The Educational Impact of Bench Model Fidelity on the Acquisition of Technical Skill

The Use of Clinically Relevant Outcome Measures

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Objective: To evaluate the impact of bench model fidelity on the acquisition of technical skill using clinically relevant outcome measures.

Methods: Fifty junior surgery residents participated in a 1-day microsurgical training course. Participants were randomized to 1 of 3 groups: 1) high-fidelity model training (live rat vas deferens; n = 21); 2) low-fidelity model training (silicone tubing; n = 19); or 3) didactic training alone (n = 10). Following training, all participants were assessed on the high- and low-fidelity bench models. Immediate outcome measures included procedure times, blinded, expert assessment of videotaped performance using checklists and global rating scales, anastomotic patency, suture placement precision, and final product ratings. Delayed outcome measures (obtained from the live rat vas deferens 30 days following training) included anastomotic patency, presence of a sperm granuloma, and the presence of sperm on microscopy.

Results: Following training, checklist ($P < 0.001$) and global rating scores ($P < 0.001$) on the bench model simulators were higher among subjects who received hands-on training, irrespective of model fidelity. Immediate anastomotic patency rates of the rat vas deferens were higher with increasing model fidelity training ($P = 0.048$). Delayed anastomotic patency rates were higher among subjects who received bench model training, irrespective of model fidelity ($P = 0.02$). Rates of sperm presence on microscopy were higher among subjects who received high-fidelity model training compared with subjects who received didactic training ($P = 0.039$) but did not differ among subjects in the high- and low-fidelity groups.

Conclusions: Surgical skills training on low-fidelity bench models appears to be as effective as high-fidelity model training for the acquisition of technical skill among novice surgeons.

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Training in surgery has historically been considered an apprenticeship. Traditionally, the early training experiences of junior surgical residents are in real operative settings, on real patients. Several factors suggest that the operating theater may no longer provide the ideal atmosphere to foster the skills of a novice surgeon. First, as pressures intensify to use operating room time and resources efficiently, less time is available for teaching and practice of fundamental technical skills.[1,2] Second, ethical concerns about teaching and learning basic surgical techniques on live human patients have been voiced.[3] Third, the movement toward increased specialization in academic teaching hospitals has resulted in more highly complex and challenging surgical problems, which demand greater surgical expertise. Finally, technical evolution in surgery has created new skill sets and techniques that must be mastered by both practicing surgeons and trainees prior to clinical application.

Reacting to this situation, many academic health centers have turned toward laboratory-based training programs to foster the development of technical skills in both junior and senior surgeons.[4–6] While the need for laboratory-based technical skills training courses has been identified,[4] there remains debate regarding the educational effectiveness of such initiatives as they currently exist. Few studies have evaluated the impact of a focused laboratory-based training program using valid and objective assessments of surgical performance. Moreover, several authors have argued that short technical skills training courses are insufficient to provide

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adequate knowledge and skill and should not be used as a substitute for hands-on experience.[7,8]

As surrogates for human anatomy, surgical skills training laboratories rely on a variety of bench model simulations. These models vary widely with respect to their level of fidelity or "realism" to living human patients. Live animal and fresh human cadaver models, considered to be of high-fidelity, are limited by availability, high costs, potential for transmission of infectious disease, and ethical concerns.[6,9] Lower-fidelity synthetic bench models sacrifice realism for portability, lower costs, and the potential for repetitive use.[6,9] Despite the intuitive belief that "the more realistic, the better," few studies have directly compared the relative attributes and educational effectiveness of live animal models versus synthetic training models on the acquisition and maintenance of surgical skill. Using microsurgery as the research platform, the current initiative was designed to evaluate the significance of bench model fidelity on the acquisition of technical skill among surgical trainees using clinically relevant outcome measures.

