was increased to ten to allow for dropout and technical malfunction of the simulator. Thirty inexperienced individuals were recruited to ensure that ten

Table 2 Construct valid metrics for basic skills

Task	Time taken (s)	Accuracy rate (%)	Total speed (cm/s)	Total no. of movements	Total path length (cm)
Camera manipulation 0°	✓	✓			
Camera manipulation 30°	✓				
Eye–hand coordination					
Clip application			✓		
Clipping and grasping	✓		✓		
Two-handed manoeuvres	✓		✓	✓	✓
Cutting	✓				
Electrocautery	✓				
Translocation of objects			✓		

subjects performed ten repetitions of the nine basic skills, a further ten subjects trained solely on the four procedural tasks, and a final ten practised on the full LC procedure. The intention was to make sure that inexperienced subjects were not trained for ten sessions on one VR module and then performed another module, as this would have influenced the results of the study inappropriately. This was not an issue for the intermediate and experienced subjects as they performed only two repetitions of each task.

The data were analysed with SPSS® version 16.0 (SPSS, Chicago, Illinois, USA) using non-parametric tests. Comparison of performance between experienced, intermediate and inexperienced groups was undertaken using the Kruskal–Wallis test and Mann–Whitney *U* test, as appropriate. Learning curve data were analysed by means of the Friedman test (non-parametric repeated-measures ANOVA). Multiple comparisons were then made to identify when skills had plateaued. $P < 0{\cdot}050$ was considered statistically significant.

Results

Fifty-seven subjects, comprising 16 experienced, 11 intermediate and 30 inexperienced operators, were recruited. Of the experienced surgeons, nine completed two sessions on the nine basic skills, 11 on the four procedural tasks and ten on the full LC procedure. Similarly, of the intermediate subjects, six completed two sessions on the nine basic skills, seven on the four procedural tasks and seven on the full LC procedure. The 30 inexperienced subjects were divided into three equal groups, the first of which performed ten repetitions of nine basic skills, the second four procedural tasks, and the final group the full LC procedure.

Basic skills

Eight of the nine basic skills demonstrated construct validity, based primarily on time taken and speed of completion (*Table 2*). 'Clipping and grasping' exhibited significant differences in time taken between inexperienced, intermediate and experienced subjects (161, 120 and 111 s respectively; $P = 0{\cdot}009$) and total speed (5·6, 7·4 and 7·9 cm/s; $P = 0{\cdot}011$). The 'two-handed manoeuvres' skill revealed group differences for time taken (171, 107 and 102 s; $P = 0{\cdot}001$) and total speed (6·3, 6·7 and 7·3 cm/s; $P = 0{\cdot}049$), as well as total number of movements (239, 128 and 128; $P = 0{\cdot}007$) (*Fig. 2*) and total path length (673, 484 and 512 cm; $P = 0{\cdot}016$) of instrument tips. There were also significant differences in these metrics for the two skills between inexperienced and intermediate, and inexperienced and experienced groups, but not between intermediate and experienced groups.

Analysis of learning curves for the inexperienced group revealed significant levels of improvement for 'clipping and grasping' and 'two-handed manoeuvres' for the aforementioned valid metrics, apart from total speed for the latter skill. All metrics were shown to plateau at between the sixth and ninth repetition for this group, but total

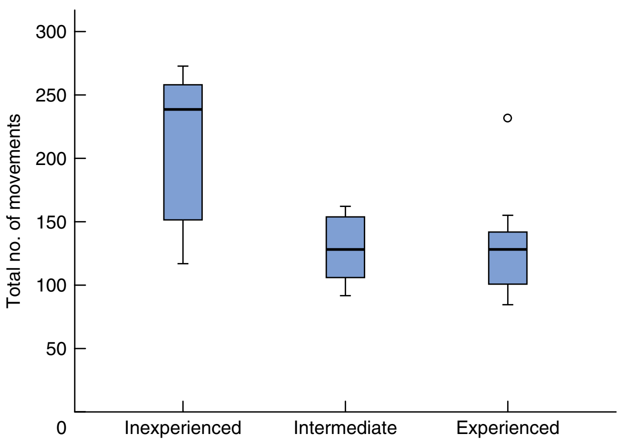


Fig. 2 Total number of movements for two-handed manoeuvres skill. Horizontal lines within boxes, boxes and whiskers represent median, interquartile range and range respectively. Circle represents an outlier ($P = 0{\cdot}007$, Kruskal–Wallis test)

speed on 'clipping and grasping' plateaued at the second repetition.

