2 Robotics Training and Simulation

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Introduction

Minimally invasive surgery (MIS) originated in the 1970s in Germany where Kurt Semm, a gynecologist and engineer at the University of Kiel, headed a team that constructed laparoscopic instrumentation to successfully perform various laparoscopic gynecological procedures, as well as the first "endoscopic appendectomy" in 1982. The general surgery community adopted this early laparoscopic technology and successfully performed the first laparoscopic cholecystectomy in 1985. Ultimately, with the advent of video recording and widespread transmission, general surgeons were able to create significant headway in the global adoption and advancement of laparoscopic surgery [1].

Compared to an open approach, advantages to MIS are well established and include reduced postoperative wound infections, blood loss, length of hospital course, postoperative analgesic requirement, and improved wound aesthetics. Disadvantages to MIS include the fulcrum effect, which requires the inversion of hand-instrument movements. In addition, there is restricted hepatic feedback, loss of depth perception, and at times, challenging ergonomics, all of which create a significant learning curve to overcome [2, 3]. With its approval in 2000 by the United States Food and Drug Administration (FDA), the da Vinci surgical system was implemented in an attempt to overcome many of the MIS limitations; its innovative design incorporated high definition three-dimensional (3D) vision, optimal visualization with 10 times magnification, elimination of the fulcrum effect, reduction of hand tremor, and vastly improved surgeon ergonomics [4]. The system is currently in its fourth generation (da Vinci Xi) and includes the following components: a surgeon console that allows the surgeon to view the operative area and manipulate the robotic instruments, a patient side cart that maintains the camera and endowrist instruments with seven degrees of freedom via articulated arms, and a 3D visualization cart [5, 6].

Rise of Robotic Surgery

The robotic surgery boom has experienced far-reaching success across the globe. Since its inception in 2000, over 1.5 million procedures have been performed using the da Vinci surgical system across many surgical specialties, including gynecology, urology, general surgery, cardiothoracic surgery, and otolaryngology. Specifically in urology, the robotic platform has rapidly overtaken open surgery as the standard way of performing a prostatectomy; in fact, 83% of

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prostatectomies are performed with robotic assistance [7]. According to the most recent 2015 statistics, 3317 da Vinci surgical systems exist worldwide with 2254 within the United States (68%), 556 in Europe (17%), 194 in Japan (6%), and 313 (9%) in the remainder of the world [8]. That represents a 43% rise seen just in the United States, alone, since 2010 [4].

With the exponential rise and adoption of robotic technology and the equally rapidly evolving landscape of the health care system, the question of how to most effectively train current and future surgeons comes into the forefront. Patient safety and its litigious ramifications are a prime concern in today's health care climate. In 1999, the Institute of Medicine published its "To Err is Human" report, revealing that as many as 98,000 preventable deaths occur in hospitals each year resulting from medical errors [9]. More recent 2013 estimates report that between 210,000 and 440,000 preventable patient deaths occur per year [10]. Astoundingly, this would place medical errors as the third leading cause of death in the United States, trailing only heart disease and cancer [11]. This issue is further compounded by mandatory reductions in duty hours allotted for resident training. Thus, the all-important question becomes how do surgical residencies incorporate robotic training into their programs while simultaneously considering patient safety, resident work hour restrictions, and procedure outcomes?

Surgical Training and Credentialing

The conventional Halstedian surgical training model was designed to be a long-term apprenticeship between a junior surgeon and his upper level residents and house staff. This method of training provided young surgeons a graduated responsibility until they were able to perform surgical procedures independently. This model has sustained great longevity; however, its inherent lack of organization can lead to variable outcomes in training [4, 12]. Consequently, in this current modern era of rapidly changing all-pervasive technological advancements in medicine, a more structured surgical training curriculum is necessary to promote effective learning as well as patient outcomes. In 2009, the American Board of Surgery (ABS) required that all general surgeons applying for board certification must have successfully completed the Fundamentals of Laparoscopic Surgery (FLS), a course designed to teach and assess basic laparoscopic skills [13]. Similarly, although not mandated by any formal organizations at this time, the Fundamentals of Robotic Surgery Skills and Training (FRS) is a basic skills proficiency curriculum composed of four modules: introduction to surgical robotic systems, didactic instructions for robotic surgery systems, psychomotor skills curriculum, and team training and communication skills. This program is funded by the Department of Defense as well as by Intuitive Surgical and is currently undergoing a validation study across 15 well-established robotic surgical centers across the world. When the validation study is complete, surgical specialties utilizing the robotic platform will be encouraged to incorporate the FRS concepts into an individualized, specialty-specific core curriculum [14].

