Simulation is increasingly recognized as an important tool to enhance surgical education. While simulation has become a cornerstone in skill training and assessment in many areas of health care, incorporation into neurosurgical curricula has lagged. The complexities of neurosurgical procedures, financial and time constraints of the field, as well as the absence of validated assessment tools and curricula have contributed to this delay in progress. Microsurgery remains an integral component of neurosurgical education and achieving proficiency in this area is critically important to neurosurgical trainees. While the nature of the microsurgical procedures varies between subspecialties such as spine, skull base, vascular, and peripheral nerve, end-to-end microanastomosis of small-caliber vessels can be considered as a prototype procedure for the acquisition of microsurgical skills because it incorporates the basic concepts and fine motor skills necessary across subspecialty areas.

A pilot study to assess the construct and face validity of the Northwestern Objective Microanastomosis Assessment Tool

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OBJECT Microsurgical skills remain an integral component of neurosurgical education. There is a need for an objective scale to assess microsurgical skills. The objective of this study was to assess the face and construct validity of a bench-training microanastomosis module and an objective assessment scale, i.e., the Northwestern Objective Microanastomosis Assessment Tool (NOMAT).

METHODS Medical students, neurosurgical residents, and postdoctoral research fellows at Northwestern University were enrolled in the study. Trainees were divided into 3 groups based on microsurgical experience: 1) experienced, 2) exposed, and 3) novices. Each trainee completed two end-to-end microanastomoses using a 1-mm and a 3-mm synthetic vessel. Two cameras were installed to capture procedural footage. One neurosurgeon blindly graded the performance of trainees using both objective and subjective methods to assess construct validity. Two neurosurgeons reviewed the contents of the simulation module to assess face validity.

RESULTS Twenty-one trainees participated in the study, including 6 experienced, 6 exposed, and 9 novices. The mean NOMAT score for experienced trainees on the 1-mm module was 47.3/70 compared with 28.0/70 and 25.8/70 for exposed and novice trainees, respectively (p = 0.02). Using subjective grading, experienced trainees performed significantly better on the 1-mm module (64.2/100) compared with exposed or novice trainees (23.3/100 and 25.0/100, respectively; p = 0.02). No statistical difference between groups was noted for the 3-mm module with both NOMAT and subjective grading. Experienced trainees took less time to perform both tasks compared with the others.

CONCLUSIONS Face and construct validities of the microanastomosis module were established. The scale and the microanastomosis module could help assess the microsurgical skills of neurosurgical trainees and serve as a basis for the creation of a microsurgical curriculum.


KEY WORDS microanastomosis; microsurgery; objective assessment scale; resident training; simulation in neurosurgery; validity; vascular disorders
track their progress and their learning curves. The aim of this study was to establish two important types of validity related to our module: 1) face validity, by examining the faithfulness of the module in replicating a real-world microsurgical setting; and 2) construct validity, by examining the ability and sensitivity of the module to assess the microsurgical performance of trainees with different levels of experience.

Methods
Microanastomosis Module
A bench module for the assessment and enhancement of resident microsurgical skills was developed in the Department of Neurological Surgery at Northwestern University’s Feinberg School of Medicine. The module consists of performing one 1-mm and one 3-mm vessel end-to-end microanastomosis using a surgical microscope, a microsurgical kit, and 8-0 and 10-0 nylon microsurgical sutures (Fig. 1A and B). An objective assessment scale—the Northwestern Objective Microanastomosis Assessment Tool (NOMAT)—was developed to assess the operator’s performance (Appendix 1). The NOMAT scale is a 14-item Likert-type assessment tool derived from the Objective Structured Assessment of Technical Skill (OSATS).

The items in the NOMAT involve surgical metrics that were carefully selected and defined by 2 experienced vascular neurosurgeons (B.R.B. and H.H.B.) and a postdoctoral research fellow (S.G.A.). These metrics take into account important technical nuances required to successfully perform a surgical microanastomosis. Operator positioning and posture are also assessed using the NOMAT scale as they may affect the ease of motion and the precision of surgical maneuvers. The importance of optimizing positioning and posture has been strongly emphasized in fields requiring eye and hand coordination such as music and sports, where good positioning and posture have been shown to correlate with better technical performance and outcome.