MATERIALS AND METHODS

Subjects

Institutional ethics approval was obtained. Junior surgery residents (total junior resident pool = 90) at the University of Toronto in postgraduate years 1 to 3 (in a 5-year curriculum) were recruited to participate in the study. Participation was voluntary and interested residents were excused from clinical duties on the day of the study. Informed consent was obtained prior to participation. On the day of the microsurgical training course, all participants completed a questionnaire to determine baseline demographic characteristics, level of surgical training, and previous exposure to microsurgery. Participants with extensive prior experience with microsurgery, defined as having performed greater than 5 microsurgical cases as the primary surgeon (ie, greater than 80% of the procedure), were excluded from the analysis.

Training Program

The microsurgical training program was divided into 4 phases:

1) Orientation phase: All participants were shown a 15-minute instructional video demonstrating basic microsurgical principles and technique and were oriented to the surgical microscope. 2) Pretest phase: The pretest phase involved assessment of baseline microsurgical ability. Using the surgical microscope, participants completed the microsurgical drill, a test that required each subject to pass two interrupted sutures (size 9–0) through synthetic tissue (Penrose drain), and tie a square surgeon's knot, followed by two additional square knots. Performance on the drill was timed and videotaped through a side port in the surgical microscope. Video recordings were assessed by blinded, expert microsurgeons using previously validated global rating scales adapted for microsurgery.[10–13] 3) Training phase: Participants were randomized to one of three educational training interventions: i) high-fidelity model (live, anesthetized rat vas deferens; n = 21; Fig. 1A); ii) low-fidelity model (silicone tubing; n = 19; Fig. 1B); or iii) didactic training alone (control group; n = 10). Participants that received hands-on model training (ie, both the high- and low-fidelity model training groups) were provided with 2 hous to practice a variety of microsurgical skills using their assigned model and the surgical microscope. Experts in the field of microsurgery were available to each participant for technical demonstration and feedback. The didactic training group received a "paper and pencil" review of the principles of microsurgery and microsurgical anastomosis. Participants were not formally evaluated during the training phase. 4) Post-test phase: During the post-test phase, all participants were assessed on the microsurgical drill, high- and low-fidelity models. Using the high-fidelity model, participants were evaluated on their abil-

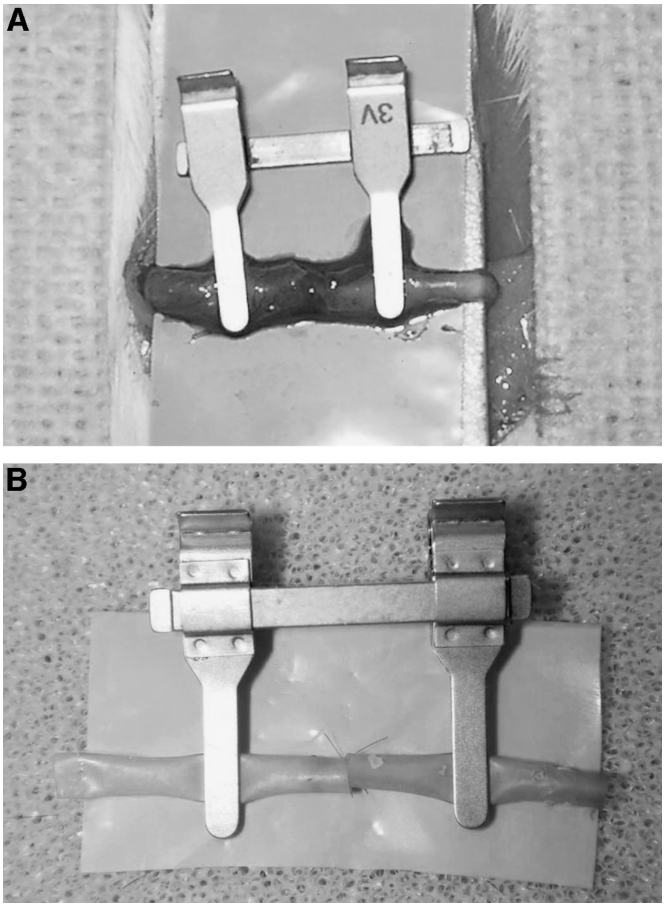

FIGURE 1. A: High-fidelity training model: live, anesthetized rat vas deferens. **B**: Low-fidelity training model: silicone tubing.