Other available training resources include the American Urological Association Education and Research (AUAER) online urologic robotic surgery course; this course is composed of nine modules designed to address the general fundamental aspects of performing robotic surgery as well as focus on key surgical steps, possible complications as well as their management, and troubleshooting during performance of basic (e.g., transperitoneal prostatectomy) and more advanced (e.g., radical cystectomy) robotic procedures. The modules contain specific aims, videos, and posttest evaluations. Additionally, the trainee is required to successfully complete the da Vinci Surgery online fundamental training module prior to starting the AUAER course [15].

Additional online video resources include the da Vinci Surgery Online Community which offers full-length narrated procedures, narrated video clips, and various procedure guides that include patient positioning, port placement, robot docking, and step-by-step surgical instructions [16]. Videourology is an online peer-reviewed videojournal and publishes novel robotic and laparoscopic surgical techniques that are easily accessible [17]. The American Urological Association surgical video library presents an additional (paid) resource for accessing video content [18].

Currently, no streamlined robotic surgery credentialing process exists [3]. Standard Operating Practices (SOPs) for urologic robotic surgery state that robotic surgery credentialing is the sole responsibility of an individual institution. SOPs suggested basic requirements include successful completion of an Accreditation Council for Graduate Medical Education (ACGME) urology residency as well as proof of the graduate's robotic surgical competence from the residency's program director. SOPs recommend that existing practitioners without prior robotic surgical experience should complete a training course, which includes basic online training modules, observation of procedures performed by an expert, and active participation using the robotic surgical system with an instructor to perform basic system functions, troubleshooting, and inanimate/animate skills exercises [19]. Such MIS training courses are available as week-long mini-fellowships at the University of California and through the da Vinci Training Pathway [20, 21]. After completion of a structured course, it is recommended that the physician undergoes proctoring by an experienced robotic surgeon until competency is deemed adequate to perform robotic surgical procedures independently [19]. As the current robotic surgery credentialing process is rather vague, the FRS will likely have ramifications for more specific institutional certification and credentialing.

Learning Curve

It is clear that a paradigm shift to performing robotic MIS has quickly occurred since the launch of the robotic surgical platform. Adaptation to robotic surgery once thought to represent a straightforward transition for experienced open surgeons, however, has proven to require a significant adjustment period. Sood et al. [3] convey this point in a robotic kidney transplantation study where the learning curves of three groups of surgeons with different levels of robotic and open experience are evaluated based on performance of the critical steps of the operation, including venous, arterial, and ureterovesical anastomoses, as well as the period of ischemia. The results clearly revealed that the group with the least amount of prior robotic experience required a significantly longer learning curve to achieve proficiency for each critical step of the procedure [14].

The notion of a "learning curve" was first applied to the airplane manufacturer industry in 1936 by Wright [22] where he hypothesized that the cost of labor in production of an airplane decreases over time with quantity produced. This concept has since been applied to various fields, including surgery, where it highlights the number of required cases a surgeon must perform to attain competence in a specific procedure. The learning curve applies to both beginner surgeons training under a supervised environment and to experienced surgeons incorporating novel techniques into their armamentarium. Along the same vein, in robotic surgery, a learning curve also pertains to the bedside surgeon as well as the entire surgical team [3].