Our scale also attempts to assess microsurgical skills directly related to the microanastomosis itself including handling of the needle and surgical instruments, manipulation and respect of vascular tissue, insertion of the sutures and knot tying, and finally, the quality of the anastomotic line off and on the pump (Fig. 1C).

Study Design
Institutional Review Board approval was obtained at Northwestern University to allow neurosurgical trainees, postdoctoral research fellows, and medical students to be filmed while performing the 1- and 3-mm surgical microanastomoses. Two important types of validity were assessed in this study: face validity and construct validity. By definition, validity can be described as “the property of being true, correct and in conformity with reality.” When evaluating an assessment tool, validity can be defined as the ability of the tool to accurately measure the event or quantity it is supposed to measure. Face validity evaluates the content of a surgical simulation module, including the fidelity of the entire surgical setting and the realism of the surgical equipment and materials used. To assess face validity, 2 experienced vascular neurosurgeons (B.R.B. and H.H.B.) at our institution reviewed and approved the contents of our simulation module.

Construct validity, on the other hand, is defined as “the ability of an assessment tool to differentiate between experts and novices performing a given task.” Naturally, experts should perform better than novices on a given surgical task due to their previous surgical experience. Therefore, a proper assessment tool should clearly demonstrate this difference to be deemed suitable for the evaluation of surgical performance. To study construct validity, the trainees were divided into 3 groups according to their general experience with microsurgery: 1) the experienced group included residents in postgraduate years 6 and 7 who had been exposed to various types of microsurgical techniques in the operating room, and postdoctoral research fellows who underwent long periods of deliberate...
practice (> 50 hours) performing the microanastomosis; 2) the exposed group included intermediate trainees in postgraduate years 3–5, who had received some microsurgical training in the operating room; and 3) the novices group included residents in postgraduate years 1 and 2, as well as medical students, who had no previous experience with microsurgery.

Each trainee performed an end-to-end microvascular anastomosis on one 1-mm and one 3-mm artificial vessel. None of the trainees received any orientation prior to or during the procedures. Only minor assistance was offered, when needed, in the form of adjusting the surgical stool or the surgical microscope (position or focus). A postdoctoral research fellow prepared the vessel (Kezlex, Ono & Co., Ltd.) in an identical fashion prior to each procedure. The vessels were placed on a clean petri dish, hydrated, and approximated to facilitate suturing. Two cameras were installed in the laboratory to capture procedural footage: 1) Camera 1 captured operator positioning and posture without showing the patient’s head, and 2) Camera 2 recorded events occurring in the operative field under the surgical microscope (Fig. 2). All the participants were dressed in surgical gowns and gloves to ensure de-identification to the rater. Video files from both cameras were de-identified and then encoded and stored on a secure hard drive. An identification spreadsheet was created to help correlate the scores to their corresponding operators for subsequent data analysis. Another encoded spreadsheet was created to document the task time (duration) of each procedure. The task time was standardized for all procedures starting at the moment of insertion of the needle through the vessel wall and ending at the time of anastomosis completion. After completion of each anastomosis (1 mm or 3 mm), a postdoctoral research fellow used an infusion pump to inject red dye into the vessel and record any vascular injury or anastomotic leak. The vessel was then opened axially to assess and rate the anastomotic line. The method used to assess the anastomotic line is illustrated in Video 1.

VIDEO 1. Clip showing an example of a “good” microsurgical performance. The method used to assess the anastomotic line is shown. Copyright Bernard R. Bendok. Published with permission. Click here to view with Media Player. Click here to view with Quicktime.

An expert vascular neurosurgeon (B.R.B.) blindly graded the performance of the participates using both an objective method (NOMAT; maximum score = 70) and a subjective method that relied on the overall performance of the operator and on whether the rater believed the microanastomosis would be viable in vivo (maximum score = 100). The rater was completely blinded to the operator’s identity. After the rating process was completed, the results were integrated into 1 spreadsheet for data analysis. Another encoded spreadsheet was created to help correlate the scores to their corresponding operators for subsequent data analysis. Results of both the NOMAT and the subjective scoring systems were compared using statistical analysis.