ity to perform bilateral (left vas deferens followed by right vas deferens), single-layer, microsurgical anastomoses of a rat vas deferens (vasovasostomy; Fig. 1A). Using the low-fidelity model, participants were evaluated on their ability to perform a single-layer, microsurgical anastomosis on the synthetic silicone tubing (Fig. 1B). To complete each anastomosis, participants were instructed to place 6 interrupted sutures at the 2, 4, 6, 8, 10, and 12 o'clock positions, using size 9–0, nonabsorbable, nylon suture. Random assignment determined whether participants began testing on the low- or high-fidelity model.

Immediate Outcome Measures: Expert Ratings

Video recordings of post-test performance were assessed by blinded, expert microsurgeons using checklists and global rating scales adapted for microsurgery.[10–13] The checklist was a detailed, dichotomous, and task-specific 30-item evaluation instrument, whereby one mark was awarded for each correctly performed step in the procedure. The global rating scale consisted of 8 items, each rated on a behaviorally anchored 5-point scale. Immediately following the post-test, the final anastomotic products (silicone tubing and extracted left vas deferens, first post-test attempt) were assessed in a blinded fashion for: i) patency of the anastomosis (yes/no; Fig. 2), ii) suture placement precision (anchored 5-point scale), and iii) overall quality of the final product (anchored 5-point scale).

Delayed Outcome Measures: Clinically Relevant Outcome Measures

The unextracted vas deferens segment (right side, second post-test attempt) remained in the living rat for a period of 30 days, after which time the rat was surgically reexplored, the remaining vas segment extracted, and tested in a blinded fashion for: i) patency of the anastomosis (yes/no), ii) presence of a sperm granuloma, an encapsulated collection of sperm suggesting a leak at the anastomotic site (yes/no), and iii) presence of sperm on microscopy from the abdominal end of the anastomosis (functional patency, yes/no).

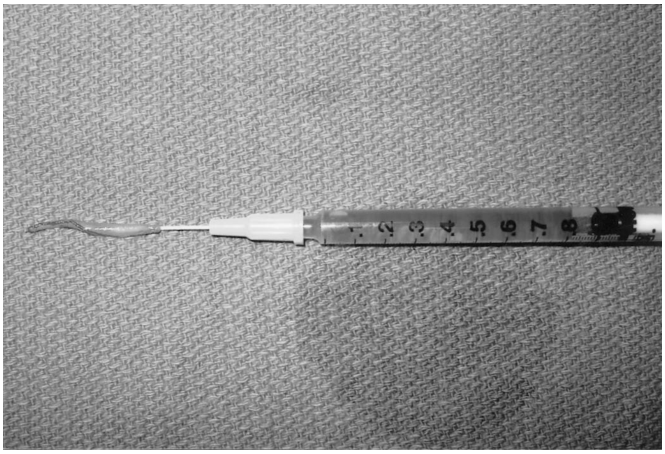

FIGURE 2. Anastomotic patency testing of the rat vas deferens (high-fidelity model) was determined by the injection of indigo carmine dye past the anastomotic site and out the opposite end of the anastomosis.

Final Evaluation

At the conclusion of the training course, participants completed a questionnaire to ascertain their impressions of the educational value and overall satisfaction with the training models used in the study.

Statistical Analysis

Analysis of variance (ANOVA) was used to assess differences in i) global rating of performance, ii) checklist, iii) suture placement, and iv) final product scores among the three groups. Relevant *a priori* contrasts were performed between hands-on training (low- and high-fidelity groups) and didactic training groups. The Kruskal-Wallis test was used to assess differences in nonparametric data (ie, measures of time) among the groups. Nominal data including i) anastomotic patency, ii) presence of sperm on microscopy, and iii) presence of a sperm granuloma were analyzed using the χ^2 test.

