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Vessel Ligation Training via an Adaptive Simulation Curriculum

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Abstract

Background—A cost-effective model for open vessel ligation is currently lacking. We hypothesized that a novel, inexpensive vessel ligation simulator can efficiently impart transferrable surgical skills to novice trainees.

Materials and Methods—VesselBox was designed to simulate vessel ligation using surgical gloves as surrogate vessels. Fourth-year medical students performed ligations using VesselBox,

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and were evaluated by surgical faculty using the Objective Structured Assessments of Technical Skills (OSATS) global rating scale and a task-specific checklist. Subsequently, each student was trained using VesselBox in an adaptive practice session guided by cumulative sum. Post-testing was performed on fresh human cadavers by evaluators blinded to pre-test results.

Results—Sixteen students completed the study. VesselBox practice sessions averaged 21.8 minutes per participant (IQR 19.5 – 27.7). Blinded post-tests demonstrated increased proficiency, as measured by both OSATS (3.23 vs 2.29, $p < 0.001$) and checklist metrics (7.33 vs 4.83, $p < 0.001$). Median speed improved from 128.2 seconds to 97.5 seconds per vessel ligated ($p = 0.001$). Following this adaptive training protocol, practice volume was not associated with post-test performance.

Conclusions—VesselBox is a cost-effective, low-fidelity vessel ligation model suitable for graduating medical students and junior residents. Cumulative sum can facilitate an adaptive, individualized curriculum for simulation training.

Keywords

surgical education; simulation; student; medical; surgical training; vascular surgery techniques; proficiency metrics

INTRODUCTION

Simulation's role in surgical education has expanded exponentially over the past decade, driven in part by concerns over resident operative preparedness in an era of work-hour restrictions [1]. In 2009, the Residency Review Committee mandated that all general surgery residents have access to a surgical skills laboratory. However, despite its prevalence, surgical simulation continues to struggle with many critical challenges, among which cost burden, skill transferability, and time resources are at the forefront [2].

Thus far, the majority of surgical simulation has been directed toward laparoscopic and endoscopic skills [3], culminating in the Fundamentals of Laparoscopic Surgery (FLS) and Fundamentals of Endoscopic Surgery. More recently, approaching traditional FLS tasks through single-incision laparoscopy simulators has become a growing focus of research, and early data suggest admirable skill retention [4]. On a more basic level, focused training in techniques such as vessel ligation during medical school is often inconsistent [5], and basic open surgical skills may not be acquired until well into the first year of residency [6]. Nevertheless, early operative encounters are almost always in the setting of open surgeries. It stands to reason that simulation in open surgical skills may be adopted to accelerate the transition to technical proficiency in the interest of patient safety [7, 8]. Unfortunately, open surgery simulators are comparatively rare, indicating that teaching programs may place less value in simulation for skills that are typically acquired in the early years of residency.

We recently described a novel, low-fidelity vessel ligation simulator: VesselBox. With negligible costs of construction and operation, VesselBox demonstrated criterion validity by effectively stratifying participants by level of operative experience [9]. The purpose of this study is to report the implementation of VesselBox within a surgical internship preparedness course. Recognizing that time is one of the most costly resources in simulation, a training

protocol was designed to tailor the duration of practice to the learning rate of individual participants in an adaptive manner. Cumulative sum (Cusum) is a sequential analysis tool that tracks learning progression in real time, and has been applied to a broad range of surgical skills [10-12]. Its overall premise is that the transition from sub-proficient to proficient performance can be captured by tracking trainees' patterns of successes and failures at a given task. Cusum's most common application is in the objective depiction of trainee learning curves, and it has also been used to demarcate thresholds of proficiency. We hypothesized that an adaptive protocol based on Cusum can be harnessed to guide efficient training using VesselBox, and that the resulting technical proficiency would be transferrable to a high-fidelity system.

METHODS

Model Design

Details regarding the VesselBox model and cost structures of implementation have been previously described [9]. In brief, VesselBox is a low-fidelity bench-top trainer that mounts a latex surgical glove within a three-sided box in order to simulate vascularized tissue in an abdominal compartment (Figure 1). Trainees are tasked with gaining proximal and distal control of the synthetic vessel (the glove "finger"), dividing the vessel, and ligating both ends with 3-0 silk suture ties. A surgical assistant is integral to proper task completion, performing only those actions which are directly requested by the participant. The simulated task assesses operative technique, instrument knowledge, and communication.

