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A Simulator Training Protocol for Endovascular Neurosurgery

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January 20th, 2020

Dear Dr. Steindel,

We are pleased to submit our revised manuscript titled: "A Simulator Training Protocol for Endovascular Neurosurgery," as an Invited Manuscript to *JoVE.*

We thank the reviewers for their time and effort. We are pleased they thought our work was "well-written", "essential", and "needed", and that the protocol was "a great addition to the literature on endovascular neurosurgery simulation". We have addressed all points raised during the review in the point-by-point response attached. All changes to the manuscript are tracked in the revised document.

Specifically, in response to reviewer comments we have provided significant additional procedural details to the simulation protocol. We have also expanded the methodological discussion of our previous work demonstrating the utility of this protocol for trainees in an academic setting, as well as updated the figures and tables based on reviewer comments.

As this revised work is one of the first to provide step-wise instructions for use of neuroendovascular training devices on three key endovascular neurosurgery procedures (diagnostic cerebral angiograms, mechanical thrombectomies, and aneurysm coil embolizations), we believe that this manuscript is now suitable for publication in *JoVE.* All authors have reviewed the revised manuscript, which has neither been published nor submitted elsewhere pending your review.

Thank you for your time and we look forward to your response.

Sincerely,

Scott Pannell, MD
Assistant Clinical Professor
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TITLE:

Simulator Training for Endovascular Neurosurgery

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KEYWORDS:
endovascular neurosurgery, simulator-based angiography, neurosurgical education, virtual reality, aneurysm coiling, mechanical thrombectomy

SUMMARY:
Simulation of complex, high-risk procedures is critical to the education of medical trainees. A protocol for simulator-based endovascular neurosurgery training in a controlled academic environment is described. The protocol includes stepwise guidelines for trainees of varying levels, with a discussion of the advantages and limitations of this model.

ABSTRACT:
Simulation-based training has become common practice across medical specialties, especially for learning complex skills performed in high-risk environments. In the field of endovascular neurosurgery, the demand for consequence- and risk-free learning environments led to the development of simulation devices valuable for medical trainees. The goal of this protocol is to provide instructive guidelines for the use of an endovascular neurosurgery simulator in an academic setting. The simulator provides trainees with the opportunity to receive realistic feedback on their knowledge of anatomy, as well as haptic feedback indicative of their success in handling the catheter-based systems without negative consequences. The utility of this specific protocol in relation to other neuroendovascular training modalities is also discussed.

INTRODUCTION:

Simulation-based training is an established educational tool for medical trainees and is particularly beneficial in high-risk fields such as endovascular neurosurgery. Multiple virtual reality training devices utilizing catheter-based systems exist, such as the ANGIO Mentor simulator (Simbionix Ltd., Airport City, Israel) and VIST-C and VIST G5 simulators (Mentice AB, Gothenburg, Sweden), with a significant body of data demonstrating the utility of training on procedural aptitude[1]. In spite of the usefulness of the simulators, step-by-step procedural instructions for their use are lacking.

Presented is a detailed protocol for the use of the ANGIO Mentor simulator, a system that supports competency improvements in common endovascular neurosurgery procedures, including diagnostic cerebral angiograms, mechanical thrombectomies, and aneurysm coil embolizations[2]. Prior work shows that after trainees of all levels performed five simulated angiograms, five thrombectomies, and ten aneurysm coil embolizations on the ANGIO Mentor simulator, they displayed significant improvements in procedural time, fluoroscopy and contrast doses, and adverse technical events[2].

The following step-by-step instructions are divided into case scenarios and can easily be integrated into an academic training curriculum for medical students, residents, or fellows[2]. It should nonetheless be noted that a basic understanding of cerebral arterial anatomy, angiography, and stroke and aneurysm treatments is needed to optimize the educational potential of the simulation device.

All procedures described below (e.g., diagnostic cerebral angiogram, coiling of carotid terminus aneurysm, mechanical thrombectomy) can be performed by a single operator using the ANGIO Mentor simulator (Simbionix Ltd.) (**Figure 1**). This training device allows neurosurgical trainees of all skill levels to gain exposure to endovascular techniques in a preclinical setting, with the three patient scenarios utilized based on a previously published curriculum for simulator-based angiography training[2]. To reproduce endovascular techniques with high fidelity, the simulator utilizes actual catheters and wires introduced through a port similar to the diaphragm of a femoral artery sheath. The wires and catheters engage internal rollers that record both rotational and translational motions, which are displayed on the monitors. Device selections and patient vital signs are also visible to the simulator operator.

PROTOCOL:

1. Simulator setup

1.1. Prior to all procedures, assemble the simulator as shown in **Figure 1** and turn on. Refer to **Table 1** for the full list of simulator equipment needed to complete each simulation.

1.2. Select the patient scenario using the software interface on the attached laptop (**Figure 1C**).

1.3. Select the appropriate arterial sheath size from the drop-down menu. This does not need to be physically inserted as part of the simulation, but will act as the femoral access site and allow subsequent entry of guidewires and catheters into the system (**Figure 1D**). Specific sheath sizes for each scenario are discussed below.