RESULTS

Subject Demographics and Pretest Results

A total of 50 surgery residents (36 male, 14 female) in postgraduate training years 1 (n = 28), 2 (n = 13), and 3 (n = 9) volunteered to participate in the study. No participants were excluded on the basis of extensive prior experience with microsurgery. Participants' specialties included general surgery (n = 14), urology (n = 10), otolaryngology (n = 7), orthopedic surgery (n = 7), plastic surgery (n = 6), neurosurgery (n = 4), cardiac surgery (n = 1), and thoracic surgery (n = 1). Mean age was 28 years (range, 24–38 years). Forty-seven participants were predominantly right-handed, 2 were predominately left-handed, and 1 was ambidextrous.

There were no significant differences in mean age, gender distribution, level of training, or prior microsurgical experience among the three training groups. Pretest microsurgical drill times and global ratings of performance were not significantly different among the training groups (Table 1).

Pre- to Post-test Changes in Microsurgical Drill Performance

Following training, differences between pre- and post-test microsurgical drill global ratings of performance were significantly greater among participants who received hands-on model training compared with those who received didactic training alone ($t_{[47]} = 3.17$, $P = 0.004$; Fig. 3). The pre- to post-test improvement in microsurgical drill global rating scores was not significantly different between the high-

TABLE 1. Subject Demographics and Pretest Performance

	Didactic	Low-Fidelity	High-Fidelity	Significance Level
No. subjects	10	19	21	
No. males/no. females	7/3	13/6	16/5	$\chi^2[2] = 0.33$, $P = 0.85$
Mean age (years)	29.0	27.6	27.9	$F[2,47] = 0.78$, $P = 0.46$
No. per post-graduate training year 1/2/3	7/2/1	9/6/4	12/5/4	$\chi^2[4] = 1.52$, $P = 0.82$
Prior microsurgical experience (no. of cases)				
Primary surgeon	0.1	0	0.6	$F[2,47] = 0.43$, $P = 0.52$
1st assistant	4.7	4.1	4.0	$F[2,47] = 0.09$, $P = 0.76$
Observer	6.7	6.6	6.6	$F[2,47] = 0.002$, $P = 0.96$
Median pretest microsurgical drill time (seconds)	630	488	426	Kruskal-Wallis $P = 0.09$
Mean pretest microsurgical drill global rating score - max. 35 (%)	14.0 (40%)	16.5 (47%)	16.8 (48%)	$F[2,47] = 1.12$, $P = 0.34$

and low-fidelity model groups (Fig. 3). Improvement in pre- to post-test microsurgical drill times were not significantly different among the 3 groups (Table 2).

Immediate Post-test Results

Post-test performance on the low-fidelity model (Fig. 4) revealed significantly greater checklist ($t_{[47]} = 4.26$, $P < 0.001$) and global rating scores ($t_{[47]} = 3.52$, $P < 0.001$) among participants who received bench model training compared with those who received didactic training alone. There were no significant differences in checklist scores ($t_{[38]} = 0.60$, $P = 0.55$) and global ratings of performance ($t_{[38]} = 1.16$, $P = 0.25$) among participants who trained on the low- and high-fidelity models (Fig. 4). Anastomotic times, suture placement precision, anastomotic patency rates, and overall quality of the final product did not differ significantly among the groups (Table 2).

Post-test performance on the high-fidelity model (Fig. 5) revealed significantly greater checklist ($t_{[47]} = 3.96$, $P < 0.001$) and global rating scores ($t_{[47]} = 4.03$, $P < 0.001$) among participants who received bench model training compared with those who received didactic training alone. There were no significant differences in checklist scores ($t_{[38]} = 1.46$, $P = 0.15$) and global ratings of performance ($t_{[38]} = 0.51$, $P = 0.61$) among participants who trained on the low- and high-fidelity models (Fig. 5). Our analysis revealed significantly faster anastomotic times among participants who received hands-on bench model training (Table 2). Immediate anastomotic patency rates of the rat vas deferens (left vas deferens, first post-test attempt) were higher with increasing model fidelity (Fig. 6, open bars). Suture placement precision and overall quality of the final product did not differ significantly among the groups (Table 2).