Assessment

To measure proficiency using VesselBox, two metrics were adopted. The Objective Structured Assessments of Technical Skills (OSATS) global rating scale (GRS) for hemostasis is a relatively subjective tool that has high inter-rater reliability [13, 14]. It assesses seven proficiency descriptors each on a 1 to 5 scale: respect for tissue, time and motion, instrument handling, knowledge of instruments, use of assistants, flow of operation, and knowledge of procedure. Additionally, an eight-item binary checklist was created by investigator consensus which captures technical components critical to proper vessel ligation (Figure 2A). Scores in each GRS category were averaged to create a composite GRS score (max = 5), while the checklist metric was scored based on the number of items properly performed (max = 8). Because neither metric accounted for speed, the time required to control and ligate each vessel was recorded as an ancillary metric.

Implementation

The study protocol was approved by the University of Virginia Institutional Review Board (IRBSBS protocol #2013-0457-00). Graduating fourth-year medical students (MS4) at the University of Virginia School of Medicine matching into general surgery or surgical specialties were recruited for voluntary study participation in the setting of a 2-week surgery internship preparedness course. An instructional video demonstrating proper vessel ligation technique using VesselBox was provided to all participants, and students were required to be able to perform a one-handed knot tie prior to course enrollment. Baseline vessel ligation proficiency was measured using video recordings as each participant ligated two vessels

using VesselBox. Camera field was limited to the simulator and the participants' forearms. The role of the surgical assistant was fulfilled by a single post-graduate year 3 (PGY 3) surgery resident (YH) for all participants. Three surgical faculty blinded to participant identity evaluated each recording using both the OSATS GRS and the task-specific checklist.

Each participant underwent a single one-on-one practice session immediately after pre-testing. Practice sessions were proctored by the same PGY 3 surgery resident (YH) for all participants. Practice sessions involved up to two demonstrations of proper vessel ligation technique, followed by repetitious practice by the participant. All practice attempts incorporated an assistant who delivered and retracted instruments as directed by the participant. Feedback was provided following each practice attempt, and each attempt was scored using the task-specific checklist. Scoring 7 or higher on the 8-point checklist was indicative of a successful attempt, while lower scores were considered failures. Learning progression was assessed after every practice attempt using a web-based automated Cusum calculator (Figure 2).

Bolsin and Colson's description of Cusum for procedural training was the basis for our practice protocol [15]. Briefly, a Cusum learning curve represents each successful practice attempt with a downward deflection and each failed attempt with an upward deflection (Figure 3). As a subject repetitively performs a task, crossing a decision interval with a positive deflection is indicative of sub-proficient performance. Cusum parameters for VesselBox training were assigned a priori to approximate the expected proficiency of a mid-level resident. By investigator consensus, these parameters included an acceptable failure rate of 5% and an unacceptable failure rate of 20%. The type 1 error rate—the rate of incorrectly accusing a proficient trainee of sub-proficient performance—was set at 10%. Using these parameters, the decision interval (h_0) was calculated as 1.41.

In order to capture real-time estimates of proficiency, Cusum calculations were iteratively applied to an updating series of 8 practice attempts. This is a simplified derivation of the exponentially-weighted moving average method of incorporating memory-loss into Cusum functions [16]. Each practice session continued until the participant had completed eight consecutive practice attempts without crossing a Cusum decision interval. For example, if a participant has completed 13 practice attempts, then a Cusum value of 0 was assigned for attempt 6. If a decision interval was not crossed between attempts 6 through 13, then that participant has demonstrated Cusum-proficiency at attempt 13. Once a participant was proficient by Cusum criteria, the practice session was terminated, and the participant then underwent post-testing on a high-fidelity, fresh human cadaver model. Participants were required to ligate a medium-sized vessel (short gastric artery, mesenteric artery branch, or extremity venous branch) using the same technique that was practiced with VesselBox. When an appropriate vessel was unavailable, friable strands of breast tissue were used as surrogate vessels. Each post-test was evaluated in person by the same three surgical faculty who performed pre-test evaluations. Evaluators were blinded to participants' pre-test results and practice session data.

