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Identifying Opportunities for Virtual Reality Simulation in Surgical Education: A Review of the Proceedings from the Innovation, Design, and Emerging Alliances in Surgery (IDEAS) Conference: VR Surgery

Jaisa Olasky, MD¹, Ganesh Sankaranarayanan, PhD², Neal E. Seymour, MD³, J. Harvey Magee⁴, Andinet Enquobahrie, PhD⁵, Ming C. Lin, PhD⁶, Rajesh Aggarwal, MD, PhD⁷, L. Michael Brunt, MD⁸, Steven D. Schwartzberg, MD⁹, Caroline G. L. Cao, PhD¹⁰, Suvaranu De, ScD², and Daniel B. Jones, MD¹¹

¹Mount Auburn Hospital, Harvard Medical School, Cambridge, MA, USA

²Rensselaer Polytechnic Institute, Troy, NY, USA

³Tufts University School of Medicine, Springfield, MA, USA

⁴University of Maryland Medical Center, Baltimore, MD, USA

⁵Kitware, Carrboro, NC, USA

⁶The University of North Carolina at Chapel Hill, NC, USA

⁷University of Pennsylvania Medical School, Philadelphia, PA, USA

⁸Washington University School of Medicine, St Louis, MO, USA

⁹Cambridge Health Alliance, Harvard Medical School, Cambridge, MA, USA

¹⁰Wright State University, Dayton, OH, USA

¹¹Beth Israel Deaconess Medical Center, Harvard Medical School, Boston, MA, USA

Abstract

Objectives—To conduct a review of the state of virtual reality (VR) simulation technology, to identify areas of surgical education that have the greatest potential to benefit from it, and to identify challenges to implementation.

Background Data—Simulation is an increasingly important part of surgical training. VR is a developing platform for using simulation to teach technical skills, behavioral skills, and entire procedures to trainees and practicing surgeons worldwide. Questions exist regarding the science

Corresponding Author: Jaisa Olasky, Department of Surgery, Mount Auburn Hospital, 330 Mount Auburn St, Ste 407, Cambridge, MA 02138, USA., jsolasky@gmail.com.

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behind the technology and most effective usage of VR simulation. A symposium was held to address these issues.

Methods—Engineers, educators, and surgeons held a conference in November 2013 both to review the background science behind simulation technology and to create guidelines for its use in teaching and credentialing trainees and surgeons in practice.

Results—Several technologic challenges were identified that must be overcome in order for VR simulation to be useful in surgery. Specific areas of student, resident, and practicing surgeon training and testing that would likely benefit from VR were identified: technical skills, team training and decision-making skills, and patient safety, such as in use of electrosurgical equipment.

Conclusions—VR simulation has the potential to become an essential piece of surgical education curriculum but depends heavily on the establishment of an agreed upon set of goals. Researchers and clinicians must collaborate to allocate funding toward projects that help achieve these goals. The recommendations outlined here should guide further study and implementation of VR simulation.

Keywords

simulation; surgical education; ergonomics; human factors study; image-guided surgery

Background

Successful incorporation of computer simulations into medical education requires high-quality tools and applications directed toward carefully vetted educational objectives. The use of virtual reality (VR) to provide a meaningful medical education experience has its practical roots in the early 1990s, with the suggestion that it might offer significant advantages over more traditional methods used in training laboratories.¹ Since that time, substantial progress has been made in development of a range of VR simulations for various medical and surgical procedure types, as well as software tools used in conjunction with high-fidelity manikin simulators to drive realistic physiologic changes associated with human disease and medical interventions.

It is not surprising that there have also been some iterations of VR simulation for surgical education. Some of these devices were validated as methods that significantly improved resident skills but most were not compared directly to a physical simulator.^{2,3} In 2004, one hundred experienced laparoscopic surgeons were tested on the MIST-VR platform and these data were used to establish guidelines for determining proficiency.⁴ More recently, Rivard et al evaluated a wide range of subjects, from medical students to experienced surgeons, on a VR laparoscopic trainer in order to further clarify which metrics correctly identify the user's skill level. They were able to validate that 22 out of 37 tested metrics provided accurate performance data.⁵ Some studies also demonstrated clinical benefits to objectives-based training using VR in training curricula for laparoscopic and flexible endoscopic surgery.⁶⁻⁸

Although more than 20 years have passed since Satava suggested surgical training with VR, despite advances in computer capabilities that have made impressive progress in VR

possible, its actual use is limited. A need exists, therefore, for careful assessment of how to leverage this technology in the face of a changing landscape in medical education.