1.4. Select the appropriate catheter(s), guidewire, and/or microsystem based on the specific scenario as discussed below (**Figure 1D**).

1.5. Turn on A (PA) and B plane (lateral) fluoroscopy on the software interface. Activate the fluoroscopy with the foot pedals (**Figure 1H**) and adjust both the patient and image intensifier positions with the joysticks (**Figure 1I**) until the correct PA and lateral views are obtained.

2. First patient scenario: Four-vessel angiography

NOTE: This scenario depicts a 52-year-old male with an unruptured left carotid terminus aneurysm found incidentally on a non-contrast computed tomography (CT) of the head.

2.1. Select a 5-French femoral sheath, a 0.035 in guidewire, and a 4-French diagnostic catheter from the drop-down menu as tools to be used in this simulation.

2.2. Insert the guidewire into the simulator machine (**Figure 1D**) until it registers on the simulation screen, signaling that access has been gained. Advance the guidewire until it is visualized in the descending thoracic aorta and continues into the aortic arch.

2.3. When the guidewire is safely in the aortic arch, hold the guidewire in place and insert a diagnostic catheter over the guidewire through the simulated femoral sheath to the aortic arch.

2.4. Remove the guidewire and utilize the fluoroscopy puff technique by gently pressing the contrast syringe (**Figure 1E**) to simulate contrast injection and briefly opacify the vessels as the catheter is advanced into the desired artery.

2.4.1. Alternatively, create a roadmap guide by selecting the feature on the software interface (**Figure 1C**) and then injecting contrast with the contrast syringe (**Figure 1E**) while the fluoroscopy foot pedal is depressed (**Figure 1H**). Next, reinsert the wire to selectively catheterize the desired vessel, advancing the catheter over the wire. Remove the wire for subsequent angiography runs. The right and left internal and external carotid arteries and the left and right vertebral arteries are all catheterized using one of these techniques.

2.5. Using the diagnostic catheter and the simulator contrast syringe (**Figure 1E**), perform angiograms of each of the above circulations by depressing the fluoroscopy pedal (**Figure 1H**) while injecting contrast with the syringe. Obtain high-magnification views of the aneurysm, if necessary. Review angiograms for adequacy prior to removing the catheter.

2.6. Once the necessary images are obtained, remove the diagnostic catheter/guidewire from the simulation sheath. Simulated closure of the femoral arteriotomy site is not performed.

3. Second patient scenario: Carotid terminus aneurysm coiling

NOTE: This scenario depicts a 52-year-old male with a known ruptured left carotid terminus aneurysm, severe headache, nonfocal exam, and a Glasgow Coma Scale of 15. Head CT demonstrates a Fisher Grade II subarachnoid hemorrhage and no hydrocephalus.

3.1. Select a 7-French femoral sheath, 6-French guide catheter, 0.035 in guidewire, 4-French diagnostic catheter, microcatheter/microwire, and coils from the drop-down menu.

3.2. Insert a diagnostic catheter over a guidewire into the aortic arch as in steps 2.2–2.3.

3.3. Insert a guide catheter over the diagnostic catheter through the femoral access site (**Figure 1D**) to the aortic arch.

3.4. Remove the guidewire and create a roadmap guide of the left common carotid artery by selecting this feature on the software interface (**Figure 1C**) and injecting contrast with the contrast syringe (**Figure 1E**) while the fluoroscopy foot pedal (**Figure 1H**) is depressed.

3.5. Reinsert the guidewire and selectively catheterize the left common carotid artery and internal carotid artery using fluoroscopy and the roadmap overlay visualized on the image projection monitor (**Figure 1B**) by leading with the guidewire and advancing the diagnostic catheter and guide catheter once safe access is gained.

3.6. When the guide catheter is within the internal carotid artery, remove the diagnostic catheter and perform angiographic runs of the left internal carotid cerebral circulation by depressing the fluoroscopy pedal (**Figure 1H**) while injecting contrast with the syringe (**Figure 1E**).

3.7. Measure the aneurysm using the calculation option on the software interface (**Figure 1C**). Keeping in mind that the coil diameter for the first coil should be 1 mm wider than the maximum aneurysm diameter, select an appropriate coil.

3.8. Insert a microcatheter and microwire through the femoral access site (**Figure 1D**), and under roadmap guidance obtained as in step 3.6, selectively catheterize the aneurysm with the microsystem.

3.9. Remove the microwire, insert the previously selected coil through the femoral access site (**Figure 1D**), and advance it slowly into the aneurysm.

3.10. Once the coil is fully inserted, perform a diagnostic cerebral angiogram by depressing the fluoroscopy pedal (**Figure 1H**) while injecting contrast with the syringe and assess the patency of the parent artery and aneurysm filling. The goal is to maintain patency of the parent artery and either completely embolize the aneurysm or provide sufficient coverage of the dome or presumed rupture point to appropriately reduce rupture risk.