Analysis

For each participant, task-specific checklist and composite GRS scores were averaged across evaluators. Pre-test and post-test outcomes were compared using Wilcoxon signed rank-sum. Both the GRS and the task-specific checklist previously demonstrated excellent inter-rater reliability [9], therefore inter-rater reliability was not reassessed. Relationships between number of practice repetitions and post-test performance were measured using Pearson product-moment correlations. Results were considered significant at 2-tailed $p < 0.05$. All data were analyzed using SAS statistical software (version 9.3; SAS Institute, Inc).

RESULTS

Sixteen medical students were enrolled, and all completed the study protocol. Eight participants were matched in general surgery (50%), 3 each in orthopedic surgery and gynecology, and 1 each in urology and interventional radiology. Ten participants were female (62.5%). Average baseline performance on pre-testing was 2.29 on the GRS (interquartile range, IQR 2.01 – 2.50) and 4.83 on the task-specific checklist (IQR 4.17 – 6.33).

Representative practice session Cusum curves of two study participants are shown in Figure 3. Because proficiency criteria specified that no decision interval may be crossed over eight consecutive practice attempts, the automated Cusum tool was designed to capture performance over an 8-repetition “window” that updates following each practice attempt. Using this system, practice session length and the number of practice attempts were tailored to individual learning rates in an adaptive manner. On average, practice sessions were 21.8 minutes in length (range 16 – 60 minutes), and comprised 10 practice attempts. However, individual learning rates varied greatly, with participants requiring anywhere from 8 to 16 practice attempts in order to satisfy Cusum proficiency criteria (Figure 4). There was no significant correlation between number of practice attempts to attain Cusum-proficiency and pre-test GRS score ($\text{corr} = -0.09$, $p = 0.738$) or pre-test checklist score ($\text{corr} = 0.01$, $p = 0.960$).

Pair-wise analysis indicated significant improvement between post-tests and pre-tests for both the GRS (3.23 vs 2.29, $p < 0.001$) and the task-specific checklist (7.33 vs 4.83, $p < 0.001$, Figure 5). Average time required to clamp, divide, and ligate both ends of each vessel improved from 128.2 seconds to 97.5 seconds per vessel ($p = 0.001$). There was no significant correlation between number of practice attempts and post-test GRS (Pearson correlation coefficient, $\text{corr} = 0.10$, $p = 0.42$), post-test checklist score ($\text{corr} = 0.21$, $p = 0.44$), magnitude of GRS improvement ($\text{corr} = 0.31$, $p = 0.24$), or magnitude of checklist score improvement ($\text{corr} = 0.05$, $p = 0.84$).

DISCUSSION

In this study, we implemented the VesselBox vessel ligation simulator within an adaptive training protocol. Although we enrolled graduating MS4s, the same approach can be applied to incoming PGY 1 residents, as these two groups frequently have comparable vessel ligation proficiency [9]. Using an adaptive curriculum, we minimized the time resources

demanded of trainees and instructors. Furthermore, we demonstrated that the skills acquired using VesselBox are likely to be transferrable to the operating room by conducting post-tests on a high-fidelity human tissue model.

The principle objective of the Surgical Skills Curriculum, created by the American College of Surgeons and the Association of Program Directors in Surgery, is the implementation of simulation training before operative experience [17]. Phase 1 of the curriculum comprises 20 modules ranging from knot-tying to FLS-type laparoscopic tasks. Notably, open vessel ligation is not represented, nor are simulators which model open vascular techniques. Because both the fixed and flexible costs associated with VesselBox are minimal, it is suitable for high-volume repetitive practice, and would be a worthy supplement to the Phase 1 Knot-Tying module. The ideal setting for incorporating VesselBox is during the orientation phase of PGY 1, prior to initial operative experiences. Technically-inexperienced trainees may extend operative duration, thereby negatively impacting length of stay and complication rate [18-21]. In addition to increases in proficiency scores, we noted substantial improvement in speed following training with VesselBox. At early phases of training, proper technique is undoubtedly more important than speed. Nevertheless, speed remains an important complementary metric that may be targeted through simulation.