To this end, engineers, educators, and surgeons held a conference in November 2013 both to review the background behind simulation technology and to propose guidelines for its use in teaching and credentialing trainees and surgeons in practice. Speakers and invited guests were sent private invitations via email and in person, based on their established work as a leader in this field. Flyers were emailed out to scientific and surgical societies that are known to have an interest in this topic as well as the Harvard community at large. This meeting was tasked with providing a comprehensive and up-to-date review of the state of VR applications in medicine and to identify the best uses and challenges associated with virtual techniques for surgical simulation and training. The proceedings of this “Innovation, Design, and Emerging Alliances in Surgery” (IDEAS) Conference served as the material organized for this review.

Methods

A group of engineers, educators, and surgeons with extensive experience in the medical applications of VR convened at the IDEAS Conference on November 23, 2013, to review the background science behind simulation technology and to collaboratively arrive at recommendations for ongoing development and better use of VR simulation in training and credentialing of students, residents, and attending surgeons. The participants included 13 engineers from Rensselaer Polytechnic Institute, Massachusetts Institute of Technology, and Harvard combined; 17 clinicians ranging from students to attendings in the fields of surgery, gynecology, and anesthesiology; 6 researchers; and 9 collaborators from industry. The symposium ran from 8:30 AM to 4 PM. The day was broken up into 3 sessions with a roundtable discussion of each topic after each session. The topics were the following:

- Session 1** Disruptive Technologies in Virtual Surgery (technology update and challenges)
- Session 2** Bridging Theory to Practice (research considerations)
- Session 3** Virtual Surgery: Realizing Clinically Meaningful Advances (clinical applications and future direction)

Once the day was completed the authors reviewed the information discussed at the roundtable.

Results

The results were broken down into 2 categories: technology-related priorities and clinical application-related priorities. The details of the technologic challenges are examined in the Discussion section; however, the encompassing themes were that engineers and researchers need to collaborate more in order to identify which topics can be taught with realistic but not necessarily medically accurate simulations such that these projects can be “fast” tracked. In addition, there was agreement that the technology to create realistic and accurate simulations does exist but currently is so time intensive that its use is prohibitive. There is a great need

for open source sharing of information to create simulations that are better and faster. The clinical priorities were the areas of student, resident, and practicing surgeon training and testing that would likely benefit from VR. These priorities were grouped into the following categories: technical skills, team training and decision-making skills, and patient safety, such as in use of electrosurgical equipment. These areas are further delineated in Figure 1 and are discussed in more detail in the discussion.

Discussion

State of VR Technology

Why Does “Grand Theft Auto” Look and Run Better Than Medical Simulation?

—Many medical professionals wrongly assume that cost and manpower are the limiting factors in this dilemma. As defined by the National Academy of Engineering, “virtual reality is an illusory environment, engineered to give users the impression of being somewhere other than where they are.”⁹ How “good” the simulation is depends on both the user’s willingness to believe it and the complexity of the environment being engineered. In any medical VR simulation, the interaction between the user and environment is more complex than the standard movie or video game, and the nature of such interaction requires the simulation to run in real time. Thereby, the requirement to achieve realism in a more complex setting but in less computation time continues to challenge engineers. Advancing the field of VR simulation is one of the current Grand Challenges that has been identified by the National Academy of Engineering.⁹

To truly “suspend the disbelief of reality,” the resolution of the video display must be high, and the screen must have very fast update (refresh) rates. These rates depend on the environment being simulated, but most medical VR simulation requires a haptic rate of at least 500 to 1000 Hz and graphic update rate of 30 Hz. If the environment appears realistic, the trainee’s emotional and physiological response to the simulation will have a more accurate translation into the operating room (OR).¹⁰

Another major factor is the fidelity of the simulation, which not only needs to appear realistic but also must be very accurate. For example, in order to create a simulation of 2 interacting objects, one must detect collision between both objects and their resulting responses that would be used to update the dynamics of the objects. For an average video game, where neither the details of deformations nor fluid simulations are that important, it only needs to look real to the user. However, for medical simulations, the physiology and tissue properties that need to be factored in are very complex to simulate correctly. Soft tissues are nonlinear and exhibit anisotropic viscoelastic behavior. Though these behaviors could be simulated accurately using sets of partial differential equations, they are still not fast enough to provide updates at 500 to 1000 Hz needed for haptic feedback, or even at 30 to 60 Hz for stereoscopic display.