Subjective Grading

Subjective grading was included in this study because it is a commonly used means to provide feedback to surgical trainees after each procedure. In our study, experienced trainees performed significantly better on the 1-mm microanastomosis (64.2/100) compared with exposed or novice trainees (58.0/70 vs 42.0/70 on the 1-mm microanastomosis, 63.0/70 vs 40.3/70 on the 3-mm microanastomosis, and 64.2/100 vs 40.3/70 on the 3-mm microanastomosis, respectively). Examples of both “good” and “poor” performances are shown in Videos 1 and 2, respectively.

FIG. 2. Camera 1 capturing de-identified operator positioning and posture (inset) and Camera 2 capturing the operative field under the surgical microscope. Figure is available in color online only.
TABLE 1. Results of the NOMAT, subjective grade, and in vivo viability ratings of the 1- and 3-mm microanastomoses in each group

<table>
<thead>
<tr>
<th>Microanastomosis*</th>
<th>Experienced (n = 6)</th>
<th>Exposed (n = 6)</th>
<th>Novice (n = 9)</th>
<th>p Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-mm vessel</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean NOMAT (range)</td>
<td>47.3 (20–64)</td>
<td>26.0 (17–40)</td>
<td>25.8 (16–36)</td>
<td>0.02</td>
</tr>
<tr>
<td>Mean subjective grade (range)</td>
<td>64.2 (25–85)</td>
<td>23.3 (10–40)</td>
<td>25.0 (0–60)</td>
<td>0.02</td>
</tr>
<tr>
<td>In vivo viability</td>
<td>5 pass, 1 fail</td>
<td>0 pass, 6 fail</td>
<td>1 pass, 8 fail</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td>Mean task time in min (range)</td>
<td>19.5 (12.0–32.9)</td>
<td>29.2 (13.6–40.2)</td>
<td>53.6 (20.9–88.4)</td>
<td>Not applicable</td>
</tr>
<tr>
<td>3-mm vessel</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean NOMAT (range)</td>
<td>47.8 (33–66)</td>
<td>45.0 (31–63)</td>
<td>39.6 (25–50)</td>
<td>0.53</td>
</tr>
<tr>
<td>Mean subjective grade (range)</td>
<td>58.3 (30–95)</td>
<td>55.0 (35–85)</td>
<td>38.3 (10–65)</td>
<td>0.29</td>
</tr>
<tr>
<td>In vivo viability</td>
<td>2 pass, 4 fail</td>
<td>3 pass, 3 fail</td>
<td>3 pass, 6 fail</td>
<td>0.94</td>
</tr>
<tr>
<td>Mean task time in min (range)</td>
<td>27.8 (13.3–53.4)</td>
<td>35.5 (22.3–48.0)</td>
<td>69.0 (32.0–113.8)</td>
<td>Not applicable</td>
</tr>
</tbody>
</table>

* Score ranges for each of the 3 tests were as follows: NOMAT (0–70), subjective grade (0–100), and in vivo viability (pass/fail).

novice trainees (23.3/100 and 25.0/100, respectively, p = 0.02; Table 1). This significant difference, however, was not found in the 3-mm vessel microanastomosis (p = 0.29; Table 1). The end product of the 1-mm microanastomosis was determined by the rater to be “viable in vivo” in 5 of 6 microanastomoses performed by experienced trainees. All other trainees, except for 1 novice, failed to achieve a “viable” end product at the end of the procedure (p < 0.01). On the other hand, 2 of 6 experienced trainees, 3 of 6 exposed trainees, and 3 of 9 novices were able to achieve a “viable” 3-mm microanastomosis at the end of the procedure (p = 0.94).

**Task Time**

Surgical task time can be a reflection of surgical skill, and thus was incorporated as a variable in our assessment of technical proficiency. Experienced trainees took much less time to perform both tasks compared with more junior trainees. The mean task time to perform a 1-mm microanastomosis was 19.5 minutes for those with experience compared with 29.2 minutes for those with some exposure to microsurgery and 53.6 minutes for novices. The mean task time to perform a 3-mm microanastomosis was 27.8 minutes for those with experience compared with 35.5 minutes and 69.0 minutes for exposed trainees and novices, respectively.