The concept of skill transferability has received increasing attention in recent years. In a systematic review focusing on endoscopic and laparoscopic models, simulation-based training was associated with superior performance in the patient setting [22]. In a randomized trial, Palter and colleagues showed that pre-operative training on an abdominal fascial closure model was associated with improved intra-operative proficiency. Furthermore, trainees who underwent simulation training retained more auditory instruction while operating, indicating that cognitive teaching could be improved by addressing basic technical proficiency through simulation [23]. Beard and colleagues previously described the criterion validity of evaluations on a bench-top vessel ligation simulator in predicting operative competence [24]. Our study corroborates these data by showing that training with VesselBox can produce a skillset that is transferrable to higher-fidelity models.

An adaptive approach to surgical skills training is intuitively appealing. Theoretically, such an approach would reduce resource demands while preserving instruction quality. Cusum has been used to demonstrate substantial variability in the learning rates for simulated upper endoscopy and laparoscopy [11, 25, 26]. Dalal and colleagues used Cusum to show that learning rates for fiberoptic upper airway endoscopy varied substantially, and concluded that training for this technique should be individualized [27]. To our knowledge, the present study is the first to report the prospective implementation of Cusum as the basis for an adaptive simulation curriculum. Corroborating Dalal's work, we found a two-fold difference in rate of proficiency acquisition across participants. In principle, this variability may reflect learning rate, innate skill, or both. Interestingly, no correlation was noted between pretest scores and the number of practice attempts needed to demonstrate proficiency, suggesting that learning rate may be the more dominant variable in this experiment. Unlike previous studies, we truncated training once proficiency was reached. Classically, educators anticipate that technical proficiency is intimately linked to practice volume. However, in the setting of our Cusum-guided adaptive protocol, there was no correlation between practice

volume and post-test proficiency. This finding provides the first prospective evidence that Cusum guidance can effectively streamline a simulation curriculum.

This study has several limitations. First, due to concerns for patient safety and pragmatic limitations, assessing skill transferability for MS4 participants in the patient setting was not feasible. Using a perfused cadaveric model or a living animal model could further improve post-test assessments by providing data on post-ligation bleeding. Second, Cusum parameters were determined by expert consensus, and were not validated a priori. Because it is still a relatively new tool in the surgical education literature, rigorous validation studies for Cusum are currently lacking and should be actively pursued. One complementary approach would be to perform a second post-test on Cusum-proficient trainees after a number of additional practice attempts to determine if Cusum correctly identified a plateau in proficiency. Within the existing data, the absence of correlation between magnitude of technical improvement and practice volume provides indirect external validation for the Cusum parameters used. Finally, pre- and post-test results could have been influenced by the different assessment methods used, given variables such as participant anxiety and model susceptibility to tissue trauma. Because these negative confounders were more pertinent to the cadaveric, in-person post-test, the true magnitude of improvement in technical proficiency may have been underestimated.

CONCLUSIONS

A low-fidelity open vessel ligation simulator can be used to improve the technical proficiency of novice trainees. The acquired skillset is most likely transferrable to the operative setting. Most importantly, simulation training can be individualized to complement the highly variable learning rates of surgical trainees by implementing a Cusum-guided, adaptive paradigm.

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REFERENCES

1. Carlin AM, Gasevic E, Shepard AD. Effect of the 80-hour work week on resident operative experience in general surgery. *Am J Surg.* 2007; 193:326–9. discussion 329-30. [PubMed: 17320528]
2. Stefanidis D, Sevdalis N, Paige J, Zevin B, Aggarwal R, Grantcharov T, Jones DB, for the Association for Surgical Education Simulation Committee. Simulation in Surgery: What's Needed Next? *Ann Surg.* 2014
3. Sturm, L.; Cosman, P.; Hewett, P.; Cregan, P.; Windsor, J.; Maddern, G. Surgical Simulation for Training: Skills Transfer to the Operating Room. ASERNIP-S Report No. 61. ASERNIP-S; Adelaide, South Australia: 2007.
4. Varley M, Choi R, Kuan K, Bhardwaj N, Trochsler M, Maddern G, Hewett P, Mees ST. Prospective randomized assessment of acquisition and retention of SILS skills after simulation training. *Surg Endosc.* 2014 [Epub].