Compounding the problem of simulation of soft tissue behavior is the detection of collisions between objects. The collisions between objects are detected using “proximity queries.” Four specific types of proximity queries are collision detection, contact points and normals, closest points and separation distance, and penetration depth. These queries become

significantly more difficult when one is modeling deformable objects such as cloth, strings, and organs. Govindaraju et al have provided an algorithm for faster and more accurate collision detection.¹¹ In addition to collision between objects, there is also self-collision in deformable models. Algorithms for modeling these features can be difficult but there continue to be significant advances in this field as well.¹² The problems of detection collisions and computing collision response (with patient-specific tissue properties) become even more challenging when the tissues and organs are cut or stitched together as their geometry topology change. Unfortunately, such scenarios happen frequently in medical procedures and would need to be modeled and taken into consideration as well.

Perhaps high level of accuracy is not always necessary for all medical simulation. In some scenarios, the goal might be for the user to experience a stressful environment while performing a small task. This feature would require far less accuracy to be realistic and usable than, for example, learning how hard to retract tissue before it either tears or bleeds. Ongoing collaboration between engineers and clinicians is essential in order to identify the simulations for which physiological accuracy is crucial.

In addition to the engineering challenges, there are logistic difficulties in creating medical VR simulation; first it is very time consuming, and second, there is a tendency to re-invent the wheel. Open source software models can provide the best platform for the development of VR medical simulations¹³ for the following reasons:

1. Unlike commercial software, open source software models have no vendor locks.
2. Since everybody is contributing and updating the code, the quality might actually be much higher than the silo-generated material.
3. They have the ability to reproduce results by other researchers.
4. Research laboratories can focus on individual components or modules without having to rewrite the entire code.
5. They avoid payment for a license or to work with just one company in order to improve already existing code/product.
6. They encourage a greater culture of transparency and collaboration (perhaps at the expense of intellectual property)
7. They allow many more medical and engineering institutes to participate in the process of testing and validation the code/product.

Incorporating this technology with a physiologically accurate simulated surgery is the next step. Such a platform allows the user to perform a simulated procedure while interacting with a simulated environment at the same time as the rest of the operative team. Training in such an environment can be fully immersive using a Head Mounted Display (HMD) or partially immersive using a large-scale display. The Life Size Collaborative Surgical Environment (LS-CollaSSLE) is an early version of this product that uses a large 70-inch projection on a white wall to provide immersion.¹⁴ When training in such an environment, the users' head motion needs to be accurately tracked so that the camera view can change accordingly to match the users perspective. The Microsoft Kinect-based head tracking system was

implemented to provide seamless interaction within the LS-CollaSSLLE. The VR² (VR within VR) simulator is a fully functional immersive surgical simulator that can generate an interactive VR environment within a virtual operating room. This simulator is capable of generating distractions such as conversations, phones ringing, pager beeps, and people walking behind the monitors. It can also create difficult scenarios such as fogging of the camera, tool malfunction, and patient physiological instability. Figure 2 shows the VBLaST-PT version of VR² in which the subject performs a virtual peg transfer task in a virtual room where distractions and interruptions are introduced. The VR² has shown construct validity in distinguishing performance with and without distractions and interruptions.¹⁵

The Virtual Electrosurgery Skill Trainer (VEST) is another VR simulator that through interactive learning modules teaches the principles of electrosurgery. It uses a 3D immersive display (from Zspace) and a tissue pad with infrared tracked stylus for interaction (Figure 3). The learning modules consist of a didactic component introduced through text on the screen and a 3D physically based simulation on the right pane. An iPad (Apple Inc) is used as an electrosurgical unit for inputs such as power and modes (cut, coag, and blend). The users can learn the concepts and techniques for cutting, coagulation, and fulguration on this device.

