Prior to the inception of surgical residency training programs over a century ago by Dr. William Halsted, surgical training was delivered by an apprenticeship model. One foundational feature of these programs was a pyramidal structure with tiers, which residents progressed through based on a graduated level of responsibility. Experience and skill were rewarded with responsibility and independence. Over the following century, North American residency programs retained much of the same format.

This type of experiential learning relies on high case volumes to gain enough exposure to achieve competence. Advances in alternative therapies and minimally invasive techniques have had an impact on surgical training volumes. Neurosurgical vascular case volumes in particular have decreased because of the increased number of endovascular options. Gaining mastery in microsurgical skills requires regular practice and cannot be achieved by observation alone. As fewer microvascular cases are per-
formed regularly in neurosurgery, educators are looking toward simulation to supplement operative exposure.6,7

There are multiple microsurgical simulation models, each with varying fidelity and validity.8–11 Basic models are low-fidelity simulations of simple tasks (e.g., suturing of silastic tubing) to allow familiarization with microsurgical instruments, the operative microscope, and knot tying.8 Intermediate fidelity includes using prosected animal and human cadaveric tissue. These more closely replicate living tissue, allowing the learner to practice tissue handling and perform microsurgical anastomosis.8 High-fidelity models use live tissues and are the gold standard for advanced surgical simulation.8,12,13 The live rat femoral artery model is an established, validated model for microsurgical skills simulation.8–11 The diameter of the rat femoral artery ranges from 0.6 mm to 1 mm depending on the age of the rat, closely mimicking intracranial vessel diameter. This model provides both tissue similarity and physiological similarity, mimicking human intracranial blood flow, tissue perfusion, and blood clotting.

Simulation as a training modality in microsurgery is well validated in the literature.9,14,15 Despite this, there has not been widespread adoption of hands-on microsurgical simulation in neurosurgical training programs. The goals of this study were to 1) review our institution’s experience with a comprehensive, longitudinal microsurgical simulation training curriculum; 2) evaluate program effectiveness, using a well-studied rating scale with strong validity evidence;12,16 and 3) evaluate whether these acquired skills lead to improvement in subsequent trainee operating room performance.

Methods

The study was approved by the animal care committee at our institution and complied with our institution’s animal care and use guidelines. The curriculum was developed by two senior authors (F.A.H. and S.P.L.) and was completed by 18 consecutive postgraduate year (PGY)–2 neurosurgery residents during November 2009 through February 2020. The curriculum spans 17 sessions over a 1-year period and is subdivided into 5 simulation modules of increasing fidelity and task complexity. To improve surgical skill acquisition and help consolidate learning, the theory of distributed practice was used.17,18 The microsurgical simulation laboratory uses a Zeiss OPMI CS NC-2 neurosurgical microscope and standard microneurosurgical instrumentation. A custom-made rat anesthesia ventilator unit is used. Monitoring is provided by an experienced registered animal health technician (L.M.D.) in compliance with institutional animal care and use guidelines.

Curriculum Summary

Module 1 is an introduction to microsurgery (Fig. 1). The operating microscope and microsurgical suturing are introduced on inanimate models. Each participant completes a running 6-0 monofilament suture along a 3-cm incision through silastic tubing 3 times. Additionally, 20 interrupted 10-0 monofilament suture knots are done in an incision in the skin simulation model.

Module 2 exposes participants to microvascular dissection in a perfused cadaveric duck wing brachial artery model (Fig. 1). Participants also view an instructional video describing the exposure of the femoral vessels in a live rat (Sprague Dawley; 250–400 g in weight).

Modules 3–5 account for the anastomosis portion of the curriculum and make use of a live rat femoral vessel model (Fig. 1). During each module, participants expose the rat femoral vessels and perform microvascular anastomosis. During module 3, femoral artery-to-artery (end-to-end) anastomosis is performed. Modules 4 and 5 involve femoral vein-to-vein (end-to-end) and femoral artery-to-vein (end-to-side) anastomoses, respectively. Each module is repeated 5 times.