3.11. Detach the coil on the software interface (**Figure 1C**) and remove the coil wire. If necessary, repeat steps 3.11 and 3.12 with additional coils until ~30% aneurysm occlusion is obtained.

3.12. Remove the microcatheter and guide catheter from the simulation sheath site (**Figure 1D**). Simulated closure of the femoral arteriotomy site is not performed.

4. Third patient scenario: Left middle cerebral artery thrombectomy

NOTE: This scenario depicts a 64-year-old female with a National Institutes of Health Stroke Scale (NIHSS) score of 12 for aphasia and right-sided weakness who was last known to be normal 4 h earlier. Head CT revealed a hyperdense left middle cerebral artery (MCA) sign and an Alberta Stroke Program Early CT score (ASPECTS) of 10, but no hemorrhage. A CT angiogram demonstrated a left M1 segment complete occlusion.

4.1. Select a 7-French femoral sheath, 6-French guide catheter, an intermediate aspiration catheter (0.068 in), 0.035 in guidewire, 4-French diagnostic catheter, microcatheter/microwire, and a stent retriever device (4 x 40 mm) from the drop-down menu.

4.2. Insert the guide catheter into the left internal carotid artery and perform angiographic runs of the left internal carotid cerebral circulation as described in steps 3.2–3.6.

4.3. Insert a triaxial system (i.e., intermediate aspiration catheter, microcatheter, and microwire) into the simulated femoral access site (**Figure 1D**) and into the left internal carotid artery.

4.4. Under roadmap guidance obtained as in step 3.5, advance the microwire and microcatheter into the left MCA and carefully past the area of occlusion. Potential complications during this maneuver include vascular perforations and/or embolizing a clot downstream.

4.5. Remove the microwire and insert a stent retriever device into the simulated femoral access site (**Figure 1D**) and advance into the MCA distal to the occlusion. Then, remove the microcatheter, leaving the stent retriever in place at the level of the occlusion.

4.6. Advance the intermediate catheter to the level of the occlusion under fluoroscopy activated by the foot pedals (**Figure 1H**).

4.7. Turn on simulated aspiration on the software interface (**Figure 1C**), and partially or fully retract the stent retriever device into the intermediate catheter by pulling back on the microwire.

4.8. Remove both the stent retriever and intermediate catheter from the simulated femoral access site (**Figure 1D**).

4.9. Perform an angiogram through the guide catheter by depressing the fluoroscopy pedal (**Figure 1H**) while injecting contrast with the syringe to ensure removal of the occlusion.

4.10. Remove the microcatheter and guide catheter from the simulation sheath site (**Figure 1D**). Simulated closure of the femoral arteriotomy site is not performed.

REPRESENTATIVE RESULTS:

The ANGIO Mentor simulator was previously shown to improve the skills of surgical trainees with varying neuroendovascular experience when performing simulated diagnostic angiograms, thrombectomies, and ruptured aneurysm coil embolizations in an academic setting[2]. In this study, performance metrics for the aforementioned procedures were established over the course of 30 days in one medical student, one neurosurgery resident, two diagnostic neuroradiology fellows, and one endovascular neurosurgery fellow. After 120 minutes of didactic instruction and a single viewing of each procedure, the trainees performed 10 sessions of each procedure (i.e., 30 total). Procedural evaluations were performed by an experienced neurointerventional attending based on total procedural time, fluoroscopy time, contrast dose, frequency of technically unsafe events (e.g., movements with insufficient leading wire, rapid forward/non-visualized device movements, accidental vessel catheterizations, coil deployments outside of the aneurysm, and number of intraprocedural ruptures), packing densities, number of coils used, and number of stent retriever passes attempted.

Based on analysis of variance (ANOVA) and Tukey's Honest Significant Difference (HSD) testing, statistically significant improvements were seen among all participants in specific performance metrics for all three procedures, including contrast utilization, fluoroscopy time, and total procedural time (**Figure 2**), in addition to significantly increased Likert Scale scores, an evaluation gauge in which a score of 1 corresponds to failure and 5 corresponds to excellence based on procedural technique (**Figure 3**). Notably, training on diagnostic angiograms resulted in an 86% reduction in total procedure time, a 75% reduction in fluoroscopy time, a 68% reduction in contrast utilization, and a 64% improvement in the overall Likert Scale performance scale ($p < 0.05$ for all variables based on performance improvements in the first five angiograms). After mechanical thrombectomy simulation, trainees demonstrated a 35% reduction in total procedure time, a 41% reduction in fluoroscopy time, a 49% reduction in contrast utilization, and a 67% improvement in overall Likert Scale performance ($p < 0.05$ for all variables based on performance improvements in the first five procedures). Participants also showed statistically significant improvements in performance after simulated aneurysm coilings, with a 42% reduction in total procedure time, a 57% reduction in fluoroscopy time, a 21% reduction in contrast utilization, and a 58% improvement in Likert Scale score ($p < 0.05$ for all variables based on performance improvements in the first five procedures). A reduction in the occurrence of unsafe events was also seen across all scenarios. Based on these data, at our institution all neuroendovascular trainees perform five simulated angiograms, five simulated thrombectomies, and ten simulated aneurysm permanent coil embolizations (the higher number or embolizations based on the technical nuances of this procedure), prior to participating in a surgery with real neuroendovascular cases.