Clinical Applications of Virtual Reality Platform

Modern methods of patient safety data collection and greater accountability for medical errors have led to more scrutiny of surgical training. Several surgical societies have forwarded curricular products that use simulation activities directed primarily at graduate medical education (GME) problems. The Association of Program Directors in Surgery (APDS) and American College of Surgeons (ACS) created a detailed resident curriculum for open and laparoscopic surgery utilizing skills laboratory-based simulation.¹⁶ Similarly, the Society of American Gastrointestinal and Endoscopic Surgeons (SAGES) developed the Fundamentals of Laparoscopic Surgery (FLS) certification test, which has an important simulation component, and had been made a prerequisite for American Board of Surgery (ABS) certification eligibility. The ABS target pass rate is 90%, which coincides with the 88% actual resident pass rate during the first 5 years after FLS began.¹⁷ In a study evaluating FLS proficiency in practicing attending surgeons who perform laparoscopic surgery on a regular basis, the baseline skills pass rate was 33%, while after practicing in the skills laboratory, this improved to more than 98%.¹⁸ Use of the skills laboratory to prepare for this exam is beneficial for residents as well.^{19,20} The ABS mandate for FLS certification may very well serve as a stimulus to surgical simulation during resident training and indirectly encourage the use of new and innovative methods, including VR.

Simulation has been established as a key part of resident training; however, there remain obstacles to more extensive simulation use in surgical GME. Some centers are limited by lack of access. Other centers reported that the simulated tasks need to better correlate with the resident curriculum, which takes a lot of dedicated work from the program and either greater resident buy-in or greater mandates to achieve.²¹⁻²³ Even with a standardized skills curriculum, residents are less likely to use a simulator when there is no specific goal associated with its use.²⁴ Some of the identified limitations might be addressed by use of VR

simulation methods and curricula. The virtual nature of the platform makes it more mobile than the physical counterpart, thus granting access to trainees and practicing surgeons worldwide who might not otherwise be able to access laboratory-based skills training. The estimated cost of the suggested APDS/ACS curriculum is over \$3000 per resident per year.²⁵ The estimated initial cost of the Fundamentals of Laparoscopic Surgery trainers is \$1680, and the testing has been estimated to be \$775 per resident.^{26,27} A VR platform may have an initial higher setup cost; however, the system would be re-usable, thus saving all the dry laboratory materials that would otherwise be required and would not demand paid personnel to set up and run.²⁸ In addition, VR simulation would diminish the need for animal models.²⁹

With these potential benefits in mind, the collaborators at the IDEAS symposium outlined the priorities for VR simulation projects and research.

Student and Resident Curriculum, Technical Skills—Beyond the dexterity skills, the ability to visualize the anatomy and relationships of key structures and hidden structures and to select the planes of dissection cannot be taught solely in a book or lecture. The future of VR is to have simulators that realistically and accurately teach the ergonomics, dexterity, steps of procedures, and the more intangible visualization all at once, without risk to the patient. In order for these VR simulation curricula to be meaningful, essential skills and milestones must be established (positives and negatives) with a priority to establish the most important ones should be developed first. It will be necessary to identify which skills need to be taught and to separate them into level-appropriate modules and what should be included in VR training. Figure 4 shows an example of how the skills could be assigned. This chart was created based on the 2008 ACS/APDS curriculum⁷ and the SCORE^{30,31} “essential basic” procedure list as well as a publication on needs assessment that queried clerkship directors and fourth-year medical students from 5 medical schools.³²

Beyond defining these essential standard modules, experts need to agree on critical errors that VR simulation would recognize and provide immediate feedback to the learner. In addition, the platform can be used for testing, to grossly identify outliers who significantly underperform. The learning curve of the task must be the same for the simulator as it is for the actual task. This can only be accomplished by achievement of the previously mentioned engineering goals that allow for accurate high-fidelity simulations.

To push the role of VR simulation further, the group declared that the ultimate goal is to have an adaptive and intelligent training and assessment system. It should not only be “level appropriate” but also have the capability to change based on recognition of the user’s performance and deficiencies to this point, as well as how quickly the learner has improved in the past. Essentially the trainee’s own personal learning curve guides his/her VR training. For example, a trainee who performs well on the standard elective laparoscopic cholecystectomy module would then be directed to a module of acute cholecystitis to help teach recognition and dissection of more difficult tissue planes. This type of curriculum would be extremely valuable and does not exist in physical dry laboratory or animal models. Software development in this area is needed to add this type of functionality to the VR simulators.

Student and Resident Education, Nontechnical Skills—The experts also agreed that there is a role for VR simulation in nontechnical/behavioral skills. The use of interactive virtual self and simulated patients as well as interaction with VR characters controlled by coworkers has been shown to have face validity and is already being used for teaching clinical surgical knowledge and team building skills to entire OR teams in a mock OR.³³⁻³⁵ A virtually simulated mock OR does not require as much space as its physical counterpart nor would all of the participants need to be in the same place and, therefore, might be more easily arranged.