Procedural tasks

'Clipping and cutting – retracted gallbladder' did not differ between the three groups based on the metrics recorded by the simulator. The 'clipping and cutting – two hands' task revealed a significant difference only for total speed (3·5, 4·1 and 4·7 cm/s for inexperienced, intermediate and experienced subjects; $P = 0{\cdot}049$). For 'Calot's triangle dissection', time taken ($P < 0{\cdot}001$), total number of movements ($P = 0{\cdot}002$), total path length ($P = 0{\cdot}011$), total speed ($P = 0{\cdot}001$), accuracy rate ($P = 0{\cdot}002$), total cautery time ($P = 0{\cdot}003$) and total cautery time without tissue contact ($P < 0{\cdot}001$) were significantly different between inexperienced, intermediate and experienced surgeons over the first session. 'Gallbladder separation' showed significant differences for time taken ($P < 0{\cdot}001$), total number of movements ($P < 0{\cdot}001$), total path length ($P = 0{\cdot}001$) and time taken to extract the gallbladder ($P < 0{\cdot}001$).

Learning curves for the ten inexperienced subjects were statistically significant ($P < 0{\cdot}001$) for time taken, total number of movements, total cautery time and total cautery time without tissue contact for 'Calot's triangle dissection', and plateaued at the seventh repetition. For 'gallbladder separation', all construct valid metrics demonstrated significant learning curves for the inexperienced subjects ($P < 0{\cdot}001$), with a plateau at the fourth session (*Fig. 3*).

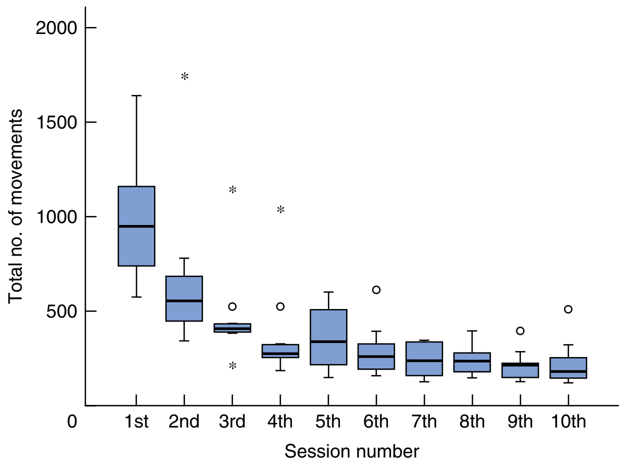


Fig. 3 Learning curve for total number of movements for gallbladder separation. Horizontal lines within boxes, boxes and whiskers represent median, interquartile range and range respectively. Circles and asterisks represent outliers and extreme cases respectively

Full procedure

The full procedure demonstrated significant differences between the three groups for time taken (1541, 673 and 816 s for inexperienced, intermediate and experienced subjects; $P = 0{\cdot}002$), time to extract the gallbladder (1487, 635 and 768 s; $P = 0{\cdot}002$), total number of movements (1021, 595 and 638; $P = 0{\cdot}006$) and total path length (2038, 1235 and 1303 cm; $P = 0{\cdot}033$). All construct valid

Table 3 Metrics for development of the training curriculum

Task	Metric	Construct valid	Learning curve	Plateau session	Benchmark level
Skills					
Clipping and grasping	Time taken (s)	✓	✓	9th	104
	Total speed (cm/s)	✓	✓	2nd	8·3*
Two-handed manoeuvres	Time taken (s)	✓	✓	6th	89
	Total no. of movements	✓	✓	8th	106
	Total path length (cm)	✓	✓	8th	440
Tasks					
Calot's triangle dissection	Time taken (s)	✓	✓	7th	278
	Total no. of movements	✓	✓	7th	241
	Total cautery time (s)	✓	✓	7th	15
Gallbladder separation	Time taken (s)	✓	✓	4th	312
	Time to extract gallbladder (s)	✓	✓	4th	219*
	Total no. of movements	✓	✓	4th	274
	Total path length (cm)	✓	✓	4th	511
Full procedure	Time taken (s)	✓	✓	2nd	548
	Time to extract gallbladder (s)	✓	✓	2nd	521*
	Total no. of movements	✓	✓	3rd	481
	Total path length (cm)	✓	✓	3rd	1012

*Metrics not included in the curriculum (*Fig. 4*).