FIGURE AND TABLE LEGENDS:

Figure 1: ANGIO Mentor Simulator complete assembly. The setup for the ANGIO Mentor simulator includes the simulator housing (**A**); an external monitor for image projection (X-ray, angiography) (**B**); a laptop for interfacing with the Simbionix Software (**C**); the simulated femoral artery sheath with an outer guide catheter, inner diagnostic microcatheter, and guidewire shown (**D**); a contrast syringe (**E**); an insufflator for balloon inflation not used in these patient scenarios

(**F**); a stent delivery device not used in these patient scenarios (**G**); foot pedals for fluoroscopy, roadmap guidance, and angiographic runs (**H**); and the operator control panel on the simulator housing where the operator is able to control patient and image intensifier positioning (**I**). The image was obtained by the authors after setting up the simulator.

Figure 2: Performance evaluation represented as percent reduction in associated measured procedure metrics with simulator training. Sample size, n = 5 trainees, performing 10 simulations per procedure (Pannell, et al.)[2]. *$p < 0.05$ based on analysis of variance (ANOVA) and Tukey's Honest Significant Difference (HSD) testing.

Figure 3: Performance evaluation represented as percent improvement in overall Likert Scale Score with simulator training. Sample size, n = 5 trainees, performing 10 simulations per procedure (Pannell, et al.).[2] *$p < 0.05$ based on analysis of variance (ANOVA) and Tukey's Honest Significant Difference (HSD) testing.

Table 1: Materials used for each scenario.

DISCUSSION:

Endovascular surgery is an expanding field that offers a minimally invasive treatment approach to a variety of pathologies. The significant risks associated with vascular injuries nonetheless provides unique educational challenges. With advances in simulation-based training, the education of trainees now allows practice in a risk-free environment that mimics real-life cases. Accordingly, endovascular simulation-based training has been shown to consistently improve performance metrics such as procedure time, fluoroscopy time, and contrast volume in a wide range of participants (e.g., patients, medical students, residents, and surgeons)[1,3]. Commonly utilized simulation training systems include the ANGIO Mentor simulator (Simbionix Ltd., Airport City, Israel) and the VIST-C and VIST G5 simulators (Mentice AB, Gothenburg, Sweden).

Repetitive simulator training with the ANGIO mentor simulator allows for improvements in basic angiography/catheter skills as well as in performance metrics such as total procedure time, fluoroscopy time, contrast utilization, image quality, reduction in unsafe techniques, and overall Likert scale performance scores[2,4-6]. Improvements in such metrics previously reported were attained by following critical steps in the above protocol. Utilizing a stepwise approach, wherein diagnostic procedures are practiced first, allows for acquisition of the basic angiographic skills that are prerequisites for the performance of more complex procedures such as aneurysm coilings, thrombectomies, and embolizations of arteriovenous malformations (AVMs). Selection of the correct toolset is an additional important component of endovascular neurosurgery, and simulator-based learning of tool selection allows trainees to gain practice in material selection in parallel to technical learning.

Advantages of the ANGIO mentor simulator include its accuracy when performing procedural sequences, starting from the initial selection of tools to the use of simulated aspiration catheters and stent retrievers to provide both a visual and tactile educational experience. Additionally, although outside of this protocol, when poor angiographic technique is used, simulated complications that may require additional procedural steps, such as arterial dissections or aneurysm ruptures, can occur. Patient-specific data can also be uploaded to the ANGIO mentor via the PROcedure Rehearsal Studio, allowing the user to rehearse a procedure prior to its real-world performance. Other training systems nonetheless have similar educational value despite minor variations in their specific technical capacities[6-8]. For example, the VIST®-C and VIST® G5 simulators from Mentice also offer training on a variety of cerebrovascular pathologies; the ability to cause and manage complications such as arterial dissections, vasospasm, and aneurysm ruptures; and uploading of patient-specific data. The utility of this system as compared to traditional in vivo clinical training for teaching carotid angiography to experienced non-neurointerventionalists was demonstrated in a prospective, randomized, and blinded trial[8].

An important technical component of endovascular neurosurgery is a refined tactile sense to avoid vessel wall dissections and perforations. In parallel to ongoing research into the development of early warning systems for dangerous levels of force buildup at the catheter tip[9], haptic feedback is an important but challenging aspect of endovascular neurosurgery simulation. While the ANGIO mentor simulator includes a haptic feedback system that is linked to complications with poor technique or use of excessive force, the tactile fidelity of this system does not completely replicate the real-world experience. Other potential future improvements of the ANGIO mentor simulator include the addition of performance metrics for procedures of higher complexity, such as stent-assisted embolectomies of tandem occlusions and the addition of liquid embolization techniques.