A complete curriculum should be designed to cover the main categories of behavioral skills: situation awareness, judgment, communication, teamwork, and decision-making as well as the ACGME Core Competences.³⁶ These nonbehavioral skills can be taught and tested either during a procedure in a technical skills module or in a stressful environment simulated in a VR mock OR. The ultimate goal for the VR simulation platform is to recognize noncritical errors, allow the user to continue to operate, to see the repercussions of their error, and be forced to recognize and repair the end result. In some cases, the VR simulation could prompt the user to choose between several options, such as “continue, convert to open, call for more experienced help, or abort.”

Safety Education—The experts at the symposium agreed that research and development of VR simulation that is able to enhance safety education and certification of trainees and practicing surgeons is a priority. Existing demonstrations of electrosurgical safety (Fundamental Use of Surgical Energy or FUSE) and difficult airways require a lot of space and equipment including an area with proper ventilation. VR simulation modules are being developed for content education and skills relating to these topics. Other areas of safety education, including the importance of the “time out” and factors leading to retained foreign objects, should be integrated into the technical skills modules as a critical fail if not performed.

Continuing Medical Education (CME)—The authors identified the incorporation of VR simulation into CME as a research priority. VR simulation models should have the capability to target VR simulation work based on the surgeon’s scope of practice. A “refresher” simulation can be developed for procedures, such as laparoscopic adrenalectomy, that are infrequent for even endocrine surgeons. The refresher could also be used for anyone who has taken a leave of absence from surgery for a significant period of time, such as serving overseas, childbirth, illness, or after deployment in the military.

Patient-Specific Rehearsal Surgery—Ongoing research in image-guided simulation should continue with the ultimate goal of allowing a practicing surgeon to complete a patient-specific rehearsal surgery that integrates the patient’s own anatomy into the simulation. Soler et al describe a method of integrating Augmented Reality technology into the operating room as a first step toward this goal. Using computed tomography scan reconstructions they displayed 3D renderings of the patient’s anatomy during the procedure. In one case they used the Da Vinci robot to view the rendering and the patient image simultaneously during the procedure.³⁷ Future research is needed to develop a VR platform

that a surgeon can use to determine not just the anatomic but also the physiologic effects of the planned steps of the surgery ahead of time.

Conclusions

Simulation has the potential to offer an adaptive and intelligent assessment and training system that is specific both to procedures and to the experience level of trainee, that is, it could provide a trackable, testable way of improving medical student and resident education. This type of education is especially vital to ensuring patient safety in technical fields, that is, surgery, anesthesia, obstetrics-gynecology, emergency medicine, and critical care medicine. The increasing number of mandatory simulation-based exams required for trainees to sit for the ABS will increase training program and resident desire to use simulators as part of their standard curriculum.

The future of simulation depends heavily on the establishment of an agreed upon set of goals for surgical trainees. The agenda of researchers and clinicians must align through collaboration across laboratories and industries to allocate funding toward projects that help achieve these goals. The areas of technology that engineers focus their energy on developing must in agreement with the areas that researchers and clinicians target. The recommendations as outlined herein should be used to guide the further study and implementation of the standardized use of real and virtual simulation as an essential part of surgical education moving forward.

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Technology	
1.	Faster interface (memory) for realistic simulations
2.	Identify which topics do and do not require accurate simulations
3.	Open source software models for better deformations/collisions
4.	Improve ergonomic simulations
5.	Create an immersive experience

Clinical Applications	
1.	Student and resident technical and non-technical skills training and evaluation
2.	Simulators that modify the program based on learner performance
3.	Safety Education
4.	Maintenance of Certification programs
5.	Patient-specific rehearsal surgery

Figure 1.
Summary of the research and implementation priorities



Figure 2. Virtual peg transfer task in a virtual operating room where distractions and interruptions are introduced