**Face Validity**

The face validity of our simulation module was defined by input from 2 experienced vascular neurosurgeons (B.R.B. and H.H.B.) who assessed the fidelity of the surgical setting, the microsurgical instruments, and the synthetic vessels. Both neurosurgeons agreed upon the suitability and coherence of the grading scale in assessing microsurgical skill.

**Discussion**

Simulation represents a unique opportunity for neurosurgical trainees to acquire and refine their skills in a safe and stress-free environment. According to the Dreyfus model of skill acquisition, the road to achieving mastery involves 5 stages of increasing skill: 1) novice, 2) advanced beginner, 3) competent, 4) proficient, and 5) expert. The main challenge to applying this model in neurosurgical education is that despite the presence of several simulation models, there are currently no validated tools to objectively assess and follow the progress of an operator’s skill level. The NOMAT scale was developed to provide neurosurgical trainees with objective means of assessing their microsurgical performance at baseline, and further allow them to track their progress and their learning curves.

Our simulation module was developed based on a thorough review of the literature with an emphasis on validation and based on the surgical experience of our departmental vascular neurosurgeons. We used a synthetic vessel model (Kezlex) to perform the microanastomoses because it was deemed to be more cost-effective, more readily available, and easier to handle, store, and maintain compared with both animal and virtual computerized models. We selected the surgical metrics of the NOMAT scale based on previously published literature, expert surgical opinion, and the OSATS scale, which was previously validated for general surgery procedures. The NOMAT scale involves technical steps and subskills that are believed to be essential to successfully performing a microsurgical anastomosis. It covers general microsurgical principles such as operator positioning and surgical microscope handling, as well as other technical aspects related to the microanastomosis itself, such as needle handling, knot-tying efficiency, spacing of sutures, and the appearance and functionality of the end anastomotic product. Using these metrics, neurosurgical trainees can repeatedly evaluate their performance at each microsurgical step, track their progress, and with adequate supervision eventually become proficient at complex microsurgical tasks. Our microanastomosis module was integrated into the simulation-based neurosurgical training course that was held at the 2012 Congress of Neurosurgical Surgeons annual meeting. Data obtained from the course showed that the module could be used to assess and track the technical proficiency of neurosurgical residents when...
performing a microsurgical anastomosis before and after receiving proper guidance and supervision. This course showed the feasibility of using the NOMAT scale in a diverse group of neurosurgical trainees of various skill levels. It was shown to be easy to use and capable of tracking the progress of operators as they learn from their seniors and refine their motor and cognitive skills. The principles of validating simulators and objective assessment scales are well established in the literature. For a simulation module to be considered valid, it should ideally be assessed for face, content, construct, concurrent, and predictive validity, as well as inter- and intrarater reliability. The data from the current study support the construct validity of the microanastomosis module and the corresponding assessment scale because the scale was able to differentiate between experienced and nonexperienced trainees, particularly with the 1-mm vessel microanastomosis (p = 0.02). This observation could be explained by the fact that the 1-mm procedure is more technically demanding compared with the 3-mm procedure and is therefore more sensitive at detecting differences in motor function and at assessing microsurgical skill. Another possible explanation could be related to the fact that experienced trainees may have a faster learning curve compared with juniors, and may thus perform better on the 1-mm vessel after having practiced once on the 3-mm vessel. Experienced trainees took less time to complete the 1- and 3-mm microanastomoses compared with nonexperienced trainees due to better understanding of the surgical equipment, smoother technique, and higher efficiency with needle insertion and knot tying. Our subjective rating scores correlated well with the NOMAT scale scores. However, even though it is commonly used in the evaluation of microsurgical performance, subjective rating does not provide trainees with constructive feedback as to what subskills they should improve. This fact justifies the need for a more objective assessment method that could provide the trainee with a baseline evaluation and with learning curves that could be used to efficiently direct training efforts. Focused training aimed at efficiently mending specific technical tasks (such as instrument positioning or a tying technique) is becoming increasingly essential, especially with the implementation of the resident hour regulations that include surgical training time as part of the 80-hour work week. Interestingly, our results have shown that postdoctoral research fellows, who underwent extensive training on the microanastomosis module, scored higher than senior residents. This observation highlights the importance of deliberate practice in neurosurgical training, especially if progress can be tracked in an objective fashion after every trial. Our assessment scale can potentially be taught to laboratory technicians who can provide constructive feedback to trainees. Additionally, videos of varying levels of performance can be posted on the web and accessed by all trainees. The feedback provided via a web-based methodology or a technician could potentiate deliberate practice. In his pioneering work on the acquisition of expert performance, Ericsson emphasized the importance of deliberate practice toward achieving and maintaining mastery. Kaufman and colleagues further stressed the importance of practice and repetition in psychomotor skill learning. In a randomized controlled evaluation of the performance of cardiothoracic surgery trainees on a microanastomosis module, Price et al. reported significantly better performance for trainees who underwent deliberate practice. The study highlighted the importance of deliberate practice in acquiring surgical skill and further stressed incorporating it into future simulation-based surgical curricula. A larger sample size or a multiinstitutional randomized controlled study may help further elucidate the importance of deliberate practice in neurosurgical training. Face validity of the microanastomosis module has been established based on the evaluation of 2 experienced vascular neurosurgeons (B.R.B. and H.H.B.). Although very subjective in nature, this type of validity is important to ensure that the module mimics reality closely, and that the overall feel of the procedure is not far from what is experienced in the actual operating theater. The surgical setting, instruments, and artificial vessels used in the microanastomosis module were all deemed to realistically recreate a bypass procedure. The purpose of our study was to provide neurosurgical residents and their mentors with a standardized tool that would enable them to assess their skill, pinpoint their technical weaknesses, and address them individually. We realize that even though this scale attempts to objectively rate performances by deconstructing complex tasks into simpler elements and general surgical principles, the Likert design that it follows does involve a minimal degree of subjective rater bias. Additionally, our scale did not detect significant differences between the performances of novices and experts using the 3-mm vessel. This may largely be due to the fact that our study population, even though inclusive of a large neurosurgery program, is still statistically small and underpowered. Repeating the study with multiple centers involved may provide more significant results. However, the goal of this study was to prove the feasibility of using the scale to detect differences in technical skill. Finally, we did not include faculty performances in the current study because the 2 main vascular neurosurgeons at our program were needed to direct resident testing and took part in designing the assessment scale, and were thus subject to the Hawthorne effect. The Hawthorne effect is the improvement of performance on a specific task based on a prior knowledge of what is being studied. Intra- and interrater reliability were not assessed in this study but will be evaluated in a separate study to show whether the NOMAT scale can produce similar results on repeated trials and among different raters.