Given its relatively high cost, difficulties in obtaining the ANGIO Mentor simulator or other simulator platforms outside of large academic centers or in developed nations potentially limits the widespread applicability of this protocol. This protocol is nonetheless likely to be very useful for senior medical students, residents, or endovascular neurosurgery trainees with a baseline knowledge of cerebrovascular anatomy and common interventional devices or procedures who generally have an academic affiliation.

Future areas of study with this technology include correlating simulator performance metrics with the real-life technical performance of diagnostic cerebral angiograms, mechanical embolectomies, and aneurysm coil embolizations, as well as patient outcomes. The use of simulation platforms for procedural competence assessments for interventionalist credentialing has also been suggested, although variability in technical discrimination between users of differing experience levels suggests further study is needed prior to utilization of simulators in this setting[10].

ACKNOWLEDGMENTS:
The authors thank all the clinical teams contributing daily to the care of neurovascular patients at UCSD.

DISCLOSURES:
AAK has previously received competitive grants from Covidien Ltd. and Penumbra Inc. and holds consulting arrangements for physician training with Stryker Neurovascular, Covidien Ltd., and

Penumbra Inc. JSP has served as a medical consultant to Stryker Neurovascular and Dart NeuroScience LLC. AAK and JSP have no direct financial interests related to this work. The remaining authors have no disclosures concerning the materials or methods used in this study or the findings specified in this paper.

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Figure 1

Figure 2

Click here to access/download;Figure;Figure 2.jpg

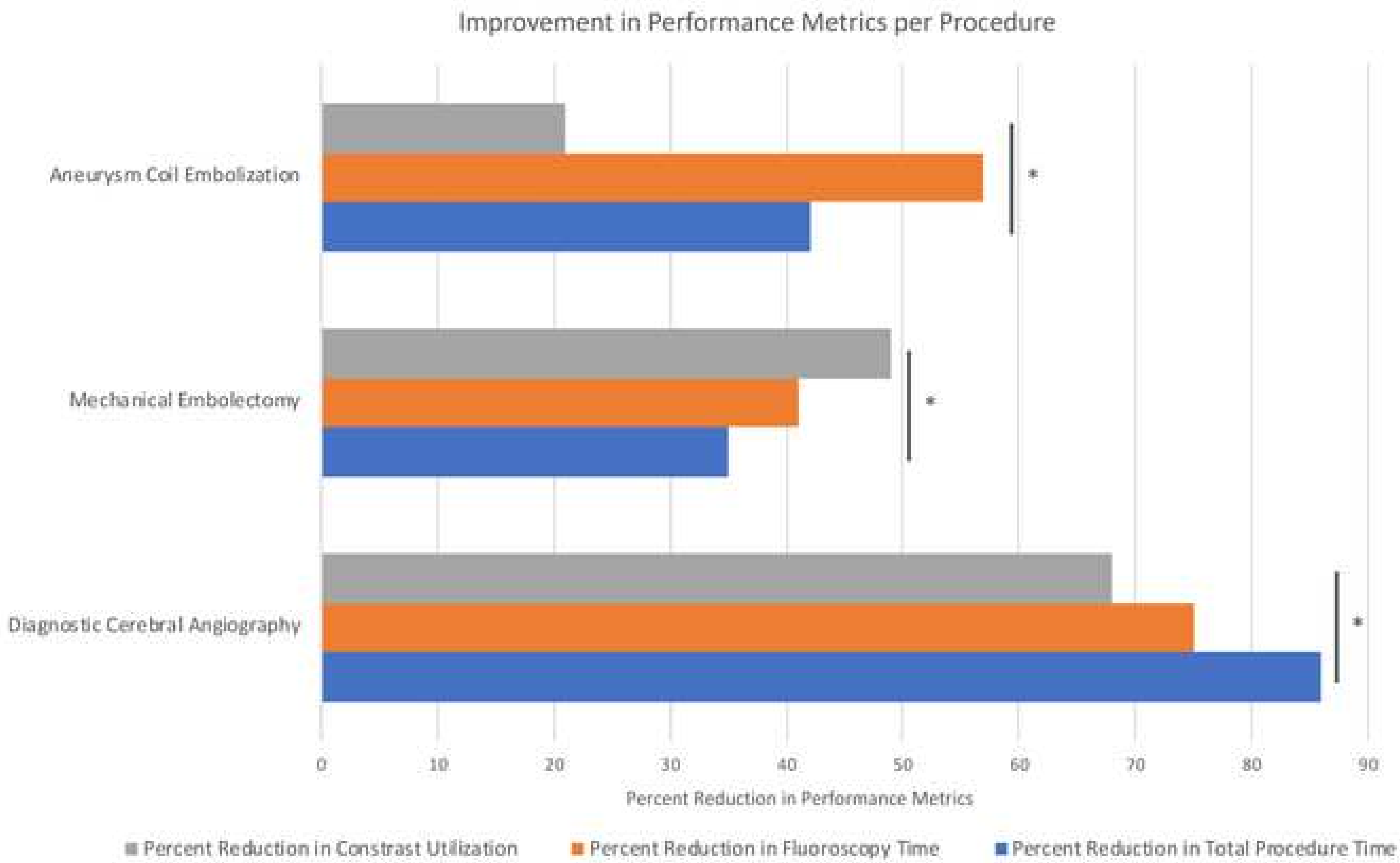

Figure 3

Click here to access/download;Figure;Figure 3.jpg

Patient Scenario #1
1) 5-French femoral sheath
2) 0.035 inch guidewire
3) 4-French diagnostic catheter