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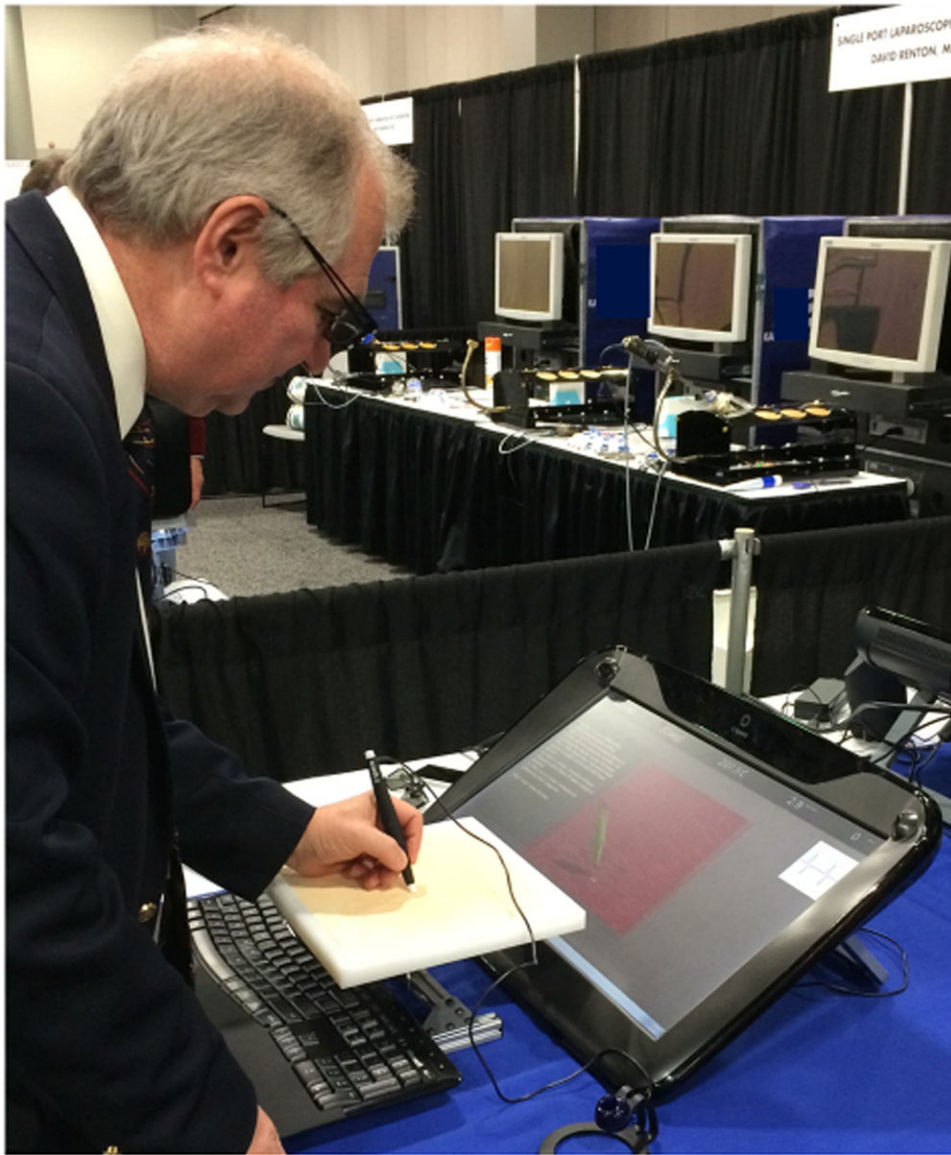


Figure 3.
The Virtual Electrosurgery Skill Trainer (VEST)

Level	Open	Lap	Universal/Both
All	When to call for help Running a code		
MS/ PGY 1	Basic airway, nasogastric tube, arterial blood gas, paracentesis, thoracentesis Chest tube and thoracentesis Central venous access Arterial line placement	Camera driving Peg transfer	Instrument names Antibiotic prophylaxis FUSE (Fundamental Use of Surgical Energy) Knot tying, Suturing
PGY 2-3	FAST (Focused abdominal sonogram) Open inguinal hernia Inguinal anatomy Incision choice Arterial anastomosis Laparotomy, open and close Bowel anastomosis Open g-tube and j-tube Tracheostomy	Trocar site location, insertion, and closure Simple laparoscopic (lap) cholecystectomy (chole) Knot pusher FLS (Fundamentals of Laparoscopic Surgery) FES (Fundamentals of Endoscopic Surgery) Percutaneous endoscopic gastrostomy	Patient positioning Choice of lap vs open Appendectomy Control of bleeding Cholangiograms Tissue handling Dissection Liver biopsy Lysis of adhesions
PGY 4-5	Trauma Laparotomy Stoma creation and takedown Thyroidectomy Pancreatectomy Liver resection	Complex lap chole Lap inguinal hernia Lap ventral hernia Diagnostic laparoscopy Bariatric surgery	Colectomy Common bile duct exploration Anti-reflux Procedures Splenectomy Gastrectomy

Figure 4.
Example of a level based skills curriculum