The curriculum is designed in alignment with educational theory and simulation instructional design evidence.17 The principles of cognitive load theory are embedded within the design to facilitate the training of novice participants. Specifically, elaboration theory20,21 is used to provide a simple to complex sequence of training tasks. Introductory modules (modules 1 and 2) provide partial-task training of the essential skills needed for microsurgical anastomoses, such as using the microscope, handling microsurgical instruments, suturing, and dissection. A series of full-task microvascular training scenarios follows. The concept of “spiral integration” is included by revisiting modules 3–5 sequentially in 5 iterations, allowing the participants to practice each task repeatedly after having performed in a slightly different scenario. By having multiple different training tasks, we also utilize the principles of “providing a range of task difficulty” and “contextual interference,” both of which improve motor and surgical skill acquisition.17

Module Performance Assessment

Each participant is assigned a number that is blinded for video recording (modules 3–5); documentation of vessel isolation time, vessel size before and after anastomosis, clipping time for anastomosis, blood loss, and total time; and video analysis. Anesthesia is continuously monitored and documented every 15 minutes. Time to task completion was measured in minutes. Task performance is graded by blinded, unbiased senior team members on a 5-point Objective Structured Assessment of Technical Skills (OSATS) Global Rating Scale assessing performance based on respect for tissue, time and motion, instrument handling, knowledge of instruments, flow of operation, and knowledge of specific procedure (Fig. 2A). Use of the OSATS framework for evaluation was chosen because of the validity evidence supporting its use in directly observed formative feedback, its high interrater reliability, and its consistent discrimination between experts and novices in the operating room.16 Its use in evaluating vascular anastomotic tasks is also well recognized.12

Translation to Operating Room Performance

Eleven of the 18 participants who completed the training curriculum (microsurgical training) and 3 participants who at the outset of the study were randomly withheld from the training (no training) had their operative performance evaluated at the PGY-5 and PGY-6 levels. These
participants were evaluated by their attending neurosurgical supervisor using a standardized form applied to all neurosurgical operations performed at our institution during their levels of neurosurgical training. The skills chosen for evaluation were superficial exposure, deep exposure, and primary case maneuvers. For example, during carotid endarterectomy, superficial exposure includes dissection from skin down to deep cervical fascia with exposure of vessels; deep exposure includes common facial vein ligation and mobilization and preparation of the common carotid artery and its branches; and primary case maneuvers includes clamping of vessels, arteriotomy and harvesting of plaque, and anastomosis. These skills were evaluated on a 3-point scale: “unable to perform,” “able to perform with supervision,” and “independent” (Fig. 2B). If a skill could not be assessed or was marked as “not applicable” to a procedure, evaluation for that individual skill was excluded. This evaluation form was developed locally at our institution by staff and residents to align with the Objectives of Training in Neurosurgery, put in place by the Royal College of Physicians and Surgeons of Canada.

Statistical Analysis

For the training modules, each participant’s first and fifth attempts at each anastomosis were assessed. Paired t-tests were used to compare these for each surgical skill in each module. The scores across all 6 surgical skills were then averaged for each attempt as a mean score. Improvement in mean scores was assessed by calculating the difference between the first and fifth attempts. Furthermore, because of the sequential completion of modules, we compared ratings in each skill obtained during the first attempt of each module using one-way ANOVA. Bonferroni correction was applied for multiple comparisons in each analysis. For translation of skills to the operating room, the limited number of subjects and differences in

FIG. 1. A: Curriculum outline. Through a 5-module, 17-session microsurgical simulation curriculum, participants are introduced to the basics of operative microscopy, microsurgical instruments, and microvascular anastomosis with increasing simulation fidelity. Basic simulation models are introduced first to teach skills of microscope and instrument handling. Intermediate models are then used to practice dissection technique. Finally, training culminates in the use of an advanced, live rat femoral vessel model to teach tissue handling, hemostasis, and microvascular anastomosis skills. B: Depiction of simulation environment. C: Artery-to-artery and vein-to-vein anastomoses. D: Artery-to-vein anastomosis.
the number of evaluations between subjects precluded robust statistical analysis.