Patient Scenario #2
1) 7-French femoral sheath
2) 0.035 inch guidewire
3) 4-French diagnostic catheter
4) 6-French guide catheter
5) Microcatheter/microwire
5) Coils

Patient Scenario #3
1) 7-French femoral sheath
2) 0.035 inch guidewire
3) 4-French diagnostic catheter
4) 6-French guide catheter
5) 0.068 inch intermediate aspiration catheter
6) Microcatheter/microwire
7) 4x40 mm stent retriever device

Name of Material/ Equipment	Company	Catalog Number
ANGIO Mentor simulator	Simbionix Ltd., Airport City, Israel	N/a

Comments/Description

The setup for the ANGIO Mentor simulator includes the simulator housing as pictured in Figure 1: (A), an external monitor for image projection (x-ray, angiography; B), a laptop for interfacing with the Simbionix Software (C), the simulated femoral artery sheath (with an outer guide-catheter, inner diagnostic microcatheter and guidewire shown; D), a contrast syringe (E), an insufflator for balloon inflation (F), a stent delivery device (G; not used in these patient scenarios), foot pedals for fluoroscopy, roadmap guidance, and angiographic runs (H), and the operator control panel on the simulator housing where the operator is able to control patient and image intensifier positioning (I).

Response to Reviewers:

The authors appreciate the time of the reviewers and their efforts in improving our manuscript. We are pleased they thought our work was “well-written”, “essential”, and “needed”, and that the protocol was “a great addition to the literature on endovascular neurosurgery simulation”. We have addressed all points raised during the review in the point-by-point response below. All changes to the manuscript are tracked in the revised document. Thank you for your continued consideration of our manuscript.

Editorial comments:

General:

1. Please take this opportunity to thoroughly proofread the manuscript to ensure that there are no spelling or grammar issues.

The authors thank the editor for this comment. The manuscript has been thoroughly proofread for spelling and grammar issues.

2. Please include at least 6 key words or phrases.

The authors thank the editor for this suggestion. Key words have been edited to include six phrases - endovascular neurosurgery, simulator-based angiography, neurosurgical education, virtual reality, aneurysm coiling, mechanical thrombectomy.

3. I understand the use of the ANGIO Mentor simulator is important for this protocol; however, please reduce the amount of times commercial language (including Simbionix) is used in the text, particularly in the Abstracts.

The authors thank the editor for this helpful recommendation. The use of commercial language has been reduced throughout the paper.

Protocol:

1. For each protocol step/substep, please ensure you answer the “how” question, i.e., how is the step performed? Alternatively, add references to published material specifying how to perform the protocol action. If revisions cause a step to have more than 2-3 actions and 4 sentences per step, please split into separate steps or substeps.

The authors thank the editor for this helpful comment. We have significantly increased the granularity of the procedural steps listed in this protocol, and broken out longer substeps when appropriate.

Results:

1. You say the differences are ‘statistically significant’-what statistical tests were done and what were their results?

The authors thank the editor for this helpful comment. We have significantly increased the methodological description of our prior study in the representative results section. Specific statistical tests performed included analysis of variance (ANOVA) and Tukey’s Honest Significant Difference (HSD) testing for all significant data reported.

References:

1. Please include at least 10 references.

2. Please do not cite product websites-all relevant information should be in the main text and/or Table of Materials.

3. Please do not abbreviate journal titles.

The authors thank the editor for these comments. The references have been updated to remove product websites, include 10 references, and list the full journal titles.

Table of Materials:
1. Please ensure the Table of Materials has information on all materials and equipment used, especially those mentioned in the Protocol.

The authors thank the editor for this helpful comment. The ANGIO Mentor simulator is the kit that includes the tools listed in the protocol. We have nonetheless updated the table of materials to include all of the materials and equipment needed that comes with this kit in the comments/description portion of the table.

Reviewers' comments:
Reviewer #1:
The manuscript is well written and describe the protocol for endovascular training on simulators. The topic is essential and is needed to have a standardized training methods

The authors thank the reviewer for their time and their positive review of our work.

Reviewer #2:
Manuscript Summary:
This work is well written. I have tried similar machine and it is very useful. This manuscript can be accepted.

The authors thank the reviewer for their effort in reviewing our manuscript, and for their approval of our protocol.