Conclusions

A validated simulation curriculum is needed in the field of neurosurgery. We developed a validated bench module for the assessment of microsurgical performance of neurosurgical trainees. The scale differentiated between novice and expert performance and provided participants with a baseline score of their technical ability. Future efforts will need to focus on assessing interrater reliability and the impact of the scale and module on performance in the operating room. The assessment of interventions and varying educational strategies as well as the impact...
of deliberate practice on performance should be assessed as well. Multinstitutional cooperation will be necessary to achieve these goals.

Appendix

This article contains an appendix that is available only in the online version.

Acknowledgments

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References

34. Singh H, Kalani M, Acosta-Torres S, El Ahmadieh TY, Loya J, Ganju A: History of simulation in medicine: from Resuscit...


Author Contributions
Conception and design: Bendok, Aoun, El Ahmadieh, Batjer. Acquisition of data: Bendok, Aoun, El Ahmadieh, El Tecle, Daou. Analysis and interpretation of data: all authors. Drafting the article: Bendok, Aoun, El Ahmadieh. Critically revising the article: all authors. Reviewed submitted version of manuscript: all authors. Approved the final version of the manuscript on behalf of all authors: Bendok. Statistical analysis: Bendok, Aoun, El Ahmadieh, El Tecle. Administrative/technical/material support: Bendok, Aoun, Batjer. Study supervision: Bendok, Aoun, Batjer.

Supplemental Information
Previous Publication
Portions of this work were presented in abstract form at the 2013 Neurosurgical Society of America annual meeting at Sea Island, Georgia, on April 8, 2013.

Videos


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Northwestern Objective Microanastomosis Assessment Tool (NOMAT)
I. Operator positioning and posture.