Surgical Simulation

Surgical simulation is a field that has risen out of necessity to help shorten the learning curve and help surgeons safely adapt to the rise in widespread adoption of minimally invasive surgery. In fact, in 2008, the American Council on Graduate Medical Education (ACGME) set a requirement that all general surgery residency programs must provide simulation and skill laboratories for its trainees [23]. Surgical simulation is not a novel idea and follows suit after the success of flight simulation in the aircraft industry, where it has proven benefits [24]. Surgical simulation has evolved over the past 20 years, first with the introduction of laparoscopic surgery and subsequent development of the robotic platform. [25] Simulation involves various types of simulator training models with the goals of reproducing an accurate depiction of the surgical field and developing a specific set of skills in the trainee that can be used effectively during an actual surgical procedure [26]. Surgical simulators can be divided into low fidelity, high fidelity, and virtual reality (VR) simulators [25, 27]. Examples of low fidelity simulators are pelvic laparoscopic trainers, which do not represent a high level of operating room realism nor do they simulate an operative procedure; however, they are cost-effective, and have been shown to improve basic laparoscopic skills. High fidelity simulators use live or cadaveric animal models with the main advantage of simulating a realistic operating room environment. Disadvantages include their substantial cost of use, difficulty with accessibility, poor tissue compliance and deficient bleeding in cadaveric models, and adjunctive requirement of veterinary support for live animal models [27]. Virtual reality simulation offers computer-generated digital reproduction of a real-world operating room experience [25].

The benefits of virtual reality surgical simulation are multiple: It fosters a safe, realistic, trainee-centered environment with the ability to make mistakes while acting out various clinical scenarios, including portions of and/or entire surgical procedures, and performing varying degree of difficulty technical skill tasks without compromising patient safety, all while tracking the surgeon's progression [24]. VR simulation has been validated for use in surgical training; the technology has been tested for face validity (realism), content validity (appropriateness), construct validity (capacity to discern between inexperienced and experienced users), concurrent validity (performance on simulator versus a gold standard), and predictive validity (capacity to predict future performance) [28, 29].

Robotic Simulators

Although numerous models are described in the literature, the following mainstream simulators will comprise the focus of discussion for VR robotic simulation training: Mimic DV-trainer, Xperience team trainer, Maestro™ AR, da Vinci skills simulator, RoSS, and SEP robot.

Mimic Technologies, Inc. (Seattle, WA) introduced the first robotic simulator, the Mimic dV-Trainer®, and installed its early version in 2007 at Indiana University's urology department. It is a portable, desktop-sized trainer and, unique in its class, in that it has the ability to simulate all three *da Vinci*® models (*S*™, *Si*™, and *Xi*™) via its MSim™ simulation technology that is able to generate a wide array of updatable 3D, surgical skill training exercises and requires a desktop computer to power the software. Over 60 surgical training exercises validated for face, content, and construct are included with concentration on the trainee's ability to attain competence in various robotic skill sets, including *EndoWrist*® manipulation, knot tying, camera use, needle control and driving, clutching, vessel dissection, basic and advanced (i.e., tube closure and anastomosis) suturing, energy control and robotic arms' movements [30, 31]. The MScore™ proficiency scoring allows the user to immediately receive objective performance metrics and compare them to experienced users' results, which may assist as a tool in the credentialing and certification process. Custom curricula can be tailored for individual users, and MShare™ enables online users to share their effective skills curricula with each other [32]. The system costs between $85,000 and $105,000 with a service contract [26].

In 2014, Mimic introduced the Xperience™ Team Trainer as well as the Maestro AR™ (Augmented Reality). The Xperience™ Team Trainer is an optional hardware add-on for the dV-Trainer; it includes an interface complete with two laparoscopic instrument ports and a built-in video monitor. This simulator enables the coordinated training to both the console surgeon and bedside surgeon through 13 skill exercises emphasizing effective object transfers, assistance with retraction, and clip application. It provides the opportunity for both surgeons to develop psychomotor tasks as well as communication skills and rehearse them in a safe setting outside of the operating room. The MScore™ performance evaluation system allows for objective skills measure of the overall team and each individual surgeon [32, 33]. Validation studies are pending for the Xperience™ Team Trainer.

The MSim™ simulation platform enabled the production of the Maestro AR™. This advanced simulation has the ability to overlay interactive 3D virtual instruments onto actual footage of a previously performed procedure. This allows the user to obtain procedure-specific skills, including identification of critical anatomical landmarks, plane dissection, and tissue retraction in this 3D "augmented reality." The partial nephrectomy and hysterectomy procedures are currently available for use on the Maestro AR™, and low anterior resection and prostatectomy modules are scheduled for future release. Validation studies are pending for this new technology [34].