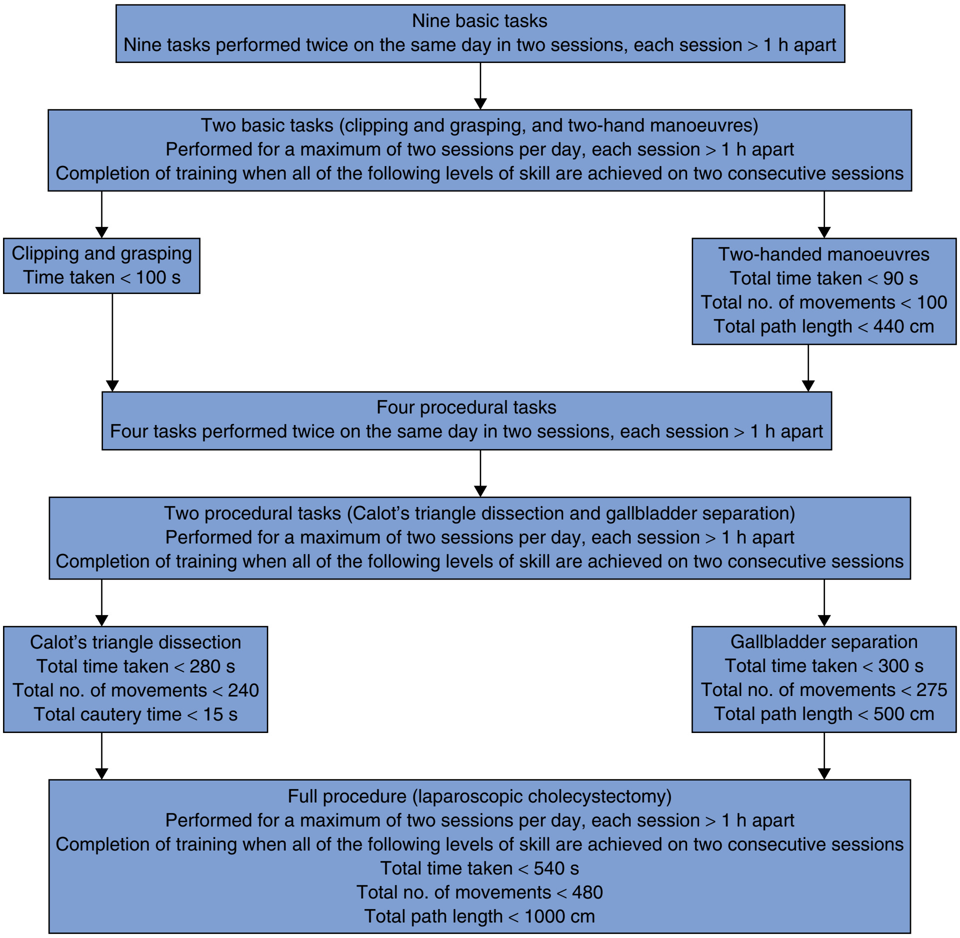


Fig. 4 Evidence-based whole-procedure virtual reality training curriculum for laparoscopic cholecystectomy

metrics again displayed significant learning curves, with a plateau at the second to third repetition ($P < 0{\cdot}001$).

Curriculum construction

The results summarized in *Table 3* were used in the development of a training curriculum. Two metrics were excluded: total speed for 'clipping and grasping' as it was felt that training to speed was inappropriate, and time to extract gallbladder for the full procedure as this was almost identical to time taken and did not add to the measurement of proficiency. The summarized outcome is a proficiency-based VR whole-procedure curriculum for training in laparoscopic cholecystectomy (*Fig. 4*).

Discussion

This study applied a stepwise process to the modules and metrics of a VR simulator, resulting in the development of a whole-procedure training curriculum for LC. The modules were deemed construct valid through comparison of performance across three levels of surgical experience. Furthermore, learning curve data were established to ensure that repetitive practice indeed improved performance in novices, as measured by the simulator. The technical skills taught by training on the simulator are thus relevant for LC, and should lead to a reduction in the time taken to achieve proficiency in real patients.