Delayed Post-test Results

Thirty-six of 50 rats (72%) survived for testing 30 days following the initial post-test phase (5 of 10 [50%] didactic group, 15 of 19 [79%] low-fidelity group, 16 of 21 [76%] high-fidelity group). In every case, the right vas deferens (second post-test attempt) was used for delayed outcome assessment. There were significantly higher delayed anastomotic patency rates among participants who received bench model training, irrespective of model fidelity (Fig. 6, shaded bars). Participants who received high-fidelity model training had significantly higher rates of sperm presence on microscopy (88%) compared with those who received didactic training alone (40%, $\chi^2[1] = 4.27$, $P = 0.039$; Table 2). There was no significant difference in the rates of sperm presence on microscopy between participants in the high- (88%) and low-fidelity (73%) model training groups ($\chi^2[1] =$

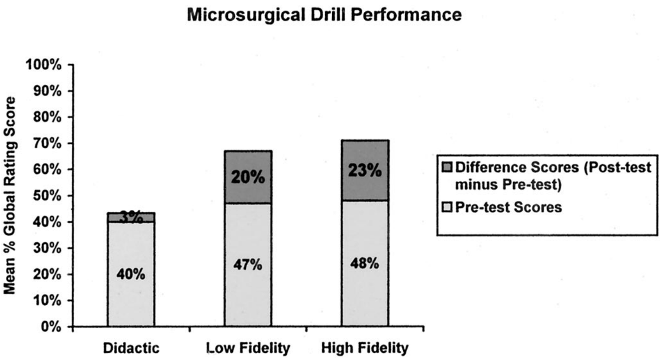

FIGURE 3. Improvements in microsurgical drill global ratings of performance were significantly greater among subjects who received hands-on bench model training versus subjects who received didactic training alone.

TABLE 2. Post-test Performance on the Microsurgical Drill, Low- and High-Fidelity Models

	Didactic	Low-Fidelity	High-Fidelity	Significance Level
Microsurgical Drill				
Time difference scores (seconds) (post-test minus pretest)	150	156	157	Kruskal-Wallis, $P = 0.57$
Global rating difference scores (post test minus pretest)	+1.2 (3.4%)	+7.0 (20%)	+8.0 (23%)	$F[2,47] = 4.78, P = 0.01$
Post-test: low-fidelity model				
Mean checklist score (max 29)	20.5 (71%)	24.8 (86%)	25.4 (88%)	$F[2,47] = 9.33, P < 0.001$
Mean global rating score (max 40)	18.9 (47%)	25.6 (64%)	28 (70%)	$F[2,47] = 6.95, P = 0.002$
Median anastomotic time (seconds)	1200	1012	1137	Kruskal-Wallis, $P = 0.76$
Mean suture placement score (1–5)	3.1	3.6	3.3	$F[2,47] = 0.99, P = 0.38$
% patent	100% (10/10)	100% (19/19)	95% (20/21)	$\chi^2\ [2] = 1.76, P = 0.41$
Mean final product score (1–5)	2.8	3.3	3.1	$F[2,47] = 1.11, P = 0.34$
Immediate post-test: high-fidelity model				
Mean checklist score (max 30)	21.9 (73%)	25.3 (84%)	26.7 (89%)	$F[2,47] = 9.03, P < 0.001$
Mean global rating score (max 40)	19.2 (48%)	27.1 (67%)	28 (70%)	$F[2,47] = 8.32, P = 0.001$
Median anastomotic time (seconds)	1963	1540	1450	Kruskal-Wallis, $P = 0.03$
% patent	20% (2/10)	33% (6/18)	62% (13/21)	$\chi^2\ [2] = 6.09, P = 0.04$
Mean suture placement score (1–5)	3	3.3	3.4	$F[2,46] = 0.87, P = 0.42$
Mean final product score (1–5)	2.7	3.3	3.5	$F[2,46] = 2.56, P = 0.08$
Delayed post-test: high-fidelity model				
% patent	20% (1/5)	87% (13/15)	81% (13/16)	$\chi^2\ [2] = 8.26, P = 0.016$
Presence of sperm on microscopy	40% (2/5)	73% (11/15)	88% (14/16)	$\chi^2\ [2] = 4.3, P = 0.12$
Presence of a sperm granuloma	60% (3/5)	73% (11/15)	63% (10/16)	$\chi^2\ [2] = 0.53, P = 0.77$