Results

Eighteen 2nd-year neurosurgical residents completed the curriculum. The anastomotic modules 3–5 were assessed using OSATS. Six hundred thirty ratings were obtained (100 for knowledge of specific task, 106 for the remainder of the skills assessed). One participant did not complete the fifth attempt for the femoral artery-to-vein anastomosis, and another did not complete the fifth attempt for the vein-to-vein anastomosis. Also, one participant did not have ratings completed for knowledge of specific task across all modules.

The overall mean score (± standard error) for the first and fifth attempts of each module is represented in Fig. 3. Scores were significantly higher on the fifth attempt compared with the first attempt for all 3 modules (p < 0.001). The mean time to completion and the mean score (± standard error) for each skill are presented in Table 1. There were significant increases in scores for all rated skills, with the only exception being two vein-to-vein module skills: time and motion and knowledge of instruments. Concerning time to completion, there was a downward trend (in minutes) between the first and fifth attempts for each anastomosis module. Significance was attained for the vein-to-vein and artery-to-vein modules (p < 0.05).

There were no significant differences between the first attempts of the 3 modules in the 6 skills investigated, using a one-way ANOVA with a p value of 0.0083 as the threshold for significance (0.05/6). However, knowledge of instruments (F = 4.99, p = 0.01) and instrument handling (F = 4.03, p = 0.02) approached significance. Knowledge of instruments scores were 2.89 ± 0.17 in the artery-to-artery module, 3.72 ± 0.19 in the vein-to-vein module, and 3.61 ± 0.18 in the artery-to-vein module (Table 1). Instrument handling scores were 2.78 ± 0.88 in the artery-to-artery module, 3.44 ± 0.51 in the vein-to-vein module, and 3.11 ± 0.68 in the artery-to-vein module (Table 1).

We determined the mean difference in scores between the first and final attempts for each skill in each module (Fig. 4). Overall, the greatest improvements occurred during the artery-to-artery module (mean difference of 1.51 ± 0.17). This module also had greater improvement compared with other modules in all the skills except for
respect for tissue, for which the artery-to-vein difference was superior. The least overall improvement (mean difference 0.79 ± 0.12) and lowest improvement across all skills occurred during the vein-to-vein module.

The skill that demonstrated the greatest overall improvement was flow of operation, with a mean difference of 1.34 ± 0.17 across all modules. The skill with the smallest improvement was respect for tissue, with a mean difference of 1.04 ± 0.12 across all modules. Each module had a different profile of improvements across skills (Fig. 4). For instance, time and motion improved the most during the artery-to-artery module (1.72 ± 0.24), while flow of operation improved the most during the vein-to-vein module (1.05 ± 0.22), and respect for tissue improved the most during the artery-to-vein module (1.32 ± 0.19).

Translation to Operating Room Performance

Table 2 reports the total evaluations and the number of evaluations scored as “independent” for each category of operative performance. Those who completed the microvascular skills training demonstrated a greater number of independent-level evaluations for superficial exposure, deep exposure, and primary case maneuvers at the PGY-5 and PGY-6 levels (Fig. 5).

Discussion

Traditional training in surgery occurs through circumstantial practice, in which skills are acquired through apprenticeship in the operating room. The training model of Halsted relies on large case volumes to achieve the neces-
sary repetition to master the skills required, and is threatened by contemporary operative constraints.23,24 There has been a conscious shift toward intentional practice in which the loss of surgical volumes is compensated by dedicated, task-specific education.25 In particular, microsurgical skills simulation training leads to higher scores on the Global Rating Scale and task-specific measurements both at the time of instruction and at 4 months, compared with didactic, lecture-based instruction.26

The curriculum at our institution was developed to provide structured and evidence-based microsurgical skills training to PGY-2 neurosurgical residents. It uses modules with well-defined objectives, delivered in a medium- and high-fidelity simulation environment. High-fidelity, live-tissue models have long been established as a gold standard for microsurgical simulation in neurosurgery, especially given the similarities in size and texture between rat femoral vessels and intracranial vessels.