Training within the curriculum commences at the basic skills modules, with two repetitions of all nine skills. This is followed by training at the two most challenging skills, evidenced by the fact that they have significant learning curves. Progression to the procedural tasks necessitates achievement of the benchmark proficiency criteria, which are based on scores derived from the performance of experienced laparoscopic surgeons. The structure of the curriculum is identical for the four procedural tasks, leading to the full-procedure module, which again has proficiency criteria for the trainee to achieve before completion of the training period. It is also important to note that the curriculum adheres to the concept of 'distributed' rather than 'massed' training schedules, with a maximum of two sessions performed per day, each at least 1 h apart[10,11]. Finally, to confirm acquisition of skill rather than attainment of a good score by chance, all benchmark levels must be achieved at two consecutive sessions.

The data from this study have clearly determined the construct validity and learning curve progression of the simulator-based modules. Interestingly, there was no difference between the performance of intermediate and experienced groups on the simulator. This is an entirely appropriate finding, as those in the intermediate group are approaching the plateau phase of their learning curve for LC. Inexperienced subjects are thus most likely to benefit from training with this curriculum. A further point to note is the increase in consistency of scores both from increasing experience levels and with repeated training of inexperienced surgeons.

Other studies have investigated the construct validity of the basic skills on the LAP Mentor™ VR simulator. McDougall and colleagues[12] analysed performance across four different levels of experience with respect to a summed score for each skill[12]. Although the outcomes in terms of construct validity for the basic skills were positive, it is uncertain whether the arbitrary nature of summed scores (as provided by the manufacturer of the simulator) is appropriate for skills measurement. It is necessary to develop the evidence for relative weights of the different components that make up these scores. However, Zhang and co-workers[13] have provided good evidence for construct validity of the basic skills on the basis of time and overall scores, in concordance with the findings of McDougall *et al.*[12].

Several previous studies have assessed the validity and learning curves of other VR simulator devices[14,15]. Although a fundamental for use of simulation in clinical training schedules, the organization of such data into a coherent, stepwise and proficiency-based training curriculum has not yet been pursued. The systematic review by Sturm and colleagues[5] stated that a number of different training strategies was used for VR-based training before transfer to the operative environment. Most studies trained subjects based on a prescribed number of repetitions; those that trained to proficiency used isolated modules based on the performance measures of experienced surgeons[16,17]. For simulation-based training to be disseminated across surgical residency programmes, it is necessary to provide 'instructions for use' of the simulator, that is a prescribed training curriculum. This will enable a standardized introduction to laparoscopic surgery, which can also ensure that a novice surgeon cannot operate on a surgical patient until prescribed proficiency criteria have been achieved.

A common complaint is the expense in terms of simulator cost and upkeep, training space and faculty time required for integration of VR curricula into residency programmes[18]. With reductions in the learning curve during real operations, it is possible that the total cost of training each surgical resident will be reduced. In terms of training schedules, this curriculum prescribes two sessions per day, at least 1 h apart. The evidence for distributed training schedules is clear, although it is uncertain whether this means practice once a day or once a week[10,11]. Flexibility in accommodating training sessions will be needed when implementing this curriculum, but this should not detract from acquisition of skill as curriculum completion is based on achievement of proficiency measures.

This training programme is not intended as a substitute for skills acquisition in the operating theatre, but it will allow part of the learning curve to be transferred to the skills laboratory[4]. The curriculum has not taken into account previous procedural or technical knowledge, nor objectively measured this before enlisting trainees into technical practice. A cognitive skills module is essential at the front end of any training programme, such as that available from the Royal College of Surgeons of England for LC[19]. Furthermore, completion of this curriculum is based on dexterity, rather than safety scores or clinical outcome measurements. This is an important aspect of research with respect to the use of technical skills rating scales and, furthermore, the integration of such scales into the simulator software[20].

It is crucial to disseminate this curriculum to other users of VR simulation, to enable external validation of the curriculum in terms of ease of use and feasibility, and to determine ultimately whether its use does actually lead to the notion of the pretrained novice who can operate with greater dexterity and skill on patients undergoing laparoscopic surgical procedures. It is then only a matter of time until other domains of surgical practice have to follow this lead of simulation-based training, with objective measurement of performance before operative intervention.

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