The *da Vinci Skills Simulator* (dVSS) was produced by Intuitive surgical in collaboration with Mimic Technologies in 2011. The simulator serves as a hardware backpack that attaches and fully integrates with the *da Vinci*® *Si*™, *Si-e*™, and *Xi*™ robotic platforms. The surgical skill exercises are partially based on Mimic's dV-Trainer software and have been previously discussed. Learners have the ability to receive immediate feedback and track their progress over time [35]. Face, content, and construct validity has been proven for the dVSS [36, 37]. The simulator costs roughly $90,000 [26].

The Robotic Surgical Simulator (RoSS™) is manufactured by Simulated Surgicals and represents a stand-alone robotic platform capable of simulating the da Vinci® robotic system. It includes 16 training modules that develop the trainee's orientation, cognitive, motor, basic and more advanced surgical skills via various training tasks. The RoSS™ incorporates the Fundamental Skills of Robotic Surgery (FSRS) and uses a standardized scoring performance system [38]. Additionally, RoSS™ boasts its HoST (Hands-on Surgical Training) system, which enables the trainee's hands to be guided through a previously performed real procedure; this provides an interactive environment for the user to perform the critical steps of a procedure in a virtual environment. Thus far, radical prostatectomy, radical hysterectomy, radical cystectomy, and lymph node dissection modules are available for the HoST system [39]. The RoSS II™ is an updated, redesigned, more compact version of the platform that possesses improved graphics and visualization. It also incorporates the RSA (Robotic Skills Assessment) Score, which provides users real-time feedback based on a timed assessment as part of the RoSS™ training curriculum measuring the trainee's safety, critical error, economy of motions, dexterity, time, and metrics [38]. Face and content, however, not construct, validity has been proven for the RoSS™ simulator [25].

The SimSurgery Educational Platform (SEP) Robot is a modified version of its laparoscopic VR platform; the laparoscopic arms of the basic VR trainer are replaced for robotic arms on the SEP robot. It offers multilevel skill training, and only includes 6 tissue manipulation, 7 basic suturing, and 8 advanced suturing exercises [40–42]. Its limitations are its lack of 3D visualization, fourth-arm manipulation, objective feedback, and procedure-specific modules [27]. However, compared to its competitors, it does represent a cost-conscious VR system ($45,000) and has proven face, content, and construct validity [25–27].

Efficacy data directly comparing various VR simulators is sparse in the literature; Table 2.1 summarizes the validity data for aforementioned VR simulators and their associated costs. Figure 2.1 displays their images.

Surgical Skills Training

The merits of VR simulation in surgical training have been established. Its use has been shown to help novice surgical trainees quickly acquire and improve a basic laparoscopic skill set. Grantcharov et al. [43] studied three groups of surgeons with varying levels of laparoscopic expertise (advanced, intermediate, and novices) using the Minimally Invasive Surgical Trainer-Virtual Reality (MIST VR), which entails six different and increasingly difficulty skill exercises, including grasping, transference, use of energy, and combinations of these tasks. Subjects in each group completed ten sessions of all tasks over a 1-month block of time. Their performance metrics were measured via

Table 2.1 Summary of the validity data for VR simulators and their associated costs

Virtual reality simulators						
	Face validity	Content validity	Construct validity	Concurrent validity	Predictive validity	Price
Mimic dV-T	+	+	+	–	–	$85–100,000
Xperience Team Trainer	n/a	n/a	n/a	n/a	n/a	
Maestro AR	n/a	n/a	n/a	n/a	n/a	
dVSS	+	+	+	–	–	$85–90,000
RoSS	+	+	n/a	–	–	$100–125,000
SEP	+	+	+	–	–	$40–45,000

dV-T dV-Trainer, *AR* augmented reality, *dVSS* da Vinci skills simulator, *RoSS* robotic surgical simulator, *SEP* SimSurgery educational platform, − no, + yes, *n/a* not available