Reviewer #3:
Manuscript Summary:
This is a great addition to the literature on endovascular neurosurgery simulation! At my institution, one of the greatest barriers to using our simulators for more frequent training is the lack of clear protocols for working the machinery without the help of a trained technician. Having a protocol like yours would really expand access to the simulator across trainee levels. To improve the quality of your manuscript, I have several suggestions that would make the protocol more accessible/easy to use.

The authors thank the reviewer for their significant suggestions for improving our manuscript. A point-by-point response to all reviewer suggestions is provided below.

Major Concerns:
1. In line 81 on page 2, you state that users must "select the appropriate arterial sheath size." To aid the clarity of the protocol, it would be helpful if you stated the size of the sheath that your group used in these experiments. Additionally, it should be mentioned if the same sheath size was used in all three scenarios. If not, the size for each scenario should be stated. If a medical student were to use your protocol, I doubt they'd have any clue what size sheath to use.

The authors thank the reviewer for this helpful suggestion. In the initial background protocol it is now specified that the selection of the appropriate catheter(s), guidewire, and/or microsystem is based on the needs of each of the patient scenarios, with the specific tools and sizing now discussed in the beginning of each patient scenario.

2. In the same vein as comment 1, it would be helpful to know the specifications of the sheaths, guidewires, microsystems, and other catheter equipment that your group used for each scenario. This should all be included in the protocol portion of the manuscript. In addition, it would be helpful if you had a table in the manuscript that listed all the required equipment for each scenario. This way, trainees can use your protocol to gather the proper supplies before doing simulations.

The authors thank the reviewer for this additionally helpful suggestion. As stated above, in the initial background protocol it is now specified that the selection of the appropriate catheter(s), guidewire, and/or microsystem is based on the needs of each of the patient scenarios. The specific tools and their sizing is now discussed in the beginning of each patient scenario and provided in a separate table.

3. The legends for figures 2 and 3 do not adequately explain what the viewer is looking at. There are no error bars, p-values, sample sizes, or any discussion of the statistical tests used to determine significance. These should be included in the figures and their respective legends so that the reader can determine for themselves the validity of the results. You should also discuss what software was used for the statistical analysis (Microsoft excel, stata, etc.). In addition, P-values should be included in the body of the manuscript for every result you discuss. This is extremely important for all published research. Without these, no work that reports results is publishable.

The authors thank the reviewer for this helpful comment. We have included the statistical methodology for all reported data, as well as the p values. We nonetheless highlight that the current manuscript is only providing the protocol used, and the data reported is a summary of our previously published work.[1] This has been clarified in the representative data section, as well as in the figure legends.

Minor Concerns:
4. Who is operating the simulator in this protocol (ie. running the roadmaps, turning on the aspirator etc.)?

The authors thank the reviewer for this helpful comment. We have clarified in the initial protocol description that all procedures described (diagnostic cerebral angiogram, coiling of carotid terminus aneurysm, mechanical thrombectomy) are performed by a single operator. This training protocol thus allows neurosurgical trainees of all skill levels to gain exposure to endovascular techniques in a pre-clinical setting.

5. It would be helpful in the protocol if you cited figure 1 when referencing different parts of the simulator. For instance, in line 85 when you refer to the foot petals, you should cite Figure 1H.

The authors thank the reviewer for this helpful suggestion. We have added citations to the figure throughout the protocol to assist the reader.

6. For the utilization of the contrast features of the Simbionix ANGIO mentor, it'd be nice if you explained how that feature works on your system in a way that a trainee could operate it without the help of a technician. I've never operated the fluoro on that particular system, so I apologize if its more straightforward than I realize.

The authors thank the reviewer for this suggestion. In the protocol for the 1st patient scenario we describe in more detail how the contrast/angiography features work with the simulator. This is also explained in subsequent patient scenarios as needed.

7. Can you comment on whether any trainees experienced major complications during their simulations (dissections etc.) and how the frequency of these changed before and after the protocol?

The authors thank the reviewer for this helpful comment. We have clarified in the representative results section technically unsafe events (including movements with insufficient leading wire, rapid forward/non-visualized device movements, accidental vessel catheterizations, coil deployments outside of the aneurysm, and number of intraprocedural ruptures) were recorded in the performance metric. We also clarify that a reduction in the occurrence of unsafe events was seen across all scenarios, as reported in our prior work.[1]

8. It should be stated in the text when the comparisons were made between procedure results. Were they between the 10th procedure and the 1st procedure? Days 1 and 30?

The authors thank the reviewer for this comment. We have clarified in the text of the representative results that the comparisons were made between the 1st and 5th procedure, and the 6th and 10th procedure. While improvements were seen at both of these time intervals, only changes between the 1st and 5th procedure reached statistical significance.[1]

9. I just want to make sure that you're using images of the Symbionix ANGIO Mentor with the permission of Symbionix. If you received permission, then please state so in the figure legend or the acknowledgements. If not, please cite the source of your image in the figure legend.