1.01, $P = 0.32$). The presence of a sperm granuloma at the anastomotic site did not significantly differ among the groups (Table 2).

Participant's Bench Model Preference

A significant majority of participants (90%) preferred working with the high-fidelity bench model over that of the low-fidelity bench model (10%) and participants rated the high-fidelity model significantly better in terms of overall educational value (ie, 6.7 vs. 5.2, respectively, on a scale of 1 to 7; $t_{[94]} = 8.64, P < 0.001$).

DISCUSSION

Effectiveness of Laboratory-Based Surgical Skills Training

In the laboratory setting, basic and advanced surgical techniques can be learned and practiced on a variety of bench

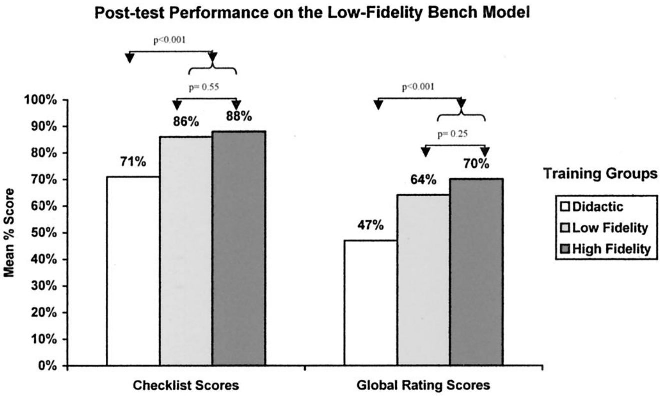

FIGURE 4. Post-test checklist and global rating scores on the low-fidelity model were significantly greater among subjects who received hands-on bench model training versus subjects who received didactic training alone.

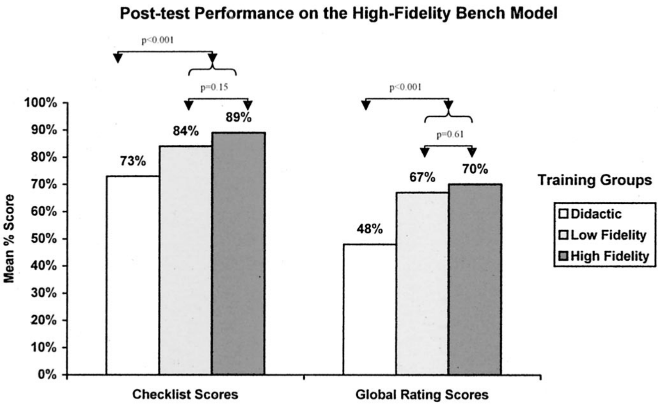

FIGURE 5. Post-test checklist and global rating scores on the high-fidelity model were significantly greater among subjects who received hands-on bench model training versus subjects who received didactic training alone.