5. Davis CR, Toll EC, Bates AS, Cole MD, Smith FC. Surgical and procedural skills training at medical school - a national review. *Int J Surg.* 2014; 12:877–882. [PubMed: 24909137]
6. Schill M, Tiemann D, Klingensmith ME, Brunt LM. Year one outcomes assessment of a masters suturing and knot-tying program for surgical interns. *J Surg Educ.* 2011; 68:526–533. [PubMed: 22000540]
7. Relles DM, Burkhart RA, Pucci MJ, Sendecki J, Tholey R, Drueding R, Sauter PK, Kennedy EP, Winter JM, Lavu H, Yeo CJ. Does resident experience affect outcomes in complex abdominal surgery? Pancreaticoduodenectomy as an example. *J Gastrointest Surg.* 2014; 18:279–85. discussion 285. [PubMed: 24222321]
8. Wilkiemeyer M, Pappas TN, Giobbie-Hurder A, Itani KM, Jonasson O, Neumayer LA. Does resident post graduate year influence the outcomes of inguinal hernia repair? *Ann Surg.* 2005; 241:879–82. discussion 882–4. [PubMed: 15912037]
9. Hu Y, Le IA, Goodrich RN, Edwards BL, Gillen JR, Smith PW, Schroen AT, Rasmussen SK. Construct validation of a cost-effective vessel ligation bench-top simulator. *J Surg Educ.* 2015; 72 [Epub].
10. Vigano L, Laurent A, Tayar C, Tomatis M, Ponti A, Cherqui D. The learning curve in laparoscopic liver resection: improved feasibility and reproducibility. *Ann Surg.* 2009; 250:772–782. [PubMed: 19801926]
11. Hu Y, Jolissaint JS, Ramirez A, Gordon R, Yang Z, Sawyer RG. Cumulative sum: a proficiency metric for basic endoscopic training. *J Surg Res.* 2014; 192:62–67. [PubMed: 24976441]
12. Tekkis PP, Senagore AJ, Delaney CP, Fazio VW. Evaluation of the learning curve in laparoscopic colorectal surgery: comparison of right-sided and left-sided resections. *Ann Surg.* 2005; 242:83–91. [PubMed: 15973105]
13. Martin JA, Regehr G, Reznick R, MacRae H, Murnaghan J, Hutchison C, Brown M. Objective structured assessment of technical skill (OSATS) for surgical residents. *Br J Surg.* 1997; 84:273–278. [PubMed: 9052454]
14. van Empel PJ, Verdam MG, Huirne JA, Bonjer HJ, Meijerink WJ, Scheele F. Open knot-tying skills: resident skills assessed. *J Obstet Gynaecol Res.* 2013; 39:1030–1036. [PubMed: 23496799]
15. Bolsin S, Colson M. The use of the Cusum technique in the assessment of trainee competence in new procedures. *Int J Qual Health Care.* 2000; 12:433–438. [PubMed: 11079224]
16. de Leval MR, Francois K, Bull C, Brawn W, Spiegelhalter D. Analysis of a cluster of surgical failures. Application to a series of neonatal arterial switch operations. *J Thorac Cardiovasc Surg.* 1994; 107:914–23. discussion 923–4. [PubMed: 8127123]
17. Scott DJ, Dunnington GL. The new ACS/APDS Skills Curriculum: moving the learning curve out of the operating room. *J Gastrointest Surg.* 2008; 12:213–221. [PubMed: 17926105]
18. Procter LD, Davenport DL, Bernard AC, Zwischenberger JB. General surgical operative duration is associated with increased risk-adjusted infectious complication rates and length of hospital stay. *J Am Coll Surg.* 2010; 210:60–5. e1–2. [PubMed: 20123333]
19. Owen RM, Perez SD, Lytle N, Patel A, Davis SS, Lin E, Sweeney JF. Impact of operative duration on postoperative pulmonary complications in laparoscopic versus open colectomy. *Surg Endosc.* 2013; 27:3555–3563. [PubMed: 23584820]
20. Tan TW, Kalish JA, Hamburg NM, Rybin D, Doros G, Eberhardt RT, Farber A. Shorter duration of femoral-popliteal bypass is associated with decreased surgical site infection and shorter hospital length of stay. *J Am Coll Surg.* 2012; 215:512–518. [PubMed: 22819641]
21. Pollei TR, Barrs DM, Hinni ML, Bansberg SF, Walter LC. Operative time and cost of resident surgical experience: effect of instituting an otolaryngology residency program. *Otolaryngol Head Neck Surg.* 2013; 148:912–918. [PubMed: 23520071]
22. Dawe SR, Pena GN, Windsor JA, Broeders JA, Cregan PC, Hewett PJ, Maddern GJ. Systematic review of skills transfer after surgical simulation-based training. *Br J Surg.* 2014; 101:1063–1076. [PubMed: 24827930]
23. Palter VN, Grantcharov T, Harvey A, Macrae HM. Ex vivo technical skills training transfers to the operating room and enhances cognitive learning: a randomized controlled trial. *Ann Surg.* 2011; 253:886–889. [PubMed: 21394017]