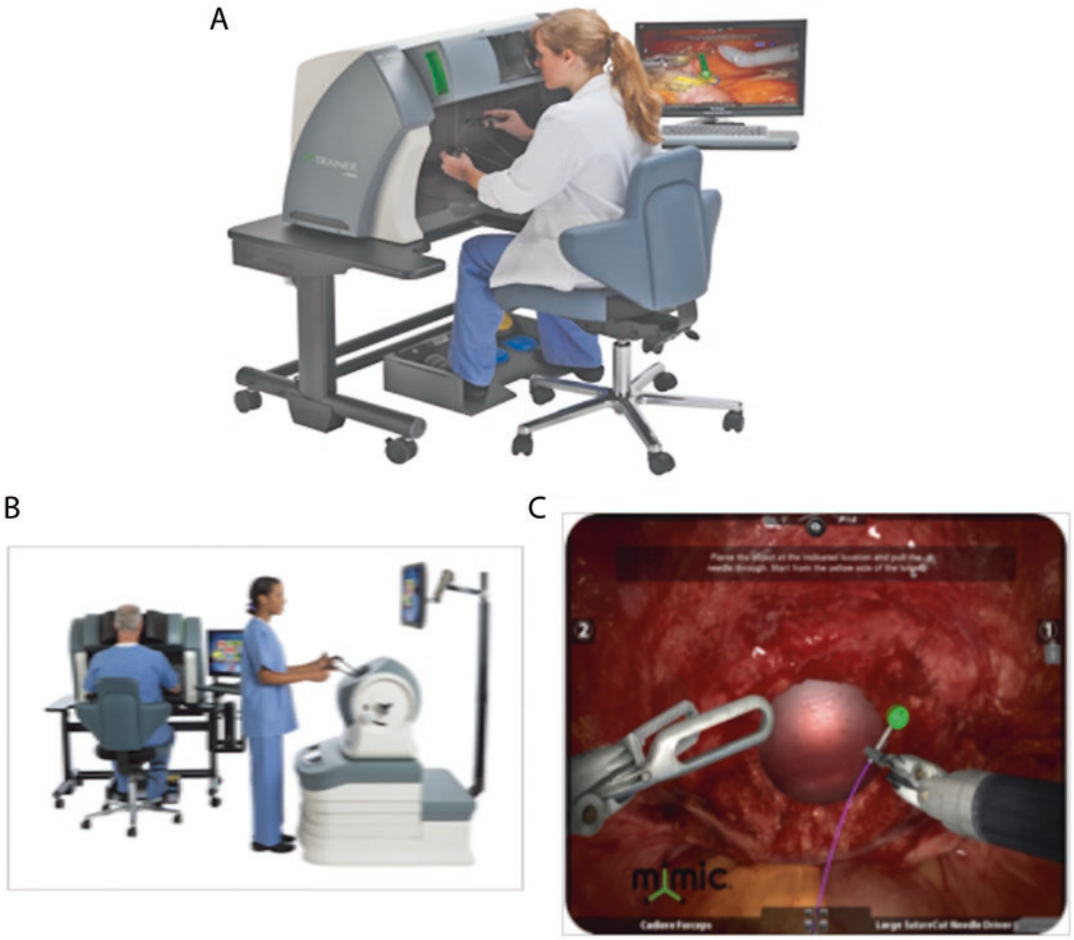

Fig. 2.1 VR Simulators: (**a**) Mimic Dv-T (courtesy of Mimic Technologies, Inc.); (**b**) Xperience Team Trainer (courtesy of Mimic Technologies, Inc.); (**c**) Maestro AR (courtesy of Mimic Technologies, Inc.); (**d**) dVSS [35]; (**e**) RoSS [38]; (**f**) SEP [42]

time to completion of tasks, errors committed, and economy of motion utilized. Although performance scores for the beginner group were significantly lower compared to the intermediate and advanced cohorts after the first trial run, the results were not significantly different after the final session, revealing that basic laparoscopic skill attainment is possible in a relatively short period of time. In fact, the beginner group's learning curves reached a steady stage just after seven, six, and five sessions for time, economy of motion, and error scores, respectively.