1. Hunched back, twisted wrists, shrugged shoulders
   - Wide range of movements

2. Good posture and positioning at first but deteriorates by the end of the procedure
   - Rarely makes wide-range movements

3. Optimally ergonomic and relaxed posture
   - Economy of movements
   - Movement is confined to the wrists and fingers

Notes to the Evaluator:

This item is included to evaluate how natural the feel of using the microscope is to the participant. It is included to promote smooth and minimalistic movements and to focus on an ergonomically correct body posture that will allow the participant to spend hours at a time seated at work in the future.
II. Use of the surgical microscope

Notes to the evaluator:

This item is included to evaluate and promote familiarity with the microscope. It will assess the ability of the participant to optimally setup the microscope from the beginning of the operation. Since most of the work is done in a single plane, frequent re-adjustment and optimization are not necessary in this experiment and should be avoided.
III. Understanding of the surgical equipment

1. Repetitively uses the wrong instrument for the task.

2. Uses the correct instrument for the task most of the time. Quickly switches to the correct instrument after a mistake.

3. Perfect matching of instruments and tasks at hand. Knows the instruments well, and chooses according to the surgical need.

Notes to the evaluator:

This item is included to test the participant’s familiarity with the surgical instruments. Available instruments will include macro-and micro-instruments in order to confuse the participant. Errors that are repeated and that are not recognized should be judged harshly (1) while errors that are quickly rectified should be considered with more leniency (3).
IV. Handling of the surgical instruments

1. Repeatedly makes unnecessary passes or awkward moves with the instruments
   Superfluous movements

2. Competent use of instruments although occasionally appears stiff or awkward

3. Fluid and effortless movements with the instruments
   Economy of motion, with punctual and targeted movements

Notes to the evaluator:

This step is included to evaluate the participant’s dexterity when it comes to microscopic movements. Every motion should appear effortless, precise and straight to its intended target. Normal physiological tremor is not a factor that is evaluated in this step, but instead awkwardness, hesitation, and waste of motion.
V. Vessel handling and respect for tissue

1. Frequently damages the vessel by inappropriate use of force, with perforation or tearing of the wall
   Tearing of the vessel by inappropriate needle or instrument handling or during knot tying

2. Acceptable/occasional accidental damage that does not affect the structural integrity of the vessel but could theoretically promote thrombosis and/or intimal damage
   Rough movements at the anastomotic line during knot tying

3. Vessel almost intact at the end of the procedure
   Absence of movements that may promote intimal endothelial damage or thrombosis
   High handling proficiency

Notes to the evaluator:

This item is included to evaluate the awareness and the control of the participants when handling microvessels, and how carefully they manipulate endothelial membranes. Movements considered damaging to the endothelium include excessive stretching of the vessel, rough grabbing of the intimal layer, or excessive compression of the vascular wall. In brief, any action that may compromise endothelial health and promote thrombosis.
VI. Needle handling and care

1. Irreparable damage to the needle requiring a new suture thread to complete the anastomosis
2. The needle is moderately damaged and deformed but still functional
3. The needle is undamaged and undeformed at the end of the procedure

Notes to the evaluator:

This item is included to evaluate the participant’s control when using the micro-needle. Although microanastomosis on live patients usually uses multiple sutures, only one suture is allowed per anastomosis in this experiment.
VII. Needle bite uniformity

1. Needle bites are very uneven between the two edges of the anastomosis
   Needle bites are very irregular from suture point to suture point

2. Approximately 50% of needle bites are even and regular

3. All needle bites are even and regular

Notes to the evaluator:

This item is included to evaluate the uniformity of needle bites on both sides of the anastomotic line. Even and sufficient bites on both edges of the anastomosis will allow the correct apposition of the two vessels, while excessive and uneven bites may lead to kinking or torsion.
VIII. Spacing of the sutures

1. Constantly irregular intervals
   A suboptimal number of suture points is used to complete the anastomosis
   (more or less than 10-12 for 3mm and 6-8 for 1mm)

2. >50% of intervals are equal and regular but a suboptimal number of suture points are used to complete the anastomosis
   (more or less than 10-12 for 3mm and 6-8 for 1mm)

3. Intervals are equal
   The number of suture points is appropriate to vessel size and matches the recommended number of suture points to use (10-12 for 3mm and 6-8 for 1mm)