24. Beard JD, Jolly BC, Newble DI, Thomas WE, Donnelly J, Southgate LJ. Assessing the technical skills of surgical trainees. *Br J Surg.* 2005; 92:778–782. [PubMed: 15810048]
25. Kolkman W, Van de Put MA, Van den Hout WB, Trimbos JB, Jansen FW. Implementation of the laparoscopic simulator in a gynecological residency curriculum. *Surg Endosc.* 2007; 21:1363–1368. [PubMed: 17165113]
26. Zhang L, Sankaranarayanan G, Arikatla VS, Ahn W, Grosdemouge C, Rideout JM, Epstein SK, De S, Schwaitzberg SD, Jones DB, Cao CG. Characterizing the learning curve of the VBLaSTPT((c)) (Virtual Basic Laparoscopic Skill Trainer). *Surg Endosc.* 2013; 27:3603–3615. [PubMed: 23572217]
27. Dalal PG, Dalal GB, Pott L, Bezinover D, Prozesky J, Bosseau Murray W. Learning curves of novice anesthesiology residents performing simulated fiberoptic upper airway endoscopy. *Can J Anaesth.* 2011; 58:802–809. [PubMed: 21710368]

Figure 1. VesselBox vessel-ligation simulator. Participants obtain control of simulated vascularized tissue (latex surgical glove) and perform simulated vessel ligation.

A. **VesselBox**

Time:

Attempt Number: 10

Completed

☐ Tie placed directly under clamp (< 2 mm)

☐ Passer tip brought under clamp tip

☐ Knots pushed down with 1st finger

☐ Knots pushed down beyond clamp tip/knot

☐ Requests clamp release while holding tension on first knot throw

☐ Square knots (alternate hand-crossing)

☐ Knots secure (does not slip with light pull)

☐ Proper suture length (not impeded by excessively long/short tail)

B.

Your Score: 7/8

Minimum score to pass: 7

You PASSED this attempt.

Attempts in this session: 1

Total number of attempts: 10

Please repeat the task

You have not reached proficiency.

Figure 2.

A) Automated Cusum calculation tool input form, showing the eight criteria comprising the task-specific checklist. B) Cusum tool output, displaying task performance and learning progress.

Figure 3.

Cusum learning progression for two study participants. Each positive deflection indicates a failed attempt; each negative deflection indicates a successful attempt. Practice session is terminated when the participant has performed eight consecutive ligation attempts without crossing a decision interval (h_0).

Figure 4. Participant proficiency windows during adaptive practice sessions, showing practice attempts which satisfied Cusum proficiency criteria. Of note is the substantial variability in repetitions needed in order to demonstrate proficiency.

Figure 5. Blinded pre- and post-test performance via the task-specific checklist and the Objective Structured Assessments of Technical Skills global rating scale. Symbols associated with each participant are consistent with practice volume data in Figure 4.