The authors thank the reviewer for this comment. The image of the simulator used at our institution was obtained by the authors after complete setup. As stated in the disclosures, the authors have no direct financial interests related to this work

10. Finally, you cite two papers to discuss how simulated endovascular neurosurgeries improve trainee skill and one of them is from your group. Since this is the crux of the paper, it'd be nice for the reader if you could cite other groups' work on this same (or a similar) topic for external validity.

The authors thank the reviewer for this comment. The purpose of the work is to provide a step-by-step training protocol for users desiring to obtain endovascular neurosurgery training in a simulated setting. Although we feel that proving the utility of this training in a rigorous manner is outside the scope of this work, we extensively cite our prior work that provides support for the improvement in user skills when completing this training protocol.[1] The discussion has also been update to cite multiple other works wherein use of the same and different simulators resulted in improvement of neuro-angiographic skills.[1-6]

Reviewer #4:
Manuscript Summary:
The AAs describe their protocol for using the Simbionix ANGIO mentor simulator for endovascular neurosurgery training in a controlled academic environment.

The authors thank the reviewer for their assessment of our manuscript. A point-by-point response to all reviewer suggestions is provided below.

Major Concerns:
Despite the topic of simulators is surely an hot topic of great interest for the neurosurgical community it was very difficult for me to understand the kind of contribution that the AAs want to give with this manuscript. It seemed to me that the purpose of the AAs was to provide guidelines for

the use of their simulator. However it was very difficult for me to understand how these guidelines were obtained. Was the simulator used by interventional radiologists with a specific experience in the procedures that are described? With what results? In other words what was the feedback obtained by experts? How did they perform on the simulator and how their performances could be evaluated? How much the simulator was found by experienced interventional radiologists to provide a realistic experience? The reader cannot understand how much realistic is the simulation experience of trainees and it appears also difficult to understand how the contribution given by the simulation to the learning curve of trainees was evaluated. It is unclear how performances of trainees were measured and how Likert scale performance score was obtained. It appears difficult to replicate the results of the study since the aim of the study are not made clear enough as well as the methods that were used to reach the aim are not clearly explained. It seems impossible to try to replicate this study elsewhere due to this lack of clarity in the study design, aims and methods.

The authors thank the reviewer for their comprehensive review of our work and suggestions for improvement. As detailed in our responses to other reviewers, we have significantly revised the manuscript to provide context for the data reported from our previously published work.[1] As the current manuscript is a technical protocol without new data, however, we have attempted to summarize our methodology and findings from this prior work in an efficient manner. Specifically, we have added details in the representative results section on the training protocol (personnel, number of repetitions per scenario, etc), performance evaluations, and statistical analyses used, as well as clarified the statistical significance of our prior findings.

The way Table 2 and 3 were obtained should be better explained and the full paper should be rewritten with a specific description of the scientific method that was employed to reach a specific aim.

The authors thank the reviewer for this helpful suggestion. The legends for Figures 2 and 3 have been updated to include the statistical methodology used as well as the p values for this previously reported data.[1] We again highlight that the current manuscript is nonetheless only providing the protocol used, and the data reported is a summary of our previously published work.[1] This has been clarified in the representative data section, as well as in the figure legends.

Minor Concerns:
Tables must be accompanied by a clear description of how data were obtained and should be interpreted.

The authors thank the reviewer for this helpful comment. As stated in response to the comment above, we have updated the figure legends to improve the clarity of the represented data.

References:

1 Pannell, J. S. *et al.* Simulator-Based Angiography and Endovascular Neurosurgery Curriculum: A Longitudinal Evaluation of Performance Following Simulator-Based Angiography Training. *Cureus*. **8** (8), e756, doi:10.7759/cureus.756, (2016).

2 Spiotta, A. M. *et al.* Diagnostic angiography skill acquisition with a secondary curve catheter: phase 2 of a curriculum-based endovascular simulation program. *Journal of Neurointerventional Surgery*. **7** (10), 777-780, doi:10.1136/neurintsurg-2014-011353, (2015).

3 Spiotta, A. M., Rasmussen, P. A., Masaryk, T. J., Benzel, E. C. & Schlenk, R. Simulated diagnostic cerebral angiography in neurosurgical training: a pilot program. *Journal of Neurointerventional Surgery*. **5** (4), 376-381, doi:10.1136/neurintsurg-2012-010319, (2013).

4 Fargen, K. M. *et al.* Experience with a simulator-based angiography course for neurosurgical residents: beyond a pilot program. *Neurosurgery*. **73 Suppl 1** 46-50, doi:10.1227/NEU.0000000000000059, (2013).

5 Fargen, K. M. *et al.* Simulator based angiography education in neurosurgery: results of a pilot educational program. *Journal of Neurointerventional Surgery*. **4** (6), 438-441, doi:10.1136/neurintsurg-2011-010128, (2012).

6 Cates, C., Lönn, L. & Gallagher, A. G. Prospective, randomised and blinded comparison of proficiency-based progression full-physics virtual reality simulator training versus invasive vascular experience for learning carotid artery angiography by very experienced operators. *BMJ Simulation and Technology Enhanced Learning.* **2**, 1-5,(2016).