Our data demonstrate a clear improvement in mean score from first to last attempt for all anastomosis tasks, as well as a reduction in time to completion. These findings are consistent with published studies on learning and skill acquisition.23 The greatest improvement was seen in artery-to-artery anastomosis. This was likely because of the lower initial scores, as it was the first high-fidelity module. On the other hand, during vein-to-vein anastomosis there was insignificant improvement in knowledge of instruments and time and motion. This may reflect a carryover effect, since the initial score for knowledge of instruments was comparatively high. The Global Rating Scale may be insufficient to identify small changes in a skill when scores already approach a maximum. Also, vein-to-vein anastomosis has added difficulty given the delicate nature of the venous structures compared with the arterial ones. This difficulty is likely reflected in lower interval improvement across all measured skills and failure to reach significance in time and motion. More than 5 attempts may be required to achieve greater interval improvement.

We found greater improvement in certain skills during some modules versus others. This supports the use of individual tasks to target improvement in desired skills. Data-driven tailoring of the curriculum could be valuable on the basis of this observation.

To determine whether particular skills carry over from sequential modules, we compared the first-attempt scores for each of the 6 skills between the modules. No significant differences were identified; however, a trend toward significance was seen in knowledge of instruments and instrument handling. Although it was anticipated that all the skills would transfer between modules to some degree, it is possible that the instrument-related skills carry over more because the same instruments are used between modules.

Despite the growing body of literature supporting the use of simulation in microsurgical training, there are inconsistencies in its adoption within neurosurgical training. In a European study surveying neurosurgical residents, it was found that 40% of trainees were dissatisfied with their microneurosurgical training and 70% were not offered structured microneurosurgical training.27 Furthermore, a review of the published literature revealed no publications assessing the specific use of the live rat femoral vessel model in microneurosurgical training. Personal communication identified no use of this model in Canadian neurosurgery training programs.

It has been shown that repetition alone can improve skill retention.5,9,28 This concept is supported by the work presented here, showing overall improvement from the first attempt to the last attempt in all 3 modules.

TABLE 2. Total number of operating room evaluations and evaluations scored as independent for participants who completed the microsurgical skills training and those who did not participate

<table>
<thead>
<tr>
<th>Skill</th>
<th>PGY-5</th>
<th></th>
<th>PGY-6</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total</td>
<td>Independent</td>
<td>Total</td>
<td>Independent</td>
</tr>
<tr>
<td>Superficial exposure</td>
<td>405</td>
<td>395</td>
<td>245</td>
<td>241</td>
</tr>
<tr>
<td>Deep exposure</td>
<td>388</td>
<td>326</td>
<td>242</td>
<td>221</td>
</tr>
<tr>
<td>Primary maneuvers</td>
<td>402</td>
<td>281</td>
<td>243</td>
<td>216</td>
</tr>
</tbody>
</table>

MT = microvascular skills training; NT = no training.

FIG. 5. The proportion of independent operating room evaluations for the 3 assessed skills: superficial exposure, deep exposure, and primary maneuvers. Those who completed the microsurgical skills training (MT) were compared with those who did not participate in the training (NT) at PGY-5 and PGY-6.
To date, there have been no studies demonstrating that skills developed in simulation are transferable to the real-life operating room setting. We compared 3 operative skills in PGY-5 and PGY-6 residents who had completed the training curriculum against those who had not. The small number of subjects and differences in the number of evaluations between subjects precluded robust statistical analysis; however, we do see a greater proportion of independent evaluations among those who completed the training curriculum. To limit comparisons, the other operative skills assessed were not analyzed; however, it stands to reason that the chosen operative skills benefited the most from the microsurgical training. Superficial and deep exposure and primary maneuvers likely use similar skills taught in the training curriculum, such as respect for tissue, time and motion, instrument handling, and flow of operation.