Furthermore, in a randomized, double-blinded study, Seymour et al. [44] showed that the surgical resident group who underwent basic task training using the MIST VR platform proved to perform subsequent laparoscopic cholecystectomy procedures faster and with a reduced error rate compared to the control group. This study pioneered the concept that transference of a surgical skill set from a simulation platform to an operative venue is, indeed, possible. Calatayud et al. [45] furthered this idea from a different training angle: the operative warm-up setting. In this randomized crossover study, surgical residents functioned as their own controls, and each group performed a total of two laparoscopic cholecystectomy procedures 2 weeks apart. The first group was randomized to perform the procedure without VR warm-up, followed 2 weeks later by undergoing VR warm-up exercises and subsequently performing the procedure. The second group first completed a VR surgical warm-up and performed the procedure; 2 weeks later, this group performed an additional laparoscopic cholecystectomy without the benefit of VR warm-up exercises. VR warm-up training constituted executing three exercises (object manipulation, clip application, and dissection) for 15 min using the Lapsim VR simulator just prior to the start time of the operative procedure. The results of the study revealed significantly higher operative surgical performance scores in the groups who performed laparoscopic cholecystectomy cases with prior surgical warm-up as measured by a validated objective structure of technical skills (OSATS) global rating scale. Lee et al. [46] helped to cement that surgical warm-up is a beneficial practice; this randomized crossover study included three junior urology residents, two senior urology residents, and three urology fellows. Each subject performed a total of four laparoscopic renal procedures in two sets divided by more than 1 week apart. During each session consisting of two procedures, each subject had the opportunity to either first perform warm-up exercises or directly proceed with the operative procedure; the actual order of events (i.e., warm-up vs. surgical procedure) was randomized. Surgical warm-up was composed of performing a 5 min electrocautery exercise on the LAP Mentor VR simulator as well as a 15 min laparoscopic suturing/knot tying task 1 h prior to the operative procedure. Psychomotor and cognitive data was obtained using electroencephalography (EEG), eye tracking technology, and video recording of the operative procedures. Mean psychomotor performance scores, as measured by hand movement smoothness, tool movement smoothness, and postural stability, proved to be significantly higher in the surgical warm-up group. The warm-up group also showed improved cognition during performance of renal surgery, as measured by mean attention, distraction, and mental workload scores. Furthermore, the surgical rehearsal cohort achieved significantly higher technical performance scores when evaluating its ability to mobilize the colon during an early portion of a renal procedure. However, during a later step of the procedure (retroperitonealizing the colon), surgical warm-up was not found to improve surgical task scores, thus, lending theory that warm-up may be applicable for a short period of time. Lendvay et al. [47] performed a trial designed to test whether VR surgical warm-up proved beneficial in a robotic dry lab situation. The group consisted of a total of 51 subjects across various fields (urology, gynecology, and general surgery) and training levels (residents and attendings). All subjects underwent robotic proficiency training and were subsequently randomized to either the surgical warm-up group or the control group. All subjects completed four trial runs: the initial three involved completion of the da Vinci VR rocking pegboard task while the final one comprised a robotic intracorporeal suturing exercise.

In all trials, the surgical warm-up group completed a brief (3–5 min) VR pegboard warm-up task while the control group read a book for 10 min prior to the required exercise. In the first three repetitions that tested similar VR exercises, the VR warm-up group proved to show significantly improved performance metrics (task times and tool path lengths) compared to the control group. The fourth trial sitting evaluated a different and more complex VR task (robotic intracorporeal suturing) designed to test generalizability of the warm-up task; results revealed the warm-up group had a significantly decreased error rate when performing this exercise compared to the control group. The next step in robotic VR warm-up training is to assess whether it transfers dry lab skills to the operating room and impacts patient safety.

Patient-specific simulation is a technological concept/advancement that is intricately related to surgical warm-up. It allows for two-dimensional data from CT scans and MRIs to be uploaded onto a VR simulator and rendered into an interactive 3D image on the stereoscopic field. In this fashion, surgeons are given the opportunity to rehearse the planned procedure using a patient's unique anatomical data in a VR environment, a concept similar to augmented reality. Currently, Simbionix holds the only commercially available patient-specific VR simulator (AngioMentor) designed for carotid endovascular stent placement. It has proven face, construct, and content validity and enables the user to track objective measures over time [48].

In addition to VR simulation, the robotic platform can also be effectively utilized to develop a basic robotic skill set using inanimate exercises. Jarc and Curet [49] proved the construct validity of nine ex-vivo tasks designed to test camera control, clutching, instrument manipulation, needle positioning, and suturing. In this study, advanced robotic surgeons significantly outperformed novice surgeons, as evident by quicker task completion times and performance scores. Furthermore, Raza et al. [50] used a commercially available inanimate vesicourethral anastomosis kit (Fig. 2.2) (3-Dmed) to prove content, construct, and concurrent validity in performing a vesicourethral anastomosis using the da Vinci robotic platform.