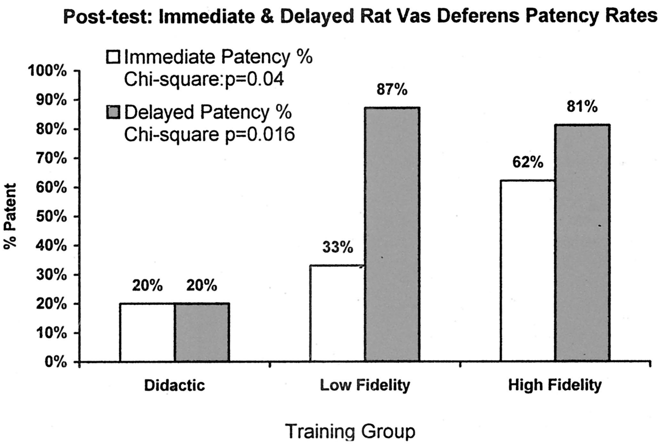

FIGURE 6. Open bars: Immediate patency rates of the rat vas deferens were higher with increasing bench model fidelity training. Solid bars: Delayed patency rates were higher among subjects who received hands-on bench model training, irrespective of model fidelity.

model simulations with the aim of better preparing trainees for the operating room experience.[4–6] Using valid, objective, and clinically relevant measures of technical performance, we found that a focused laboratory-based training course in microsurgery significantly improved the immediate acquisition of technical skill among novice microsurgeons who received hands-on model training, compared with their counterparts who received didactic training alone. Our findings support the work of Mastumoto et al,[14] who found that novices who received hands-on training in endourologic stone extraction demonstrated significant improvement in technical skill when compared with a didactic training control group. It appears that to maximize the immediate educational benefits of laboratory-based technical skills training, surgical educators must combine the cognitive elements necessary for learning a new skill with the opportunity for hands-on practice.

While immediate technical skill acquisition has been the focus of attention for most surgical educators, the retention of surgical skills acquired in the training laboratory and the impact of ongoing practice on the maintenance of skill has yet to be formally addressed. We are currently conducting formal studies in this area.[15]

Impact of Model Fidelity on the Acquisition of Technical Skill

To simulate living human anatomy and tissue properties, surgical skills laboratories rely on a variety of bench model simulations that allow trainees to practice fundamental surgical techniques prior to their clinical application. These models vary widely with respect to their degree of fidelity or "realism" to actual living human tissue. Live animal models have the benefit of providing a living simulation that is generally faithful to operative reality. The use of animals, however, is associated with several obstacles including high cost, limited availability, the need for specialized facilities and personnel, and legal and ethical concerns.[6,9] By contrast, inanimate bench models sacrifice realism for safety, portability, availability, reproducibility, and lower costs.[6,9]

The current investigation was designed to examine the ethical, financial, and educational justification of high-fidelity models in the training of novice surgeons and to systematically test the assumption that the degree of fidelity in a bench model is proportional to its effectiveness as a training tool. To our knowledge, this study is the first to formally evaluate the educational impact of bench model fidelity by combining objective and valid instruments to measure technical skill (global rating scales and checklists) with meaningful clinical and physiologic outcomes (patency rates, presence of sperm on microscopy, presence of sperm granuloma). When surgical performance was measured using checklists and global rating scales, our findings support the work of Matsumoto et al,[14] who showed that endoscopic training on a low-fidelity bench model conferred the same degree of benefit as training on a high-fidelity model. Similarly, Anastakis et al[16] reported that technical skills acquired on low-fidelity bench models transfers to improved performance on higher-fidelity human cadaver models, strongly supporting the potential for transfer into the operating room with real patients. When surgical performance was measured using meaningful clinical outcomes, including immediate and delayed anastomotic patency rates and the presence of sperm on microscopy, overall we found that training with low-fidelity bench models is as effective as training with high-fidelity, live animal models for the acquisition of technical skill among surgical trainees.