We demonstrated that training in microvascular skills using a simulated environment may be transferable to the operating room. This finding applies to diverse operations besides those specifically using microvascular techniques. Figure 2B depicts the category and subcategory of neurosurgical procedures performed by residents at the PGY-5 and PGY-6 levels that existed within the Objectives of Training in Neurosurgery of the Royal College of Physicians and Surgeons of Canada at the outset of this study. The transfer of skills applies to procedures closely mimicking the simulated microsurgical training environment and possibly transcends procedure type to benefit diverse neurosurgical operations. Analysis comparing skills translation based on procedure category could not be performed because of lack of power but could provide the basis for further study.

Operative evaluations were assessed 3 and 4 years following the completion of the original skills training during PGY-2. The greater proportions of independent evaluations seen in those who participated in the training support the notion that skills transferable from the simulated environment may be durable at least during the residency training period. This encourages the early application of dedicated simulation teaching in neurosurgical training as it may provide benefits throughout the duration of training. Future work will investigate early skills translation during the course of the microvascular skills training and assess how skills are developed or lost throughout residency training.

There are challenges to the development of a simulation curriculum. Protecting the resident training time is one challenge. Each 2nd-year neurosurgery resident attends one half-day session twice a month for microsurgery. A second main challenge concerns laboratory access and associated costs. High-fidelity simulation involves the use of an operating microscope and anesthesia equipment, in addition to the costs associated with supporting live animals ($78 per laboratory session), supplies ($51 per laboratory session), the animal health technician ($264 per laboratory session), and space to host the simulation laboratory. During the first 5 years, costs were covered by a peer-reviewed grant (“Neurosurgical and Neurovascular Skills Training Utilizing Models of Cerebrovascular Disease” grant from the Academic Medical Organization of Southwestern Ontario [AMOSO], 2010). Once established within the training program, costs were assumed by discretionary funds within the residency program budget. Operating costs in our institution amounted to $6682.87 per trainee per annum. Cost reduction strategies lowered these costs by following the 3 R’s applicable to the use of live animals: replacement, reduction, and refinement. Concerning replacement, while chicken wings have been used as a vascular training model, duck wings from a local abattoir were substituted for live rat in module 2. The use of simulators in vascular anastomosis may present future opportunities for reduction, although to date we have found no effective replacement for the live rat anastomosis model in the simulation of human tissue dissection, hemostasis, and suturing in a microneurosurgical environment. Concerning reduction, we replaced commercial purchase of rats by obtaining old breeder rats and used rats from fellow researchers that had reached their study endpoints. The optimum use of rats is via bilateral vessels on the same animal, cutting the number required by half. Finally, concerning refinement, tissue alternatives such as silastic tubing are being used. Although most academic neurosurgical training centers have access to the necessary equipment to implement a training curriculum, dedicated funding, protected time, and laboratory space close to trainee clinical work areas are important to ensure success.

Conclusions

We evaluated an evidence-based, high-fidelity microsurgical simulation curriculum for neurosurgical trainees. The curriculum uses the live anesthetized rat femoral vessel simulation module to provide training in dissection, control of bleeding, and instrument control during microsurgery. There was a significant improvement in the 6 measured skills throughout the simulation curriculum, supporting its use as an effective teaching model. Furthermore, we present encouraging results regarding the transferability of skills to the operative environment and the durability of these skills over a 3- to 4-year period.

Acknowledgments

This study was funded in part by a 2010 grant from the Academic Medical Organization of Southwestern Ontario (AMOSO) entitled “Neurosurgical and Neurovascular Skills Training Utilizing Models of Cerebrovascular Disease.”

References

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