Novel Avenues of Surgical Grading

In this ever-expansive online technological age, novel avenues of surgical grading have been explored and developed. Crowdsourcing is one such method and involves seeking out responses from a large, heterogeneous cohort of people from an online community to assist in finding a solution to a problem, in this case, evaluating surgical performance; this has been termed crowd-sourced

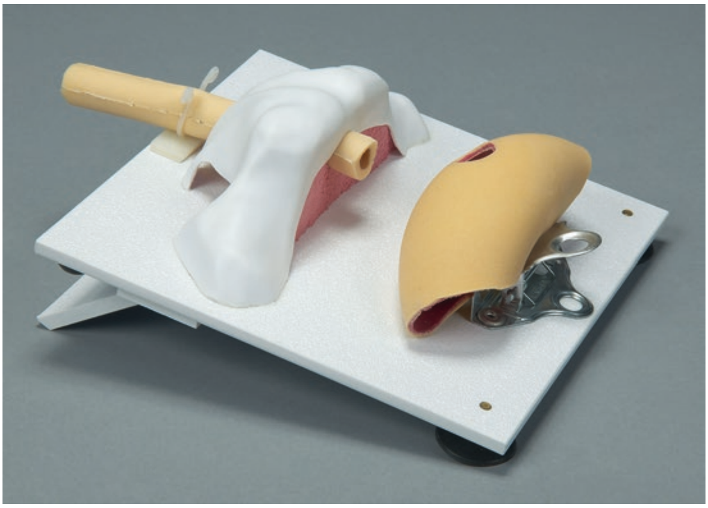

Fig. 2.2 Inanimate vesicourethral anastomosis model (courtesy of 3-DMED)

assessment of technical skills (C-SATS). Studies involving C-SATS have recently revealed that the surgically inexperienced online community is equally effective as experienced surgeons in evaluating performance during dry lab robotic videos as well as brief animate videos performed by surgeons of varying experience levels. Surgical performance was graded using a validated surgical grading tool, the Global Evaluative Assessment of Robotic Skills (GEARS), which evaluates the following five domains: depth perception, bimanual dexterity, efficiency, force sensitivity, and robotic control [51, 52]. While C-SATS will certainly not serve to replace a surgical trainee's invaluable feedback from his experienced mentor, it may have a supplementary role for receiving further feedback in a timely fashion [51].

Along a similar train of thought, video-based peer evaluation via social networking is another innovative surgical evaluation grading tool. In a recent randomized control trial, a total of 41 urology and gynecology residents performed a running anastomosis exercise (Tubes simulator task) in three different sessions over 6 weeks. The 20 subjects in the intervention group received peer feedback after each session after their videos were de-identified and uploaded to a social networking site while the control group did not receive video-based peer feedback. Feedback was provided using GEARS as well as summative remarks. While mean scores for both subject groups were similar for the first session, the intervention residents scored significantly higher and completed the tasks substantially faster than the control group after the second and third sessions [53]. Consequently, this method has shown to improve simulation training performance metrics and holds promise for the evaluation and improvement of real-world robotic operative procedures.

Conclusion

It is clear that the booming use of robotic technology has brought an overwhelming sense of enthusiasm to the field of minimally invasive surgery. In turn, with the pervasive acceptance of this technology, efficiently training the new wave of surgeons as well as existing ones comes into the forefront, as this is essential to patient safety, medicolegal aspects, and health care expenditure. VR robotic simulation has clearly shown to be beneficial in helping trainees rapidly acquire a basic surgical armamentarium that can be transferred to the operative theatre. Furthermore, VR simulation is currently being used to create training curriculums and potentially play a role in credentialing and licensing. While the benefits of VR simulation are clear, however, one also has to take into account its substantial cost, and the fact that it has not yet been studied or shown to ultimately impact patient outcomes, the overarching driving force in the medical landscape. Thus, while new technology continues to become incorporated into mainstream medicine, we must find a way to utilize it in a safe, smart, and effective manner.

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