A significant advantage of high-fidelity model training was only observed in terms of *immediate* anastomotic patency rates of rat vas deferens (left side). Interestingly, the patency advantage offered by high-fidelity model training disappeared at the time of *delayed* patency testing, 30 days following initial training. In every case, delayed patency testing of the anastomotic segment was performed following each participant's second attempt (post-test) at the high-fidelity model (rat vas deferens, right side). We speculate that hands-on model training with the low-fidelity model provided subjects with a basic foundation of skills and an appreciation for the "key constructs" of the surgical task (as evidenced by equivalent post-test checklist and global rating scores among the low and high-fidelity groups). Through repeated exposure to the high-fidelity model, participants initially trained on the low-fidelity model, *but not those limited to didactic training*, were able to build upon such constructs and skills and elevate their surgical performance.

With respect to financial resources, training on high-fidelity models can be costly. Accounting for the costs of the live animals, anesthetic, animal care technician, and other disposables (ie, surgical gloves, sponges, saline solution), the cost of training with the high-fidelity model amounted to $55 (CDN) per trainee. By comparison, the cost of training with the synthetic silicone tubing amounted to only $1.50 (CDN) per trainee. The results of this investigation suggest that laboratory-based surgical skills training can be both effective and affordable.

Despite the demonstrated educational value of low-fidelity models, surgical trainees are often skeptical about their utility.[6] Consistent with this attitude, participants in the current investigation expressed an overwhelming preference for the educational merits of training with the high-fidelity model. The reasons for the apparent discrepancy between bench model preference and bench model utility are not entirely clear. We speculate that junior residents in surgery have a strong desire to participate in live operative procedures in which a variety of functioning tissues are exposed and manipulated, regardless of the educational benefit. Until such questions are better understood, surgical educators must be cautious not to ignore the value of high-fidelity models in maintaining interest and enthusiasm for learning among surgical trainees.

In our surgical skills training center at the University of Toronto, we have for some time used a combination of high- and low-fidelity models for reasons of convenience and cost[6] but without empirical justification. The current study clearly supports the use of both types of models, with different indications for use, and we now have empirical evidence of educational effectiveness for both types. For surgical educators looking to incorporate laboratory-based surgical skills training into the curriculum of their residency program, a reasonable strategy would be to begin by having novice trainees learn on a low-fidelity bench model that captures the key constructs of the surgical task. Once proficient, the trainee can then progress in a graduated manner to practice on models of higher fidelity. A graduated approach to laboratory-based surgical skills training is financially responsible, promotes enthusiasm for learning by exposing trainees to a variety of bench models, and simulates the manner in which trainees are provided with opportunities to develop technical skill in the real operative setting.

Outcome Measures

Several investigators have used procedure times as an objective measure of surgical performance.[14,17] However, in terms of evaluating the technical performance of novice surgeons, time may fail to capture some essential elements that characterize effective surgeons and its reliability may be limited. For example, trainees in particular may not complete or be aware of all the necessary steps in a procedure, therefore leading to faster procedure times. In the current study, procedure times proved to be an inconsistent measure of surgical performance.

Transfer to the Clinical Setting

The ultimate end point with respect to the instructional effectiveness of the simulated environment is whether the skills acquired translate into improved performance in the clinical setting. While the current study does not directly address this issue, there is recent evidence that this is the case. Naik et al[18] demonstrated that novice anesthesiologists who received technical skills training (fiberoptic intubation) on simple bench models effectively transferred these skills to the clinical setting on live patients. In addition, Scott et al[19] found that training on a laparoscopic simulator resulted in significantly improved performance on laparoscopic tasks in the operating room.

CONCLUSION

Surgical skills training on low-fidelity bench models can be as effective as high-fidelity, live animal model training for the acquisition of microsurgical skill among novice surgeons. The educational benefits of laboratory-based technical skills training are maximized by combining the cognitive elements necessary for learning a new skill with the opportunity for repeated hands-on practice. Ultimately, "the improved practice of surgery depends on the practice of surgery."[20] Clinically relevant outcome measures support the use of expert ratings of performance and further validate laboratory-based surgical skills training and the assessment of technical skill.

Future work should be directed toward enhancing our understanding of the durability of the skill sets acquired in the training laboratory and whether such skills transfer into improved performance in the operating room.

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