Notes to the evaluator:

This item is included to evaluate the uniformity of needle bites on both sides of the anastomotic line. Equidistant bites on both edges of the anastomosis (provided that the operator is using the recommended number of suture points for the selected vessel size) will allow the correct apposition of the two vessels, while excessive and uneven bites may lead to kinking or torsion.
IX. Knot tying

1. Knots are too loose and could potentially be undone
   - Knots are tight enough to cut through or shred the vessel
   - Wastes a lot of thread and requires multiple (>3 total) new suture threads to finish the anastomosis

2. Acceptable knot quality but uneven or irregular
   - The sutures are cut at an inappropriate length
   - Requires 1 additional suture thread to finish the anastomosis

3. Perfect square knots with good knot strength and tension
   - Appropriate suture length
   - Finished the entire anastomosis using only one suture thread

Notes to the evaluator:

This item is included to evaluate the control and the capacity of the participant to tie strong square knots without injuring the vessel in the process or wasting sutures.
X. Microsurgical efficiency with the needle

1. Many unnecessary moves
   - Multiple attempts needed to grasp the needle
   - Multiple passes required to successfully bite the tissue
   - Loses the needle frequently in the surgical field

2. Few unnecessary moves
   - Few attempts to successfully grasp the needle
   - Few passes are required to successfully bite the tissue

3. No wasted moves, grasps only once
   - Economy of movement and efficiency
   - Mostly single attempts/passes to successfully bite the tissue

Notes to the evaluator:

This item is included to assess the operator’s dexterity using the micro-needle. Emphasis should be placed on economy of time and motion, and ease of manipulation of the needle.
XI. Microsurgical efficiency with knot tying

1. Many unnecessary moves
   - Multiple attempts needed to grasp the suture and tie the knot
   - Multiple suture breaks or kinks from excessive force

2. Few unnecessary moves
   - Few attempts to successfully grasp the suture
   - Minimal breaks that do not impede knot tying

3. No wasted moves
   - Economy of movement and efficiency
   - Mostly single attempts/passes to successfully tie a knot

Notes to the evaluator:

This item is included to assess the operator’s dexterity using the micro-thread. Emphasis should be placed on economy of time and motion, and ease of manipulation of the thread specifically during knot-tying. Breaks in the nylon thread specific to this experiment are indicative of a use of excessive force, and can severely impede knot tying.
XII. Evaluation of the completed anastomosis- Off-pump

1. Severe vessel kinking, angulation, or torsion
   - Vessel completely deformed
   - Did not complete the anastomosis

2. No vascular torsion
   - Mild vessel kinking

3. Good anastomotic line
   - Anastomosis predicted to be functional

Notes to the evaluator:
This item is included to evaluate the general aspect of the anastomosis, and detect any structural imperfection that may be a predictor of suboptimal functioning.
XIII. Evaluation of the completed anastomosis- On-pump

1. Jet of fluid originating from between adjacent sutures
   - Profuse oozing without specific focus point
   - Vessel sewn shut: No flow

2. Moderate oozing without specific focus points

3. Slight oozing originating mostly from needle entry and exit points that would be controlled in vivo by the application of cotton

Notes to the evaluator:

This item is included to evaluate the tightness of the anastomotic line. Slight oozing is recognized as a good prognostic sign.
XIV. Evaluation of the completed anastomosis- Examination of the lumen

1. >70% lumen stenosis, Back wall caught by a suture point

2. 10% to 50% lumen stenosis Overlapping vessel edges with minimal compromise Free back wall

3. No considerable stenosis that would restrict the vessel and blood flow

**Notes to the evaluator:**

*This step is included to evaluate the patency of the anastomosis. After the anastomosis is completed, the vessel is dissected in a ring-like fashion to allow a look inside the lumen. Passive dilation using the jeweler pickups will also be attempted to demonstrate elasticity of the anastomotic region.*
<table>
<thead>
<tr>
<th>Decision</th>
<th>Pass:</th>
<th>Fail:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall grade on 100</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Notes to the evaluator:**

*Please provide a pass-fail judgment of the overall performance of the operator based on whether or not you believe the final product would be viable in vivo.*

*Please also provide an overall score for the operator’s performance*